Vidya Jyothi Institute of Technology

An Autonomous Institution

(Accredited by NAAC, Approved by AICTE New Delhi & Permanently Affiliated to JNTUH)

Aziz Nagar Gate, C.B. Post, Hyderabad-500 075

DEPARTMENT OF ELECTRICNGAL & ELECTRONICS ENGINEERING

Course Name : **COMPUTER METHODS IN POWER SYSTEMS**

Course Designation : **CORE**

Prerequisites : **NETWORKS AND POWER SYSTEMS**

Year & Sem : **III B Tech – II Semester**

Course Coordinator

Dr.C.N.Ravi
Professor
EEE Dept

C.N. Ravi

HOD/EEE

Head of the Department
Department of Electrical & Electronics Engg
Vidya Jyothi Institute of Technology
HYDERABAD-500 075.

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COURSE FILE INDEX

1. Vision and Mission of Institution
2. Vision and Mission of Department
3. PEOs, POs, PSOs
4. Academic Calendar
5. Syllabus
6. Course objectives and course outcomes
7. Cos Mapping with Pos and PSOs
8. Time table
9. Lesson Plan
10. Course delivery Plan and Record of Class work
11. Student list
12. Assignment I and II (CO, PO, BL) (please enclose two sample copies)
13. Mid I , MID-II Questions paper (CO , PO , BL)
14. Previous End semester Question papers
15. Content Beyond Syllabus MAPPING WITH Pos and PSOs
16. Teaching Learning Methods
17. Course Assessment/Attainment(Direct Attainment)
18. Course End Survey (Indirect Attainment)
19. Course closure report
20. Course Material

Course Faculty

HOD/EEE

Head of the Department
Department of Electrical & Electronics Engg
Vidya Jyothi Institute of Technology
HYDERABAD-500 075,

PRINCIPAL
Vidya Jyothi Institute of Technology
Himayatnagar (Vill), C.B. Post.,
Hyderabad-75.

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Vision of the Institution

- To develop into a reputed Institution at National and International level in Engineering, Technology and Management by generation and dissemination of knowledge through intellectual, cultural and ethical efforts with human values.
- To foster Scientific temper in promoting the world class professional and technical expertise.

Mission of the Institution

- To create state-of-the-art infrastructure facilities for optimization of knowledge acquisition.
- To nurture the students holistically and make them competent to excel in the global scenario.
- To promote R&D and consultancy through strong industry-institute interaction to address the societal problems.

Name of the Faculty: Dr.C.N. Ravi **Designation:** Professor

Program me & Regulation : R18 **Academic Year:** 2020-21

Course Code: A17231 Course Name: COMPUTER METHODS IN POWER SYSTEMS

Credits: 03

Department: EEE **Year** III **Semester** II

Vision of the Department

- To become a reputed department in the impartation of professional and technical expertise in the field of Electrical and Electronics Engineering.

Mission of the Department

- Imparting Quality Technical Education by provision of state-of-the-art laboratories.
- Preparing the students to think innovatively and find effective solutions to address engineering and societal problems with a multi-disciplinary approach maintaining continuous industry interaction
- Encouraging team work and preparing the students for lifelong learning with ethical responsibility for a successful professional career.

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Programme Educational Outcomes (PEOs)

PEO1: Equip graduates with a sound foundation in mathematics, science and engineering fundamentals, necessary to build a prospective career.

PEO2: Graduates will excel in giving solutions to real-time problems through technical expertise and operational skill set in the field of Electrical Engineering.

PEO3: Graduates will act with integrity in catering the need-based requirements blended with ethics and

Programme Outcomes (POs)

Engineering Graduates will be able to:

1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

2. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

Program Specific Outcomes (PSOs)

PSO1: Conceptualize electrical and electronics systems, employ control strategies for power electronics related applications to prioritize societal requirements.

PSO 2: Apply the appropriate techniques and modern engineering hardware and software tools in electrical engineering to engage inmulti-disciplinary environments

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Assessment Plan

S.No.	Test/Examination	Units/ Topics Covered	COs covered	Proposed Date	Maximum Marks
1	Assignment I	Unit-1,Unit-2 and Unit-3 (Half)	CO1,CO2,CO3	6/2/2020	5
2	Mid I	Unit-1,Unit-2 and Unit-3 (Half)	CO1,CO2,CO3	25/09/2020	20
3	Assignment II	Unit-3(Half),Unit-4 and Unit-5	CO3,CO4,CO5	9/4/2020	5
4	Mid II	Unit-3(Half),Unit-4 and Unit-5	CO3,CO4,CO5	01/03/2021	20

Direct Assessment (Internal Examination & External Examination)	Indirect Assessment (Course End Survey)
2.25	2.83

C.N. Bri

Course Faculty **Course Co-Ordinator** **HOD**

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B.Tech II & III Year Revised Academic Calendar for the Academic Year 2020-21

FIRST SEMESTER		**Commencement of Class Work 17.07.2020**	
	FROM	**TO**	**DURATION**
I Spell of Instructions (Online)	17.07.2020	09.10.2020	12 WEEKS
Mid -II & End Semester Examinations of Previous Semester	14.10.2020	12.11.2020	5 WEEKS
Practical Examinations of Previous Semester	16.11.2020	21.11.2020	1 WEEK
Revision of Syllabi of Current Semester	23.11.202	05.12.2020	2 WEEKS
Betterment Examinations of Previous Semester	02.12.2020	05.12.2020	4 DAYS
I Mid Examinations of Current Semester	07.12.2020	15.12.2020	1 WEEK
Practical Classes of Current Semester	16.12.2020	19.12.2020	4 DAYS
II Spell of Instructions (Online)	21.12.2020	20.02.2021	9 WEEKS
Practical Examinations	24.02.2021	03.03.2021	1 WEEK
II Mid & End Semester Examinations	05.03.2021	22.03.2021	2 WEEKS
Betterment Examinations	24.03.2021	27.03.2021	4 DAYS
SECOND SEMESTER		**Commencement of Class Work 30.03.2021**	
I Spell of Instructions	30.03.2021	22.05.2021	8 WEEKS
I Mid Examinations	24.05.2021	29.05.2021	1 WEEK
II Spell of Instructions	31.05.2021	24.07.2021	8 WEEKS
II Mid Examinations	26.07.2021	31.07.2021	1 WEEK
Practical Examinations	02.08.2021	07.08.2021	1 WEEK
Betterment Examinations	09.08.2021	12.08.2021	4 DAYS
End Semester Examinations	13.08.2021	28.08.2021	2 WEEKS

COE **DEAN EXAMS.** **DIRECTOR**

B. Tech. EEE III Year II Semester

L	T	P	C
3	0	0	3

COMPUTER METHODS IN POWER SYSTEMS

Prerequisites: Power Systems-I, Power Systems –II, Electrical Circuit Theory and Mathematics
Course Objectives: Upon completion of the course students will be able to

- formulate Y-bus and Z-bus matrices
- apply computer methods for analysis of any general power transmission system
- conduct investigations of short circuits of any general power transmission system
- analyze stability of power system

Course Outcome:

CO1: Demonstrate the knowledge and ability to develop Y-bus and Z-bus matrices.
CO2: Know the importance of load flow studies and its importance.
CO3: Analyze various types of faults in power systems.
CO4: Assess Steady state stability in power systems.
CO5: Determine the transient state stability.

UNIT I: POWER SYSTEM NETWORK MATRICES

Graph Theory: Definitions, Bus Incidence Matrix, Y-bus formation by Singular Transformation Methods and Direct Inspection methods, Numerical Problems.

FORMATION OF Z-BUS: Partial network, Algorithm for the Modification of Z-bus Matrix for addition element for the following cases: Addition of element from a new bus to reference, Addition of element from a new bus to an old bus, Addition of element between an old bus to reference and Addition of element between two old busses (Numerical Problems). Modification of Z-bus for the changes in network (Problems).

NIT II: POWER FLOW STUDIES

Necessity of Power Flow Studies – Data for Power Flow Studies – Derivation of Static load flow equations, classification of Buses and their relevance to Power Flow.**LOAD FLOW SOLUTION USING GAUSS SEIDEL METHOD:** Acceleration Factor, Load flow solution without and with P-V buses, Algorithm and Flowchart. Numerical Load flow Solution for Simple Power Systems (Max. 3-Buses): Determination of Bus Voltages, Injected Active and Reactive Powers (Sample One Iteration only) and finding Line Flows/Losses for the given Bus Voltages.

NEWTON RAPHSON METHOD IN RECTANGULAR AND POLAR CO-ORDINATES FORM: Load Flow Solution without and with PV Busses- Derivation of Jacobian Elements, Algorithm and Flowchart (Max. 3-Buses)

DECOUPLED AND FAST DECOUPLED METHODS: Comparison of Different Methods – DC load Flow.

UNIT III SHORT CIRCUIT ANALYSIS

PER-UNIT SYSTEM OF REPRESENTATION: Per-Unit equivalent reactance network of a three phase Power System, Numerical Problems.Needs and assumptions for short circuit analysis

SYMMETRICAL FAULT ANALYSIS: Short Circuit Current and MVA Calculations, Fault levels, Application of Series Reactors, Numerical Problems.

SYMMETRICAL COMPONENT THEORY: Symmetrical Component Transformation, Positive, Negative and Zero sequence components: Voltages, Currents and Impedances.Sequence Networks: Positive, Negative and Zero sequence Networks, Numerical Problems.

UNSYMMETRICAL FAULT ANALYSIS: LG, LL, LLG faults without and with fault impedance, Numerical Problems.

UNIT IV STEADY STATE STABILITY ANALYSIS

lementary concepts of Steady State, Dynamic and Transient Stabilities. Description of Steady State Stability Power Limit, Transfer Reactance, ynchronizing Power Coefficient, Power Angle Curve and Determination of Steady State stability and methods to improve steady state stability.

UNIT V TRANSIENT STABILITY ANALYSIS

Derivation of Swing Equation. Determination of Transient Stability by Equal Area Criterion, Application of Equal Area Criterion, Case study – sudden loss of parallel lines, Critical Clearing Angle Calculation- Solution of Swing Equation: Point-by-Point Method. Methods to improve Stability - Application of Auto Reclosing and Fast Operating Circuit Breakers.

TEXT BOOKS:

1. Power System Analysis, Dr.N.V.Ramana, Pearson Education India, 2011.
2. Computer methods in power system analysis, Stagg and EL-Abiad, Mc-Graw hill, 1987
3. Modern Power System Analysis – by I.J.Nagrath&D.P.Kothari, Tata McGraw-Hill Publishing Company, 4th edition.

REFERENCE BOOKS:

1. Power System Analysis, A. Nagoorkani, RBA Publications, 3rd edition
2. Power System Analysis and Stability, S.S. Vadhera, Khanna Publications
3. Power System Analysis, Hadi Saadat, Tata McGraw Hill,2002.
4. Power System Analysis by J.J. Grainger and W.D. Stevenson, McGraw Hill,2016
5. Computer techniques and models in power systems, By K.Uma Rao, I.K.International, 2010
6. Computer Techniques in Power System Analysis by M.A.Pai, TMH Publications,1979
7. Power System Analysis, Grainger and Stevenson, Tata McGraw Hill.

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DEPARTMENT OF ELECTRICNGAL & ELECTRONICS ENGINEERING

Course Name: Computer Methods in Power Systems

Course Objectives

- Formulate Y-bus and Z-bus matrices
- Apply computer methods for analysis of any general power transmission system
- Conduct investigations of short circuits of any general power transmission system
- Analyze stability of power system

Course Outcome

CO1	Demonstrate the knowledge and ability to develop Y-bus and Z-bus matrices.
CO2	Know the importance of load flow studies and its importance.
CO3	Analyze various types of faults in power systems.
CO4	Assess Steady state stability in power systems.
CO5	Determine the transient state stability.

COMPUTER METHODS IN POWER SYSTEMS

Course Outcomes: At the end of the course the student will be able to:

CO1	Compute Y-bus and Z-bus matrices
CO2	Apply the concepts of load flow studies in power systems.
CO3	Analyze faults using for unit system
CO4	Examine steady state stability of power system.
CO5	Investigate transient stability of power system.

ProgramMatrix

	Program Outcomes(POs)												PSOs	
COs	DomainSpecific POs					DomainIndependent Pos								
	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2
CO1	3	3	2	2	2	-	-	-	-	-	-	2	2	-
CO2	3	3	3	3	2	-	-	-	-	-	-	2	2	-
CO3	3	3	3	3	2	-	-	-	-	-	-	2	3	-
CO4	3	3	3	3	2	-	-	-	-	-	-	2	3	-
CO5	3	3	3	3	2	-	-	-	-	-	-	2	3	-
	3	3	2.8	2.8	2	-	-	-	-	-	-	2	2.6	-

COs - POs and COs - PSOs Justification

COs	POs	Level	Description
CO1	**PO1**	**3**	Highly correlated as graph theory and formation of network matrices explains knowledge of mathematics and engineering fundamentals.
CO1	**PO2**	**3**	Highly correlated as computation of network matrices analyzes complexity of power systems engineering problem.
CO1	**PO3**	**2**	Medium correlated as network matrix are used to design the power system to meet the specific needs of the society
CO1	**PO4**	**2**	Medium correlated as network matrix forms the base to analysis the structure of power system
CO1	**PO5**	**2**	Medium correlated as conventional mathematical tools used for prediction and modeling of complex power systems
CO1	**PO12**	**2**	Medium correlated as the fundamentals of graph theory and network matrix need for life-long learning in the broadest context of technological change
CO1	**PSO1**	**2**	Medium correlated as graph theory and network matrix employ control strategies for power electronics related applications to power systems.
CO2	**PO1**	**3**	Highly correlated as concept of load flow requires the knowledge of mathematics, and an engineering specialization to the solution of complex power systems problems
CO2	**PO2**	**3**	Highly correlated as load flow studies analyze complex engineering problems reaching substantiated conclusions using engineering sciences
CO2	**PO3**	**3**	Highly correlated as load flow studies used to design solutions for the specified needs of public

CO2	**PO4**	**3**	Highly correlated as load flow studies uses research-based knowledge and research methods including analysis and interpretation of data
CO2	**PO5**	**2**	Medium correlated to use modern engineering and IT tools for the solution of load flow studies.
CO2	**PO12**	**2**	Medium correlated as the load flow studies need for life-long learning in the broadest context of technological change
CO2	**PSO1**	**2**	Medium correlated as load flow studies employ control strategies for power electronics related applications to power systems.
CO3	**PO1**	**3**	Highly correlated as per unit analysis requires the knowledge of mathematics, and an engineering specialization to the solution of complex power systems problems
CO3	**PO2**	**3**	Highly correlated as per unit analysis and fault analysis, analyze complex engineering problems using first principles of mathematics, and engineering sciences
CO3	**PO3**	**3**	Highly correlated as per unit analysis and fault analysis required for complex engineering problems that meet the specified needs with appropriate consideration for the public and environmental considerations.
CO3	**PO4**	**3**	Highly correlated as per unit analysis and fault analysis uses research-based knowledge and research methods including analysis and interpretation of data to provide valid conclusions
CO3	**PO5**	**2**	Medium correlated to use modern engineering and IT tools for per unit calculation and fault analysis.
CO3	**PO12**	**2**	Medium correlated as the per unit need for life-long learning in the broadest context of technological change
CO3	**PSO1**	**3**	Highly correlated as per unit analyze employ control strategies for power electronics related applications to power systems.
CO4	**PO1**	**3**	Highly correlated as steady state stability requires the knowledge of mathematics, and an engineering specialization to the solution of complex power systems problems
CO4	**PO2**	**3**	Highly correlated as steady state stability analyze complex engineering problems using first principles of mathematics, and engineering sciences
CO4	**PO3**	**3**	Highly correlated as steady state stability required for complex engineering problems that meet the specified needs with appropriate consideration for the public and environmental considerations.
CO4	**PO4**	**3**	Highly correlated as steady state stability uses research-based knowledge and research methods including analysis and interpretation of data to provide valid conclusions
CO4	**PO5**	**2**	Medium correlated to use modern engineering and IT tools for steady state stability.
CO4	**PO12**	**2**	Medium correlated as the steady state stability for life-long learning in the broadest context of technological change
CO4	**PSO1**	**3**	Highly correlated as transient stability employ control strategies for power electronics related applications to power systems.
CO5	**PO1**	**3**	Highly correlated as transient stability requires the knowledge of mathematics, and an engineering specialization to the solution of complex power systems problems

CO5	**PO2**	**3**	Highly correlated as transient stability analyze complex engineering problems using first principles of mathematics, and engineering sciences
CO5	**PO3**	**3**	Highly correlated as transient stability required for complex engineering problems that meet the specified needs with appropriate consideration for the public and environmental considerations.
CO5	**PO4**	**3**	Highly correlated as transient stability uses research-based knowledge and research methods including analysis and interpretation of data to provide valid conclusions
CO5	**PO5**	**2**	Medium correlated to use modern engineering and IT tools for transient stability
CO5	**PO12**	**2**	Medium correlated as the transient stability for life-long learning in the broadest context of technological change
CO5	**PSO1**	**3**	Highly correlated as transient stability employ control strategies for power electronics related applications to power systems.

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DEPARTMENT OF ELECTRICAL&ELECTRONICS ENGINEERING

Academic year: 2020-21
Section: EEE-B

Year & Semester: III B.Tech-II Sem
W. E. F: 30-03-2021

ONLINE CLASSES TIME TABLE

Day/ Hours	9.30 AM to 10.30 AM	10.40 AM to 11.40 AM	11.50 AM to 12.50 PM	02.00 PM to 03.00 PM
MON	EMMI	SGP	PSD	ICA
TUE	CMPS	SGP	OE	EMMI
WED	PSD	EMMI	OE	CMPS
THU	ICA	CMPS	OE	MC-IV
FRI	MC-IV	ICA	SGP	PSD
SAT	ICA	CMPS	EMMI	SGP

S.NO	Name of the Subject	Name of the Faculty
1	Switchgear and Protection(SGP)	Mr.T.Parameshwar
2	Electrical Measurements & Measuring Instruments(EMMI)	Mr.B.Sudhakar Reddy
3	Computer Methods in Power Systems(CMPS)	Dr.C.N.Ravi
4	Power Semiconductor Drives(PSD)	Mr.B.Rajesh
5	Integrated Circuits and Applications(ICA)	Mr.P.Nageswara Rao
6	Personality Development and Behavioural Skills(MC-IV)	Mr.A.Surender
7	Open Elective(OE)	

Class In charge **Mr.B.Sudhakar Reddy**

Time Table I/C

HOD

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DEPARTMENT OF ELECTRICAL&ELECTRONICS ENGINEERING

Academic year: 2020-21
Section: EEE-A (Fast Track)

Year & Semester: III B.Tech-II Sem
W. E. F: 30-03-2021

ONLINE CLASSES TIME TABLE

Day/ Hours	9.30 AM to 10.30 AM	10.40 AM to 11.40 AM	11.50 AM to 12.50 PM	02.00 PM to 03.00 PM
MON	PSD	ICA	CMPS	EMMI
TUE	MC-IV	SGP	OE	ICA
WED	CMPS	SGP	OE	MC-IV
THU	EMMI	UEE	OE	PSD
FRI	SGP	CMPS	EMMI	UEE
SAT	UEE	PSD	ICA	CMPS

S.No.	Name of the Subject	Name of the Faculty
1	Switchgear and Protection(SGP)	Dr.A.Srujana
2	Electrical Measurements & Measuring Instruments(EMMI)	Mr.B.Sudhakar Reddy
3	Computer Methods in Power Systems(CMPS)	Dr.C.N.Ravi
4	Power Semiconductor Drives(PSD)	Mr.B.Rajesh
5	Integrated Circuits and Applications(ICA)	Mr.P.Nageswara Rao
6	Personality Development and Behavioural Skills(MC-IV)	Dr.V.Murali
7	Utilization of Electrical Energy(UEE)	Mr.D.Srinivas
8	Open Elective(OE)	

Class In charge **Mr.B.Rajesh**

Time Table I/C

H.O.D

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Lesson Plan Schedule

(Regulation R- 15)

Name of the Faculty: Dr. C. N. Ravi **Year/ Sem:** III , II

Course Name: COMPUTER METHODS IN POWER SYSTEMS **Course Code: 02**

S NO	Lecture Hour	Teaching Aids required	Topics to be covered	Books no./Page No.
Unit-1: Power System Network Matrices				
1	1	BB	Definitions in Graph Theory	TB1- (27 to 30)
2	1	BB	Bus Incidence Matrix	TB1- (31 to 48)
3	1	LCD	Y-bus formation by Singular Transformation	TB1- (31 to 48)
4	1	BB	Numerical Problems in Singular Transformation	TB1- (31 to 48)
5	1	BB	Methods and Direct Inspection methods, Numerical Problems	TB1- (31 to 48)
6	1	LCD	Partial network, Algorithm for the Modification of Z-bus Matrix	RB4- (4.2 to 4.9)
7	1	BB	Addition of element from a new bus to reference	RB4- (4.2 to 4.9)
8	1	BB	Addition of element from a new bus to an old bus	RB4- (4.2 to 4.9)
9	1	LCD	Addition of element between an old bus to reference	RB4- (4.2 to 4.9)
10	1	BB	Addition of element between two old busses	RB4- (4.2 to 4.9)
11	1	BB	Numerical Problems for Z-Bus formation	TB1- (79 to 91)
12	1	LCD	Modification of Z-bus for the changes in network (Problems)	TB1- (27 to 30)
Unit-II: POWER FLOW STUDIES				
13	1	BB	Necessity of Power Flow Studies and Data requirements for Power Flow Studies	TB1- (27 to 30)
14	1	LCD	Derivation of Static load flow equations	TB1- (31 to 48)
15	1	BB	classification of Buses and their relevance to Power Flow	TB1- (31 to 48)
16	1	BB	Acceleration Factor and Load flow solution without and with P-V buses	TB1- (31 to 48)

			in Gauss Seidel method	
17	1	LCD	Algorithm and Flowchart for GS method	TB1- (31 to 48)
18	1		Numerical load flow solution for simple power systems (Max. 3-Buses)	RB4- (4.2 to 4.9)
19	1	BB	Determination of bus voltages, injected active and reactive powers (sample one iteration only) and finding line flows/losses for the given bus voltages.	RB4- (4.2 to 4.9)
20	1	BB	Derivation of Jacobian Elements and load flow solution without and with pv busses using NR method	RB4- (4.2 to 4.9)
21	1	LCD	Algorithm and Flowchart of NR method	RB4- (4.2 to 4.9)
22	1	BB	Decoupled and fast decoupled methods load flows	RB4- (4.2 to 4.9)
23	1	BB	Comparison of Different Methods	TB1- (79 to 91)
24	1	LCD	DC load Flow	TB1- (27 to 30)
Unit-III: SHORT CIRCUIT ANALYSIS				
25	1	BB	Per-Unit equivalent reactance network of a three phase Power System,	TB1- (27 to 30)
26	1	LCD	Needs and assumptions for short circuit analysis	TB1- (31 to 48)
27	1	BB	Numerical Problems	TB1- (31 to 48)
28	1	BB	Short Circuit Current and MVA Calculations and application of Series Reactors in fault level	TB1- (31 to 48)
29	1	LCD	Numerical Problems	TB1- (31 to 48)
30	1		Symmetrical Component Transformation of Positive, Negative and Zero sequence Voltages, Currents and Impedances	RB4- (4.2 to 4.9)
31	1	BB	Positive, Negative and Zero sequence Networks formation	RB4- (4.2 to 4.9)
32	1	BB	Numerical Problems	RB4- (4.2 to 4.9)
33	1	LCD	LG faults without and with fault impedance	RB4- (4.2 to 4.9)
34	1	BB	LL faults without and with fault impedance	RB4- (4.2 to 4.9)
35	1	BB	LLG faults without and with fault	TB1- (79 to 91)

			impedance	
36	1	LCD	Numerical Problems	TB1- (27 to 30)
Unit- IV: STEADY STATE STABILITY ANALYSIS				
37	1	BB	Elementary concepts of steady state stability	TB1- (27 to 30)
38	1	LCD	Basics of dynamic and transient stabilities	TB1- (31 to 48)
39	1	BB	Description of steady state stability power limit	TB1- (31 to 48)
40	1	BB	Transfer reactance of single machine to infinite bus	TB1- (31 to 48)
41	1	LCD	Synchronizing power coefficient	TB1- (31 to 48)
42	1	BB	Rotor angle stability	RB4- (4.2 to 4.9)
43	1	BB	Voltage and frequency stability	RB4- (4.2 to 4.9)
44	1	LCD	Swing equation	RB4- (4.2 to 4.9)
45	1	BB	Two finite machine analysis	RB4- (4.2 to 4.9)
46	1	BB	Power angle curve	RB4- (4.2 to 4.9)
47	1	LCD	Determination of steady state stability	TB1- (79 to 91)
48	1	BB	Methods to improve steady state stability	TB1- (27 to 30)
Unit- V: TRANSIENT STABILITY ANALYSIS				
49	1	BB	Derivation of Swing Equation	TB1- (27 to 30)
50	1	LCD	Determination of transient stability	TB1- (31 to 48)
51	1	BB	Equal area criterion to find transient stability	TB1- (31 to 48)
52	1	BB	Application of equal area criterion	TB1- (31 to 48)
53	1	BB	Case study sudden loss of parallel lines	TB1- (31 to 48)
54	1	LCD	Transient fault clearing before critical angle	RB4- (4.2 to 4.9)
55	1	BB	Critical clearing angle calculation	RB4- (4.2 to 4.9)
56	1	BB	Solution of swing equation	RB4- (4.2 to 4.9)
57	1	BB	Point-by-point method.	RB4- (4.2 to 4.9)
58	1	LCD	Methods to improve stability	RB4- (4.2 to

				4.9)
59	1	BB	Application of auto reclosing circuit breakers	TB1- (79 to 91)
60	1	BB	Fast operating circuit breakers	TB1- (27 to 30)

A) TEXT BOOKS

1. Power System Analysis, Dr.N.V.Ramana, Pearson Education India, 2011.
2. Computer methods in power system analysis, Stagg and EL-Abiad, Mc-Graw hill, 1987
3. Modern Power System Analysis – by I.J.Nagrath & D.P.Kothari, Tata McGraw-Hill Publishing Company, 4th edition.

B) REFERENCES:

1. Power System Analysis, A.Nagoorkani, RBA Publications, 3rd edition
2. Power System Analysis and Stability, S.S. Vadhera, Khanna Publications
3. Power Sytem Analysis, Hadi Saadat, Tata McGraw Hill,2002.
4. Power System Analysis by J.J. Grainger and W.D. Stevenson, McGraw Hill,2016
5. Computer techniques and models in power systems, By K.Uma Rao, I.K.International, 2010
6. Computer Techniques in Power System Analysis by M.A.Pai, TMH Publications,1979
7. Power System Analysis, Grainger and Stevenson, Tata McGraw Hill.

Faculty I/C

HOD

L - Lecture
A - Assignment
T - Text Books
R - References

BB - Black Board
LCD - Liquid Crystal Display
MD - Model Demo
FV - Field Visit

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Course Delivery Plan & Record of class work

Unit-I

S No	Proposed		Topics To Be Covered	Teaching Aids used	Execution	
	DATE	HOURS			DATE	HOURS
1	18-07-2020	1	Definitions in Graph Theory	LCD	18-07-2020	1
2	22-07-2020	1	Bus Incidence Matrix	BB	22-07-2020	1
3	25-07-2020	1	Y-bus formation by Singular Transformation	BB	25-07-2020	1
4	27-07-2020	1	Numerical Problems in Singular Transformation	BB	27-07-2020	1
5	28-07-2020	1	Methods and Direct Inspection methods, Numerical Problems	LCD	28-07-2020	1
6	29-07-2020	1	Partial network, Algorithm for the Modification of Z-bus Matrix	LCD	29-07-2020	1
7	03-08-2020	1	Addition of element from a new bus to reference	BB	03-08-2020	1
8	05-08-2020	1	Addition of element from a new bus to an old bus	BB	05-08-2020	1
9	10-08-2020	1	Addition of element between an old bus to reference	BB	10-08-2020	1
10	12-08-2020	1	Addition of element between two old busses	LCD	12-08-2020	1
11	17-08-2020	1	Numerical Problems for Z-Bus formation	BB	17-08-2020	1
12	19-08-2020	1	Modification of Z-bus for the changes in network (Problems)	LCD	19-08-2020	1

Justification for deviation (if Any)

NIL

C. V. Rani
Course faculty

HOD

Unit-II

S No	Proposed		Topics To Be Covered	Teaching Aids used	Execution	
	DATE	HOURS			DATE	HOURS
13	24-08-2020	1	Necessity of Power Flow Studies and Data requirements for Power Flow Studies	LCD	24-08-2020	1
14	24-08-2020	1	Derivation of Static load flow equations	BB	24-08-2020	1
15	26-08-2020	1	classification of Buses and their relevance to Power Flow	BB	26-08-2020	1
16	29-08-2019	1	Acceleration Factor and Load flow solution without and with P-V buses in Gauss Seidel method	BB	29-08-2019	1
17	02-09-2020	1	Algorithm and Flowchart for GS method	LCD	02-09-2020	1
18	05-09-2020	1	Numerical load flow solution for simple power systems (Max. 3-Buses)	LCD	05-09-2020	1
19	07-09-2020	1	Determination of bus voltages, injected active and reactive powers (sample one iteration only) and finding line flows/losses for the given bus voltages.	BB	07-09-2020	1
20	09-09-2020	1	Derivation of Jacobian Elements and load flow solution without and with pv busses using NR method	BB	09-09-2020	1
21	14-09-2020	1	Algorithm and Flowchart of NR method	BB	14-09-2020	1
22	16-09-2020	1	Decoupled and fast decoupled methods load flows	LCD	16-09-2020	1
23	19-09-2020	1	Comparison of Different Methods	BB	19-09-2020	1
24	21-09-2020	1	DC load Flow	LCD	21-09-2020	1

Justification for deviation (if Any)

NIL

C.N.

Course faculty

HOD

Unit-III

S No	Proposed		Topics To Be Covered	Teaching Aids used	Execution	
	DATE	HOURS			DATE	HOURS
25	23-09-2020	1	Per-Unit equivalent reactance network of a three phase Power System,	LCD	23-09-2020	1
26	26-09-2020	1	Needs and assumptions for short circuit analysis	BB	26-09-2020	1
27	28-09-2020	1	Numerical Problems	BB	28-09-2020	1
28	30-09-2020	1	Short Circuit Current and MVA Calculations and application of Series Reactors in fault level	BB	30-09-2020	1
29	03-10-2020	1	Numerical Problems	LCD	03-10-2020	1
30	05-10-2020	1	Symmetrical Component Transformation of Positive, Negative and Zero sequence Voltages, Currents and Impedances	LCD	05-10-2020	1
31	23-11-2020	1	Positive, Negative and Zero sequence Networks formation	BB	23-11-2020	1
32	25-11-2020	1	Numerical Problems	BB	25-11-2020	1
33	28-11-2020	1	LG faults without and with fault impedance	BB	28-11-2020	1
34	02-12-2020	1	LL faults without and with fault impedance	LCD	02-12-2020	1
35	19-12-2020	1	LLG faults without and with fault impedance	BB	19-12-2020	1
36	21-12-2020	1	Numerical Problems	LCD	21-12-2020	1

Justification for deviation (if Any)

NIL

C.N. Ravi
Course faculty

HOD

Unit-IV

S No	Proposed		Topics To Be Covered	Teaching Aids used	Execution	
	DATE	HOURS			DATE	HOURS
37	28-12-2020	1	Elementary concepts of steady state stability	LCD	28-12-2020	1
38	30-12-2020	1	Basics of dynamic and transient stabilities	BB	30-12-2020	1
39	31-12-2020	1	Description of steady state stability power limit	BB	31-12-2020	1
40	02-01-2021	1	Transfer reactance of single machine to infinite bus	BB	02-01-2021	1
41	04-01-2021	1	Synchronizing power coefficient	LCD	04-01-2021	1
42	06-01-2021	1	Rotor angle stability	LCD	06-01-2021	1
43	07-01-2021	1	Voltage and frequency stability	BB	07-01-2021	1
44	09-01-2021	1	Swing equation	BB	09-01-2021	1
45	11-01-2021	1	Two finite machine analysis	BB	11-01-2021	1
46	18-01-2021	1	Power angle curve	LCD	18-01-2021	1
47	20-01-2021	1	Determination of steady state stability	BB	20-01-2021	1
48	21-01-2021	1	Methods to improve steady state stability	LCD	21-01-2021	1

Justification for deviation (if Any)

NIL

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Unit-V

S No	Proposed		Topics To Be Covered	Teaching Aids used	Execution	
	DATE	**HOURS**			**DATE**	**HOURS**
49	23-01-2021	1	Derivation of Swing Equation	LCD	23-01-2021	1
50	25-01-2021	1	Determination of transient stability	BB	25-01-2021	1
51	25-01-2021	1	Equal area criterion to find transient stability	BB	25-01-2021	1
52	27-01-2021	1	Application of equal area criterion	BB	27-01-2021	1
53	28-01-2021	1	Case study sudden loss of parallel lines	LCD	28-01-2021	1
54	30-01-2021	1	Transient fault clearing before critical angle	LCD	30-01-2021	1
55	01-02-2021	1	Critical clearing angle calculation	BB	01-02-2021	1
56	02-02-2021	1	Solution of swing equation	BB	02-02-2021	1
57	03-02-2021	1	Point-by-point method.	BB	03-02-2021	1
58	04-02-2021	1	Methods to improve stability	LCD	04-02-2021	1
59	05-02-2021	1	Application of auto reclosing circuit breakers	BB	05-02-2021	1
60	06-02-2021	1	Fast operating circuit breakers	LCD	06-02-2021	1

Justification for deviation (if Any)

NIL

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Syllabus Covered As Per Course Delivery Plan

Details/Duration	First 4 Weeks	Second 4 Weeks	Third 4 Weeks	End Of Semester
Percentage of Syllabus covered	25%	50%	75%	100%
Signature of staff with date	C.N. 7/9/20	C.N. 5/10 20	C.N. 4/1/21	C. 6/2/21
Signature of HOD with date	2/9/20	5/10	4/1	6/2
Signature of Auditor with date	7/9/20	5/10/20	4/1/21	6/2/21

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Name List of III-A Section

S. No.	ROLL No.	NAME OF THE STUDENT
1	18911A0201	Anirudh Soni
2	18911A0202	Bandi Aditya
3	18911A0204	Bhukya Pranay Naik
4	18911A0208	Dangeti Tarun
5	18911A0210	Desham Akhil Reddy
6	18911A0211	Dev Kumar Jaiswal
7	18911A0213	Gangi Sharadha
8	18911A0214	Ganthi Sahithi
9	18911A0216	Janga Charanya
10	18911A0218	K S Keshava Rao
11	18911A0219	Kamasani Shyam Kumar
12	18911A0223	Kondoju Prasanna
13	18911A0225	Mandiga Naveen
14	18911A0227	Mohammed Abdul Kareem
15	18911A0230	Mudelli Chandra Vamshi Reddy
16	18911A0231	Mushanolla Shivani
17	18911A0237	Nikhil Bansal
18	18911A0238	P Venkata Sandeep Reddy
19	18911A0240	Parvataneni Jaya Sindhu Sai
20	18911A0242	Reddy Sai Sushma Tanguturi
21	18911A0245	Sidduluri Vanaja
22	18911A0246	Sivaraju Naga Sri Gowri
23	18911A0247	Subburu Sai Kumar
24	18911A0248	Tammali Akhil Kumar
25	18911A0249	Thaviti Reddy Sunil Chandra
26	18911A0250	Thota Nikhitha
27	18911A0252	Vishnumolakala Deva Harsha
28	18911A0257	Chelakalapelly Sanjay
29	18911A0259	Chukka Akanksha
30	18911A0260	Daravath Linga
31	18911A0262	E Haritha
32	18911A0263	Gaini Sai Kiran
33	18911A0267	Inala Sai Ram
34	18911A0268	Janak Urmisha Reddy
35	18911A0270	Kamepalli Likhith Sai Chandra
36	18911A0272	Koppula Prashanth Reddy
37	18911A0275	Kurukuntla Venu Sagar

S. No.	ROLL No.	NAME OF THE STUDENT
38	18911A0277	Manne Shivakumar
39	18911A0282	Munugala Vineetha
40	18911A0285	P Juhitha Reddy
41	18911A0287	Pasuladi Manisha
42	18911A0292	Pothula Sai Pranavi
43	18911A0295	Rajesh Janampeta
44	18911A0299	Seetharampally Aravind Reddy
45	18911A02A0	Shubham Maroo
46	18911A02A3	Toorpu Pratyusha
47	19915A0201	A Saikishore Reddy
48	19915A0202	Arva Arun Kumar
49	19915A0204	Badepally Sai Ganesh
50	19915A0207	Gurrala Shashikumar
51	19915A0208	Kona Sai Kumar
52	19915A0210	Kuna Ramya
53	19915A0211	Lakum Keshini
54	19915A0212	M Ashrita
55	19915A0214	Mangali Sai Kumar
56	19915A0216	Merugu Pavan Kumar
57	19915A0217	Motapalukula Vamshi Krishna
58	19915A0218	Nathi Ram Kiran
59	19915A0220	Pathuri Anjani Reddy
60	19915A0221	Polaji Sanjay
61	19915A0223	Putta Priyanka
62	19915A0226	Vangala Sai Ganesh Reddy

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Staff In-charge

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S. No.	ROLL No.	NAME OF THE STUDENT
1	18911A0203	Bandi Praneeth
2	18911A0205	Chakravadhanula Sirish Dhaveji
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4	18911A0209	Dasi Geethika
5	18911A0212	Enigala Gunateja
6	18911A0215	Guguloth Ramdas
7	18911A0220	Kareti Pavankumar
8	18911A0221	Khwaja Sohail Ahmed
9	18911A0224	Mabbu Saimani Tharun
10	18911A0226	Matam Vignesh
11	18911A0228	Mohammed Ahmed Baig
12	18911A0232	Naidu Mohannaga Vamsi
13	18911A0234	Nama Lakshmi
14	18911A0241	Rachamalla Manasa
15	18911A0243	Sabavat Sachin
16	18911A0254	Belley Mahesh
17	18911A0255	Boda Sowjanya
18	18911A0256	Chava Naga Vardhan
19	18911A0258	Chintapalli Samara Simha Reddy
20	18911A0261	Dharmasagaram Sumanth Kumar
21	18911A0264	Gali Brahma Reddy
22	18911A0265	Goundla Sriilekha
23	18911A0266	Gudupally Ashwith Reddy
24	18911A0269	K Tejal
25	18911A0271	Karre Mounika
26	18911A0273	Korivi Narsing Sai Kiran
27	18911A0278	Md Muzammil Hussain
28	18911A0281	Mudavath Naresh
29	18911A0283	N Shishir Reddy
30	18911A0284	Nandyala Swetha
31	18911A0286	P Micheal Joseph
32	18911A0288	Patlolla Supriya
33	18911A0289	Peddolla Dinesh Karthik
34	18911A0290	Pogaku Varalakshmi
35	18911A0291	Pothiganti Mounika Reddy
36	18911A0293	Puntikura Rohini
37	18911A0294	R Akshay Kumar

S. No.	ROLL No.	NAME OF THE STUDENT
38	18911A0298	Samhitha Sampath
39	18911A02A1	Siddavaram Sravan
40	18911A02A4	Vaddepelly Rohith
41	18911A02A5	Vorusu Vamshi
42	18911A02A6	Yalagala Hari Krishna
43	18915A0216	K Praneeth
44	19915A0203	B Manjula
45	19915A0205	C Kalyan Sagar
46	19915A0206	Md Musthafa Maveeya Maaza
47	19915A0209	Katam Harshavardhan
48	19915A0213	M Rajesh
49	19915A0215	M Shiva Vara Prasad
50	19915A0219	N Somashekar
51	19915A0222	P Santosh
52	19915A0224	S Jashwanth Kumar
53	19915A0225	V Rajeshkumar Reddy
54	19915A0227	Veeraboina Sandeep
55	17911A0204	Arrola Shashikanth
56	17911A0217	Gopa Vigneshwar
57	17911A0223	Kotte Venkat Akhil
58	17911A0250	Marepally Rajavardhan Reddy
59	17911A0292	P.Laxman
60	17911A0293	Pendyala Balaji
61	16911A0263	G Akhilesh
62	16911A0223	B.Sireesha
63	17911A0251	Amgoth Shirisha

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ASSIGNMENT – I (AY 2020-2021)

COURSE NAME CMPS **Year & Semester: III/II**

S.No.	Questions	COs	POs	B.L
1	What is primitive network?	CO1	1,2,3,7&12	1,[illegible]
2	What is formula to find Ybus using singular transformation method?	CO1	1,2,3,7&12	1,2
3	Explain the necessity of power flow studies ?	CO2	1,2,3,7&12	1
4	Compare G-S method and NR method?	CO2	1,2,3,7&12	1
5	Define per unit value and What is the need of symmetrical components?	CO3	1,2,3,7&12	1,2

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ASSIGNMENT – II (AY -2020-2021)

COURSE NAME:CMPS **Year & Semester: III/II**

S.No.	Questions	COs	POs	B.L
1	What is the need of fault analysis?	CO3	1,2,3,7&12	,2
2	Define the synchronizing Co-efficient ?	CO4	1,2,3,7&12	2
3	What are the methods to improve stability of power system?	CO4	1,2,3,7&12	2
4	Define critical clearing angle and critical clearing time ?	CO5	1,2,3,7&12	,2
5	Define swing equation and swing curve ?	CO5	1,2,3,7&12	,2

ASSIGNMENT - I

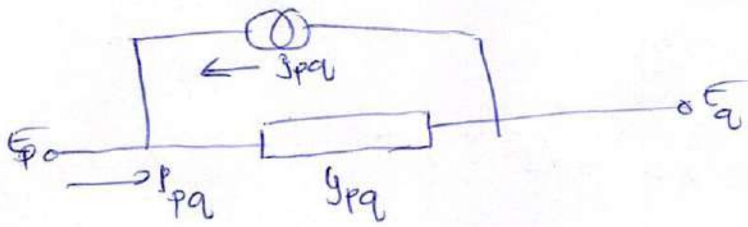
Q. 1. what is primitive network ?
write the performance equation of primitive network in admittance form?

Ans: **Primitive network :**

Primitive network is a set of uncoupled elements which gives information regarding the characteristics of individual elements only.

The primitive network can be represented in the impedance form (or) in the admittance form

Primitive network in admittance form:



$$\overleftarrow{v_{pq}} = E_p - E_q$$

$$i_{pq} + j_{pq} = y_{pq} \cdot v_{pq}$$

$$\bar{i} + \bar{j} = [\bar{y}] . \bar{v}$$

This is the performance equation of primitive network in admittance form.

Q. 2. what is the formula to find Y_{bus} using singular transformation method ?

Ans: Performance equation of primitive admittance network is $\bar{i} + \bar{j} = [\bar{y}] . \bar{v}$ — ①

Q.3. Explain the necessity of power flow studies?

Ans: A power flow study is a steady state analysis whose target is to determine the voltage current and real and reactive power flow in a system under a given load conditions

Need for power flow:

1. To find losses in the system
2. To find the Current static of power system
3. To find low voltage buses
4. To find size and location
5. To solve short circuit studies.

Q.4. Compare G-S method and NR-method ?

Ans:

	G.S Method	NR method
1	Linear Converget	1. quadratic converget
2.	Easy ~~to~~ in programming the load flow equations	2. Programming is difficult
3.	Less Memory Requirement	3. more memory Requirement
4.	Time taken for one ~~itera~~ iteration is less	4. Time taken for one iteration is high
5.	Acceleration factor is used to reduce the no. of iterations	5. acceleration factor is not used
6.	less accuracy	6. more accuracy
7.	Used for small power system	7. Used for large power system

ASSIGNMENT - II

Q. 1. what is the need of fault - Analysis ?

Ans: Fault Analysis aims to determine the causes that have led to certain failures (especially repetitive breakdowns and those with a high cost) to take preventive measure to avoid that it is important to emphasize this dual function to fault analysis.

Fault analysis helps to determine the cause of breakdown and propose measures that avoid these failures, once having identified these causes.

Q. 2 Define synchronising co-efficient ?

Ans: we know that power transferred by a synchronous machine connected to infinite bus is given by:

$$P_e = \frac{V_1 V_2}{X} \sin\delta \quad \text{—— ①}$$

In above equation, the load angle δ is variable differentiating ① w.r. to δ we get

$$\frac{dP_e}{d\delta} = \frac{V_1 V_2}{X} \cos\delta \quad \text{—— ②}$$

for order to have minimum value equ^n ② must be equated to zero.

$$\frac{dP_e}{d\delta} = \frac{V_1 V_2}{X} \cos\delta = 0 \qquad \delta = 90^\circ$$

sub $\delta = 90^\circ$ in — ① we get

3. Using Higher excitation voltages improves system stability.

4. The excitation systems which respond rapidly also improves stability of the system.

Improvement of Transient state stability limit

1. By using fast acting voltage regulator

2. By using fast acting speed governor

3. By using high inertia rotor.

Q.4 Define Critical Clearing angle and Critical clearing time ?

Ans. Critical Clearing Angle:

If any fault occurs in a system, which leads to increases in the load angle and if it is not cleared before Critical clearing time, then the system becomes unstable. The angle at which the fault becomes clear before losing the synchronism is nothing but Critical clearing angle

$$\cos\delta_c = \frac{(\delta_m-\delta_0)\sin\delta_0 - r_1\cos\delta_0 + r_2\cos\delta_m}{r_2-r_1}$$

where $\delta_m = \pi - \sin^{-1}\left(\frac{\sin\delta_0}{r_2}\right)$

Critical clearing time:

It is the maximum time during which a disturbance can be applied without the system losing its stability

$$\therefore t_{cr} = \sqrt{\frac{2H\,\delta_{cr}-\delta_0}{\pi f P_m}}$$

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III Year B.Tech II Semester 1st Mid Exam

Branch: EEE	Duration: 90Min
Sub: COMPUTER METHODS IN POWER SYSTEMS	Marks: 20
Date: 15.06.2021	Session:

Course Outcomes:

1 Deduce Y-bus and Z-bus matrices of the power system

2 Evaluate load flow solutions using computer methods

3 Compare various types of short circuits in power system

4 Apply knowledge of mathematics to analyze steady state and transient stability

Bloom's Level:

Remember	I
Understand	II
Apply	III
Analyze	IV
Evaluate	V
Create	VI

<table>
<tr><th colspan="2" rowspan="2">PART-A (3Q×2M =6Marks)
ANSWER ALL THE QUESTIONS</th><th colspan="2">Course Outcomes</th><th rowspan="2">Bloom's Level</th><th rowspan="2">Marks</th></tr>
<tr><th>CO</th><th>PO</th></tr>
<tr><td>1.i)</td><td>Define the terms, i) Branch ii) tree with examples?</td><td>1</td><td>1,2,3</td><td>I</td><td>2</td></tr>
<tr><td colspan="6">[OR]</td></tr>
<tr><td>ii)</td><td>What are the two methods of forming Ybus matrix</td><td>1</td><td>1,2,3</td><td>I</td><td>2</td></tr>
<tr><td>2.i)</td><td>What is acceleration factor?</td><td>2</td><td>1,2,3</td><td>II</td><td>2</td></tr>
<tr><td colspan="6">[OR]</td></tr>
<tr><td>ii)</td><td>What is the Necessity of Power Flow Studies?</td><td>2</td><td>1,2,3</td><td>II</td><td>2</td></tr>
<tr><td>3.i)</td><td>How to find the per unit value of the actua value?</td><td>3</td><td>1,2,3</td><td>III</td><td>2</td></tr>
<tr><td colspan="6">[OR]</td></tr>
<tr><td>ii)</td><td>Outline the need of fault analysis?</td><td>3</td><td>1,2,3</td><td></td><td>2</td></tr>
<tr><th colspan="2" rowspan="2">PART-B (5+5+4= 14 Marks)
ANSWER ALL THE QUESTIONS</th><th colspan="2">Course Outcomes</th><th rowspan="2">Bloom's Level</th><th rowspan="2">Marks</th></tr>
<tr><th>CO</th><th>PO</th></tr>
<tr><td>4.i.a)</td><td>Derive the expression for bus admittance matrices by singular transformation method</td><td>1</td><td>1,2,3</td><td>II</td><td>3</td></tr>
<tr><td>b)</td><td>Define is bus incidence matrix</td><td>1</td><td>1,2,3</td><td>II</td><td>2</td></tr>
<tr><td colspan="6">[OR]</td></tr>
<tr><td>ii</td><td>Find the Y-bus of the power system given below
<table>
<tr><th>Element</th><th>Positive sequence reactance</th></tr>
<tr><td>1-2 (1)</td><td>0.2</td></tr>
<tr><td>1-2 (2)</td><td>0.3</td></tr>
<tr><td>1-3</td><td>0.5</td></tr>
<tr><td>2-3</td><td>0.6</td></tr>
<tr><td>2-4</td><td>0.3</td></tr>
<tr><td>3-4</td><td>0.4</td></tr>
</table></td><td>1</td><td>1,2,3</td><td>III</td><td>5</td></tr>
<tr><td>5. i.a)</td><td>Write the voltage equation of PQ bus</td><td>2</td><td>1,2,3</td><td>II</td><td>2</td></tr>
<tr><td>b)</td><td>Compare GS, NR, Decoupled power flow methods</td><td>2</td><td>1,2,3</td><td>II</td><td>3</td></tr>
<tr><td colspan="6">[OR]</td></tr>
<tr><td>ii.</td><td>Explain GS method load flow with neat flowchart</td><td>2</td><td>1,2,3</td><td>II</td><td>5</td></tr>
<tr><td>6.i)</td><td>What are the advantages of per unit system</td><td>3</td><td>1,2,3</td><td>II</td><td>4</td></tr>
<tr><td colspan="6">[OR]</td></tr>
</table>

Vidya Jyothi Institute of Technology (Autonomous)

(Accredited by NAAC & NBA, Approved By A.I.C.T.E., New Delhi, Permanently Affiliated to JNTU, Hyderabad)
(Aziz Nagar, C.B.Post, Hyderabad -500075)

II & III B.Tech II Semester MID II Examination, August/Sep-2021

Subject: **COMPUTER METHODS IN POWER SYSTEMS** **Branch: EEE**
Time: 90 Minutes **Max Marks: 20**

Note: This question paper contains two ***Parts A and B.***
Part A is compulsory which carries 6 Marks.
Part B consists of 3 questions. Answer all the questions.

Bloom's Level:

Remember	I
Understand	II
Apply	III
Analyze	IV
Evaluate	V
Create	VI

	PART-A (3Q×2M =6Marks)	**Outcomes**		**Bloom's Level**	**Marks**
ANSWER ALL THE QUESTIONS		**CO**	**PO**		
1.i)	Write the expressions for unbalanced voltages in terms of symmetrical components?	3	1,2,4	II	2
	[OR]				
ii)	List different types of unsymmetrical fault	3	1,2,4	II	2
2.i)	What is the significance of synchronizing power coefficients?	4	1,2,3	III	2
	[OR]				
ii)	Define inertia constant	4	1,2,3	III	2
3.i)	Define Transient stability	4	1,2,3	III	2
	[OR]				
ii)	What is auto re-closing in circuit breaker	4	1,2,3	III	2
	PART-B (4+5+5= 14 Marks)	**Outcomes**		**Bloom's Level**	**Marks**
ANSWER ALL THE QUESTIONS		**CO**	**PO**		
4. a)	The line current in three phase supply are 12+j24A, 16-j2A, and -4-j6A. The phase sequence is 'abc'. Calculate the sequence components of currents	3	1,2,3	IV	4
	[OR]				
b)	Derive LG fault current equation for the power system without fault impedance	3	1,2,3	IV	4
5. i)	What is power system stability? Define stability limit of the system	4	1,2,3	III	5
	[OR]				
ii.	Explain the methods to improve steady state stability of power system	4	1,2,3	III	5
6.i)	What is equal area criterion? Explain how it can be used to study stability	4	1,2,3	III	5
	[OR]				
ii)	Explain the point by point method of determining swing equation	4	1,2,3	III	5

VJIT(A)

DEAN EXAMS

Vidya Jyothi Institute of Technology (Autonomous)

R18

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(Aziz Nagar, C.B.Post, Hyderabad -500075)

Subject Code:A26220

III B.Tech II Semester Regular Examination August/September- 2021

Subject: Computer Methods in Power Systems
Branch : EEE
Time: 3 Hours
Max. Marks:75

Bloom's Level.:

Remember	L1
Understand	L2
Apply	L3
Analyze	L4
Evaluate	L5
Create	L6

ANSWER ANY FIVE QUESTIONS	**5QX15M = 75 M**	**Bloom's Level**	**Marks**
1 a)	Define the following terms with suitable example A) Tree B) Branch C) Link D) Co-Tree v. Basic loop	L1	5M
b)	Derive the Bus Admittance matrix by singular transforamtion method.	L6	10M
2	Derive the formula for Z bus using building algorithm for the addition of link with mutual coupling to other elements.	L6	15M
3 a)	Compare Gauss- Seidel (G-S) method and Newton Raphson(N-R) methods.	L5	7M
b)	Discuss the algorithm for Newton Raphson(N-R) method using recatangular coordinates when PV buses are absent.	L2	8M
4	Derive load flow algorithm using Gauss -Seidel method with flow chart and discuss advantages of the method.	L6	15M
5 a)	Determine an expression for the fault current for a line-to-line fault at an unloaded generator.	L3	7M
b)	The line currents in a 3 phase supply to an un balanced load are respectively Ia = 10 + j20; Ib = 12 - j10; Ic = -3 - j5 Amp. phase sequence is abc. Determine the sequence components of currents.	L3	8M
6 a)	What is short circuit MVA rating of a Bus? Give physical significance of it and explain the role of series reactors in power system.	L1	8M
b)	Three generators are rated as follows: Generator 1:100 MVA, 33 kV, and reactance 10%, Generator 2:150 MVA, 32 kV, reactance 8% and Generator 3:110 MVA, 30 KV, reactance 12%. Determine the reactance of the generators corresponding to Base values of 200 MVA and 35 kV	L3	7M
7 a)	Explain about steady state stability power limit and synchronizing power co-efficient.	L2	8M
b)	What is meant by power angle curve and write its significance?	L1	7M
8	Explain determination of transient stability by equal area criterion and write application of equal area criterion.	L3	15M

VJIT(A)

CONTENT BEYOND SYLLABUS

S.No.	Date	Topics Covered	Details Of The Resource Person	Mapping With POs, PSOs
1	20/08/20	Optimal power flow	Dr. C. N. Ravi Professor	PO1,PO2,PO3,PSO1
2	30/09/20	Reactive power control	Mr.P. Nageshwara Rao Assoc.Prof	PO1,PO2,PO3,PO4,PSO2
3	09/01/21	Use of FACTS devices	Dr. C. N. Ravi Professor	PO1,PO2,PO3,PSO1

Vidya Jyothi Institute of Technology

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Aziz Nagar Gate, C.B. Post, Hyderabad-500 075

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Innovative Teaching Methods 2019-20

Title of Innovative method/activity : Simulation based teaching and learning

Name of the faculty : Dr. C. N. Ravi

Designation : Professor

Course Name : Computer Methods Power Systems

Objectives of method: Simulation is used to observe the load flow in graphical and numerical, to assess the performance of an existing system or predict the performance of a planned system, comparing alternative solutions and designs.

Topic Covered through activity: Load flow solution using Gauss Seidel method

Description of method: Power Flow studies, commonly known as load flow is important part of power system analysis. They are necessary for planning, economic scheduling, and control of an existing system as well a planning its future expansion. The problem consists of determining the magnitudes and phase angle of voltages at each bus and active and reactive power flow in each line. In solving a power flow problem, the system is assumed to be operating under balanced conditions and single phase model is used. Four quantities are associated with each bus. These are voltage magnitude $|V|$, phase angle δ , real power P and reactive power Q. The system buses are generally classified into three types

Slack Bus (Swing Bus): is taken as reference bus where the magnitude and phase angle of the voltages are specified.

Load Bus (PQ Bus): at this bus active and reactive powers are specified. The magnitude and phase angles of the bus voltages are to be determined.

Generator Bus (PV Bus): They are also known as voltage controlled bus. At these buses, real power and voltage magnitude are specified. The limits on the values of the reactive power are also specified. The phase angles of the voltages and reactive power are to be determined.

Gauss Seidel (GS) method is standard method to find the power flow in the power system. For solution of GS method the following equations are solved iteratively.

Voltage equation,

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k\neq i}}^{n} Y_{ik}V_k\right]$$

Real and reactive power are calculated using the following equations,

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\cos(\theta_{ik} - \delta_i + \delta_k)$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_k)$$

Current flow in the transmission line is, $I_{ij} = y_{ij}(V_i - V_j)$

Complex power flow in the line is, $S_{ij} = V_i I^*_{ij}$

Power Loss, $S_{Lij} = S_{ij} - S_{ji}$

Simulation software: "PowerWorld" Simulator is freeware software. This simulator is an interactive power system simulation package designed to simulate high voltage power system operation.

A three bus test case is simulation using the Gauss Seidel method and the power flows are given in the figure 1. The power flow is satisfies all the constraints and all meters are shown in blue colour.

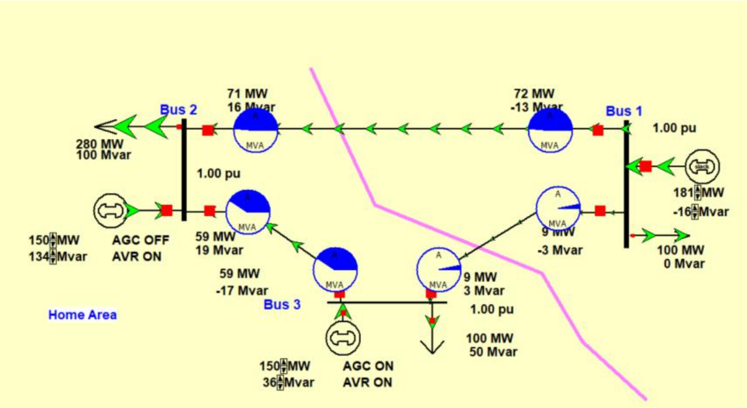

Figure 1: Power flow for the load is 280 MW in bus-2.

Figure 2 shows the power flow for the load increased to 380 MW in bus-2. Now the transmission line connected to bus 1 and bus-2 is reached its 95% loading capacity and the meters are shown in orange colour. This indicates the power flow is reached its near maximum limit in the particular transmission line and needs an attention.

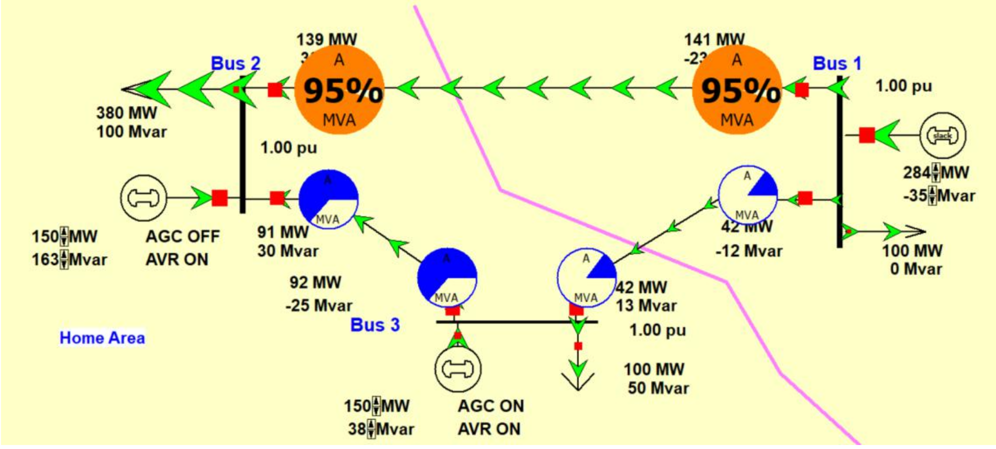

Figure 2: Power flow for the load is 380 MW in bus-2.

In figure 3 the transmission line reached its maximum limit and colour is changed to red. This red colour alerts and need attention either to trip or load shedding.

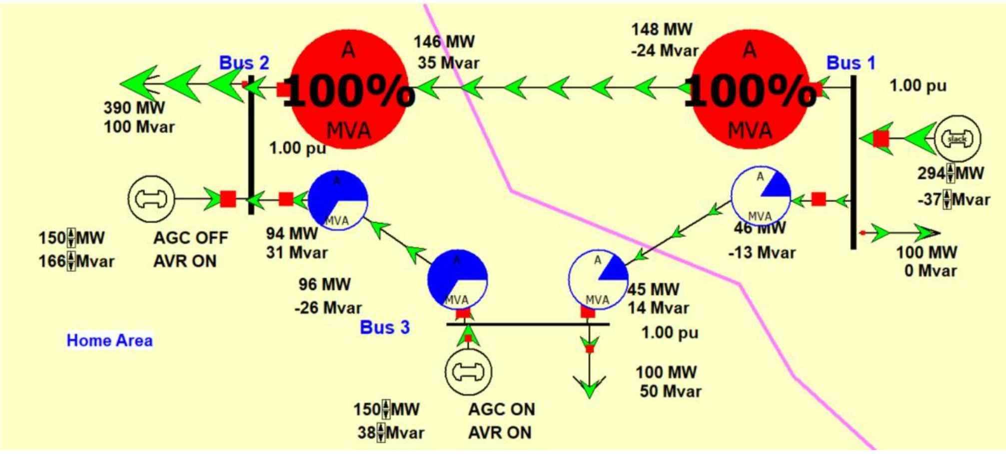

Figure 3: Power flow for the load is 390 MW in bus-2

Outcome: Students are able to understand the practical aspects and need of power flow study. Types of buses, electrical parameters (|V| , δ , P and Q) associated with each bus are understand by the them. Effect of change in load or generation in the power system is visualized and interpreted by the students.

For review contact: ravicn@vjit.ac.in

Academic Year: 2020-21
III B.Tech. II Sem
Course: CMPS

Faculty: Dr. C. N. Ravi

S.No	Reg.No	MID I Threshold 60%							MID1	MID II Threshold 60%							MID 2	Threshold 60% (45M)
		ASM - I (5)	PART-A			PART-B				ASM - II (5)	PART-A			PART-B				End Exam (75M)
			Q1 (2M)	Q2 (2M)	Q3 (2M)	Q4 (5M)	Q5 (5M)	Q6 (4M)			Q1 (2M)	Q2 (2M)	Q3 (2M)	Q4 (5M)	Q5 (5M)	Q6 (4M)		
1	16915A0223	5	1	1	1	0	1	3	**12**	5	2	2	1	2	2	1	**15**	A
2	16911A0263	5	1	1	2	1	2	3	**15**	5	1	1	0	1	0	0	**8**	22
3	17911A0204	5	1	2	2	4	3	3	**20**	5	1	0	1	0	0	0	**7**	22
4	17911A0217	5	2	2	2	3	2	1	**17**	5	2	2	2	1	3	3	**18**	27
5	17911A0223	5	2	2	2	4	4	2	**21**	5	2	1	2	3	2	2	**17**	30
6	17911A0250	5	2	2	2	5	5	4	**25**	5	2	1	1	4	5	3	**21**	24
7	17911A0251	0	AB	AB	AB	AB	AB	AB	**0**	0	AB	AB	AB	AB	AB	AB	**0**	A
8	17911A0292	5	2	2	2	1	3	3	**18**	5	2	2	1	2	3	3	**18**	31
9	17911A0293	5	1	1	2	0	0	3	**12**	5	2	1	1	2	2	2	**15**	22
10	18915A0216	5	2	2	2	3	2	3	**19**	5	AB	AB	AB	AB	AB	AB	**5**	37
11	18911A0201	5	2	2	2	3	2	3	**19**	5	2	2	1	2	1	0	**13**	33
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13	18911A0203	5	2	2	2	5	5	4	**25**	5	2	2	1	5	4	3	**22**	49
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17	18911A0208	5	2	2	1	5	5	4	**24**	5	1	1	0	1	0	0	**8**	56
18	18911A0209	5	2	2	2	5	4	3	**23**	5	1	2	1	4	3	2	**18**	43
19	18911A0210	5	2	2	1	3	2	1	**16**	5	1	1	0	1	0	0	**8**	65
20	18911A0211	5	1	1	1	0	0	3	**11**	5	1	1	1	0	0	1	**9**	57
21	18911A0212	5	2	2	2	5	5	4	**25**	5	2	2	1	5	4	4	**23**	58
22	18911A0213	5	2	2	1	5	5	4	**24**	5	2	2	1	5	4	3	**22**	37

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24	18911A0215	5	2	2	1	3	2	1	**16**	5	AB	AB	AB	AB	AB	AB	**5**	59
25	18911A0216	5	2	2	1	5	4	4	**23**	5	2	2	2	5	4	3	**23**	57
26	18911A0218	5	AB	AB	AB	AB	AB	AB	**5**	5	1	1	2	0	0	0	**9**	22
27	18911A0219	5	2	2	1	3	2	1	**16**	5	2	2	2	5	4	4	**24**	47
28	18911A0220	5	2	2	1	3	2	1	**16**	5	2	1	2	4	5	3	**22**	26
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34	18911A0227	5	2	2	1	4	4	3	**21**	5	2	2	1	4	4	2	**20**	56
35	18911A0228	5	2	2	2	2	1	0	**14**	5	2	2	1	4	4	2	**20**	43
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40	18911A0237	5	2	2	2	5	5	4	**25**	5	2	2	2	5	4	4	**24**	57
41	18911A0238	5	2	2	2	5	5	4	**25**	5	1	2	2	4	3	3	**20**	56
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44	18911A0242	5	2	2	1	3	2	4	**19**	5	2	2	1	3	3	2	**18**	53
45	18911A0243	5	2	2	1	5	4	3	**22**	5	2	2	2	5	5	4	**25**	29
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48	18911A0247	5	2	2	1	5	5	4	**24**	5	AB	AB	AB	AB	AB	AB	**5**	47
49	18911A0248	5	2	2	1	4	4	3	**21**	5	1	1	0	1	2	1	**11**	46
50	18911A0249	5	2	2	2	5	5	4	**25**	5	2	2	1	4	4	3	**21**	51
51	18911A0250	5	2	1	2	2	2	2	**16**	5	2	1	0	2	2	2	**14**	45
52	18911A0252	5	2	2	2	5	4	3	**23**	5	1	2	1	4	3	2	**18**	56

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57	18911A0258	5	2	2	2	3	2	3	**19**	5	2	2	2	2	2	1	**16**	26
58	18911A0259	5	1	2	2	4	3	3	**20**	5	2	2	2	5	4	3	**23**	55
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65	18911A0266	5	2	2	2	5	5	4	**25**	5	2	2	2	5	5	4	**25**	61
66	18911A0267	5	2	2	1	5	4	4	**23**	5	2	2	1	4	4	2	**20**	61
67	18911A0268	5	2	2	2	5	5	4	**25**	5	2	2	2	5	4	4	**24**	62
68	18911A0269	5	1	2	2	4	3	3	**20**	5	2	2	1	5	4	3	**22**	58
69	18911A0270	5	2	2	1	5	4	4	**23**	5	2	2	1	3	2	2	**17**	53
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71	18911A0272	5	2	1	0	2	2	2	**14**	5	2	2	1	2	1	0	**13**	48
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73	18911A0275	5	1	1	2	0	2	2	**13**	5	2	2	1	5	4	4	**23**	57
74	18911A0277	5	1	1	2	0	2	2	**13**	5	2	2	1	2	1	0	**13**	62
75	18911A0278	5	2	2	2	5	4	3	**23**	5	2	2	2	5	4	4	**24**	27
76	18911A0281	5	1	1	2	1	2	1	**13**	5	AB	AB	AB	AB	AB	AB	**5**	47
77	18911A0282	5	2	2	1	5	4	3	**22**	5	2	2	1	3	3	2	**18**	60
78	18911A0283	5	2	2	2	2	1	0	**14**	5	AB	AB	AB	AB	AB	AB	**5**	35
79	18911A0284	5	2	2	2	3	4	2	**20**	5	2	2	2	5	4	4	**24**	52
80	18911A0285	5	2	2	2	1	2	1	**15**	5	1	1	1	1	2	1	**12**	66
81	18911A0286	5	2	2	1	3	2	3	**18**	5	AB	AB	AB	AB	AB	AB	**5**	56
82	18911A0287	5	1	2	2	4	3	2	**19**	5	2	1	1	2	2	2	**15**	50

83	18911A0288	5	2	2	1	3	2	1	**16**	5	1	1	1	0	0	1	**9**	68
84	18911A0289	5	2	2	2	5	5	4	**25**	5	2	2	2	5	4	3	**23**	61
85	18911A0290	5	2	2	2	2	2	1	**16**	5	2	2	1	5	4	3	**22**	59
86	18911A0291	5	2	2	1	5	4	4	**23**	5	1	2	2	4	3	3	**20**	53
87	18911A0292	5	2	2	1	2	2	1	**15**	5	2	2	2	5	4	4	**24**	69
88	18911A0293	5	2	1	0	2	2	2	**14**	5	2	2	2	3	3	2	**19**	55
89	18911A0294	5	1	2	1	4	3	2	**18**	5	1	1	1	1	2	1	**12**	39
90	18911A0295	5	1	0	0	0	0	0	**6**	5	AB	AB	AB	AB	AB	AB	**5**	63
91	18911A0296	5	2	2	1	4	4	2	**20**	5	2	2	2	2	2	1	**16**	A
92	18911A0298	5	2	2	2	5	4	4	**24**	5	2	2	2	5	5	4	**25**	43
93	18911A0299	5	1	2	2	4	3	2	**19**	5	1	1	2	1	0	0	**10**	59
94	18911A02A0	5	AB	AB	AB	AB	AB	AB	**5**	5	2	2	2	3	2	2	**18**	36
95	18911A02A1	5	2	1	0	2	2	2	**14**	5	1	1	2	1	0	1	**11**	36
96	18911A02A3	5	2	2	2	5	5	4	**25**	5	2	2	1	4	4	2	**20**	66
97	18911A02A4	5	1	2	1	4	3	2	**18**	5	1	1	2	1	0	0	**10**	38
98	18911A02A5	5	1	2	2	4	3	2	**19**	5	2	1	1	2	2	2	**15**	52
99	18911A02A6	5	2	2	1	3	2	1	**16**	5	1	1	2	0	0	1	**10**	41
100	19915A0201	5	1	2	2	4	3	2	**19**	5	2	2	2	5	4	3	**23**	68
101	19915A0202	5	2	2	1	4	4	3	**21**	5	2	2	2	5	4	3	**23**	52
102	19915A0203	5	2	2	2	3	2	1	**17**	5	1	2	2	4	3	3	**20**	60
103	19915A0204	5	2	2	1	5	5	4	**24**	5	2	2	2	5	4	4	**24**	64
104	19915A0205	5	2	2	1	4	4	3	**21**	5	2	2	2	3	3	2	**19**	8
105	19915A0206	5	1	2	2	4	3	2	**19**	5	2	2	2	5	4	3	**23**	0
106	19915A0207	5	2	2	1	5	5	4	**24**	5	2	2	2	5	4	3	**23**	51
107	19915A0208	5	2	2	2	3	2	1	**17**	5	2	2	2	3	3	2	**19**	56
108	19915A0209	5	2	2	2	5	5	4	**25**	5	2	2	2	5	4	4	**24**	28
109	19915A0210	5	1	2	2	4	3	2	**19**	5	2	2	1	5	4	3	**22**	58
110	19915A0211	5	2	2	2	3	2	1	**17**	5	2	2	2	5	4	3	**23**	50
111	19915A0212	5	1	1	0	1	2	2	**12**	5	2	2	1	3	3	2	**18**	62
112	19915A0213	5	2	2	2	5	5	4	**25**	5	2	2	2	5	5	4	**25**	40

113	19915A0214	5	2	2	1	3	2	2	**17**	5	2	2	2	5	4	4	**24**	52
114	19915A0215	5	AB	AB	AB	AB	AB	AB	**5**	5	2	2	2	5	5	4	**25**	27
115	19915A0216	5	2	2	2	5	3	4	**23**	5	2	2	2	4	5	4	**24**	59
116	19915A0217	5	2	2	2	5	4	3	**23**	5	2	2	2	3	3	2	**19**	44
117	19915A0218	5	1	2	1	4	3	2	**18**	5	AB	AB	AB	AB	AB	AB	**5**	45
118	19915A0219	5	2	2	1	2	1	0	**13**	5	2	2	2	3	2	3	**19**	16
119	19915A0220	5	2	2	2	5	4	3	**23**	5	1	2	2	4	3	3	**20**	56
120	19915A0221	5	2	2	2	5	5	4	**25**	5	2	2	2	5	5	4	**25**	59
121	19915A0222	5	2	2	2	4	4	2	**21**	5	2	1	2	2	2	3	**17**	30
122	19915A0223	5	2	2	2	4	4	2	**21**	5	2	2	2	3	2	2	**18**	63
123	19915A0224	5	2	2	2	4	4	3	**22**	5	2	2	2	3	2	3	**19**	50
124	19915A0225	5	1	2	2	4	3	3	**20**	5	2	2	2	3	3	3	**20**	56
125	19915A0226	5	1	2	2	4	3	2	**19**	5	2	2	2	4	4	3	**22**	62
126	19915A0227	5	2	2	2	2	2	1	**16**	5	AB	AB	AB	AB	AB	AB	**5**	48
Average marks		4.9603	**1.8**	**1.8**	**1.6**	**3.5**	**3.1**	**2.5**		**5.0**	**1.8**	**1.8**	**1.5**	**3.4**	**3.0**	**2.4**		**47.4**
No of students attemped		**126**	**120**	**120**	**120**	**120**	**120**	**120**		**126**	**109**	**109**	**109**	**109**	**109**	**109**		**121**
No of students scored 60%		**125.0**	**93.0**	**101.0**	**74.0**	**92.0**	**72.0**	**63.0**		**125.0**	**84.0**	**83.0**	**60.0**	**78.0**	**72.0**	**57.0**		**79.0**
%of students scored 60%		**99.2**	**77.5**	**84.2**	**61.7**	**76.7**	**60.0**	**52.5**		**99.2**	**77.1**	**76.1**	**55.0**	**71.6**	**66.1**	**52.3**		**65.3**
CO ATTAINMENT		**3**	**3**	**3**	**2**	**3**	**2**	**1**		**3**	**3**	**3**	**1**	**3**	**2**	**1**		**2**

ASSESSMENT OF COs FOR THE COURSE						
CO	Method	value	Average	Internal Exam	External Exam	Overall CO Attainment
CO 1	**MID I Q1**	3.0	2.75			
	MID I Q3	2.0				
	MID I Q4	3.0				
	ASM-I	3.0				

CO 2	**MID I Q2**	3.0	2.75	2.55	2.00	2.14
	MID1 Q4	3.0				
	MID I Q5	2.0				
	ASM-I	3.0				
CO 3	**MID I Q6**	1.0	2.50			
	MID 2 Q4	3.0				
	ASM-I	3.0				
	ASM-II	3.0				
CO 4	**MID 2 Q1**	3.0	2.25			
	MID 3 Q3	1.0				
	MID 2 Q5	2.0				
	ASM-II	3.0				
CO5	**MID 2 Q2**	3.0	2.50			
	MID 2 Q4	3.0				
	MID 2 Q6	1.0				
	ASM-II	3.0				

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Aziz Nagar Gate, C.B. Post, Hyderabad-500 075

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

BATCH 2020 - 2021

Course End Survey Analysis

III/IIYear/Sem (Academic Year 2020 -2021)					
III/II	**Substantially High**	**Moderate**	**Low**	**Total**	**Attainment**
CMPS	91	23	14	128	2.59

	3	**2**	**1**	**Assessment**	**TOTAL**
CO1	90	20	16	**2.42**	**128**
CO2	95	20	11	2.66	128
CO3	94	22	10	2.66	128
CO4	89	26	11	2.61	128
CO5	88	28	10	2.61	128
	91.2	23.2	11.6	2.59	

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Batch 2020 -2021

COURSE CLOSURE REPORT

S.No	Parameters	Section	A&B SEC
		Course Name	**CMPS**
		Allotted Faculty	**Dr. C.N. Ravi**
1	Quality of I/II-mid question papers(As per Blooms Taxonomy or not) submitted to the exam section		Yes. As per blooms taxonomy.
2	No of students registered for the exam		**128**
3	No of students appeared for the exam		**128**
4	No of students passed		**127**
5	**Pass percentage**		**99%**
6	End exam result analysis (pass percentage > 90%)		**4**
7	End exam result analysis (pass percentage 80% to 90%)		**22**
8	End exam result analysis (pass percentage 70% to 80%)		**23**
9	End exam result analysis (pass percentage 60% to 70%)		**41**
10	End exam result analysis (pass percentage <60%)		**38**

C.N. Ravi

Faculty

HOD

Unit – I

Syllabus

UNIT I: POWER SYSTEM NETWORK MATRICES
Graph Theory: Definitions, Bus Incidence Matrix, Y-bus formation by Singular Transformation Methods and Direct Inspection methods, Numerical Problems.
FORMATION OF Z-BUS: Partial network, Algorithm for the Modification of Z-bus Matrix for addition element for the following cases: Addition of element from a new bus to reference, Addition of element from a new bus to an old bus, Addition of element between an old bus to reference and Addition of element between two old busses (Numerical Problems). Modification of Z-bus for the changes in network (Problems).

Graph Theory

T2: Page-28

A graph is a mathematical structure consisting of a set of points called VERTICES or NODES and a set of LINES or BRANCH linking some pair of vertices. If the direction of the branch is given then it is said to be oriented graph. For finding network matrices in power system oriented graphs are required.

Network (power system) components are replaced by single line called elements and their terminals are called nodes, which describe the geometrical structure. A graph is the geometrical interconnection of the elements of a power system. A sub graph is any subset of elements of the graph.

Tree

A connected sub-graph containing all nodes of a graph but no closed path is called tree. The elements of a tree are called branches. Number of branches in a tree is b.

b=n – 1 ➔ where, n is the number of nodes in the graph

Co-Tree

The complement of the tree of a graph is called Co-Tree. The elements of the connected graph that are not included in the tree are called links and form the Co-Tree. The number of link is *l*.

l = e – b ➔ where, e is number of elements in the graph

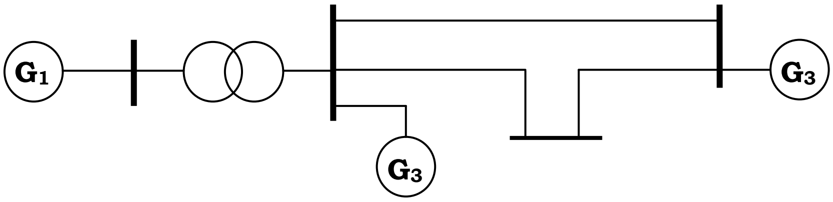
Basic loop

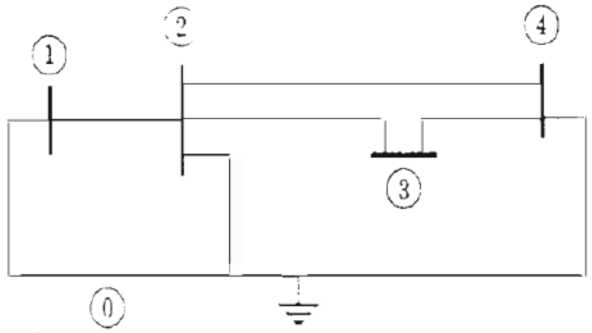
If a link is added to the tree, a loop will be formed. The loop which has only one link is called basic loop

Cut-Set

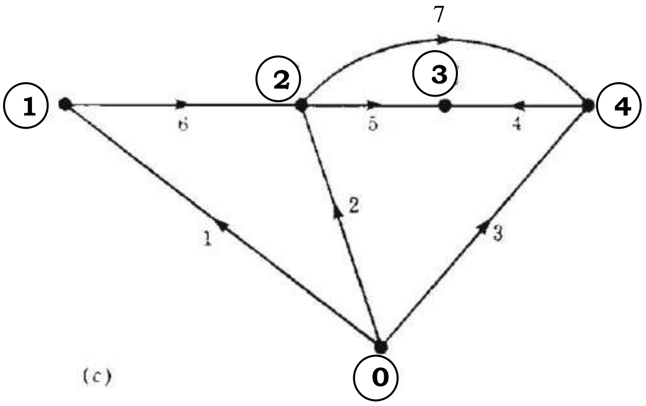
A cut-set is a set of elements that, if removed, divides a connected graph into two connected sub-graphs. Independent cut-sets are called basic cut-sets. The number of basic cut-sets is equal to number of branches.

Consider the power system shown below, which consists of 3 generators, 3 transmission lines and one transformer. For this connected line diagram and a graph is given in the figure (b) and (c) respectively.





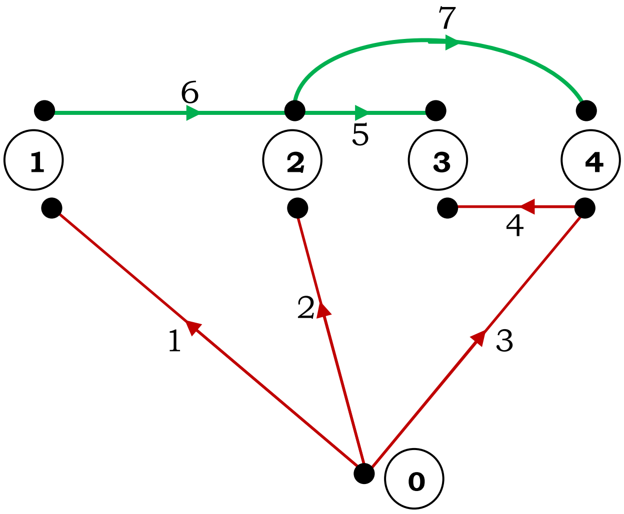
(b)



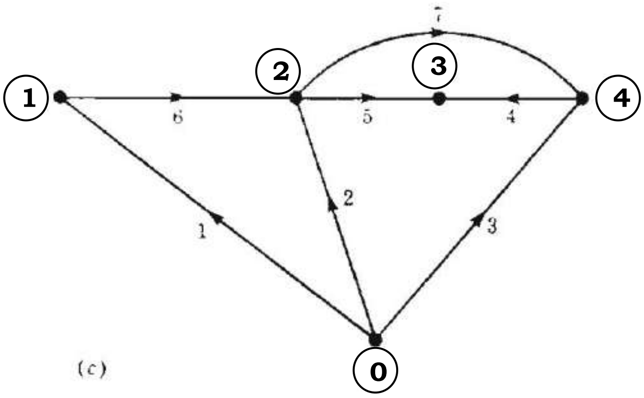
(c)

In the below diagram red colour lines are branches forms the Tree of the above power system. The green lines are links forms the Co-Tree. There are 4 branches and 3 links. Total 7 elements, 5 nodes.

T2: Page-29



For the below graph the element node incidence matrix is formulated, the number row of the matrix is equal to number of elements of the graph and number of column is equal to number of nodes in the graph. For the below graph number of row=7 and column=5.



(c)

T2: Page-31

$$\hat{A} = \begin{array}{c|c|c|c|c|c} e \backslash n & ⓪ & ① & ② & ③ & ④ \\ \hline 1 & 1 & -1 & & & \\ 2 & 1 & & -1 & & \\ 3 & 1 & & & & -1 \\ 4 & & & & -1 & 1 \\ 5 & & & 1 & -1 & \\ 6 & & 1 & -1 & & \\ 7 & & & 1 & & -1 \end{array}$$

The value of the matrix cell is 1 when the corresponding element in node is the starting point, -1 when the corresponding element in the node is end point. Bases on this the entries are shown in the below figure.

In the incidence matrix, the reference node column ‘0’ is removed to get bus incidence matrix, which is denoted by ‘A’ and given below.

$$A = \begin{array}{c|c|c|c|c} e \backslash \text{bus} & ① & ② & ③ & ④ \\ \hline 1 & -1 & & & \\ 2 & & -1 & & \\ 3 & & & & -1 \\ 4 & & & -1 & 1 \\ 5 & & 1 & -1 & \\ 6 & 1 & -1 & & \\ 7 & & 1 & & -1 \end{array}$$

For the same power system, the impedance values of the elements are given in the below table, Find the admittance matrix?

S.N.	Elements	From-To buses	Impedance
1	e1 (G1)	0-1	j0.6
2	e2 (G2)	0-2	j0.5
3	e3 (G3)	0-4	j0.5
4	e4 (TL1)	4-3	j0.2
5	e5 (TL2)	2-3	j0.3
6	e6 (TFR)	1-2	j0.1
7	e7 (TL3)	2-4	j0.4

For this table, Incidence Matrix (Â) is formulated and given below,

$[Y]_{bus}=[A]^T[y][A]$

T2: Page-44

row = Num. of element = 7
column = Num. of node/bus = 5

$$\hat{A}=\begin{array}{c} \begin{array}{ccccc} 0 & 1 & 2 & 3 & 4 \end{array} \\ \begin{bmatrix} A11 & A12 & A13 & A14 & A15 \\ A21 & A22 & A23 & A24 & A25 \\ A31 & A32 & A33 & A34 & A35 \\ A41 & A42 & A43 & A44 & A45 \\ A51 & A52 & A53 & A54 & A55 \\ A61 & A62 & A63 & A64 & A64 \\ A71 & A72 & A73 & A74 & A75 \end{bmatrix} \end{array} = \begin{array}{c} \begin{array}{ccccc} 0 & 1 & 2 & 3 & 4 \end{array} \\ \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 \end{bmatrix} \end{array}$$

The first column of the incidence matrix is corresponds to reference node ‘0’. and highlighted by red colour. Bus incidence matrix is derived by excluding the reference node ‘0’ and given below.

Bus Incidence Matrix

$$A=\begin{array}{c} \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \\ \begin{bmatrix} A12 & A13 & A14 & A15 \\ A22 & A23 & A24 & A25 \\ A32 & A33 & A34 & A35 \\ A42 & A43 & A44 & A45 \\ A52 & A53 & A54 & A55 \\ A62 & A63 & A64 & A65 \\ A72 & A73 & A74 & A75 \end{bmatrix} \end{array} = A = \begin{array}{c} \begin{array}{cccc} 1 & 2 & 3 & 4 \end{array} \\ \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 \\ 0 & 1 & -1 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix} \end{array}$$

Primitive impedance matrix is the matrix which is square matrix has a size equal to number of elements of the graph. Impedance of each element forms the diagonal element of the primitive impedance matrix. Primitive means it is not connected and considered as an individual. Here the number of element is 7 and hence the matrix size is 7x7, whose values are given below.

Primitive impedance matrix

$$[z]=\begin{bmatrix} j0.6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & j0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & j0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & j0.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & j0.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & j0.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & j0.4 \end{bmatrix}$$

The inverse of the primitive impedance matrix is the primitive admittance matrix as given below and value of the matrix is as follows,

Primitive admittance matrix, $[y]=[z]^{-1}$

$$[y]=\begin{bmatrix} 1/j0.6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/j0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/j0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/j0.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/j0.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/j0.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1/j0.4 \end{bmatrix}$$

$$[y]=\begin{bmatrix} -j1.67 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -j2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -j2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -j5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -j3.33 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -j10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -j2.5 \end{bmatrix}$$

Singular Transformation Method (Analytical Method)

Singular transformation method is one method to find the admittance (Y) bus matrix. This is best method when the impedance of the elements has mutual coupling effect. The formula to find the Y-bus is given below,

$[Y]_{bus}=[A]^T[y][A]$

The values of bus incidence matrix and primitive admittance matrix are substituted below,

$$[Y]_{bus}=\begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 \\ 0 & 1 & -1 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}^T \times \begin{bmatrix} -j1.67 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -j2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -j2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -j5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -j3.33 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -j10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -j2.5 \end{bmatrix} \times \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 \\ 0 & 1 & -1 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

After the bus incidence matrix transpose the matrices becomes,

$[Y]_{bus} =$

$$\begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 1 & -1 & 1 \\ 0 & 0 & 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & -1 \end{bmatrix} \times \begin{bmatrix} -j1.67 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -j2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -j2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -j5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -j3.33 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -j10 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -j2.5 \end{bmatrix} \times \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 \\ 0 & 1 & -1 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

First two matrix are reduced into one matrix by multiplying row of the fire matrix with the column of second matrix,

$$[Y]_{bus} = \begin{bmatrix} j1.67 & 0 & 0 & 0 & 0 & -j10 & 0 \\ 0 & j2 & 0 & 0 & -j3.33 & j10 & -j2.5 \\ 0 & 0 & 0 & j5 & j3.33 & 0 & 0 \\ 0 & 0 & j2 & -j5 & 0 & 0 & j2.5 \end{bmatrix} \times \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 1 \\ 0 & 1 & -1 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

Similarly, the resultant two matrix are multiplied and Y-bus is derived below.

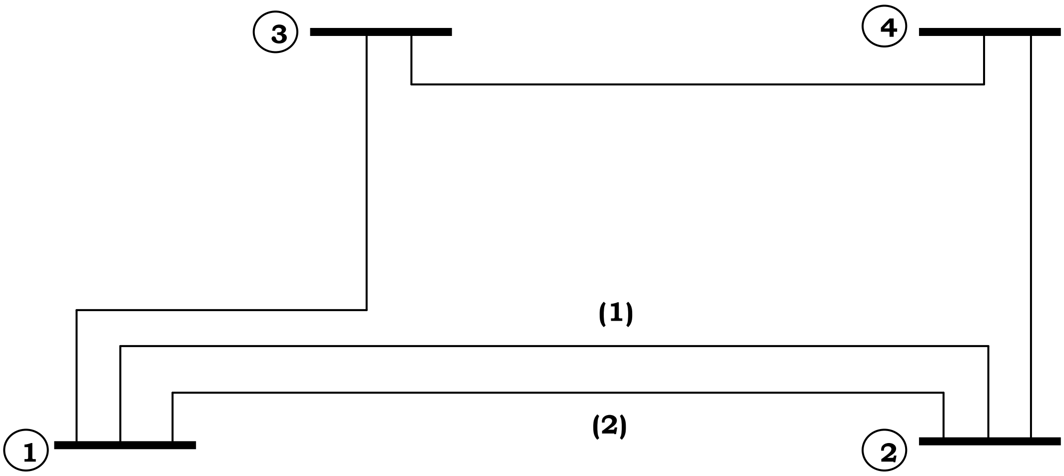
$$[Y]_{bus} = \begin{bmatrix} -j11.67 & j10 & 0 & 0 \\ j10 & -j17.33 & j3.33 & j2.5 \\ 0 & j3.33 & -j8.33 & j5 \\ 0 & j2.5 & j5 & -j9.5 \end{bmatrix}$$

This $[Y]_{bus}$ is the admittance matrix of the given power system.

Find the admittance matrix of the power system given below

Table 3.4 Impedances for sample network

	Self		*Mutual*	
Element number	*Bus code* p–q	*Impedance* $z_{pq,pq}$	*Bus code* r–s	*Impedance* $z_{pq,rs}$
1	1–2(1)	0.6		
2	1–3	0.5	1–2(1)	0.1
3	3–4	0.5		
4	1–2(2)	0.4	1–2(1)	0.2
5	2–4	0.2		



Bus Incidence Matrix, $A = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}$

Primitive - Self Impedance

$$[\mathrm{z}] = \begin{bmatrix} j0.6 & 0 & 0 & 0 & 0 \\ 0 & j0.5 & 0 & 0 & 0 \\ 0 & 0 & j0.5 & 0 & 0 \\ 0 & 0 & 0 & j0.4 & 0 \\ 0 & 0 & 0 & 0 & j0.2 \end{bmatrix}$$

First Mutual Impedance between element 1 and element 2

$$[\mathrm{z}] = \begin{bmatrix} j0.6 & j0.1 & 0 & 0 & 0 \\ j0.1 & j0.5 & 0 & 0 & 0 \\ 0 & 0 & j0.5 & 0 & 0 \\ 0 & 0 & 0 & j0.4 & 0 \\ 0 & 0 & 0 & 0 & j0.2 \end{bmatrix}$$

Second Mutual Impedance between element 1 and element 4

$$[\mathrm{z}] = \begin{bmatrix} j0.6 & j0.1 & 0 & j0.2 & 0 \\ j0.1 & j0.5 & 0 & 0 & 0 \\ 0 & 0 & j0.5 & 0 & 0 \\ j0.2 & 0 & 0 & j0.4 & 0 \\ 0 & 0 & 0 & 0 & j0.2 \end{bmatrix}$$

Primitive admittance matrix

$[y] = [z]^{-1}$

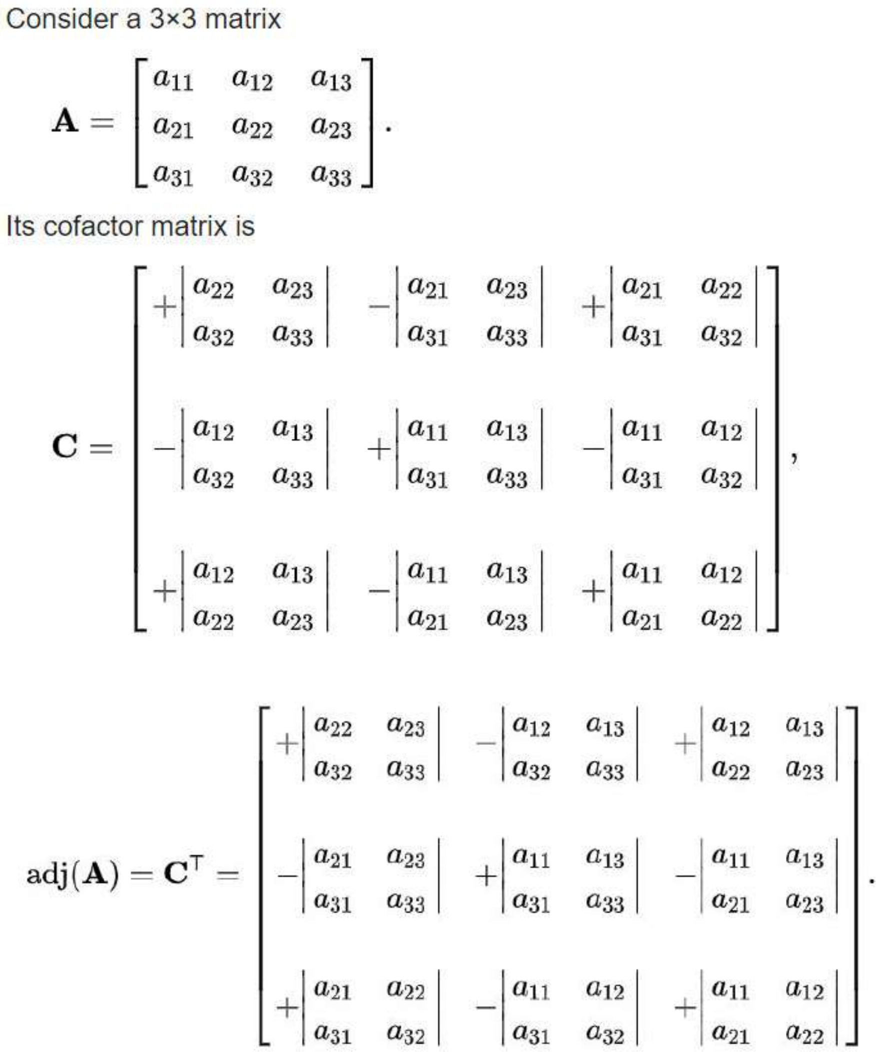
$$[\mathrm{y}] = inv\left(\begin{bmatrix} j0.6 & j0.1 & 0 & j0.2 & 0 \\ j0.1 & j0.5 & 0 & 0 & 0 \\ 0 & 0 & j0.5 & 0 & 0 \\ j0.2 & 0 & 0 & j0.4 & 0 \\ 0 & 0 & 0 & 0 & j0.2 \end{bmatrix}\right)$$

From this consider the sub-matrix

$M = \begin{bmatrix} 0.6 & 0.1 & 0.2 \\ 0.1 & 0.5 & 0 \\ 0.2 & 0 & 0.4 \end{bmatrix}$ and find the inverse of this matrix

Inverse of M = $\frac{1}{|M|}\text{Adjoint}\,(M)$

***************** Steps to find Inverse of Matrix *************************



Consider a 3×3 matrix

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}.$$

Its cofactor matrix is

$$\mathbf{C} = \begin{bmatrix} +\begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} & -\begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} & +\begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} \\ \\ -\begin{vmatrix} a_{12} & a_{13} \\ a_{32} & a_{33} \end{vmatrix} & +\begin{vmatrix} a_{11} & a_{13} \\ a_{31} & a_{33} \end{vmatrix} & -\begin{vmatrix} a_{11} & a_{12} \\ a_{31} & a_{32} \end{vmatrix} \\ \\ +\begin{vmatrix} a_{12} & a_{13} \\ a_{22} & a_{23} \end{vmatrix} & -\begin{vmatrix} a_{11} & a_{13} \\ a_{21} & a_{23} \end{vmatrix} & +\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \end{bmatrix},$$

$$\operatorname{adj}(\mathbf{A}) = \mathbf{C}^{\mathsf{T}} = \begin{bmatrix} +\begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} & -\begin{vmatrix} a_{12} & a_{13} \\ a_{32} & a_{33} \end{vmatrix} & +\begin{vmatrix} a_{12} & a_{13} \\ a_{22} & a_{23} \end{vmatrix} \\ \\ -\begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} & +\begin{vmatrix} a_{11} & a_{13} \\ a_{31} & a_{33} \end{vmatrix} & -\begin{vmatrix} a_{11} & a_{13} \\ a_{21} & a_{23} \end{vmatrix} \\ \\ +\begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} & -\begin{vmatrix} a_{11} & a_{12} \\ a_{31} & a_{32} \end{vmatrix} & +\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} \end{bmatrix}.$$

Inverse of A = $A^{-1} = \frac{1}{|A|}\text{Adj}(A)$

****

For the considered sub-matrix

$$M = \begin{bmatrix} 0.6 & 0.1 & 0.2 \\ 0.1 & 0.5 & 0 \\ 0.2 & 0 & 0.4 \end{bmatrix}$$

Determinate of M = |M| = 0.6x(0.5x0.4 – 0)-0.1x(0.1x0.4 – 0)+0.2x(0-0.2x0.5)

|M| = 0.096

Inverse of M = $\frac{1}{|M|}\text{Adjoint}\left(M\right)$

$$M^{-1} = \begin{bmatrix} 2.08 & -0.417 & -1.04 \\ -0.417 & 2.08 & 0.208 \\ -1.04 & 0.208 & 3.02 \end{bmatrix}$$

Update this sub-matrix first, second row and column into first, second row and column of the Primitive admittance matrix [y], and third row and column of sub-matrix into fourth row and column of the Primitive admittance matrix [y]. The third row and column of the [y] is zeros except the diagonal and hence the reciprocal of this element 1/0.5 is considered. The fifth row and column of the [y] is zeros except the diagonal and hence the reciprocal of this element 1/0.2 is considered. The substitute [y] matrix is given below,

Primitive admittance matrix

$$[y] = \begin{bmatrix} 2.08 & -0.417 & 0 & -1.04 & 0 \\ -0.417 & 2.08 & 0 & 0.208 & 0 \\ 0 & 0 & 1/0.5 & 0 & 0 \\ -1.04 & 0.208 & 0 & 3.02 & 0 \\ 0 & 0 & 0 & 0 & 1/0.2 \end{bmatrix}$$

After the reciprocal the final [y] is given below,

$$[y] = \begin{bmatrix} 2.08 & -0.417 & 0 & -1.04 & 0 \\ -0.417 & 2.08 & 0 & 0.208 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ -1.04 & 0.208 & 0 & 3.02 & 0 \\ 0 & 0 & 0 & 0 & 5 \end{bmatrix}$$

Formula of Bus admittance matrix is given below,

$[Y]_{bus} = [A]^T[y][A]$

The values of bus incidence matrix [A] and primitive admittance [y] is substituted and given below,

$$[\mathrm{Y}]=\begin{bmatrix}1 & -1 & 0 & 0\\ 1 & 0 & -1 & 0\\ 0 & 0 & 1 & -1\\ 1 & -1 & 0 & 0\\ 0 & 1 & 0 & -1\end{bmatrix}^{T}\begin{bmatrix}2.08 & -0.417 & 0 & -1.04 & 0\\ -0.417 & 2.08 & 0 & 0.208 & 0\\ 0 & 0 & 2 & 0 & 0\\ -1.04 & 0.208 & 0 & 3.02 & 0\\ 0 & 0 & 0 & 0 & 5\end{bmatrix}\begin{bmatrix}1 & -1 & 0 & 0\\ 1 & 0 & -1 & 0\\ 0 & 0 & 1 & -1\\ 1 & -1 & 0 & 0\\ 0 & 1 & 0 & -1\end{bmatrix}$$

$$[\mathrm{Y}]=\begin{bmatrix}1 & 1 & 0 & 1 & 0\\ -1 & 0 & 0 & -1 & 1\\ 0 & -1 & 1 & 0 & 0\\ 0 & 0 & -1 & 0 & -1\end{bmatrix}\begin{bmatrix}2.08 & -0.417 & 0 & -1.04 & 0\\ -0.417 & 2.08 & 0 & 0.208 & 0\\ 0 & 0 & 2 & 0 & 0\\ -1.04 & 0.208 & 0 & 3.02 & 0\\ 0 & 0 & 0 & 0 & 5\end{bmatrix}\begin{bmatrix}1 & -1 & 0 & 0\\ 1 & 0 & -1 & 0\\ 0 & 0 & 1 & -1\\ 1 & -1 & 0 & 0\\ 0 & 1 & 0 & -1\end{bmatrix}$$

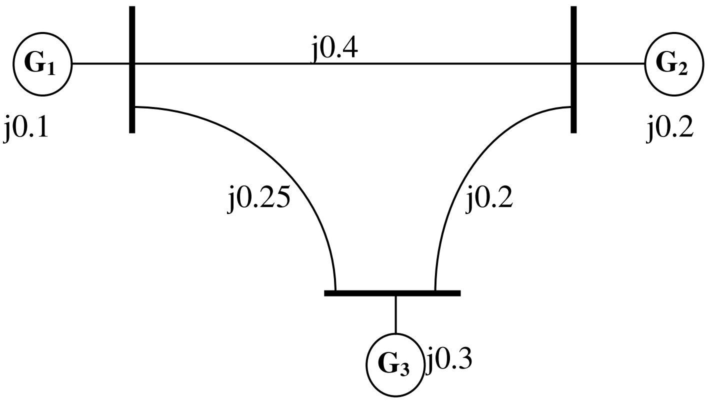
$$[\mathrm{Y}]=\begin{bmatrix}0.623 & 1.871 & 0 & 2.188 & 0\\ -1.04 & 0.209 & 0 & -1.98 & 5\\ 0.417 & -2.08 & 2 & -0.208 & 0\\ 0 & 0 & -2 & 0 & -5\end{bmatrix}\begin{bmatrix}1 & -1 & 0 & 0\\ 1 & 0 & -1 & 0\\ 0 & 0 & 1 & -1\\ 1 & -1 & 0 & 0\\ 0 & 1 & 0 & -1\end{bmatrix}$$

$$[\mathrm{Y}]=\begin{bmatrix}4.682 & -2.811 & -1.871 & 0\\ -2.811 & 8.02 & -0.209 & -5\\ -1.871 & -0.209 & 4.08 & -2\\ 0 & -5 & -2 & 7\end{bmatrix}$$

In the above matrix operator 'j' is not included for simplicity. Now it has to include and it will '-j' for admittance and hence the final bus admittance matrix is

$$[\mathrm{Y}]=-j\times\begin{bmatrix}4.682 & -2.811 & -1.871 & 0\\ -2.811 & 8.02 & -0.209 & -5\\ -1.871 & -0.209 & 4.08 & -2\\ 0 & -5 & -2 & 7\end{bmatrix}$$

P3) Compute the bus admittance matrix for the power system shown below by using singular transformation method



Solution:

S.N.	Elements	From-To buses	Impedance
1	e1 (G1)	0-1	j0.1
2	e2 (G2)	0-2	j0.2
3	e3 (G3)	0-3	j0.3
4	e4 (TL1)	1-2	j0.4
5	e5 (TL2)	2-3	j0.2
6	e6 (TL3)	3-1	j0.25

Bus Incidence Matrix, A (6 rows, 3 columns)

$$A = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

Primitive impedance matrix, [z] (6 rows, 6 columns)

$$[z] = j \times \begin{bmatrix} 0.1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.25 \end{bmatrix}$$

Primitive admittance matrix, $[y]=[z]^{-1}$

$$[y] = -j \times \begin{bmatrix} 1/0.1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/0.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/0.3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/0.4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/0.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/0.25 \end{bmatrix}$$

$$[y] = -j \times \begin{bmatrix} 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3.33 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 \end{bmatrix}$$

In singular transformation method,

$[Y]_{bus} = [A]^T[y][A]$

$$[Y]_{bus} = -j \times \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}^T \times \begin{bmatrix} 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3.33 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 \end{bmatrix} \times \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$[Y]_{bus} = -j \times \begin{bmatrix} -1 & 0 & 0 & 1 & 0 & -1 \\ 0 & -1 & 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 0 & -1 & 1 \end{bmatrix} \times \begin{bmatrix} 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3.33 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 \end{bmatrix} \times \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$[Y]_{bus} = -j \times \begin{bmatrix} -10 & 0 & 0 & 2.5 & 0 & -4 \\ 0 & -5 & 0 & -2.5 & 5 & 0 \\ 0 & 0 & -3.33 & 0 & -5 & 4 \end{bmatrix} \times \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$[Y]_{bus} = -j \times \begin{bmatrix} 16.5 & -2.5 & -4 \\ -2.5 & 12.5 & -5 \\ -4 & -5 & 12.33 \end{bmatrix}$$

P4) Form Y_{bus} for the given network

Element	Positive sequence reactance
1-2	0.2
1-2	0.3
1-3	0.5
2-3	0.6
2-4	0.3
3-4	0.4

Solution:

Element Number	Element	Positive sequence reactance
e1	1-2	0.2
e2	1-2	0.3
e3	1-3	0.5

e4	2-3	0.6
e5	2-4	0.3
e6	3-4	0.4

Bus Incidence Matrix, A (6 rows, 4 columns)

$$A = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

Primitive impedance matrix, [z] (6 rows, 6 columns)

$$[z] = j \times \begin{bmatrix} 0.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.4 \end{bmatrix}$$

Primitive admittance matrix, $[y]=[z]^{-1}$

$$[y] = -j \times \begin{bmatrix} 1/0.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/0.3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/0.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/0.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/0.4 \end{bmatrix}$$

$$[y] = -j \times \begin{bmatrix} 5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3.33 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.67 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.33 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.5 \end{bmatrix}$$

In singular transformation method,
$[Y]_{bus} = [A]^T[y][A]$

$$[Y]_{bus}=-j\times\begin{bmatrix}1&-1&0&0\\1&-1&0&0\\1&0&-1&0\\0&1&-1&0\\0&1&0&-1\\0&0&1&-1\end{bmatrix}^T\times\begin{bmatrix}5&0&0&0&0&0\\0&3.33&0&0&0&0\\0&0&2&0&0&0\\0&0&0&1.67&0&0\\0&0&0&0&3.33&0\\0&0&0&0&0&2.5\end{bmatrix}\times\begin{bmatrix}1&-1&0&0\\1&-1&0&0\\1&0&-1&0\\0&1&-1&0\\0&1&0&-1\\0&0&1&-1\end{bmatrix}$$

$$[Y]_{bus}=-j\times\begin{bmatrix}1&1&1&0&0&0\\-1&-1&0&1&1&0\\0&0&-1&-1&0&1\\0&0&0&0&-1&-1\end{bmatrix}\times\begin{bmatrix}5&0&0&0&0&0\\0&3.33&0&0&0&0\\0&0&2&0&0&0\\0&0&0&1.67&0&0\\0&0&0&0&3.33&0\\0&0&0&0&0&2.5\end{bmatrix}\times\begin{bmatrix}1&-1&0&0\\1&-1&0&0\\1&0&-1&0\\0&1&-1&0\\0&1&0&-1\\0&0&1&-1\end{bmatrix}$$

$$[Y]_{bus}=-j\times\begin{bmatrix}5&3.33&2&0&0&0\\-5&-3.33&0&1.67&3.33&0\\0&0&-2&-1.67&0&2.5\\0&0&0&0&-3.33&-2.5\end{bmatrix}\times\begin{bmatrix}1&-1&0&0\\1&-1&0&0\\1&0&-1&0\\0&1&-1&0\\0&1&0&-1\\0&0&1&-1\end{bmatrix}$$

$$[Y]_{bus}=-j\times\begin{bmatrix}10.33&-8.33&-2&0\\-8.33&13.33&-1.67&-3.33\\-2&-1.67&6.17&-2.5\\0&-3.33&-2.5&5.83\end{bmatrix}$$

Derive the expression for bus admittance matrices by singular transformation method (bus admittance and impedance matrix)

T2: Page-43

The bus admittance matrix Y_{bus} can be derived from the bus incidence matrix – A. The performance equation of the primitive network

$$\bar{i}+\bar{j}=[y]\times\bar{v}$$

The above equation is pre-multiplied by transpose of bus incidence matrix - A^t, then

$$A^t\bar{i}+A^t\bar{j}=A^t[y]\times\bar{v} \qquad (1)$$

Since the matrix A shows the incidence of elements to buses, $A^t\bar{i}$ is a vector in which each element is the algebraic sum of the current through the network elements terminating at a bus. In accordance with Kirchhoff's law, the algebraic sum of the currents at a bus is zero. Then

$$A^t\bar{i}=0 \qquad (2)$$

Similarly, $A^t\overline{j}$ gives the algebraic sum of the source currents at each bus and equals the vector of impressed bus currents, therefore

$$\overline{I}_{BUS} = A^t\overline{j} \tag{3}$$

Substituting equation (2) and (3) into equation (1), yields

$$\overline{I}_{BUS} = A^t[y]\times\overline{v} \tag{4}$$

Power into the network $(\overline{I^*}_{BUS})^t\overline{E}_{BUS}$ and the sum of the power in the primitive network is $(\overline{j}^*)^t\overline{v}$. The power in the primitive and interconnected networks must be equal. Hence

$$(\overline{I^*}_{BUS})^t\overline{E}_{BUS} = (\overline{j}^*)^t\overline{v} \tag{5}$$

Taking the conjugate transpose of the equation (3)

$$(\overline{I^*}_{BUS})^t = (\overline{j}^*)^t A^*$$

Since A is a real matrix, $A^* = A$

and

$$(\overline{I^*}_{BUS})^t = (\overline{j}^*)^t A \tag{6}$$

Substituting equation (6) into equation (5)

$$(\overline{j}^*)^t A\overline{E}_{BUS} = (\overline{j}^*)^t\overline{v}$$

Since this equation is valid for all values of $\overline{j}$, it follows that

$$A\overline{E}_{BUS} = \overline{v} \tag{7}$$

Substituting equation (7) into equation (4),

$$\overline{I}_{BUS} = A^t[y]\times A\overline{E}_{BUS} \tag{8}$$

Since the performance equation of the network is

$$\overline{I}_{BUS} = Y_{BUS}\overline{E}_{BUS} \tag{9}$$

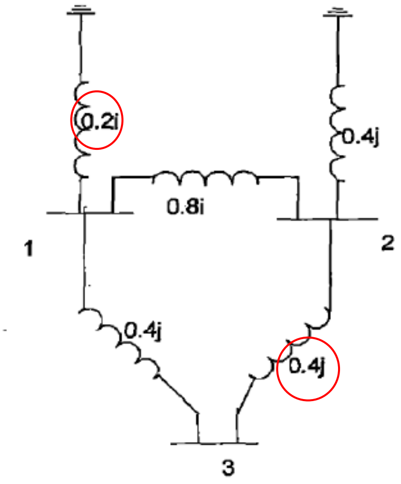
It follows from the equation (8) and (9), that

$$\boxed{Y_{BUS} = A^t[y]A} \tag{10}$$

The bus impedance matrix can be obtained from

$$\boxed{Z_{BUS} = Y_{BUS}^{-1} = (A^t[y]A)^{-1}} \tag{11}$$

Impedance Matrix



Z_{bus} matrix size = Number of bus = 3

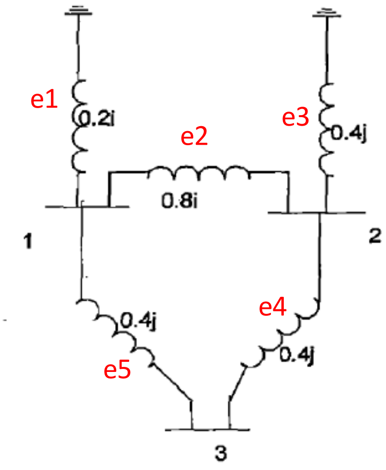
Number of element = 5

Number of steps = number of element = 5

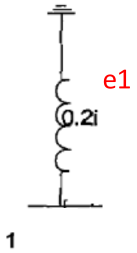
To add elements, **Number of Types = 4**

1. Z_b is added from a new bus to the reference bus (i.e. a new branch is added and the dimension of Z_{BUS} goes up by one). This is type-I modification.
2. Z_b is added from a new bus to an old bus (i.e., a new branch is added and the dimension of Z_{BUS} goes up by one). This is type-2 modification.
3. Z_b connects an old bus to the reference bus (i.e., a new loop is formed but the dimension of Z_{BUS} does not change). This is type-3 modification.
4. Z_b connects two old buses (i.e., new loop is formed but the dimension of Z_{BUS} does not change). This is type-4 modification.
5. Z_b connects two new buses (Z_{BUS} remains unaffected in this case). This situation can be avoided by suitable numbering of buses and from now on wards will be ignored

Find the Impedance bus for the given below power system network?

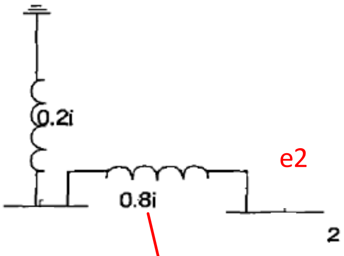


Step-1: (element e1) ➔ Type -1: branch impedance Z_b connects New bus to reference bus



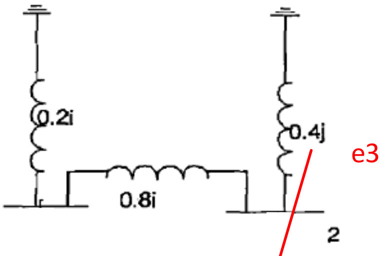
$$Z_{bus}=[0.2]$$

Step-2: (element e2)➔Type-2: branch impedance Z$_b$ connects New bus to old bus



$$Z_{bus}=\begin{bmatrix}\boxed{0.2} & 0.2\\ 0.2 & 0.2+0.8\end{bmatrix}=\begin{bmatrix}0.2 & 0.2\\ 0.2 & 1.0\end{bmatrix}$$

Step-3: (element e3)➔ Type-3: branch impedance Z$_b$ connects old bus to reference bus



$$Z_{bus}=\begin{bmatrix}0.2 & 0.2 & 0.2\\ 0.2 & 1.0 & 1.0\\ 0.2 & 1.0 & 1.0+0.4\end{bmatrix}=\begin{bmatrix}0.2 & 0.2 & 0.2\\ 0.2 & 1.0 & 1.0\\ 0.2 & 1.0 & 1.4\end{bmatrix}$$

$$Z_{11}^{new}=Z_{11}-\frac{Z_{13}\times Z_{31}}{Z_{33}}$$

$$Z_{11}^{new}=0.2-\frac{0.2\times 0.2}{1.4}=0.171$$

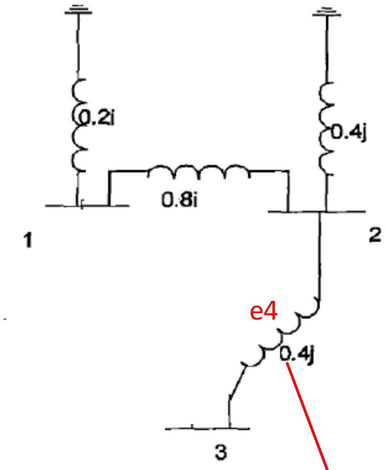
$$Z_{12}^{new}=Z_{12}-\frac{Z_{13}\times Z_{32}}{Z_{33}}=0.2-\frac{0.2\times 1.0}{1.4}=0.057$$

$$Z_{21}^{new}=Z_{12}^{new}$$

$$Z_{22}^{new}=Z_{22}-\frac{Z_{23}\times Z_{32}}{Z_{33}}=1.0-\frac{1.0\times 1.0}{1.4}=0.286$$

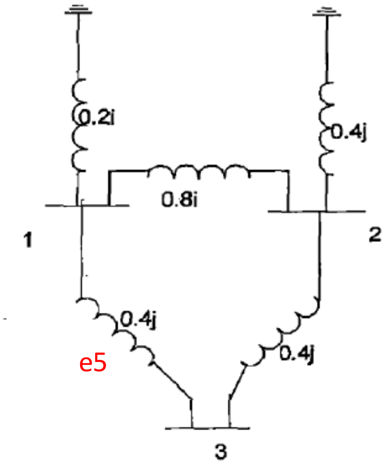
$$Z_{bus}=\begin{bmatrix}0.171 & 0.057\\ 0.057 & 0.286\end{bmatrix}$$

Step-4: (element e4) ➔ Type 2: branch impedance Z_b connects New bus to old bus



$$Z_{bus}=\begin{bmatrix}0.171 & 0.057 & 0.057\\ 0.057 & 0.286 & 0.286\\ 0.057 & 0.286 & 0.286+0.4\end{bmatrix}=\begin{bmatrix}0.171 & 0.057 & 0.057\\ 0.057 & 0.286 & 0.286\\ 0.057 & 0.286 & 0.686\end{bmatrix}$$

Step-5: (element e5) ➔ Type-4: branch impedance Z_b connects Between two old buses



$$Z_{bus}=\begin{bmatrix}0.171 & 0.057 & 0.057 & 0.057-0.171\\ 0.057 & 0.286 & 0.286 & 0.286-0.057\\ 0.057 & 0.286 & 0.686 & 0.686-0.057\\ 0.057-0.171 & 0.286-0.057 & 0.686-0.057 & Z_{44}\end{bmatrix}$$

$$Z_{44}=Z_b+(Z_{33}+Z_{11}-2\times Z_{13})=0.4+(0.686+0.171-2\times 0.057)=1.143$$

$$Z_{bus}=\begin{bmatrix}0.171 & 0.057 & 0.057 & -0.114\\ 0.057 & 0.286 & 0.286 & 0.229\\ 0.057 & 0.286 & 0.686 & 0.629\\ -0.114 & 0.229 & 0.629 & 1.143\end{bmatrix}$$

$$Z_{11}^{new}=Z_{11}-\frac{Z_{14}\times Z_{41}}{Z_{44}}$$

$$Z_{11}^{new} = 0.171 - \frac{-0.114 \times -0.114}{1.143} = 0.159$$

$$Z_{12}^{new} = Z_{12} - \frac{Z_{14} \times Z_{42}}{Z_{44}} = 0.057 - \frac{-0.114 \times 0.229}{1.143} = 0.080$$

$$Z_{13}^{new} = Z_{13} - \frac{Z_{14} \times Z_{43}}{Z_{44}} = 0.057 - \frac{-0.114 \times 0.629}{1.143} = 0.119$$

$$Z_{21}^{new} = Z_{12}^{new}$$

$$Z_{22}^{new} = Z_{22} - \frac{Z_{24} \times Z_{42}}{Z_{44}} = 0.286 - \frac{0.229 \times 0.229}{1.143} = 0.240$$

$$Z_{23}^{new} = Z_{23} - \frac{Z_{24} \times Z_{43}}{Z_{44}} = 0.286 - \frac{0.229 \times 0.629}{1.143} = 0.156$$

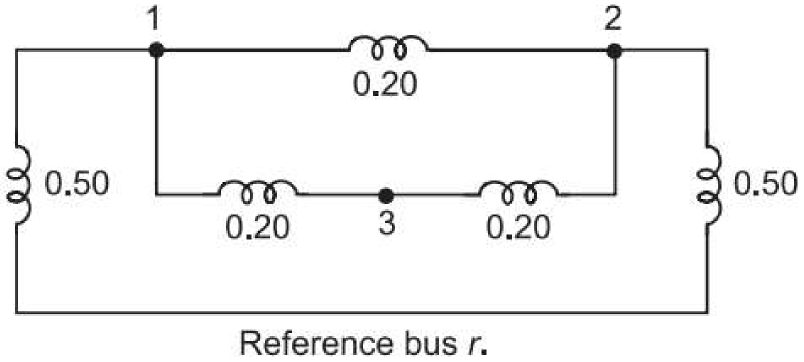
$$Z_{31}^{new} = Z_{13}^{new}$$

$$Z_{32}^{new} = Z_{23}^{new}$$

$$Z_{33}^{new} = Z_{33} - \frac{Z_{34} \times Z_{43}}{Z_{44}} = 0.686 - \frac{0.629 \times 0.629}{1.143} = 0.339$$

$$Z_{bus} = j \times \begin{bmatrix} 0.159 & 0.080 & 0.119 \\ 0.080 & 0.240 & 0.156 \\ 0.119 & 0.156 & 0.339 \end{bmatrix}$$

2) Obtain the Impedance bus for the following network

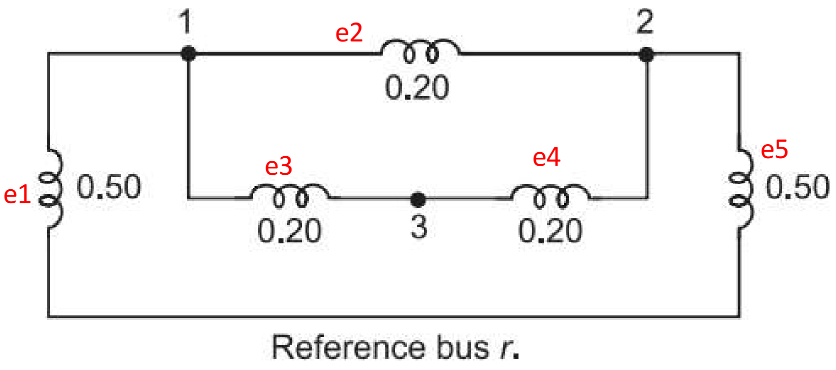


Solution:

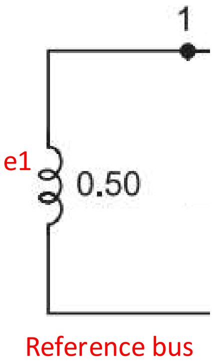
Number of elements = 5 ➔ number of steps = 5

Number of bus = 3 ➔ Z_{bus} size is 3x3

Elements are numbered as follows,

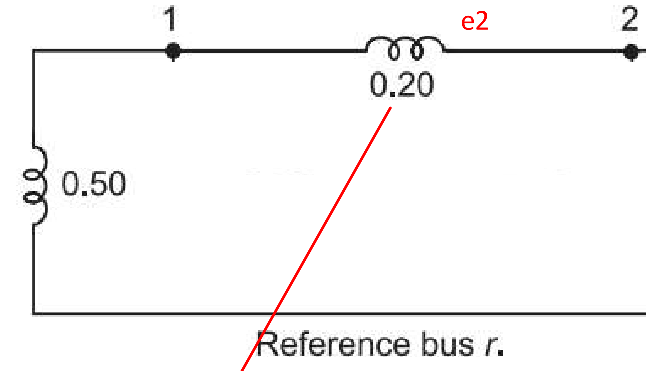


Step 1: (element e1) ➔ Type -1: branch impedance Zb connects New bus to reference bus



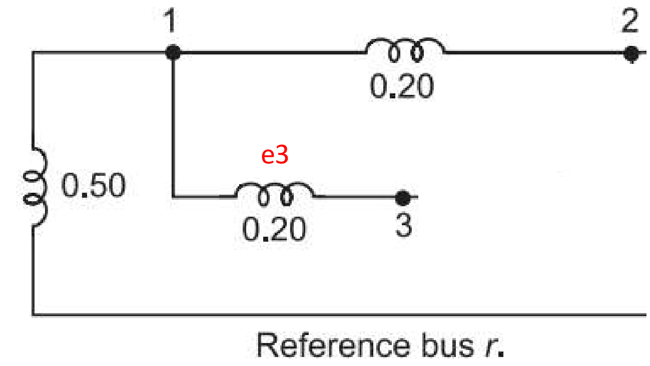
$Z_{bus} = [0.5]$

Step-2: (element e2)➔Type-2: branch impedance Zb connects New bus to old bus



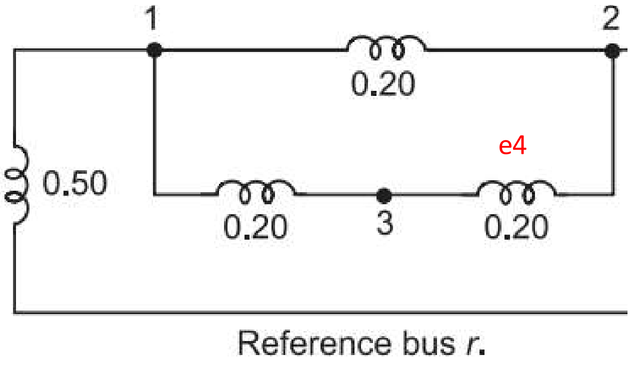
$$Z_{bus} = \begin{bmatrix} \boxed{0.5} & 0.5 \\ 0.5 & 0.5+0.2 \end{bmatrix} = \begin{bmatrix} 0.5 & 0.5 \\ 0.5 & 0.7 \end{bmatrix}$$

Step-3: (element e3)➔Type-2: branch impedance Zb connects New bus to old bus



$$Z_{bus}=\begin{bmatrix}0.5 & 0.5 & 0.5\\ 0.5 & 0.7 & 0.5\\ 0.5 & 0.5 & 0.5+0.2\end{bmatrix}=\begin{bmatrix}0.5 & 0.5 & 0.5\\ 0.5 & 0.7 & 0.5\\ 0.5 & 0.5 & 0.7\end{bmatrix}$$

Step-4: (element e4)➔Type-4: branch impedance Z_b connects Between two old buses



$$Z_{bus}=\begin{bmatrix}0.5 & 0.5 & 0.5 & 0.5-0.5\\ 0.5 & 0.7 & 0.5 & 0.5-0.7\\ 0.5 & 0.5 & 0.7 & 0.7-0.5\\ 0.5-0.5 & 0.5-0.7 & 0.7-0.5 & Z_{44}\end{bmatrix}=\begin{bmatrix}0.5 & 0.5 & 0.5 & 0\\ 0.5 & 0.7 & 0.5 & -0.2\\ 0.5 & 0.5 & 0.7 & 0.2\\ 0 & -0.2 & 0.2 & Z_{44}\end{bmatrix}$$

$$Z_{44}=Z_b+(Z_{33}+Z_{22}-2\times Z_{32})=0.2+(0.7+0.7-2\times 0.5)=0.6$$

$$Z_{bus}=\begin{bmatrix}0.5 & 0.5 & 0.5 & 0\\ 0.5 & 0.7 & 0.5 & -0.2\\ 0.5 & 0.5 & 0.7 & 0.2\\ 0 & -0.2 & 0.2 & 0.6\end{bmatrix}$$

Reduce the matrix size by one

$$Z_{11}^{new}=Z_{11}-\frac{Z_{14}\times Z_{41}}{Z_{44}}$$

$$Z_{11}^{new}=0.5-\frac{0\times 0}{0.4}=0.5$$

$$Z_{12}^{new}=Z_{12}-\frac{Z_{14}\times Z_{42}}{Z_{44}}=0.5-\frac{0\times 0}{0.4}=0.5$$

$$Z_{13}^{new}=Z_{13}-\frac{Z_{14}\times Z_{43}}{Z_{44}}=0.5-0=0.5$$

$$Z_{bus}=\begin{bmatrix}0.5 & 0.5 & 0.5 & 0\\ 0.5 & 0.7 & 0.5 & -0.2\\ 0.5 & 0.5 & 0.7 & 0.2\\ 0 & -0.2 & 0.2 & 0.6\end{bmatrix}$$

$$Z_{21}^{new}=Z_{12}^{new}$$

$$Z_{22}^{new}=Z_{22}-\frac{Z_{24}\times Z_{42}}{Z_{44}}=0.7-\frac{-0.2\times -0.2}{0.6}=0.633$$

$$Z_{23}^{new}=Z_{23}-\frac{Z_{24}\times Z_{43}}{Z_{44}}=0.5-\frac{-0.2\times 0.2}{0.6}=0.566$$

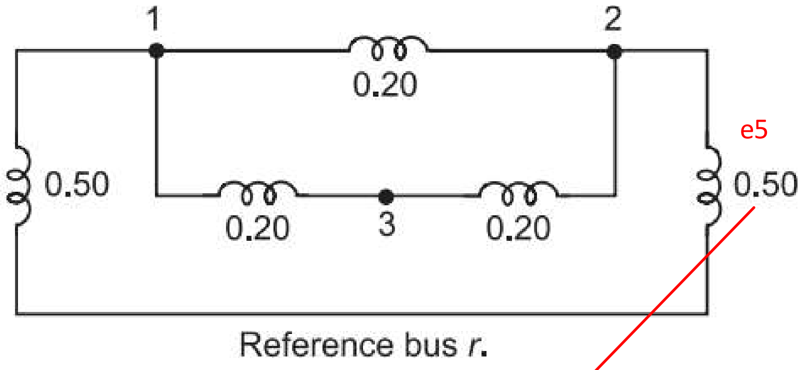
$$Z_{31}^{new}=Z_{13}^{new}$$

$$Z_{32}^{new}=Z_{23}^{new}$$

$$Z_{33}^{new}=Z_{33}-\frac{Z_{34}\times Z_{43}}{Z_{44}}=0.7-\frac{0.2\times 0.2}{0.4}=0.633$$

$$Z_{bus}=\begin{bmatrix}0.5 & 0.5 & 0.5\\ 0.5 & 0.633 & 0.566\\ 0.5 & 0.566 & 0.633\end{bmatrix}$$

Step-5: (element e5)➔ Type-3: branch impedance Z_b connects old bus to reference bus



$$Z_{bus}=\begin{bmatrix}0.5 & 0.5 & 0.5 & 0.5\\ 0.5 & 0.633 & 0.566 & 0.633\\ 0.5 & 0.566 & 0.633 & 0.566\\ 0.5 & 0.633 & 0.566 & 0.633+0.5\end{bmatrix}$$

$$Z_{bus}=\begin{bmatrix}0.5 & 0.5 & 0.5 & 0.5\\ 0.5 & 0.633 & 0.566 & 0.633\\ 0.5 & 0.566 & 0.633 & 0.566\\ 0.5 & 0.633 & 0.566 & 1.133\end{bmatrix}$$

Reduce the matrix size by one

$$Z_{11}^{new}=Z_{11}-\frac{Z_{14}\times Z_{41}}{Z_{44}}$$

$$Z_{11}^{new}=0.5-\frac{0.5\times 0.5}{1.133}=0.279$$

$$Z_{12}^{new}=Z_{12}-\frac{Z_{14}\times Z_{42}}{Z_{44}}=0.5-\frac{0.5\times 0.633}{1.133}=0.220$$

$$Z_{13}^{new} = Z_{13} - \frac{Z_{14} \times Z_{43}}{Z_{44}} = 0.5 - \frac{0.5 \times 0.566}{1.133} = 0.250$$

$$Z_{bus} = \left[\begin{tikzcd} 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.633 \arrow[rr] \arrow[dd] \arrow[rrdd] & 0.566 & 0.633 \\ 0.5 & 0.566 & 0.633 & 0.566 \\ 0.5 & 0.633 & 0.566 & 1.133 \end{tikzcd}\right]$$

$$Z_{21}^{new} = Z_{12}^{new}$$

$$Z_{22}^{new} = Z_{22} - \frac{Z_{24} \times Z_{42}}{Z_{44}} = 0.633 - \frac{0.633 \times 0.633}{1.133} = 0.279$$

$$Z_{23}^{new} = Z_{23} - \frac{Z_{24} \times Z_{43}}{Z_{44}} = 0.566 - \frac{0.633 \times 0.566}{1.133} = 0.249$$

$$Z_{31}^{new} = Z_{13}^{new}$$

$$Z_{32}^{new} = Z_{23}^{new}$$

$$Z_{33}^{new} = Z_{33} - \frac{Z_{34} \times Z_{43}}{Z_{44}} = 0.633 - \frac{0.566 \times 0.566}{1.133} = 0.350$$

$$Z_{bus} = j \times \begin{bmatrix} 0.279 & 0.220 & 0.250 \\ 0.220 & 0.279 & 0.249 \\ 0.250 & 0.249 & 0.350 \end{bmatrix}$$

Unit – II

Syllabus

UNIT II: POWER FLOW STUDIES

Necessity of Power Flow Studies – Data for Power Flow Studies – Derivation of Static load flow equations, classification of Buses and their relevance to Power Flow. **LOAD FLOW SOLUTION USING GAUSS SEIDEL METHOD:** Acceleration Factor, Load flow solution without and with P-V buses, Algorithm and Flowchart. Numerical Load flow Solution for Simple Power Systems (Max. 3-Buses): Determination of Bus Voltages, Injected Active and Reactive Powers (Sample One Iteration only) and finding Line Flows/Losses for the given Bus Voltages.
NEWTON RAPHSON METHOD IN RECTANGULAR AND POLAR CO-ORDINATES FORM: Load Flow Solution without and with PV Busses- Derivation of Jacobian Elements, Algorithm and Flowchart (Max. 3-Buses)
DECOUPLED AND FAST DECOUPLED METHODS: Comparison of Different Methods – DC load Flow.

What is the Necessity of Power Flow Studies?

Power flow studies are necessary for planning, economical operation, scheduling and exchange of power between utilities. It is also required for stability analysis, contingency analysis and state estimation.

The result of power flow studies gives the bus voltage magnitude and phase angle, real and reactive power injection at all the buses and **line loss**.

1. **Load flow** study is the steady state analysis of power system network.
2. Load flow study determines the operating state of the system for a given loading.
3. Load flow solves a set of simultaneous non linear algebraic power equations for the two unknown variables ($|V|$ and $\angle\delta$) at each node in a system.
4. To solve non linear algebraic equations it is important to have fast, efficient and accurate numerical algorithms.
5. The output of the load flow analysis is the voltage and phase angle, real and reactive power (both sides in each line), line losses and slack bus power

Bus Classification

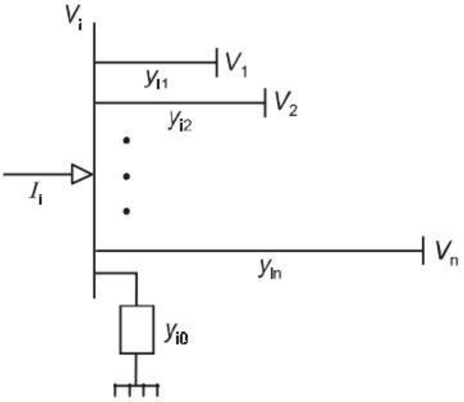
A bus is node has incoming and outgoing feeders. It is associated with four parameters; they are Voltage magnitude $|V|$, phase angle δ, real power P and reactive power Q.

Bus type	Specified quantity	To find quantity
Slack bus	$|V|$, δ	P, Q
Generator bus	P, $|V|$	Q, δ
Load bus	P, Q	$|V|$, δ

Basic steps for Power flow studies

1) Find Y_{bus} for the given power system
2) Make initial estimate for voltage
3) Find the equations for $|V|$, δ, P and Q
4) Find the error mismatch and stop when the error value is within tolerance

Bus loading equation



Net injected current I_i into the bus i can be written as:

$$I_i = y_{i0}V_i + y_{i1}(V_i - V_1) + y_{i2}(V_i - V_2) + \dots + y_{in}(V_i - V_n)$$

$$\therefore \quad I_i = (y_{i0} + y_{i1} + y_{i2} \dots y_{in})\, V_i - y_{i1}V_1 - y_{i2}V_2 \dots y_{in}V_n$$

Let us define

$$Y_{ii} = y_{i0} + y_{i1} + y_{i2} + \dots + y_{in}$$

$$Y_{i1} = -y_{i1}$$

$$Y_{i2} = -y_{i2}$$

$$\vdots$$

$$Y_{in} = -y_{in}$$

$$\therefore \quad I_i = Y_{ii}V_i + Y_{i1}V_1 + Y_{i2}V_2 + \dots + Y_{in}V_n$$

or

$$I_i = Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k$$

The real and reactive power injected at bus i is

$$P_i - jQ_i = V_i^* I_i$$

$$\therefore \quad I_i = \frac{P_i - jQ_i}{V_i^*}$$

From eqns (7.9) and (7.10) we get

$$\frac{P_i - jQ_i}{V_i^*} = Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k$$

$$\therefore \quad Y_{ii}V_i = \frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k$$

$$\boxed{V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k\right]}$$

Calculation of net Injected power

$$\frac{P_i - jQ_i}{V_i^*} = Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k$$

$$\therefore \qquad P_i - jQ_i = V_i^* \left[Y_{ii}V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k \right]$$

Let $\quad Y_{ii} = |Y_{ii}| \angle \theta_{ii}, \quad Y_{ik} = |Y_{ik}| \angle \theta_{ik}, \quad V_i = |V_i| \angle \delta_i$

$$\therefore \qquad V_i^* = |V_i| \angle -\delta_i, \quad V_k = |V_k| \angle \delta_k$$

$$\therefore \qquad P_i - jQ_i = |V_i|^2 |Y_{ii}| \angle \theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik}||V_i||V_k| \angle \theta_{ik} + \delta_k - \delta_i$$

$$\therefore \quad P_i - jQ_i = |V_i|^2 \, |Y_{ii}| \cos \theta_{ii} + j |V_i|^2 \, |Y_{ii}| \, \sin \theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik}||V_i||V_k| \cos(\theta_{ik} + \delta_k - \delta_i)$$

$$+ j \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik}||V_i||V_k| \sin(\theta_{ik} + \delta_k - \delta_i)$$

Separating real and imaginary part of eqn. (7.14)

$$P_i = |V_i|^2 \, |Y_{ii}| \cos \theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik}||V_i||V_k| \cos(\theta_{ik} + \delta_k - \delta_i)$$

$$\therefore \qquad P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k)$$

and

$$-Q_i = |V_i|^2 \, |Y_{ii}| \sin \theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} |Y_{ik}||V_i||V_k| \sin(\theta_{ik} + \delta_k - \delta_i)$$

$$\therefore \qquad Q_i = - \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k)$$

CONSIDERATION OF P-|*V*| BUSES

For *P*-*Q* buses, the real and reactive powers $P_i^{\text{scheduled}}$ and $Q_i^{\text{scheduled}}$ are known. Starting with initial values of the voltages, set of voltage equations can be solved iteratively. For the voltage-controlled buses (*P*-|*V*| buses), where $P_i^{\text{scheduled}}$ and $|V_i|$ are specified, first eqn. (7.16) is solved for Q_i^{p+1} i.e.

$$Q_i^{p+1} = -\sum_{k=1}^{n} |V_i|^p |V_k|^p |Y_{ik}| \sin(\theta_{ik} - \delta_i^p + \delta_k^p) \qquad ...(7.17)$$

Then set of voltage equations are solved. However, at *P*-|*V*| buses, since $|V_i|$ is specified, only the imaginary part of V_i^{p+1} is retained and its real part is selected in order to satisfy.

$$\left(e_i^{p+1}\right)^2 + \left(f_i^{p+1}\right)^2 = |V_i|^2 \qquad ...(7.18)$$

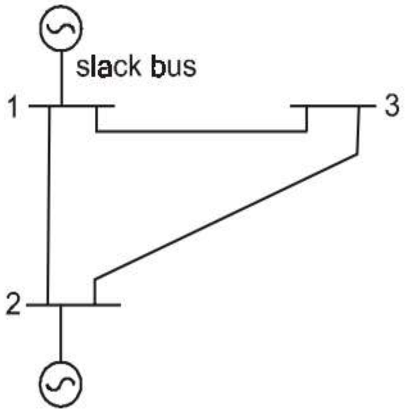
$$\therefore \qquad e_i^{p+1} = \left\{|V_i|^2 - \left(f_i^{p+1}\right)^2\right\}^{\frac{1}{2}} \qquad ...(7.19)$$

Where

e_i^{p+1} = real part of V_i^{p+1}

f_i^{p+1} = imagining part of V_i^{p+1}

Using Gauss Seidel method, determine the phasor values of the voltages at bus 2 and 3. Take base MVA=100.



Bus code *i* – *k*	Impedance Z_{ik}
1-2	0.02 + *j*0.04
1-3	0.01 + *j*0.03
2-3	0.0125 + *j*0.025

Bus code *i*	Assumed bus voltage	Generation		Load	
		MW	MVAr	MW	MVAr
1 (slack bus)	1.05 + *j*0.0	–	–	0	0
2	1 + *j*0.0	50	30	305.6	140.2
3	1 + *j*0.0	0.0	0.0	138.6	45.2

Step 1:

$$PL_2 = \frac{305.6}{100} = 3.056 \text{ pu}; \qquad QL_2 = \frac{140.2}{100} = 1.402 \text{ pu}$$

$$PL_3 = \frac{138.6}{100} = 1.386 \text{ pu}; \qquad QL_3 = \frac{45.2}{100} = 0.452 \text{ pu}$$

Convert all the generation in per-unit values.

$$P_{g2} = \frac{50}{100} = 0.50 \text{ pu}; \qquad Q_{g2} = \frac{30}{100} = 0.30 \text{ pu}$$

Compute net-injected power at bus 2 and 3.

$$P_2 = P_{g2} - P_{L2} = (0.5 - 3.056) = \boxed{-2.556 \text{ pu}}$$

$$Q_2 = Q_{g2} - Q_{L2} = (0.3 - 1.402) = \boxed{-1.102 \text{ pu}}$$

$$P_3 = P_{g3} - P_{L3} = 0 - 1.386 = -1.386 \text{ pu}$$

$$Q_3 = Q_{g3} - Q_{L3} = 0 - 0.452 = -0.452 \text{ pu}$$

Step 2: Y-Bus Formation

$$y_{12} = y_{21} = \frac{1}{Z_{12}} = \frac{1}{0.02 + j0.04} = (10 - j20)$$

$$y_{13} = y_{31} = \frac{1}{Z_{13}} = \frac{1}{(0.01 + j0.03)} = (10 - j30)$$

$$y_{23} = y_{32} = \frac{1}{Z_{23}} = \frac{1}{(0.0125 + j0.025)} = (16 - j32)$$

$$Y_{11} = y_{12} + y_{13} = (10 - j20) + (10 - j30) = (20 - j50)$$

$$Y_{22} = y_{21} + y_{23} = y_{12} + y_{23} = (26 - j52)$$

$$Y_{33} = y_{13} + y_{23} = (26 - j62)$$

$$Y_{11} = 53.85\angle{-68.2^\circ}; \qquad Y_{22} = 58.13\angle{-63.4^\circ}$$

$$Y_{33} = 67.23\angle{-67.2^\circ}$$

$$Y_{12} = -y_{12} = -(10 - j20) = -10 + j20 = 22.36\angle{116.6^\circ}$$

$$Y_{12} = Y_{21}$$

$$Y_{13} = Y_{31} = -y_{13} = -(10 - j30) = 31.62\angle{108.4^\circ}$$

$$Y_{23} = Y_{32} = -y_{23} = -(16 - j32) = 35.77\angle{116.6^\circ}$$

$$Y_{\text{BUS}} = \begin{bmatrix} 53.85\angle -68.2^\circ & 22.36\angle 116.6^\circ & 31.62\angle 108.4^\circ \\ \boxed{22.36\angle 116.6^\circ} & \boxed{58.13\angle -63.4^\circ} & \boxed{35.77\angle 116.6^\circ} \\ 31.62\angle 108.4^\circ & 35.77\angle 116.6^\circ & 67.23\angle -67.2^\circ \end{bmatrix}$$

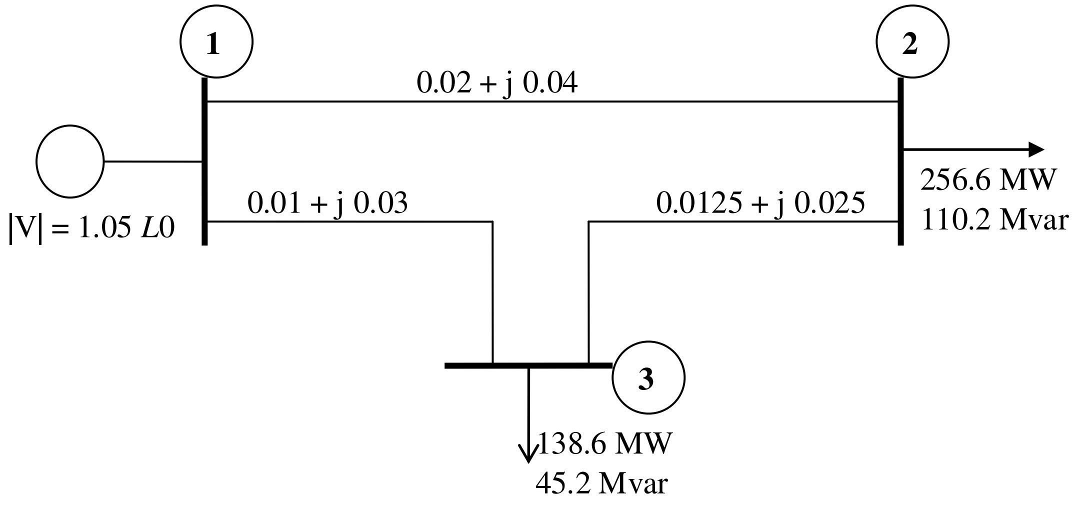
Step 3: Voltage calculation

$$V_2^{(p+1)} = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{\left(V_2^{(p)}\right)^*} - Y_{21}V_1 - Y_{23}V_3^{(p)}\right]$$

$$V_3^{(p+1)} = \frac{1}{Y_{33}}\left[\frac{P_3 - jQ_3}{\left(V_3^{(p)}\right)^*} - Y_{31}V_1 - Y_{32}V_2^{(p+1)}\right]$$

$$\boxed{\begin{aligned} V_2^{(1)} &= 0.98305\angle -1.8^\circ \\ V_3^{(1)} &= 1.0011\angle -2.06^\circ \end{aligned}}$$

2) Find the bus voltages at the end of first iteration using GS method. Take base MVA as 100.



Step 1:

PL_2 = 256.6 MW / 100 MVA = 2.566 PU

QL_2 = 110.2 MVAR / 100 MVA = 1.102 PU

PL_3 = 138.6 / 100 = 1.386 PU

QL_3 = 45.2 / 100 = 0.452 PU

P_2 = PG_2 - PL_2 = -2.566 PU

Q_2 = QG_2 - QL_2 = -1.102 PU

P_3 = PG_3 - PL_3 = -1.386 PU

Q_3 = QG_3 – QL_3 = -0.452 PU

Step 2:

Diagonal Elements

Y_{11} = (1/(0.02+0.04i))+(1/(0.01+0.03i)) = **20-50i = 53.8516∟-68.2332**

Y_{22} = (1/(0.02+0.04i))+(1/(0.0125+0.025i)) = **26-52i = 58.1378∟-63.4671**

Y_{33} = (1/(0.01+0.03i))+(1/(0.0125+0.025i)) = **26-62i = 67.2309∟-67.2831**

Off – Diagonal Elements

Y_{12} = -1/(0.02+0.04i) = **-10+20i = 22.3607∟116.6242**

Y_{13} = -1/(0.01+0.03i) = **-10+30i = 31.6228∟108.4899**

Y_{23} = -1/(0.0125+0.025i) = **-16+32i = 35.7771∟116.6242**

$$Y_{bus} = \begin{bmatrix} 53.8516\angle -68.2332 & 22.3607\angle 116.6242 & 31.6228\angle 108.4899 \\ 22.3607\angle 116.6242 & 58.1378\angle -63.4671 & 35.7771\angle 116.6242 \\ 31.6228\angle 108.4899 & 35.7771\angle 116.6242 & 67.2309\angle -67.2831 \end{bmatrix}$$

Step 3: Finding bus voltages

Zeroth iteration

V_1 = 1.05 ∟0

V_2^0 = 1 + j 0 = 1.0 ∟0 ➔ Assumed value

V_3^0 = 1 + j 0 = 1.0 ∟0 ➔ Assumed value

First iteration

V_2^1 = ?

$$V_2^1 = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{(V_2^0)^*} - Y_{21}V_1 - Y_{23}V_3^0\right]$$

$$V_2^1 = \frac{1}{58.1378\angle -63.4671}\left[\frac{\text{-} 2.566 + \text{j}1.102}{1.0} - 22.3607\angle 116.6242 \times (1.05) - 35.771\angle 116.6242 \times (1)\right]$$

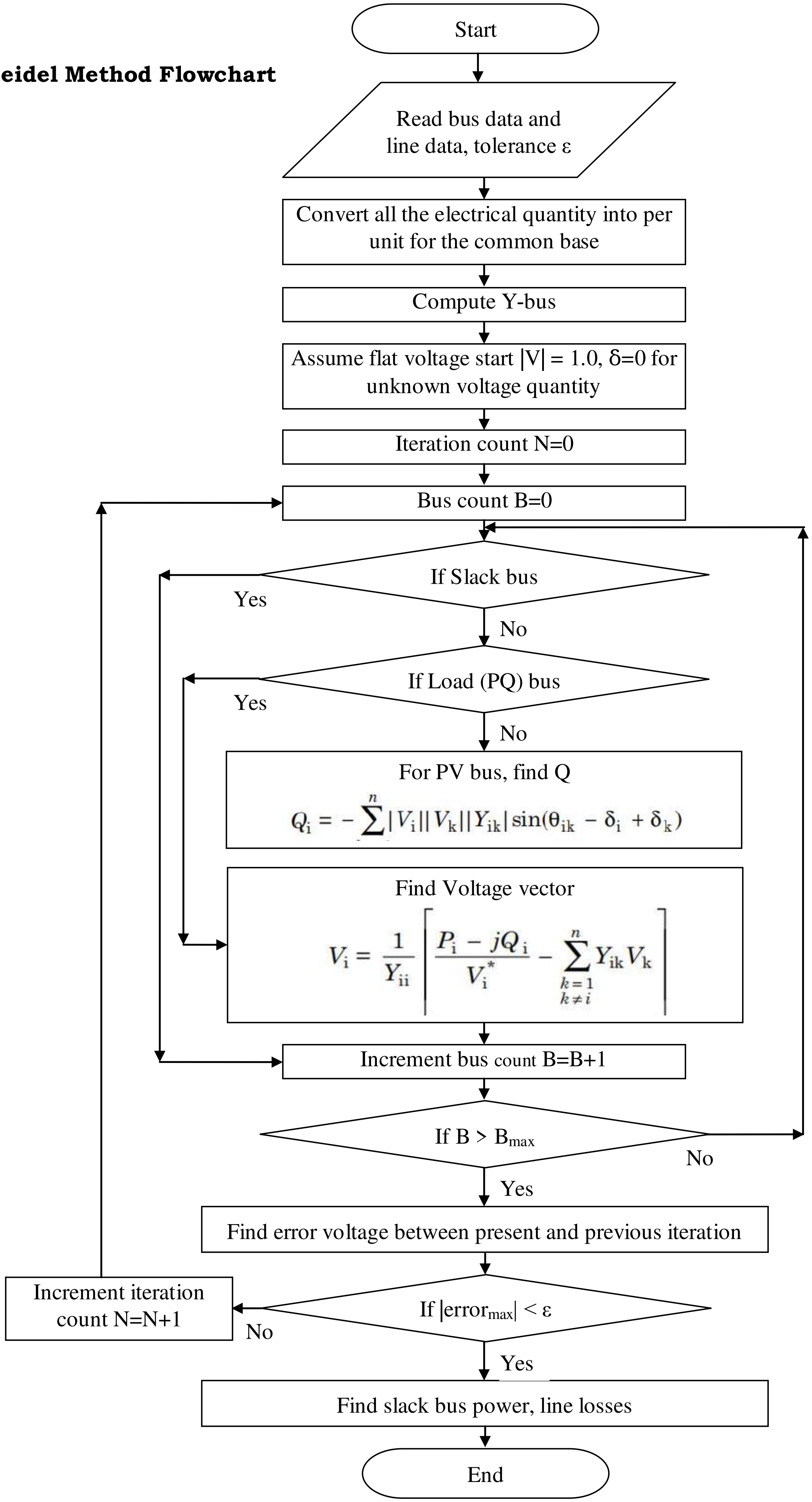
=0.9825-j0.031 = **0.983∟-1.808**

$$V_3^1 = \frac{1}{Y_{33}}\left[\frac{P_3 - jQ_3}{(V_3^0)^*} - Y_{31}V_1 - Y_{32}V_2^1\right]$$

$$V_3^1 = \frac{1}{67.2309\angle -67.2831}\left[\frac{\text{-}1.386 + 0.452\text{i}}{(1.0)} - 31.6228\angle 108.4899 \times (1.05) - 35.7771\angle 116.6242 \times (0.983\angle \text{-}1.808)\right]$$

= 1.0 – j0.0353 = **1.0 ∟-2.022**

Gauss Seidel Method Flowchart



What is Acceleration Factor?

An acceleration factor is a value that can be used to **speed up the convergence** and reduce the number of required alteration in a Gauss Seidel method of power flow analysis. It is denoted by α and the value is from 1.2 to 2.0.

$$V_i^{k+1}{}_{Accelerated} = V_i^k + \alpha(V_i^{k+1} - V_i^k)$$

How to handle Load flow solution without and with P-V buses?

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_k)$$

$$\boxed{V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik}V_k\right]}$$

NEWTON RAPHSON (NR) METHOD

$$P_{\mathrm{i}} = \sum_{k=1}^{n} |V_{\mathrm{i}}||V_{\mathrm{k}}||Y_{\mathrm{ik}}| \cos(\theta_{\mathrm{ik}} - \delta_{\mathrm{i}} + \delta_{\mathrm{k}}) \qquad \text{...(7.50)}$$

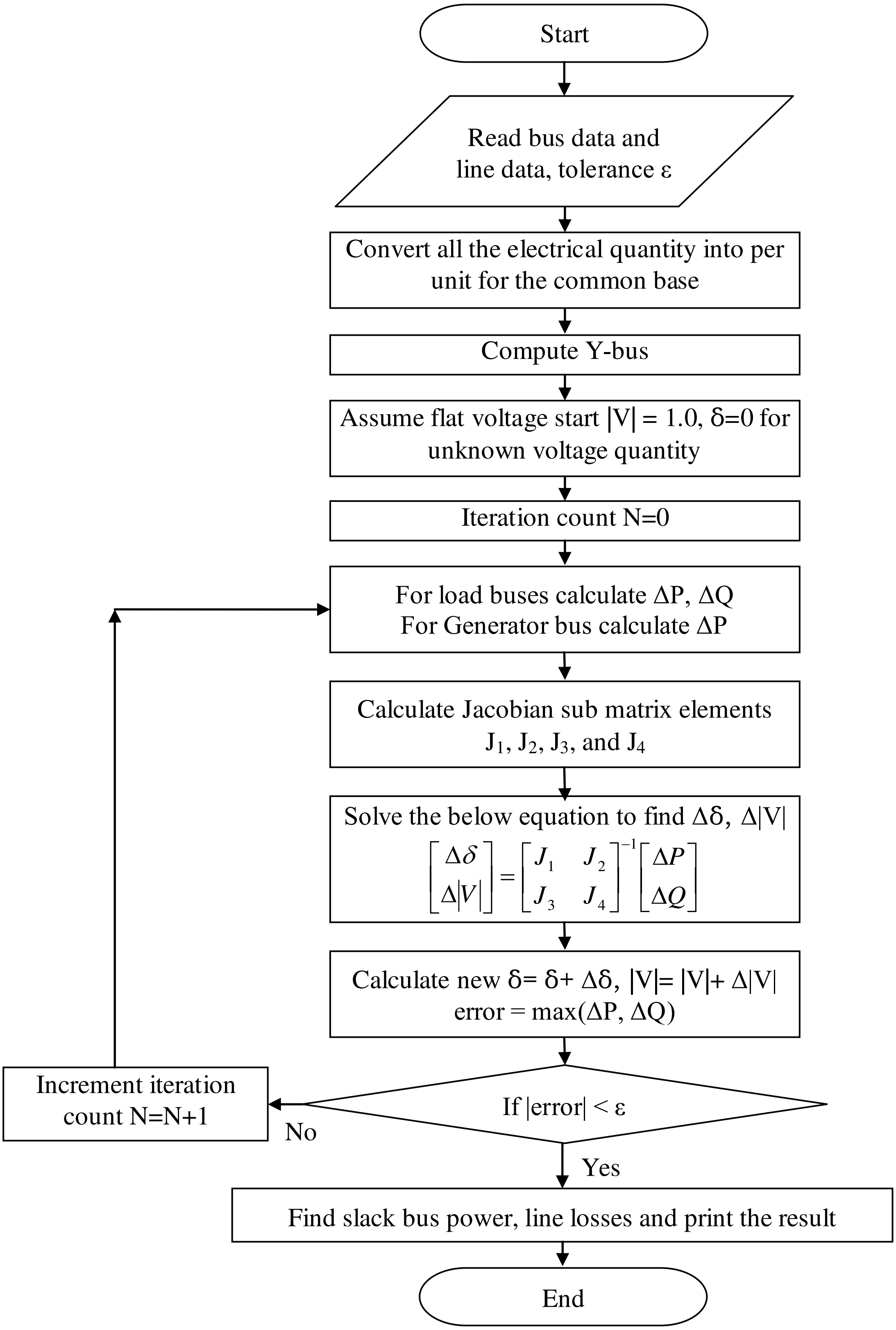
$$Q_{\mathrm{i}} = -\sum_{k=1}^{n} |V_{\mathrm{i}}||V_{\mathrm{k}}||Y_{\mathrm{ik}}| \sin(\theta_{\mathrm{ik}} - \delta_{\mathrm{i}} + \delta_{\mathrm{k}}) \qquad \text{...(7.51)}$$

$$\therefore \left[\begin{array}{c} \Delta P_2^{(\mathrm{p})} \\ \vdots \\ \Delta P_{\mathrm{n}}^{(\mathrm{p})} \\ \hline \Delta Q_2^{(\mathrm{p})} \\ \vdots \\ \Delta Q_{\mathrm{n}}^{(\mathrm{p})} \end{array}\right] = \left[\begin{array}{ccc|ccc} \left(\frac{\partial P_2}{\partial \delta_2}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial P_2}{\partial \delta_{\mathrm{n}}}\right)^{(\mathrm{p})} & \left(\frac{\partial P_2}{\partial |V_2|}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial P_2}{\partial |V_{\mathrm{n}}|}\right)^{(\mathrm{p})} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \left(\frac{\partial P_{\mathrm{n}}}{\partial \delta_2}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial P_{\mathrm{n}}}{\partial \delta_{\mathrm{n}}}\right)^{(\mathrm{p})} & \left(\frac{\partial P_{\mathrm{n}}}{\partial |V_2|}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial P_{\mathrm{n}}}{\partial |V_{\mathrm{n}}|}\right)^{(\mathrm{p})} \\ \hline \left(\frac{\partial Q_2}{\partial \delta_2}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial Q_2}{\partial \delta_{\mathrm{n}}}\right)^{(\mathrm{p})} & \left(\frac{\partial Q_2}{\partial |V_2|}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial Q_2}{\partial |V_{\mathrm{n}}|}\right)^{(\mathrm{p})} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \left(\frac{\partial Q_{\mathrm{n}}}{\partial \delta_2}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial Q_{\mathrm{n}}}{\partial \delta_{\mathrm{n}}}\right)^{(\mathrm{p})} & \left(\frac{\partial Q_{\mathrm{n}}}{\partial |V_2|}\right)^{(\mathrm{p})} & \cdots & \left(\frac{\partial Q_{\mathrm{n}}}{\partial |V_{\mathrm{n}}|}\right)^{(\mathrm{p})} \end{array}\right] \left[\begin{array}{c} \Delta \delta_2^{(\mathrm{p})} \\ \vdots \\ \Delta \delta_{\mathrm{n}}^{(\mathrm{p})} \\ \hline \Delta |V_2|^{(\mathrm{p})} \\ \vdots \\ \Delta |V_{\mathrm{n}}|^{(\mathrm{p})} \end{array}\right] \qquad \text{...(7.52)}$$

In the above equation, bus-1 is assumed to be the slack bus.

Eqn. (7.52) can be written is short form i.e.,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad \text{...(7.53)}$$



NEWTON RAPHSON (NR) Method Flowchart

7.13 DECOUPLED LOAD FLOW SOLUTION

Transmission lines of power systems have a very low R/X ratio. For such system, real power mismatch ΔP are less sensitive to changes in the voltage magnitude and are very sensitive to changes in phase angle $\Delta\delta$. Similarly, reactive power mismatch ΔQ is less sensitive to changes in angle and are very much sensitive on changes in voltage magnitude. Therefore, it is reasonable to set elements J_2 and J_3 of the Jacobain matrix to zero. Therefore, eqn. (7.53) reduces to

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad ...(7.54)$$

or

$$\Delta P = J_1.\Delta\delta \quad ...(7.55)$$

$$\Delta Q = J_4.\Delta|V| \quad ...(7.56)$$

For voltage controlled buses, the voltage magnitudes are known. Therefore, if m buses of the system are voltage controlled, J_1 is of the order $(n-1) \times (n-1)$ and J_4 is of the order $(n-1-m) \times (n-1-m)$.

Now the diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k\neq i}}^{n} |V_i||V_k||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_k) \quad ...(7.57)$$

off-diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_k} = -|V_i||V_k||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_k)_{k\neq i} \quad ...(7.58)$$

The diagonal elements of J_4 are

$$\frac{\partial Q_i}{\partial |V_i|} = -2|V_i||Y_{ii}|\sin\theta_{ii} - \sum_{\substack{k=1 \\ k\neq i}}^{n} |V_k||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_k) \quad ...(7.59)$$

$$\frac{\partial Q_i}{\partial |V_k|} = -|V_i||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_k)_{k\neq i} \quad ...(7.60)$$

The terms $\Delta P_i^{(p)}$ and $\Delta Q_i^{(p)}$ are the difference between the scheduled and calculated values at bus i known as power residuals, given by

$$\Delta P_i^{(p)} = P_i^{\text{scheduled}} - P_{i\,(\text{calculated})}^{(p)} \quad ...(7.61)$$

$$\Delta Q_i^{(p)} = Q_i^{\text{scheduled}} - Q_{i\,(\text{calculated})}^{(p)} \quad ...(7.62)$$

The new estimates for bus voltage magnitudes and angles are,

$$|V_i|^{(p+1)} = |V_i|^{(p)} + \Delta|V_i|^{(p)} \quad ...(7.63)$$

$$\delta_i^{(p+1)} = \delta_i^{(p)} + \Delta\delta_i^{(p)} \quad ...(7.64)$$

7.14 DECOUPLED LOAD FLOW ALGORITHM

Step-1: Read system data

Step-2: Form Y_{BUS} matrix

Step-3: For load buses $P_i^{\text{scheduled}}$ and $Q_i^{\text{scheduled}}$ are specified. Voltage magnitudes and phase angles are set equal to the slack bus values, or $|V_i| = 1.0$, $|\delta_i| = 0.0$ radian.

For voltage controlled buses, where $|V_i|$ and $P_i^{\text{scheduled}}$ are specified, phase angles are set equal to the slack bus angle, i.e. $\delta_i^{(0)} = 0.0$ radian.

Step-4: For load buses, $P_i^{(p)}$ and $Q_i^{(p)}$ are calculated using eqns. (7.50) and (7.51) and $\Delta P_i^{(p)}$ and $\Delta Q_i^{(p)}$ are calculated from eqns. (7.61) and (7.62).

Step-5: For voltage controlled buses, $P_i^{(p)}$ and $\Delta P_i^{(p)}$ are computed using eqns. (7.50) and (7.61) respectively.

Step-6: Compute elements of J_1 and J_4 using equations (7.57) – (7.60).

Step-7: Solve equations (7.55) and (7.56) for computing $\Delta\delta$ and $\Delta|V|$.

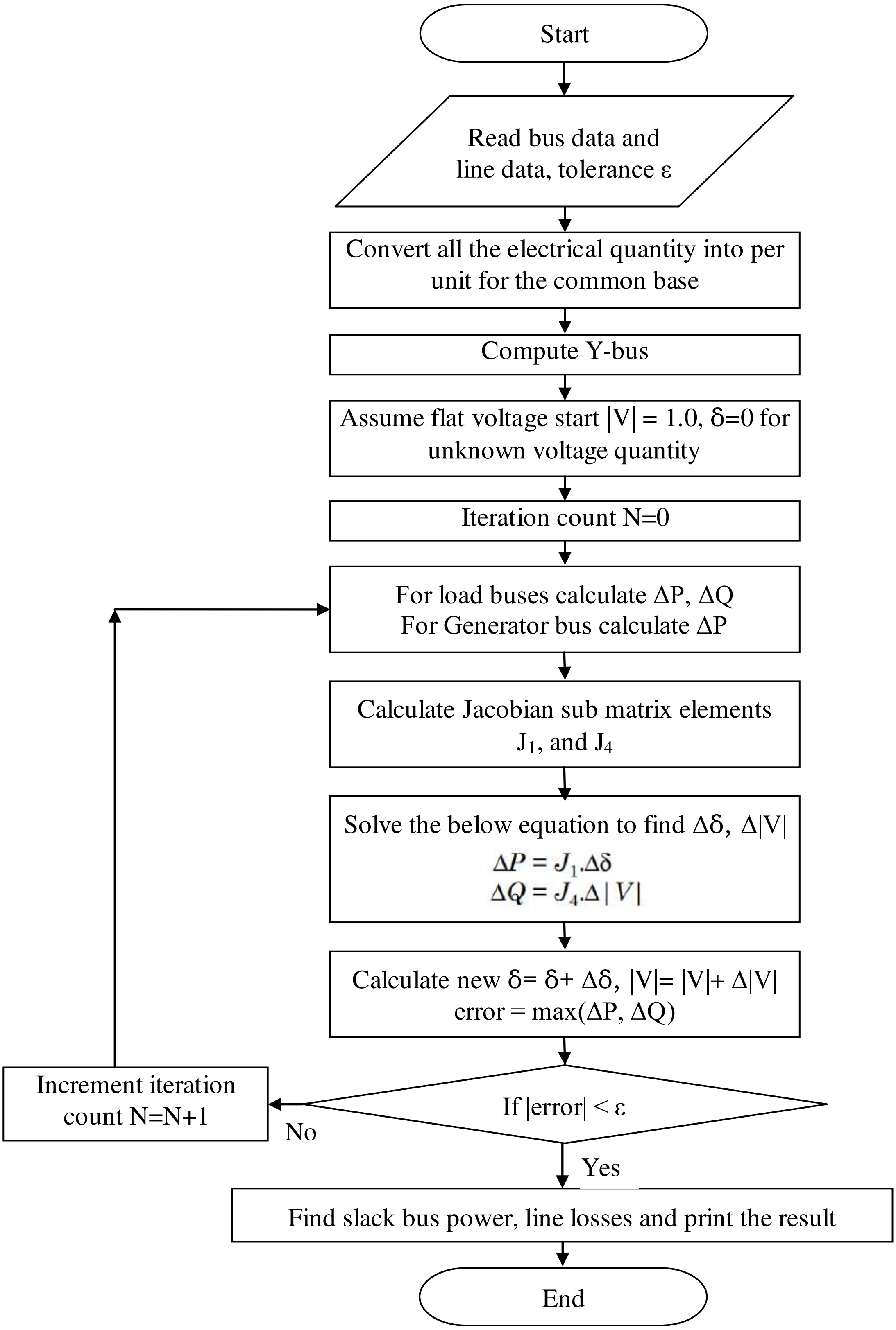
Step-8: Compute new voltage magnitudes and phase angles using eqns. (7.63) and (7.64).

Step-9: Check for convergence, i.e. if

$\max|\Delta P_i^{(p)}| \le \in$ and

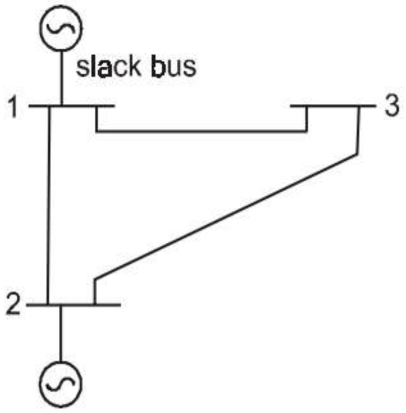
$\max|\Delta Q_i^{(p)}| \le \in$., solution has converged go to Step-10, otherwise, go to step-4.

Step-10: Print output results.



Decoupled Method Flowchart

Using Decoupled method, determine the phasor values of the voltages at bus 2 and 3. Take base MVA=100.



Bus code *i* – *k*	Impedance Z_{ik}
1-2	0.02 + *j*0.04
1-3	0.01 + *j*0.03
2-3	0.0125 + *j*0.025

		Generation		Load	
Bus code *i*	Assumed bus voltage	MW	MVAr	MW	MVAr
1 (slack bus)	1.05 + *j*0.0	–	–	0	0
2	1 + *j*0.0	50	30	305.6	140.2
3	1 + *j*0.0	0.0	0.0	138.6	45.2

Step 1:

$$PL_2 = \frac{305.6}{100} = 3.056 \text{ pu}; \qquad QL_2 = \frac{140.2}{100} = 1.402 \text{ pu}$$

$$PL_3 = \frac{138.6}{100} = 1.386 \text{ pu}; \qquad QL_3 = \frac{45.2}{100} = 0.452 \text{ pu}$$

Convert all the generation in per-unit values.

$$P_{g2} = \frac{50}{100} = 0.50 \text{ pu}; \qquad Q_{g2} = \frac{30}{100} = 0.30 \text{ pu}$$

Compute net-injected power at bus 2 and 3.

$$P_2 = P_{g2} - P_{L2} = (0.5 - 3.056) = \boxed{-2.556 \text{ pu}}$$

$$Q_2 = Q_{g2} - Q_{L2} = (0.3 - 1.402) = \boxed{-1.102 \text{ pu}}$$

$$P_3 = P_{g3} - P_{L3} = 0 - 1.386 = -1.386 \text{ pu}$$

$$Q_3 = Q_{g3} - Q_{L3} = 0 - 0.452 = -0.452 \text{ pu}$$

Step 2: Y-Bus Formation

$$y_{12} = y_{21} = \frac{1}{Z_{12}} = \frac{1}{0.02 + j0.04} = (10 - j20)$$

$$y_{13} = y_{31} = \frac{1}{Z_{13}} = \frac{1}{(0.01 + j0.03)} = (10 - j30)$$

$$y_{23} = y_{32} = \frac{1}{Z_{23}} = \frac{1}{(0.0125 + j0.025)} = (16 - j32)$$

$$Y_{11} = y_{12} + y_{13} = (10 - j20) + (10 - j30) = (20 - j50)$$
$$Y_{22} = y_{21} + y_{23} = y_{12} + y_{23} = (26 - j52)$$
$$Y_{33} = y_{13} + y_{23} = (26 - j62)$$
$$Y_{11} = 53.85 \angle -68.2° \,; \qquad Y_{22} = 58.13 \angle -63.4°$$
$$Y_{33} = 67.23 \angle -67.2°$$

$$Y_{12} = -y_{12} = -\ (10 - j20) = -10 + j20 = 22.36 \angle 116.6°$$
$$Y_{12} = Y_{21}$$
$$Y_{13} = Y_{31} = -y_{13} = -\ (10 - j30) = 31.62 \angle 108.4°$$

$$Y_{23} = Y_{32} = -y_{23} = -\ (16 - j32) = 35.77 \angle 116.6°$$

$$Y_{BUS} = \begin{bmatrix} 53.85 \angle -68.2° & 22.36 \angle 116.6° & 31.62 \angle 108.4° \\ \boxed{22.36 \angle 116.6°} & \boxed{58.13 \angle -63.4°} & \boxed{35.77 \angle 116.6°} \\ 31.62 \angle 108.4° & 35.77 \angle 116.6° & 67.23 \angle -67.2° \end{bmatrix}$$

Step 3:

From eqns. (7.50) and (7.51)

$$P_2 = |V_2|\,|V_1|\,|Y_{21}|\cos(\theta_{21} - \delta_2 + \delta_1) + |V_2|^2 |Y_{22}|\cos\theta_{22}$$
$$+\ |V_2|\,|V_3|\,|Y_{23}|\cos(\theta_{23} - \delta_2 + \delta_3)$$
$$P_3 = |V_3|\,|V_1|\,Y_{31}|\cos(\theta_{31} - \delta_3 + \delta_1) + |V_3|\,|V_2|\,|Y_{32}|$$
$$\cos(\theta_{32} - \delta_3 + \delta_2) +\ |V_3|^2 |Y_{33}|\cos\theta_{33}$$
$$Q_2 = -|V_2|\,|V_1|\,|Y_{21}|\sin(\theta_{21} - \delta_3 + \delta_1) - |V_2|^2 |Y_{22}|$$
$$\sin\theta_{22} -\ |V_2|\,|V_3|\,|Y_{23}|\sin(\theta_{23} - \delta_2 + \delta_3)$$
$$Q_3 = -|V_3|\,|V_1|\,|Y_{31}|\sin(\theta_{31} - \delta_3 + \delta_1) - |V_3|\,|V_2|\,|Y_{32}|$$
$$\sin(\theta_{32} - \delta_3 + \delta_2) - |V_3|^2 |Y_{33}|\sin\theta_{33}$$

$$\frac{\partial P_2}{\partial \delta_2} = |V_2||V_1||Y_{21}|\sin(\theta_{21} - \delta_2 + \delta_1) + |V_2||V_3||Y_{23}|\sin(\theta_{23} - \delta_2 + \delta_3)$$

$$\frac{\partial P_2}{\partial \delta_3} = -|V_2||V_3||Y_{23}|\sin(\theta_{23} - \delta_2 + \delta_3)$$

$$\frac{\partial P_3}{\partial \delta_2} = -|V_3||V_2||Y_{32}|\sin(\theta_{32} - \delta_3 + \delta_2)$$

$$\frac{\partial P_3}{\partial \delta_3} = |V_3||V_1||Y_{31}|\sin(\theta_{31} - \delta_3 + \delta_1) + |V_3||V_2||Y_{32}|\sin(\theta_{32} - \delta_3 + \delta_2)$$

$$\frac{\partial Q_2}{\partial |V_2|} = -|V_1||Y_{21}|\sin(\theta_{21} - \delta_2 + \delta_1) - 2|V_2||Y_{22}|\sin\theta_{22} - |V_3||Y_{23} \sin(\theta_{23} - \delta_2 + \delta_3)$$

$$\frac{\partial Q_2}{\partial |V_3|} = -|V_2||Y_{23}|\sin(\theta_{23} - \delta_2 + \delta_3)$$

$$\frac{\partial Q_3}{\partial |V_2|} = -|V_3||Y_{32}|\sin(\theta_{32} - \delta_3 + \delta_2)$$

$$\frac{\partial Q_3}{\partial |V_3|} = -|V_1||Y_{31}|\sin(\theta_{31} - \delta_3 + \delta_1) - |V_2||Y_{32}|\sin(\theta_{32} - \delta_3 + \delta_2) - 2|V_3||Y_{33}|\sin\theta_{33}$$

Data

$|Y_{22}| = 58.13$, $\theta_{22} = -1.106$ rad $= -63.4°$

$|Y_{33}| = 67.23$, $\theta_{33} = -1.173$ rad $= -67.2°$

$|Y_{21}| = 22.36$, $\theta_{21} = 116.6° = 2.034$ rad

$|Y_{23}| = 35.77$, $\theta_{23} = 116.6° = 2.034$ rad

$|Y_{31}| = 31.62$, $\theta_{31} = 108.4° = 1.892$ rad

$|V_1| = 1.05$, $\delta_1 = 0.0$ rad, $|V_2|^{(0)} = 1.0$, $\delta_2^{(0)} = 0.0$ rad

$|V_3|^{(0)} = 1.0$, $\delta_3^{(0)} = 0.0$ rad

$$\frac{\partial P_2}{\partial \delta_2} = |V_2||V_1||Y_{21}|\sin(\theta_{21} - \delta_2 + \delta_1) + |V_2||V_3||Y_{23}|\sin(\theta_{23} - \delta_2 + \delta_3)$$

$$\frac{\partial P_2}{\partial \delta_2} = 1.05 \times 22.36 \sin(116.6°) + 35.77 \sin(116.6°) = 52.97$$

$$\frac{\partial P_2}{\partial \delta_3} = -|V_2||V_3||Y_{23}|\sin(\theta_{23} - \delta_2 + \delta_3)$$

$$\frac{\partial P_3}{\partial \delta_2} = -35.77 \sin(116.6°) = -31.98$$

$$\frac{\partial P_3}{\partial \delta_3} = 1.05 \times 31.62 \sin(108.4°) + 35.77 \sin(116.6°) = 63.48$$

$$\frac{\partial Q_2}{\partial |V_2|} = -1.05 \times 22.36 \sin(116.6°) - 2 \times 58.13 \times \sin(-63.4°) - 35.77 \times \sin(116.6°)$$

$$= -21 + 103.95 - 31.98 = 50.97$$

$$\frac{\partial Q_3}{\partial |V_3|} = -1.05 \times 31.62 \times \sin(108.4°) - 35.77 \times \sin(116.6°) - 2 \times 67.23 \times \sin(-67.2°)$$

$$= -31.50 - 31.98 + 123.95 = 60.47$$

$$\frac{\partial Q_3}{\partial |V_2|} = -35.77 \sin(116.6°) = -31.98$$

$$J_1^{(0)} = \begin{bmatrix} 52.97 & -31.98 \\ -31.98 & 63.48 \end{bmatrix}$$

$$J_4^{(0)} = \begin{bmatrix} 50.97 & -31.98 \\ -31.98 & 60.47 \end{bmatrix}$$

For this problem J_1 and J_4 as computed above, assumed constant throughtout the iterative process

$$P_{2(\text{cal})}^{(0)} = 1.05 \times 22.36 \cos(116.6°) + 58.13 \cos(-63.4°) + 35.77 \cos(116.6°)$$

$$\therefore \quad P_{2(\text{cal})}^{(0)} = -0.50$$

$$P_{3(\text{cal})}^{(0)} = 1.05 \times 31.62 \cos(108.4°) + 35.77 \cos(116.6°) + 67.23 \cos(-67.2°)$$

$$\therefore \quad P_{3(\text{cal})}^{(0)} = -0.44$$

$$Q_{2(\text{cal})}^{(0)} = -1.05 \times 22.36 \sin(116.6°) - 58.13 \sin(-63.4°) - 35.77 \sin(116.6°)$$

$$\therefore \quad Q_{2(\text{cal})}^{(0)} = -1.0$$

$$Q_{3(\text{cal})}^{(0)} = -1.05 \times 31.62 \sin(108.4°) - 35.77 \sin(116.6°) - 67.23 \times \sin(-67.2°)$$

$$\therefore \quad Q_{3(\text{cal})}^{(0)} = -1.503$$

$$P_{2(\text{sch})} = -2.556$$

$$P_{3(\text{sch})} = -1.386$$

$$Q_{2(\text{sch})} = -1.102$$

$$Q_{3(\text{sch})} = -0.452$$

$$\Delta P_2^{(0)} = P_{2(\text{sch})} - P_{2(\text{cal})}^{(0)} = -2.556 - (-0.5) = -2.056$$

$$\Delta P_3^{(0)} = P_{3(\text{sch})} - P_{3(\text{cal})}^{(0)} = -1.386 - (-0.44) = -0.946$$

$$\Delta Q_2^{(0)} = Q_{2(\text{sch})} - Q_{2(\text{cal})}^{(0)} = -1.102 - (-1) = -0.102$$

$$\Delta Q_3^{(0)} = Q_{3(\text{sch})} - Q_{3(\text{cal})}^{(0)} = -0.452 - (-1.503) = 1.051$$

$$\therefore \begin{bmatrix} \Delta P_2^{(0)} \\ \Delta P_3^{(0)} \end{bmatrix} = \begin{bmatrix} 52.97 & -31.98 \\ -31.98 & 63.48 \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(0)} \\ \Delta \delta_3^{(0)} \end{bmatrix}$$

$$\therefore \begin{bmatrix} \Delta \delta_2^{(0)} \\ \Delta \delta_3^{(0)} \end{bmatrix} = \begin{bmatrix} 52.97 & -31.98 \\ -31.98 & 63.48 \end{bmatrix}^{-1} \begin{bmatrix} -2.056 \\ -0.946 \end{bmatrix}$$

$$\therefore \quad \Delta \delta_2^{(0)} = -0.0687 \text{ radian} = -3.936°$$

$$\therefore \quad \Delta \delta_3^{(0)} = -0.0495 \text{ radian} = -2.837°$$

Similarly

$$\therefore \begin{bmatrix} \Delta Q_2^{(0)} \\ \Delta Q_3^{(0)} \end{bmatrix} = \begin{bmatrix} 50.97 & -31.98 \\ -31.98 & 60.47 \end{bmatrix} \begin{bmatrix} \Delta |V_2|^{(0)} \\ \Delta |V_3|^{(0)} \end{bmatrix}$$

$$\therefore \begin{bmatrix} \Delta |V_2|^{(0)} \\ \Delta |V_3|^{(0)} \end{bmatrix} = \begin{bmatrix} 50.97 & -31.98 \\ -31.98 & 60.47 \end{bmatrix}^{-1} \begin{bmatrix} -0.102 \\ 1.051 \end{bmatrix}$$

$$\therefore \quad \Delta |V_2|^{(0)} = 0.01332$$

$$\Delta |V_3|^{(0)} = 0.0244$$

$$\therefore \quad \delta_2^{(1)} = \delta_2^{(0)} + \Delta \delta_2^{(0)} = -0.0687 \text{ radian} = -3.936°$$

$$\delta_3^{(1)} = \delta_3^{(0)} + \Delta \delta_3^{(0)} = -0.0495 \text{ radian} = -2.837°$$

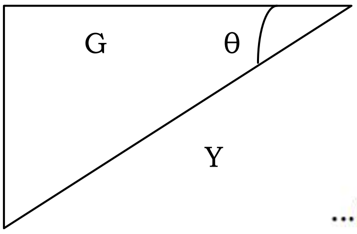
$$|V_2|^{(1)} = |V_2|^{(0)} + \Delta |V_2|^{(0)} = 1.0 + 0.01332 = 1.01332$$

$$|V_3|^{(1)} = |V_3|^{(0)} + \Delta |V_3|^{(0)} = 1.0 + 0.0244 = 1.0244$$

7.15 FAST DECOUPLED LOAD FLOW

The diagonal elements of J_1 described by eqn. (7.57) may be written as:

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{k=1}^{n} |V_i|\,|V_k|\,|Y_{ik}|\,\sin(\theta_{ik} - \delta_i + \delta_k) - |V_i|^2\,|Y_{ii}|\,\sin\theta_{ii} \qquad \ldots(7.65)$$



Using eqns. (7.65) and (7.51), we get

$$\frac{\partial P_i}{\partial \delta_i} = -Q_i - |V_i|^2\,|Y_{ii}|\,\sin\theta_{ii}$$

$$\therefore \qquad \frac{\partial P_i}{\partial \delta_i} = -Q_i - |V_i|^2 B_{ii} \qquad \ldots(7.66)$$

where $B_{ii} = |Y_{ii}|\,\sin\theta_{ii}$ is the imaginary part of the diagonal elements of the bus admittance matrix. In a practical power system, $B_{ii} >> Q_i$ and hence we may neglect Q_i. Further simplification is obtained by assuming $|V_i|^2 \approx |V_i|$, which gives,

$$\frac{\partial P_i}{\partial \delta_i} = -|V_i|B_{ii} \qquad \ldots(7.67)$$

Under normal operating conditions, $\delta_k - \delta_i$ is quite small. Therefore, $\theta_{ik} - \delta_i + \delta_k \approx \theta_{ik}$ and eqn. (7.58) reduces to

$$\frac{\partial P_i}{\partial \delta_k} = -|V_i|\,|V_k|B_{ik}$$

Assuming $|V_k| \approx 1.0$

$$\frac{\partial P_i}{\partial \delta_k} = -|V_i|B_{ik} \qquad \ldots(7.68)$$

Similarly, the diagonal elements of J_4 as given by eqn. (7.59) may be written as:

$$\frac{\partial Q_i}{\partial |V_i|} = -|V_i|\,|Y_{ii}|\sin\theta_{ii} - \sum_{k=1}^{n} |V_i|\,|V_k|\,|Y_{ik}|\,\sin(\theta_{ik} - \delta_i + \delta_k) \qquad \ldots(7.69)$$

Using eqns. (7.69) and (7.51), we get,

$$\frac{\partial Q_i}{\partial |V_i|} = -|V_i|\,|Y_{ii}|\sin\theta_{ii} + Q_i$$

$$\therefore \qquad \frac{\partial Q_i}{\partial |V_i|} = -|V_i|B_{ii} + Q_i \qquad \ldots(7.70)$$

Again $B_{ii} >> Q_i$, Q_i may be neglected.

$$\therefore \qquad \frac{\partial Q_i}{\partial |V_i|} = -|V_i|B_{ii} \qquad \ldots(7.71)$$

Assuming $\theta_{ik} - \delta_i + \delta_k \approx \delta_{ik}$, eqn. (7.60) can be written as:

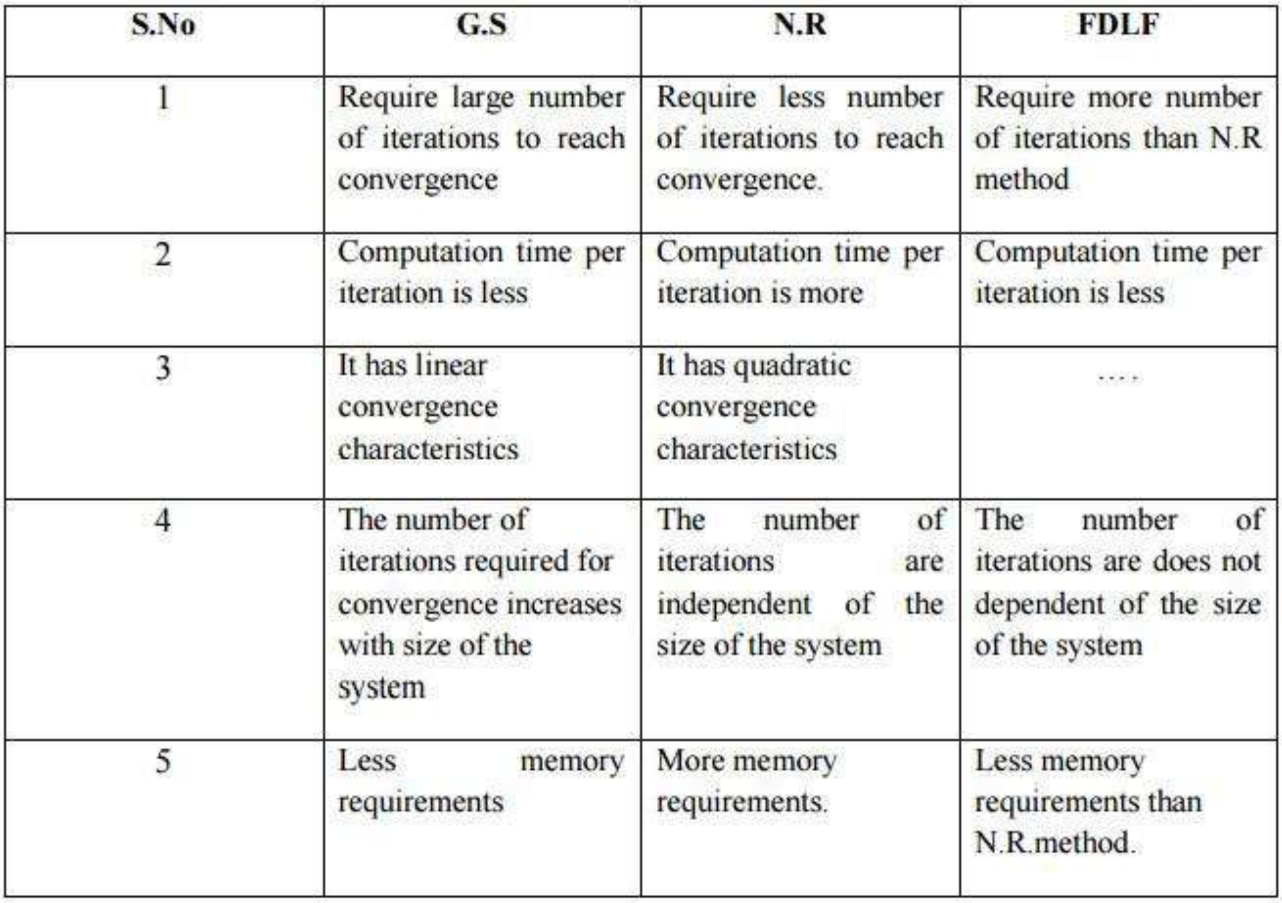
$$\frac{\partial Q_i}{\partial |V_k|} = -|V_i|B_{ik} \qquad \ldots(7.72)$$

Therefore, eqns. (7.55) and (7.56) take the following form:

$$\frac{\Delta P}{|V_i|} = -B' \ \Delta\delta \qquad \text{...(7.73)}$$

$$\frac{\Delta Q}{|V_i|} = -B'' \ \Delta\delta \qquad \text{...(7.74)}$$

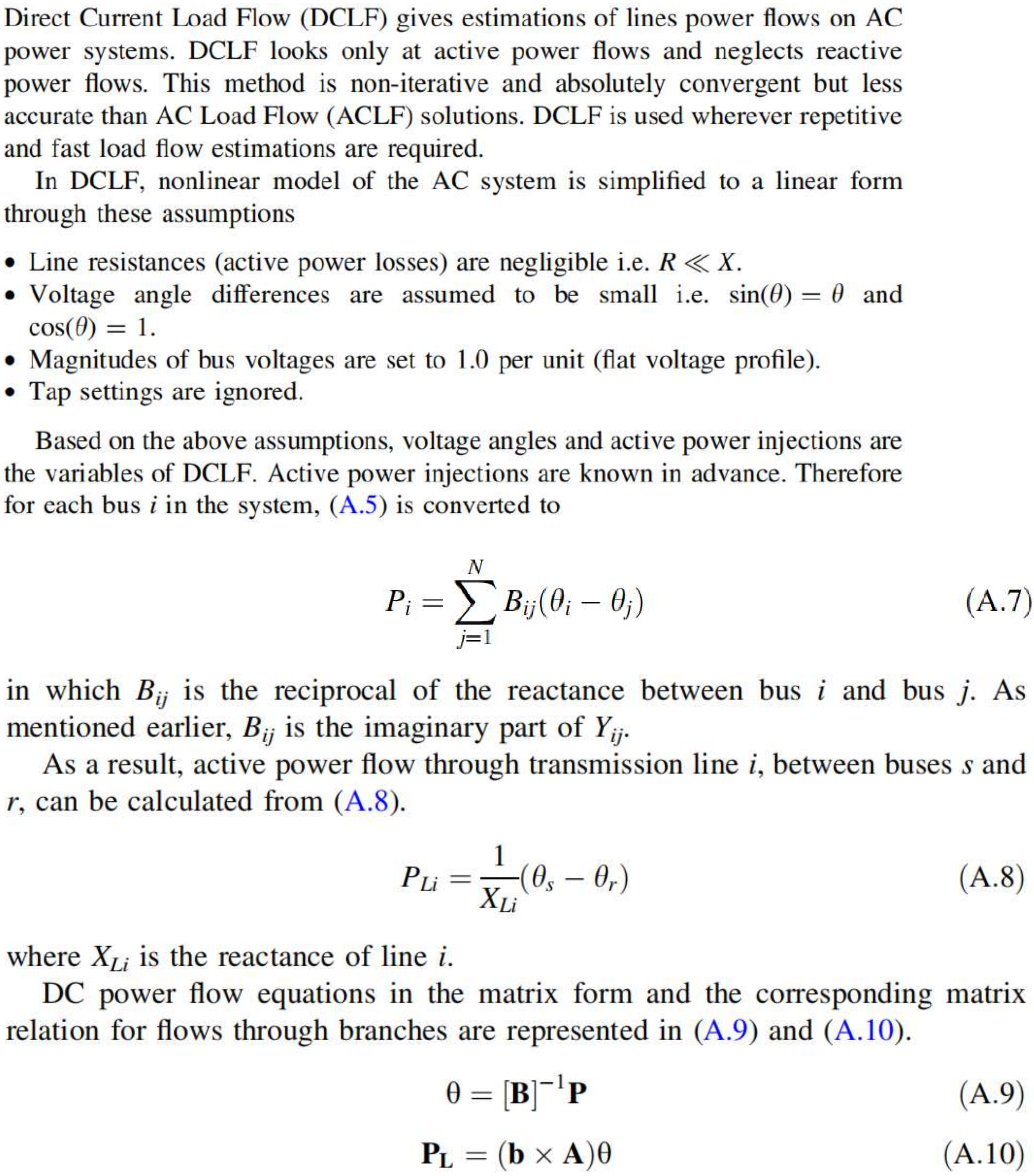
B' and B'' are the imaginary part of the bus admittance matrix Y_{BUS}. B' and B'' are constant-matrices and they need to be inverted once. The decoupled and fast decoupled power flow solutions requires more interations than the coupled NR method but requires less computing time per iteration.



S.No	G.S	N.R	FDLF
1	Require large number of iterations to reach convergence	Require less number of iterations to reach convergence.	Require more number of iterations than N.R method
2	Computation time per iteration is less	Computation time per iteration is more	Computation time per iteration is less
3	It has linear convergence characteristics	It has quadratic convergence characteristics	....
4	The number of iterations required for convergence increases with size of the system	The number of iterations are independent of the size of the system	The number of iterations are does not dependent of the size of the system
5	Less memory requirements	More memory requirements.	Less memory requirements than N.R.method.

DC load Flow

DC power flow is a commonly used tool for contingency analysis. Recently, due to its simplicity and robustness, it also becomes increasingly used for the real-time dispatch and techno-economic analysis of power systems. It is a simplification of a full power flow looking only at active power.



Direct Current Load Flow (DCLF) gives estimations of lines power flows on AC power systems. DCLF looks only at active power flows and neglects reactive power flows. This method is non-iterative and absolutely convergent but less accurate than AC Load Flow (ACLF) solutions. DCLF is used wherever repetitive and fast load flow estimations are required.

In DCLF, nonlinear model of the AC system is simplified to a linear form through these assumptions

- Line resistances (active power losses) are negligible i.e. $R \ll X$.
- Voltage angle differences are assumed to be small i.e. $\sin(\theta) = \theta$ and $\cos(\theta) = 1$.
- Magnitudes of bus voltages are set to 1.0 per unit (flat voltage profile).
- Tap settings are ignored.

Based on the above assumptions, voltage angles and active power injections are the variables of DCLF. Active power injections are known in advance. Therefore for each bus i in the system, (A.5) is converted to

$$P_i = \sum_{j=1}^{N} B_{ij}(\theta_i - \theta_j) \tag{A.7}$$

in which B_{ij} is the reciprocal of the reactance between bus i and bus j. As mentioned earlier, B_{ij} is the imaginary part of Y_{ij}.

As a result, active power flow through transmission line i, between buses s and r, can be calculated from (A.8).

$$P_{Li} = \frac{1}{X_{Li}}(\theta_s - \theta_r) \tag{A.8}$$

where X_{Li} is the reactance of line i.

DC power flow equations in the matrix form and the corresponding matrix relation for flows through branches are represented in (A.9) and (A.10).

$$\theta = [\mathbf{B}]^{-1}\mathbf{P} \tag{A.9}$$

$$\mathbf{P_L} = (\mathbf{b} \times \mathbf{A})\theta \tag{A.10}$$

where

P	N × 1 vector of bus active power injections for buses 1, …, N
B	N × N admittance matrix with R = 0
$\boldsymbol{\theta}$	N × 1 vector of bus voltage angles for buses 1, …, N
$\mathbf{P_L}$	M × 1 vector of branch flows (M is the number of branches)
b	M × M matrix (b_{kk} is equal to the susceptance of line k and non-diagonal elements are zero)
A	M × N bus-branch incidence matrix

Each diagonal element of **B** (i.e. B_{ii}) is the sum of the reciprocal of the lines reactances connected to bus i. The off-diagonal element (i.e. B_{ij}) is the negative sum of the reciprocal of the lines reactances between bus i and bus j.

A is a connection matrix in which a_{ij} is 1, if a line exists from bus i to bus j; otherwise zero. Moreover, for the starting and the ending buses, the elements are 1 and −1, respectively.

Example A.1 A simple example is used to illustrate the points discussed above. A three-bus system is considered. This system is shown in Fig. A.1, with the details given in Tables A.1 and A.2.

With base apparent power equal to 100 MVA, **B** and **P** are calculated as follows

$$\mathbf{B} = \begin{bmatrix} 23.2435 & -17.3611 & -5.8824 \\ -17.3611 & 28.2307 & -10.8696 \\ -5.8824 & -10.8696 & 16.7519 \end{bmatrix} \quad \mathbf{P} = \begin{bmatrix} \text{Unknown} \\ 0.53 \\ -0.9 \end{bmatrix}$$

As bus 1 is considered as slack,[1] the first row of **P** and the first row and column of **B** are disregarded. θ_2 and θ_3 are then calculated using (A.9) as follows.

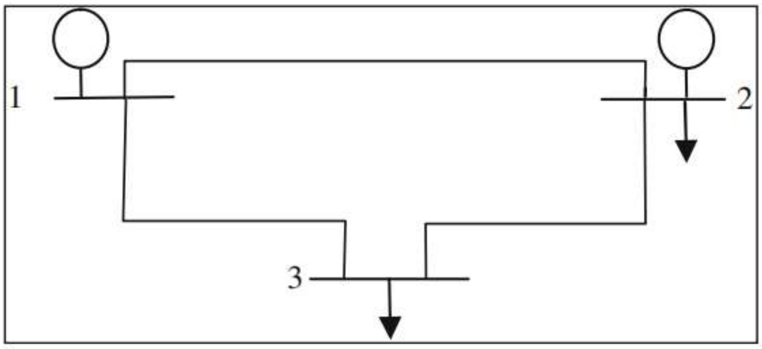


Fig. A.1 Three-bus system

Table A.1 Loads and generations

Bus number	Bus type	P_D (MW)	Q_D (MVAr)	P_G (MW)
1	Slack	0	0	Unknown
2	PV	10	5	63
3	PQ	90	30	0

Table A.2 Branches

Line number	From bus	To bus	X (p.u.)	Rating (MVA)
1	1	2	0.0576	250
2	2	3	0.092	250
3	1	3	0.17	150

$$\begin{bmatrix}\theta_2\\ \theta_3\end{bmatrix}=\begin{bmatrix}28.2307 & -10.8696\\ -10.8696 & 16.7519\end{bmatrix}^{-1}\begin{bmatrix}0.53\\ -0.9\end{bmatrix}=\begin{bmatrix}-0.0025\\ -0.0554\end{bmatrix}\text{Radian}=\begin{bmatrix}-0.1460^\circ\\ -3.1730^\circ\end{bmatrix}$$

A and **b** are then calculated as

$$\mathbf{A}=\begin{bmatrix}1 & -1 & 0\\ 0 & 1 & -1\\ 1 & 0 & -1\end{bmatrix}\quad \mathbf{b}=\begin{bmatrix}17.3611 & 0 & 0\\ 0 & 10.8696 & 0\\ 0 & 0 & 5.8824\end{bmatrix}$$

Therefore, the transmission flows are calculated using (A.10) as follows

$$\begin{bmatrix}P_{L1}\\ P_{L2}\\ P_{L3}\end{bmatrix}=\text{BaseMVA}\times\mathbf{b}\times\mathbf{A}\times\theta$$

$$=100\times\begin{bmatrix}17.3611 & 0 & 0\\ 0 & 10.8696 & 0\\ 0 & 0 & 5.8824\end{bmatrix}\times\begin{bmatrix}1 & -1 & 0\\ 0 & 1 & -1\\ 1 & 0 & -1\end{bmatrix}\times\begin{bmatrix}0\\ -0.0025\\ -0.0554\end{bmatrix}$$

$$=\begin{bmatrix}4.4243\\ 57.4243\\ 32.5757\end{bmatrix}\text{MW}$$

Comparison of DC and AC power flow

S. No	AC power flow	DC power flow
1	Real (P) and reactive power (Q) is calculated	Only real power (P) is calculated
2	Resistance and reactance are considered	Resistance is neglected and only reactance is considered
3	Iterative procedure gives the real and reactive power	Matrix operation gives the real power and no iterative process
4	Takes more time for the calculation	Compute fast to get real power
5	Non linear model	Linear model

Unit – III

Syllabus

UNIT III SHORT CIRCUIT ANALYSIS
PER-UNIT SYSTEM OF REPRESENTATION: Per-Unit equivalent reactance network of a three phase Power System, Numerical Problems. Needs and assumptions for short circuit analysis
SYMMETRICAL FAULT ANALYSIS: Short Circuit Current and MVA Calculations, Fault levels, Application of Series Reactors, Numerical Problems.

SYMMETRICAL COMPONENT THEORY: Symmetrical Component Transformation, Positive, Negative and Zero sequence components: Voltages, Currents and Impedances. Sequence Networks: Positive, Negative and Zero sequence Networks, Numerical Problems.
UNSYMMETRICAL FAULT ANALYSIS: LG, LL, LLG faults without and with fault impedance, Numerical Problems.

What is the Necessity of Per-Unit?

The various component of power system like alternator, motors and transformers, etc.., have their voltage, power, current and impedance rating in KV, KVA, KA and ohm respectively. Hence, for analysis purpose the base value is chosen for voltage, power, current and impedance. All the voltage, power, current and impedance ratings of the components are expressed as a % or per unit of the base value.

Explain the importance of Per Unit System?

What is the Per Unit System? Why it is required in power system calculation?

What are the advantages of Per Unit System?

Formulas Used:

$$\text{Per Unit value} = \frac{\text{Actual Value}}{\text{Base Value}}$$

1. Base MVA,
2. Base KV,
3. Base Value of Impedance, $Z_b = \dfrac{(\text{Base KV})^2}{\text{Base MVA}}$
4. Base Value of Current, $I_b = \dfrac{\text{Base MVA}}{\text{Base KV}}$

For change of base:

$$Z_{pu}^{new} = Z_{pu}^{old} \times \left(\frac{\text{old base KV}}{\text{new base KV}} \right)^2 \times \left(\frac{\text{new base MVA}}{\text{old base MVA}} \right)$$

$$\text{New base KV on HT side} = \text{base KV on LT side} \times \left(\frac{\text{HT rating of transform er}}{\text{LT rating of transform er}} \right)$$

$$\text{New base KV on LT side} = \text{base KV on HT side} \times \left(\frac{\text{LT rating of transform er}}{\text{HT rating of transform er}} \right)$$

Algorithm:

1) Get base MVA and base KV values
2) Get actual impedance value in ohms
3) Calculate the base Impedance value using the formula
4) Calculate the Per Unit value of the Impedance of power system components
5) Display the Result

Exercise Problems

1) A **3 phase generator with rating 1000KVA, 33KV** has its armature resistance and synchronous reactance as **20 ohm/ph** and **70 ohm/ph**. calculate the **Per Unit Impedance** Value of the generator.

Manual Calculation

Base Impedance, $Z_b = \frac{(\text{Base KV})^2}{\text{Base MVA}}$

MVA base=1000KVA = 1 MVA

Base KV = 33KV

$$Z_b = \frac{(33)^2}{1}$$

Z_b = **1089 ohms**

Z_{Actual} = R+jX = (20+j70) ohms

$$Z_{pu} = \frac{Z_{\text{Actual}}}{Z_{\text{Base}}}$$

$$Z_{pu} = \frac{20 + j70}{1089}$$

Z_{pu} = 0.0184 + j 0.0643 pu

Exercise Problem

2) Calculate the **Per Unit reactance** value of the given transmission line of length **64km** having the **reactance of 0.5 ohm/km**. Take Base MVA = 300 and Base KV=230.

Solution:

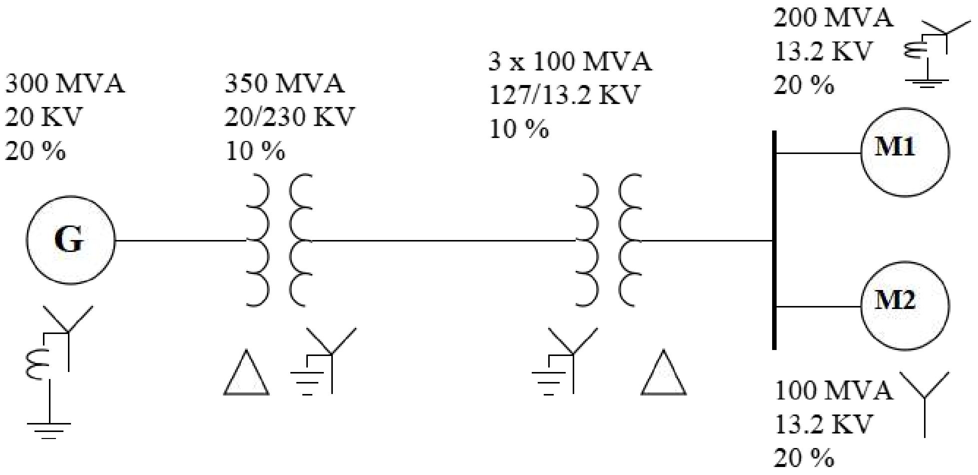
Z_{base} = $(KV_{base})^2$ / MVA_{base} = 230^2 / 300 = **176.333 ohms**

Z_{actual} = 64 x j0.5 = **j32 ohms**

Z_{pu} = Z_{actual} / Z_{base} = (0+j32) / 176.333 = **0 + j 0.1815 pu**

Exercise Problem

3) A 300 MVA, 20 KV, 3 phase generator has a sub transient reactance of 20%. The generator supplies 2 synchronous motors through a 64 km transmission line having transformers both ends. In this T_1 is 3 phase transformer and T_2 is made of 3 single phase transformer of rating 100 MVA, 127 / 13.2 KV, 10% reactance. Series reactance of the transmission line is 0.5 ohm/km. **select the generator rating as base values**.



Solution:

Base Mega Volt Ampere, $\mathbf{MVA_{b,new}}$ = 300 MVA

Base Kilo Volt, $\mathbf{KV_{b,new}}$ = 20 KV

Reactance of Generator G

p.u reactance of generator = 20 % = **0.2 pu**

Reactance of Transformer T_1

$$Z_{pu}^{new} = Z_{pu}^{old} \times \left(\frac{\text{old base KV}}{\text{new base KV}} \right)^2 \times \left(\frac{\text{new base MVA}}{\text{old base MVA}} \right)$$

$X_{pu,\ old}$ = 10% = 0.1 pu

$KV_{b,\ old}$=20 KV

$MVA_{b,\ old}$=350 MVA

The new pu reactance of T_1 = $X_{pu,\ old}$ * ($KV_{b,\ old}$ / $KV_{b,\ new}$)^2 * ($MVA_{b,\ new}$ / $MVA_{b,\ old}$)

= 0.1 * $(20/20)^2$ * (300/350) = **0.0857 pu**

Reactance of Transmission Line

Reactance per km = j 0.5 Ω

Total reactance = 64* j0.5 = j32 Ω

Z_{Actual}=j32 Ω

$MVA_{b,\ new}$ = 300 MVA

$KV_{b,\ new}$ (LT side)= **20KV**

$$\text{New base KV on HT side} = \text{base KV on LT side} \times \left(\frac{\text{HT rating of transform er}}{\text{LT rating of transform er}}\right)$$

New base KV on HT side of T_1 = Base KV on LT side * (HT voltage rating of T_1 / LT voltage rating of T_1)

= 20 * (230/20) = 230 KV

$KV_{b,\ new}$ = 230KV

$MVA_{b,\ new}$ = 300 MVA

Base impedance, $\mathbf{Z_b}$ = $(KV_b)^2$ / MVA_b = 230^2 / 300 = **176.33 Ω**

Per Unit reactance of Transmission Line=($\mathbf{Z_{Actual}/Z_b}$)=(32 / 176.33) = **0.1815 pu**

Reactance of Transformer T_2

$KV_{b,\ new}$ = 230KV

$MVA_{b,\ new}$ = 300 MVA

Voltage ratio of **line voltage** of 3 phase transformer bank = (√3 * 127)/13.2=**220/13.2** KV

$MVA_{b,\ old}$= 3 x 100 = 300 MVA

$KV_{b,\ old}$ = 220KV

$X_{pu,\ old}$ = 10 % = 0.1 pu

New pu reactance of T_2 = $X_{pu,\ old}$ *($KV_{b,\ old}$ / $KV_{b,\ new}$)^2 * ($MVA_{b,\ new}$ / $MVA_{b,\ old}$)

= 0.1 *(220/230)^2 * (300/300)

= **0.0915 pu**

Reactance of M_1

$$\text{New base KV on LT side} = \text{base KV on HT side} \times \left(\frac{\text{LT rating of transform er}}{\text{HT rating of transform er}}\right)$$

$$\text{New base KV on LT side} = 230 \times \left(\frac{13.2}{220}\right)$$

New base KV, **$KV_{b,\ new}$=13.8 KV**

$MVA_{b,\ new}$=300 MVA

$KV_{b,\ old}$=13.2 KV

$MVA_{b,\ old}$=200 MVA

$X_{pu,\ old}$ = 20% = 0.2 pu

pu reactance of M_1 = **$X_{pu,\ old}$ *($KV_{b,\ old}$ / $KV_{b,\ new}$)^2 * ($MVA_{b,\ new}$ / $MVA_{b,\ old}$)**

= 0.2*(13.2/13.8)^2 * (300/200) = **0.2745 pu**

Reactance of M_2

$KV_{b,\ new}$=13.8 KV

$MVA_{b,\ new}$=300 MVA

$KV_{b,\ old}$=13.2 KV

$MVA_{b,\ old}$=100 MVA

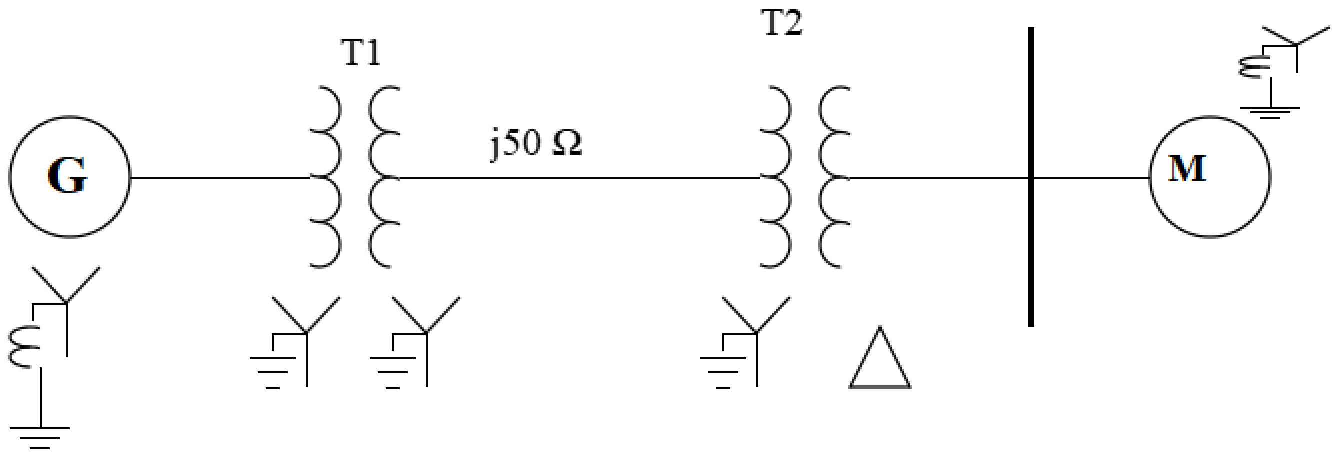
$X_{pu,\ old}$ = 20% = 0.2 pu

pu reactance of M_2 = $X_{pu,\ old}$ *($KV_{b,\ old}$ / $KV_{b,\ new}$)^2 * ($MVA_{b,\ new}$ / $MVA_{b,\ old}$)

= 0.2*(13.2/13.8)^2 * (300/100) = **0.549 pu**

Exercise Problem

4) Calculate the Per Unit values for the given single line diagram of the power system. Take base MVA as **100 and base KV as 220** in 50 ohm line. The ratings of the generator, motor and transformers are given below:



Generator: 40 MVA, 25 KV, X" = 20%

Synchronous motor: 50 MVA, 11 KV, X" = 30%

Y-Y Transformer: 40 MVA, 33 / 220 KV, X=15%

Y-Δ Transformer: 30 MVA, 11 / 220 KV (Δ / Y), X=15%

Solution:

Base Mega Volt Ampere, **$MVA_{b,new}$ = 100 MVA**

Base Kilo Volt, **$KV_{b,new}$ = 220 KV**

Reactance of Transmission line

Base impedance, $\mathbf{Z_b}$ = $(KV_{b,new})^2$ / $MVA_{b,new}$ = 220^2 / 100 = **484 Ω**

$\mathbf{Z_{Actual}}$ **= 50 Ω**

pu reactance = (Actual Reactance / Base impedance) = 50 / 484 = **0.1033 pu**

Reactance of Transformer T_1

New base KV on LT side of T_1 = Base KV on HT side * (LT rating / HT rating)

= 220 * (33 / 220) = 33 KV

$\mathbf{KV_{b,new}}$ **= 33 KV**

$\mathbf{MVA_{b,new}}$ **= 100 MVA**

$MVA_{b, old}$= 40 MVA,

$KV_{b, old}$ = 33 KV,

$X_{pu, old}$=15% = 0.15 pu

pu reactance = $X_{pu, old}$ * $(KV_{b, old} / KV_{b, new})^2$ * $(MVA_{b, new} / MVA_{b, old})$

= $0.15*(33/33)^2$ * (100 / 40) = **0.375 pu**

Reactance of Generator G

$\mathbf{KV_{b,new}}$ **= 33 KV**

$\mathbf{MVA_{b,new}}$ **= 100 MVA**

$MVA_{b, old}$= 40 MVA,

$KV_{b, old}$ = 25 KV,

$X_{pu, old}$=20% = 0.2 pu

New pu reactance = $X_{pu, old}$ * $(KV_{b, old} / KV_{b, new})^2$ * $(MVA_{b, new} / MVA_{b, old})$

= 0.2 * $(25/33)^2$ * (100/40) = **0.287 pu**

Reactance of Transformer T_2

Base KV on LT side = Base KV on HT side * (LT rating / HT rating)

= 220 * (11/220) = **11 KV**

$\mathbf{KV_{b,new}}$ **= 11 KV**

$\mathbf{MVA_{b,new}}$ **= 100 MVA**

$MVA_{b, old}$= 30 MVA,

$KV_{b, old}$ = 11 KV,

$X_{pu, old}$=15% = 0.15 pu

pu reactance = $X_{pu, old}$ * $(KV_{b, old} / KV_{b, new})^2$ * $(MVA_{b, new} / MVA_{b, old})$

= 0.15 * $(11/11)^2$ * (100/30) = **0.5 pu**

Reactance of Synchronous Motor

$KV_{b,new}$ = 11 KV

$MVA_{b,new}$ = 100 MVA

$MVA_{b,\ old}$= 50 MVA,

$KV_{b,\ old}$ = 11 KV,

$X_{pu,\ old}$=30% = 0.3 pu

pu reactance $X_{pu,new} = X_{pu,\ old} * (KV_{b,\ old} / KV_{b,\ new})^2 * (MVA_{b,\ new} / MVA_{b,\ old})$

$= 0.3 * (11/11)^2 * (100/50) =$ **0.6 pu**

SYMMETRICAL FAULT ANALYSIS

What is fault in power system?

Fault is a defect and not able to provide supply to the healthy loads. It happens due to partial or full damage of insulation. This fault creates abnormal voltage and current in the power system. This will harm the healthy devices connected in the power system and hence it has to be avoided or protected. There are two types of fault

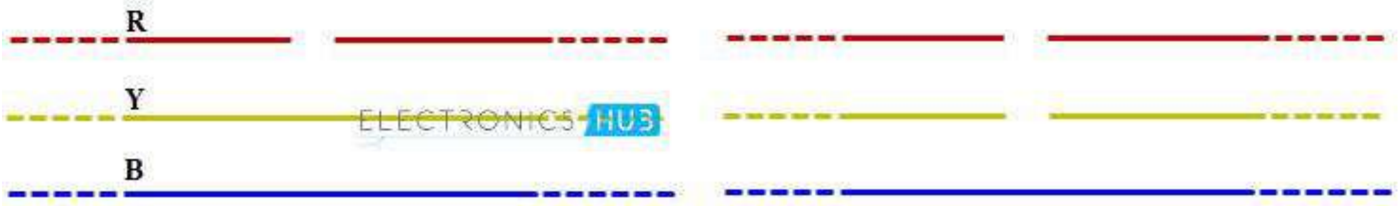
1) Open circuit fault
2) Short circuit fault

Open Circuit Faults

These faults occur due to the failure of one or more conductors. The figure below illustrates the open circuit faults for single, two and three phases (or conductors) open condition.

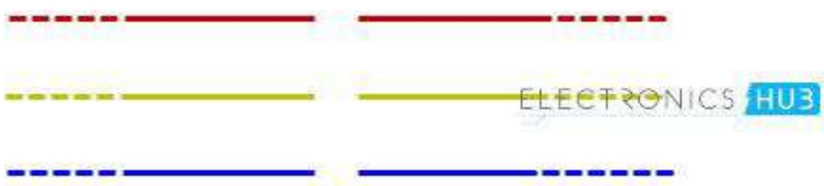
The most common causes of these faults include joint failures of cables and overhead lines, and failure of one or more phase of circuit breaker and also due to melting of a fuse or conductor in one or more phases. Open circuit faults are also called as series faults

Open-circuit Faults



(a). Single-phase open-circuit

(a). Two-phase open-circuit



(a). Three-phase open-circuit

Consider that a transmission line is working with a balanced load before the occurrence of open circuit fault. If one of the phase gets melted, the actual loading of the alternator is reduced and this cause to raise the acceleration of the alternator, thereby it runs at a speed slightly greater than synchronous speed. This over speed causes over voltages in other transmission lines.

Thus, single and two phase open conditions can produce the unbalance of the power system voltages and currents that causes great damage to the equipments.

Causes

Broken conductor and **malfunctioning of circuit breaker** in one or more phases.

Effects

- Abnormal operation of the system
- Danger to the personnel as well as animals
- Exceeding the voltages beyond normal values in certain parts of the network, which further leads to insulation failures and developing of short circuit faults.

Although open circuit faults can be tolerated for longer periods than short circuit faults, these must be removed as early as possible to reduce the greater damage.

Short Circuit Faults

A short circuit can be defined as an abnormal connection of very low impedance between two points of different potential, whether made intentionally or accidentally.

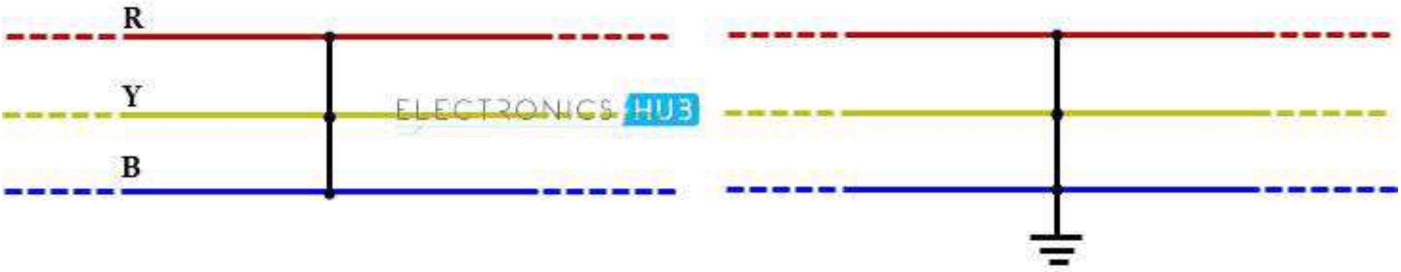
These are the most common and severe kind of faults, resulting in the flow of abnormal high currents through the equipment or transmission lines. If these faults are allowed to persist even for a short period, it leads to the extensive damage to the equipment.

Short circuit faults are also called as shunt faults. These faults are caused due to the insulation failure between phase conductors or between earth and phase conductors or both.

The various possible short circuit fault conditions include three phase to earth, three phase clear of earth, phase to phase, single phase to earth, two phase to earth and phase to phase plus single phase to earth as shown in figure.

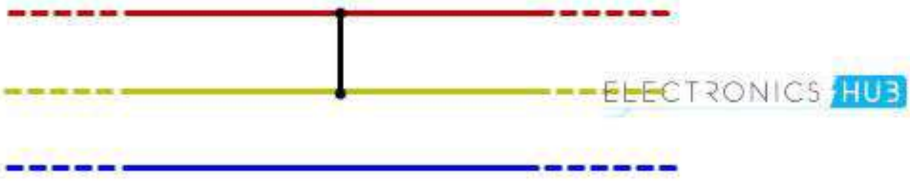
The three phase fault clear of earth and three phase fault to earth are balanced or symmetrical short circuit faults while other remaining faults are unsymmetrical faults

Short-circuit Faults

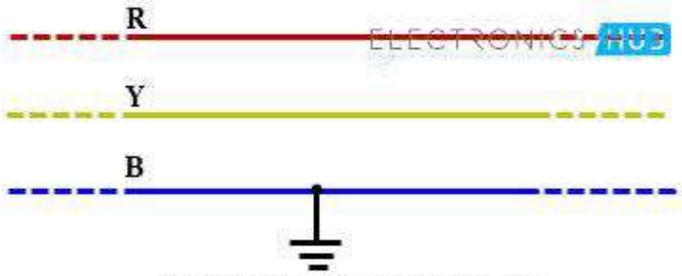


(a). Three-phase clear of earth

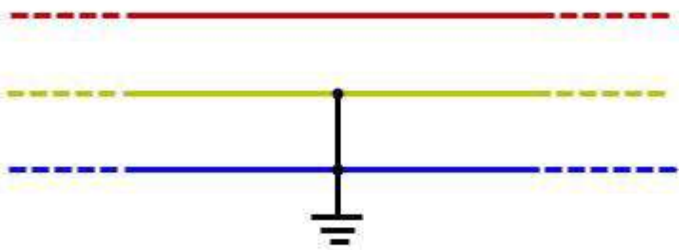
(b). Three-phase-to-earth



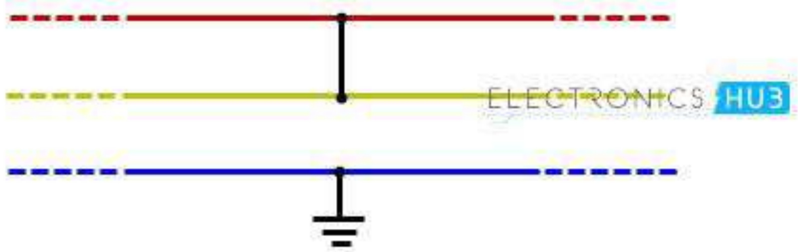
(c). Phase-to-phase



(d). Single-phase-to-earth



(e). Two-phase-to-earth



(f). Phase-to-phase plus single-phase-to-earth

Causes

These may be due to internal or external effects

- Internal effects include breakdown of transmission lines or equipment, aging of insulation, deterioration of insulation in generator, transformer and other electrical equipments, improper installations and inadequate design.
- External effects include overloading of equipments, insulation failure due to lighting surges and mechanical damage by public.

Effects

- Arcing faults can lead to fire and explosion in equipments such as transformers and circuit breakers.
- Abnormal currents cause the equipments to get overheated, which further leads to reduction of life span of their insulation.
- The operating voltages of the system can go below or above their acceptance values that creates harmful effect to the service rendered by the power system.
- The power flow is severely restricted or even completely blocked as long as the short circuit fault persists.

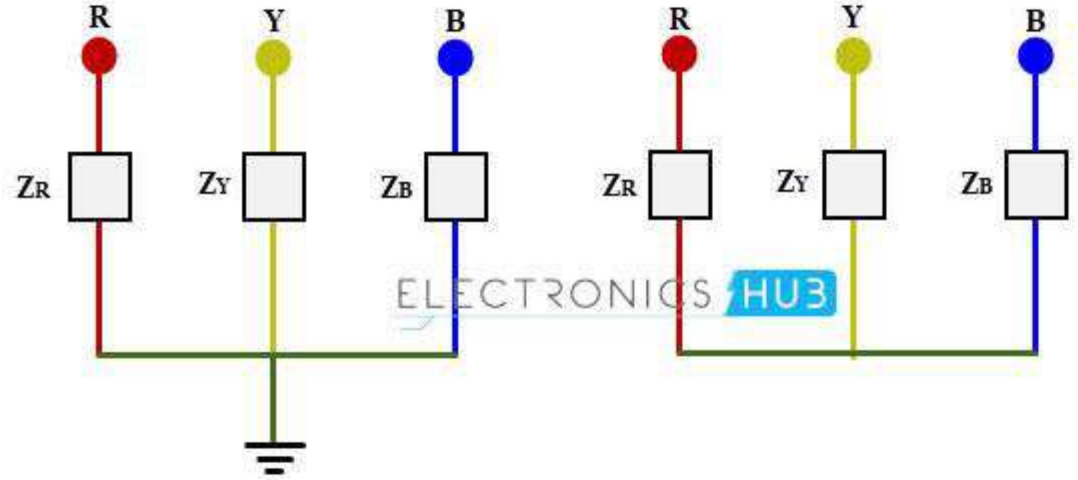
Symmetrical and Unsymmetrical Faults

As discussed above that faults are mainly classified into open and short circuit faults and again these can be symmetrical or unsymmetrical faults.

Symmetrical Faults

Symmetrical fault is also called as balanced fault. This fault occurs when all the three phases are simultaneously short circuited.

These faults rarely occur in practice as compared with unsymmetrical faults. Two kinds of symmetrical faults include line to line to line (L-L-L) and line to line to line to ground (L-L-L-G) as shown in figure below.



(a). Three-phase-to-earth (L-L-L-G) (b). Three-phase-fault (L-L-L)

A rough occurrence of symmetrical faults is in the range of 2 to 5% of the total system faults. However, if these faults occur, they cause a very severe damage to the equipments even though the system remains in balanced condition.

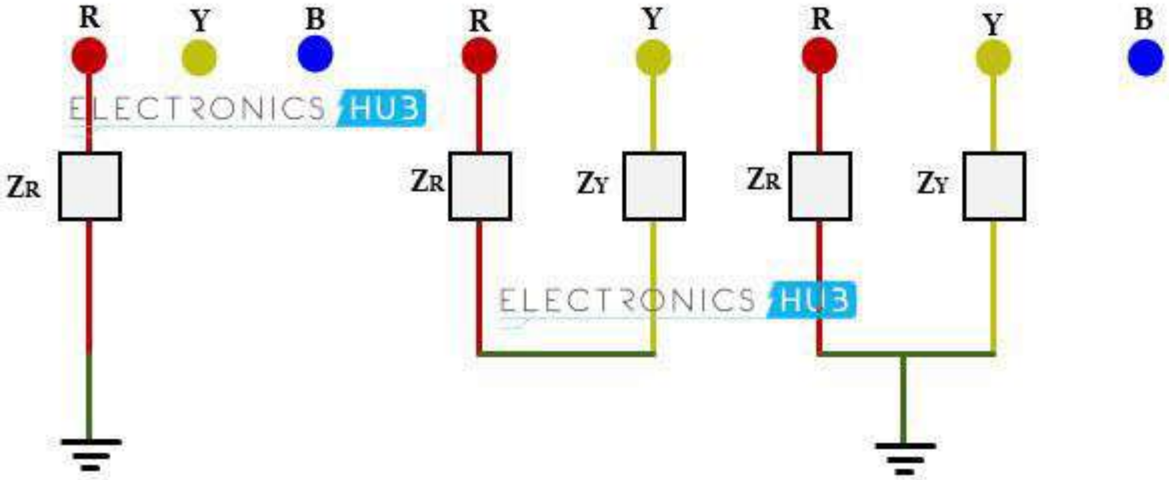
The analysis of these faults is required for selecting the rupturing capacity of the circuit breakers, choosing set-phase relays and other protective switchgear. These faults are analyzed on per phase basis using bus impedance matrix or Thevenins's theorem.

Unsymmetrical Faults

The most common faults that occur in the power system network are unsymmetrical faults. This kind of fault gives rise to unsymmetrical fault currents (having different magnitudes with unequal phase displacement). These faults are also called as unbalanced faults as it causes unbalanced currents in the system.

Up to the above discussion, unsymmetrical faults include both open circuit faults (single and two phase open condition) and short circuit faults (excluding L-L-L-G and L-L-L).

The figure below shows the three types of symmetrical faults occurred due to the short circuit conditions, namely phase or line to ground (L-G) fault, phase to phase (L-L) fault and double line to ground (L-L-G) fault.



(a). Single-phase-to-earth (LG fault) (b). Phase-to-phase (L-L) (e). Two-phase-to-earth (L-L-G)

A single line-to-ground (LG) fault is one of the most common faults and experiences show that 70-80 percent of the faults that occur in power system are of this type. This forms a short circuit path between the line and ground. These are very less severe faults compared to other faults.

A line to line fault occur when a live conductor get in contact with other live conductor. Heavy winds are the major cause for this fault during which swinging of overhead conductors may touch together. These are less severe faults and its occurrence range may be between 15-20%.

In double line to ground faults, two lines come into the contact with each other as well as with ground. These are severe faults and the occurrence these faults is about 10% when compared with total system faults.

Unsymmetrical faults are analyzed using methods of unsymmetrical components in order to determine the voltage and currents in all parts of the system. The analysis of these faults is more difficult compared to symmetrical faults.

This analysis is necessary for determining the size of a circuit breaker for largest short circuit current. The greater current usually occurs for either L-G or L-L fault.

Protection Devices against Faults

When the fault occurs in any part of the system, it must be cleared in a very short period in order to avoid greater damage to equipments and personnel and also to avoid interruption of power to the customers.

The fault clearing system uses various protection devices such as relays and circuit breakers to detect and clear the fault. Some of these fault clearing or faults limiting devices are given below.

Fuse

It opens the circuit whenever a fault exists in the system. It consists of a thin copper wire enclosed in a glass or a casing with two metallic contacts. The high fault current rises the temperature of the wire and hence it melts. A fuse necessitates the manual replacement of wire each time when it blows.

Low current Fuse

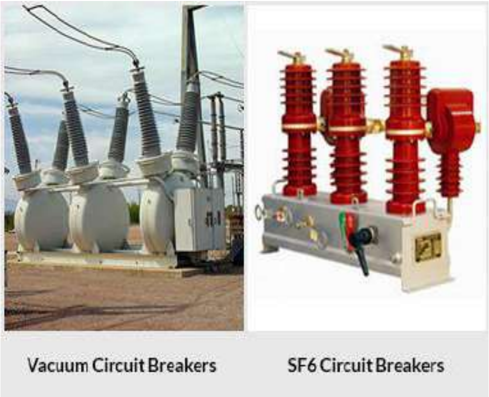
Rewire able Fuse

HRC Fuse

Circuit Breaker

It is the most common protection device that can make or break the circuit either manually or through remote control under normal operating conditions.

There are several types of circuit breakers available depending on the operating voltage, including air brake, oil, vacuum and SF6 circuit breakers.



Miniature Circuit Breaker

Protective Relays

These are the fault detecting devices. These devices detect the fault and initiate the operation of the circuit breaker so as to isolate the faulty circuit. A relay consists of a magnetic coil and contacts (NC and NO). The fault current energizes the coil and this causes to produce the field, thereby the contacts get operated.

Relay Photo

Some of the types of protective relays include

- Electro Magnetic relays
- Impedance relays
- Directional relays
- Pilot relays
- Differential relays

What is fault analysis?

Short circuit study is one of the basic power system analysis problems. It is also known as fault analysis. When a fault occurs in a power system, bus voltages reduce and large current flows in the lines. This may cause damage to the equipments. Hence faulty section should be isolated from the rest of the network immediately on the occurrence of a fault. To isolate the faulty section relay and circuit breakers are used.

The calculation of currents in network elements for different types of faults occurring at different locations is called SHORT CIRCUIT STUDY. The results obtained from the short circuit study are used to find the relay settings and the circuit breaker ratings which are essential for power system protection

What is Short Circuit Analysis?

Short circuit analysis essentially consists of determining the steady state solution of a linear network with balanced three phase excitation. Such an analysis provides currents and voltages in a power system during the faulted condition. This information is needed to determine the required interrupting capacity of the circuit breakers and to design proper relaying system

What is the Need for short circuit analysis?

A Short Circuit Analysis will help to ensure that personnel and equipment are protected by establishing proper interrupting ratings of protective devices (circuit breaker and fuses). To design the protective scheme and for settings of the relay and circuit breaker short circuit analysis is important.

The purpose of short circuit analysis of power systems is to assess the vulnerability of the system to abnormal conditions resulting from a partial or complete breakdown of the power system.

What are the assumptions in short circuit analysis?

As it is usual in most short circuit studies, some basic assumptions are made to facilitate the computational task of fault analysis. These basic assumptions are as follows

(i) **All load currents are negligible**

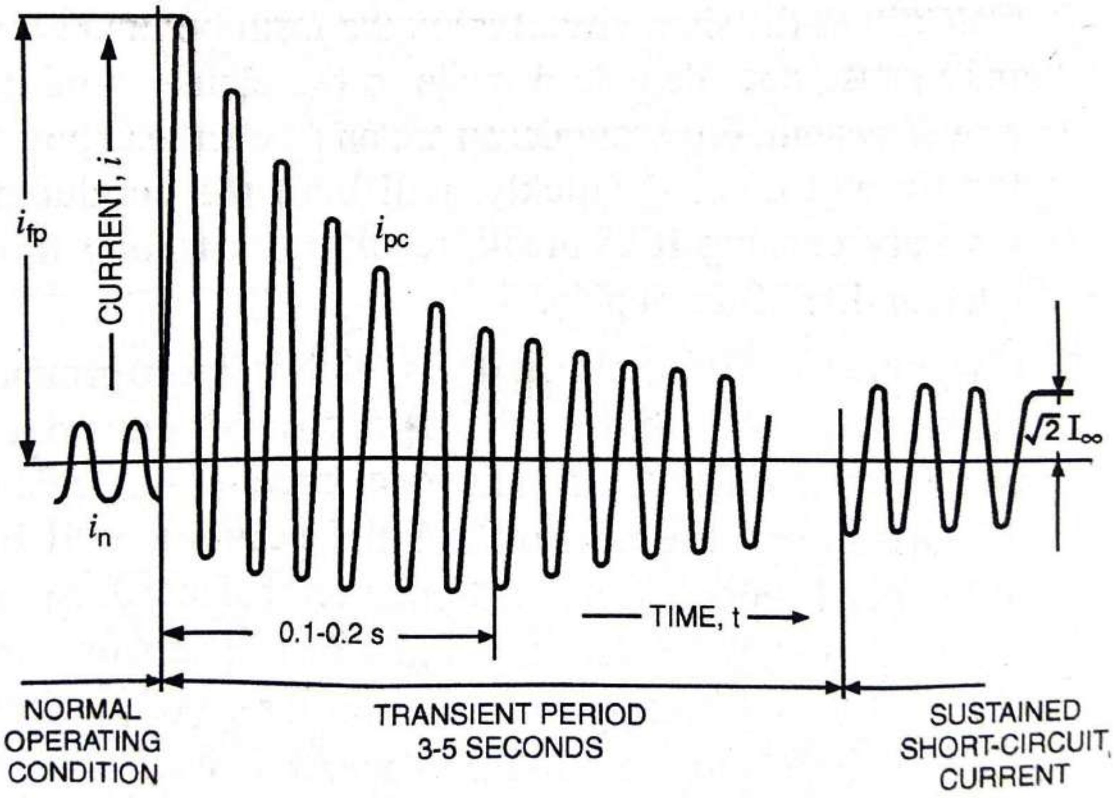
(ii) All generated voltages are equal in phase and magnitude to the positive sequence **pre-fault voltage. i.e 1.0 pu and angle 0^0**

(iii) The **networks are balanced** except at the fault points.

(iv) All **shunt admittances (line charging susceptance, etc.) are negligible**

(v) System **resistance** is neglected

Fault current



Current wave form

Symmetrical Faults

Symmetrical (L-L-L) fault occurs infrequently, as for example, when a line, which has been made safe for maintenance and/or repairs by clamping all the three phases to earth, is accidently made alive or when, due to slow fault clearance, an earth fault spreads across to the other two phases or when a mechanical excavator cuts quickly through a whole cable. It is an important type of fault in that it results in an easy calculation and generally, a pessimistic answer.

The analysis of symmetrical (L-L-L) faults includes the determination of the voltage at any point (or bus) in the power system network, the current in any branch and value of reactance necessary to limit the fault current to any desired value. Such calculations provide the necessary data for selection of circuit breakers and design of protective scheme.

The circuit breaker MVA breaking capacity is based on 3-phase fault MVA. Since the circuit breakers are manufactured in preferred standard sizes, e.g., 250, 500, 750 MVA, high precision is not required in calculations of 3-phase fault level at a point in a power system. Moreover, the system impedances are also never known accurately.

It is customary to perform the short circuit analysis under the following simplifying assumptions:

1. Load currents are considered negligible as compared to fault currents.

2. Shunt elements in the transformer model that account for magnetizing current and core loss are neglected. The transformer is represented by a reactance in series, as transformer resistance is quite low in comparison with its reactance.

3. Shunt capacitances of the transmission lines are neglected.

4. System resistance is neglected and only inductive reactance of the system is taken into account. This assumption cannot be applied in case overhead lines or underground cables of

considerable length are included in the network. A transmission line is represented by series reactance (and resistance).

5. The emfs of all the generators are assumed to be equal to 1 ∠0° per unit. This means that the system voltage is at its nominal value and the system is operating on no load at the time of occurrence of fault. The selection of zero phase for one source is arbitrary and convenient. Assuming that all sources are in phase and of the same magnitude is equivalent to neglecting pre-fault load current. When desirable, the load current can be taken into account, at a later stage by superposition.

6. The effect of dc component is accounted for by using correction factors. The correction or multiplying factor for determination of breaking capacity of a circuit breaker depends on the speed of the circuit breaker. For example, a two-cycle circuit breaker might require a factor 1.4 whereas with an eight-cycle breaker a factor 1.0 would be sufficient.

Generator reactances are normally taken as their subtransient values in order to depict the most pessimistic condition. However, if transient current is to be determined, then transient reactances should be used.

For simple systems, calculations can be made by network reduction technique, which will be discussed here. However, for modern complex systems, ac network analyzers or digital computers are used for fault calculations.

Network Reduction Technique:

Because of the balanced nature of fault and the system, any condition which applies to one phase applies equally to the remaining two phases. Thus the problem is reduced itself to a single phase problem involving a single supply source acting through the equivalent network impedance up to the fault. The equivalent network impedance up to the fault can be obtained by network reduction that involves series- parallel combinations and star/delta or delta/star conversion of reactances.

Various steps involved in the short circuit calculations are given below:

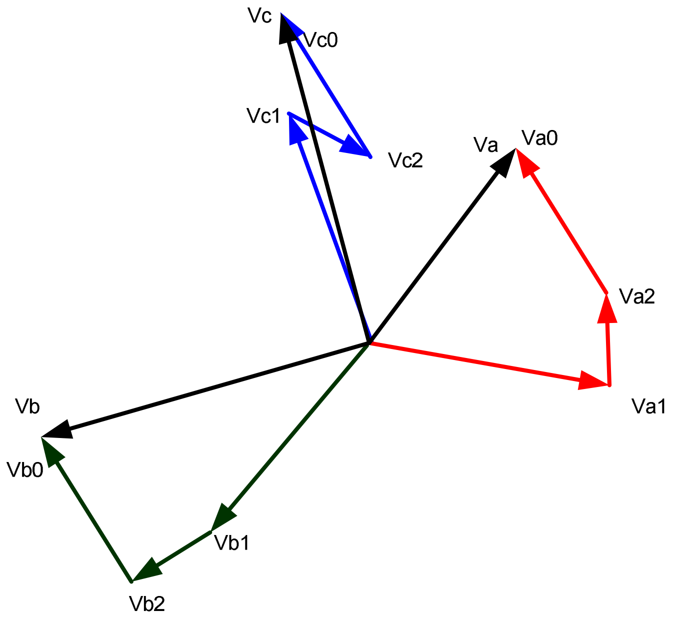
1. Make out a single line diagram of the complete network indicating on each component, its rating, voltage, resistance and reactance.

2. Choose a common base kVA (or MVA) and convert all the resistances and reactances in per unit values as referred to common base kVA (or MVA).

3. From the single line diagram draw a single line reactance (or impedance) diagram showing one phase and neutral. In this diagram write down the reactances (or impedances) of the elements in per unit values, determined under step 2.

4. Reduce the reactance (or impedance) diagram, by network reduction technique keeping the identity of the fault point intact. Find the reactance of the system as seen from the fault point (Thevenin reactance).

An Introduction to Symmetrical Components, System Modeling and Fault Calculation



Presented at the

30th Annual
HANDS-ON Relay School
March 11 - 15, 2013

Washington State University
Pullman, Washington

By Stephen Marx, and Dean Bender
Bonneville Power Administration

Introduction

The electrical power system normally operates in a balanced three-phase sinusoidal steady-state mode. However, there are certain situations that can cause unbalanced operations. The most severe of these would be a fault or short circuit. Examples may include a tree in contact with a conductor, a lightning strike, or downed power line.

In 1918, Dr. C. L. Fortescue wrote a paper entitled "Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks." In the paper Dr. Fortescue described how arbitrary unbalanced 3-phase voltages (or currents) could be transformed into 3 sets of balanced 3-phase components, Fig I.1. He called these components "symmetrical components." In the paper it is shown that unbalanced problems can be solved by the resolution of the currents and voltages into certain symmetrical relations.

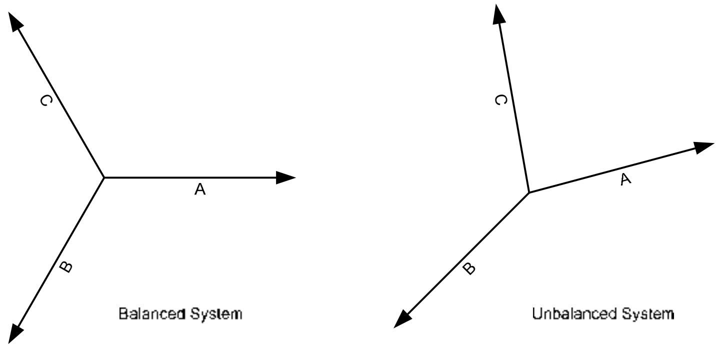


Fig I.1

By the method of symmetrical coordinates, a set of unbalanced voltages (or currents) may be resolved into systems of balanced voltages (or currents) equal in number to the number of phases involved. The symmetrical component method reduces the complexity in solving for electrical quantities during power system disturbances. These sequence components are known as positive, negative and zero-sequence components, Fig I.2

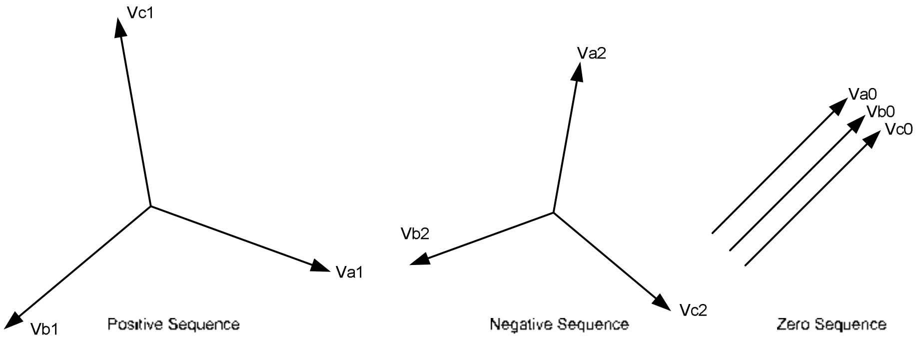


Fig I.2

The purpose of this paper is to explain symmetrical components and review complex algebra in order to manipulate the components. Knowledge of symmetrical components is important in performing mathematical calculations and understanding system faults. It is also valuable in analyzing faults and how they apply to relay operations.

1. Complex Numbers

The method of symmetrical components uses the commonly used mathematical solutions applied in ordinary alternating current problems. A working knowledge of the fundamentals of algebra of complex numbers is essential. Consequently this subject will be reviewed first.

Any complex number, such as $a + jb$, may be represented by a single point *p*, plotted on a Cartesian coordinates, in which a is the abscissa on the x axis of real quantities and b the ordinate on the y axis of imaginary quantities. This is illustrated in Fig. 1.1

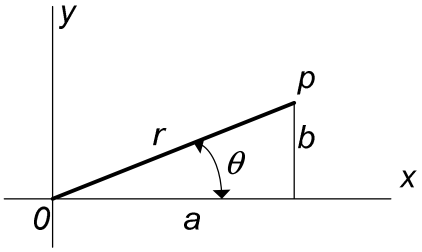


Fig. 1.1

Referring to Fig. 1.1, let r represent the length of the line connecting the point *p* to the origin and θ the angle measured from the x-axis to the line *r*. It can be observed that

$$a = r \cdot \cos\theta \qquad (1.1)$$

$$b = r \cdot \sin\theta \qquad (1.2)$$

2. Properties of Phasors

A vector is a mathematical quantity that has both a magnitude and direction. Many quantities in the power industry are vector quantities. The term phasor is used within the steady state alternating linear system. It is used to avoid confusion with spatial vectors: the angular position of the phasor represents position in time, not space. In this document, phasors will be used to document various ac voltages, currents and impedances.

A phasor quantity or phasor, provides information about not only the magnitude but also the direction or angle of the quantity. When using a compass and giving directions to a house, from a given location, a distance and direction must be provided. For example one could say that a house is 10 miles at an angle of 75 degrees (rotated in a clockwise direction from North) from where I am standing. Just as we don’t say the other house is -10 miles away, the magnitude of the phasor is always a positive, or rather the absolute value of the "length of the phasor." Therefore giving directions in the opposite direction, one could say that a second house is 10 miles at an angle of 255 degrees. The quantity could be a potential, current, watts, etc.

Phasors are written in polar form as

$$Y = |Y|\angle\theta \tag{2.1}$$

$$= |Y|\cos\theta + j|Y|\sin\theta \tag{2.2}$$

where Y is the phasor, $|Y|$ is the amplitude, magnitude or absolute value and θ is the phase angle or argument. Polar numbers are written with the magnitude followed by the $\angle$ symbol to indicate angle, followed by the phase angle expressed in degrees. For example $Z = 110\angle 90^o$. This would be read as 110 at an angle of 90 degrees. The rectangular form is easily produced by applying Eq. (2.2)

The phasor can be represented graphically as we have demonstrated in Fig. 1.1, with the real components coinciding with the x axis.

When multiplying two phasors it is best to have the phasor written in the polar form. The magnitudes are multiplied together and the phase angles are added together. Division, which is the inverse of multiplication, can be accomplished in a similar manner. In division the magnitudes are divided and the phase angle in the denominator is subtracted from the phase angle in the numerator.

Example 2.1

Multiply $A \cdot B$ where $A = 5\angle 35^o$ and $B = 3\angle 45^o$.

Solution

$$A \cdot B = 5\angle 35^o \cdot 3\angle 45^o = (5 \cdot 3)\angle(35^o + 45^o)$$
$$= 15\angle 80^o$$

Example 2.2

Solve $\frac{C}{D}$ where $C = 15\angle 35^o$ and $D = 3\angle 50^o$.

Solution

$$\frac{C}{D} = \frac{15\angle 35^o}{3\angle 50^o} = \left(\frac{15}{3}\right)\angle(35^o - 50^o)$$
$$= 5\angle -15^o$$

3. The j and a operator

Recall the operator j. In polar form, $j = 1\angle 90^o$. Multiplying by j has the effect of rotating a phasor 90^o without affecting the magnitude.

Table 3.1 - Properties of the vector *j*

$$1 = 1.0 + j0.0$$
$$j = 1\angle 90^o$$
$$j^2 = 1\angle 180^o = -1$$
$$j^3 = 1\angle 270^o = -j$$
$$-j = 1\angle -90^o$$
$$j = \sqrt{-1}$$

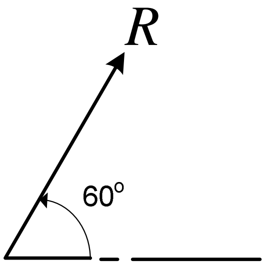
Example 3.1

Compute jR where $R = 10\angle 60^o$.

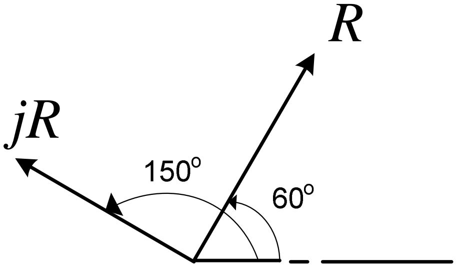
Solution

$$jR = 1\angle 90^o (10\angle 60^o)$$
$$= 10\angle 150^o$$

Notice that multiplication by the *j* operator rotated the Phasor $\overline{R}$ by 90^o, but did not change the magnitude. Refer to Fig. 3.1



(a) $\overline{R}$



(b) $j\overline{R}$

Fig. 3.1. *j* effects

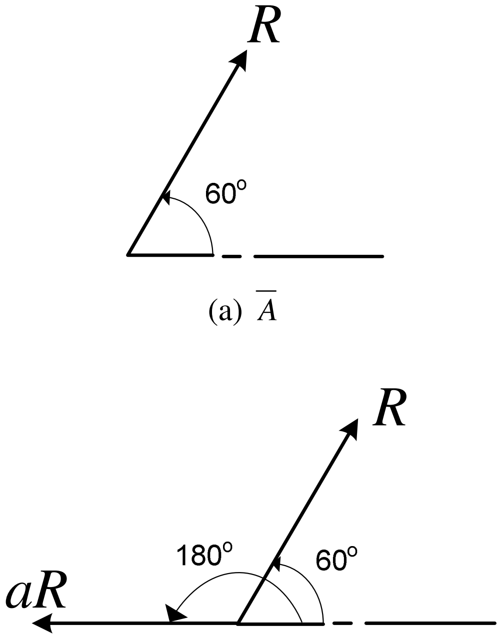
In a similar manner the *a* operator is defined as unit vector at an angle of 120°, written as $a = 1\angle 120^o$. The operator a^2, is also a unit vector at an angle of 240°, written $a^2 = 1\angle 240^o$.

Example 3.2

Compute aR where $R = 10\angle 60^o$.

Solution

$$aR = 1\angle 120^o (10\angle 60^o)$$
$$= 10\angle 180^o$$



(a) $\overline{A}$

(b) $j\overline{R}$

Fig. 3.2. *a* effects

Table 3.2 - Properties of the vector *a*

$1 = 1.0 + j0.0$

$a = 1\angle 120^o$

$a^2 = 1\angle 240^o$

$a^3 = 1\angle 360^o = 1\angle 0^o$

$1 + a^2 + a = 0$

$a + a^2 = -1$

$1 + a = 1\angle 60^o$

$1 + a^2 = 1\angle -60^o$

$a - a^2 = j\sqrt{3}$

$a^2 - a = -j\sqrt{3}$

$1 - a = \sqrt{3}\angle -30^o$

$1 - a^2 = \sqrt{3}\angle 30^o$

4. The three-phase System and the relationship of the $\sqrt{3}$

In a Wye connected system the voltage measured from line to line equals the square root of three, $\sqrt{3}$, times the voltage from line to neutral. See Fig. 4.1 and Eq. (4.1). The line current equals the phase current, see Eq. (4.2)

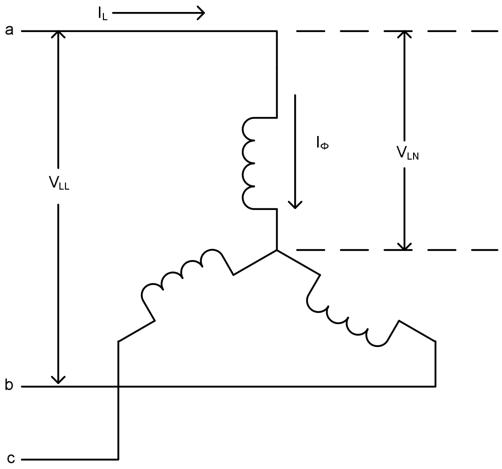


Fig. 4.1

$$V_{LL} = \sqrt{3}V_{LN} \tag{4.1}$$
$$I_L = I_\Phi \tag{4.2}$$

In a Delta connected system the voltage measured from line to line equals the phase voltage. See Fig. 4.2 and Eq. (4.3). The line current will equal the square root of three, $\sqrt{3}$, times the phase current, see Eq. (4.4)

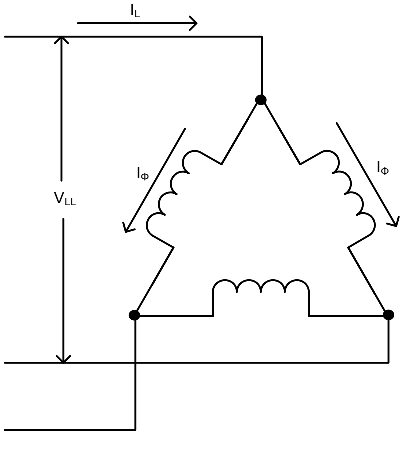


Fig. 4.2

$$V_{LL} = V_\Phi \tag{4.3}$$
$$I_L = \sqrt{3}I_\Phi \tag{4.4}$$

The power equation, for a three phase system, is

$$S = \sqrt{3} V_{LL} I_L \tag{4.5a}$$

$$P = \sqrt{3} V_{LL} I_L \cos \psi \tag{4.5b}$$

$$Q = \sqrt{3} V_{LL} I_L \sin \psi \tag{4.5c}$$

where S is the apparent power or complex power in volt-amperes (VA). P is the real power in Watts (W, kW, MW). Q is the reactive power in VARS (Vars, kVars, MVars).

5. The per-unit System

5.1 Introduction

In many engineering situations it is useful to scale, or normalize, dimensioned quantities. This is commonly done in power system analysis. The standard method used is referred to as the *per-unit* system. Historically, this was done to simplify numerical calculations that were made by hand. Although this advantage is eliminated by the calculator, other advantages remain.

- Device parameters tend to fall into a relatively narrow range, making erroneous values conspicuous.
- Using this method all quantities are expressed as ratios of some base value or values.
- The *per-unit* equivalent impedance of any transformer is the same when referred to either the primary or the secondary side.
- The *per-unit* impedance of a transformer in a three-phase system is the same regardless of the type of winding connections (wye-delta, delta-wye, wye-wye, or delta-delta).
- The *per-unit* method is independent of voltage changes and phase shifts through transformers where the base voltages in the winding are proportional to the number of turns in the windings.
- Manufactures usually specify the impedance of equipment in per-unit or percent on the base of its nameplate rating of power (usually kVA) and voltage (V or kV).

The *per-unit* system is simply a scaling method. The basic *per-unit* scaling equation is

$$per - unit = \frac{actual\_value}{base\_value} \tag{5.1}$$

The base value always has the same units as the actual value, forcing the *per-unit* value to be dimensionless. The base value is always a real number, whereas the actual value may be complex. The subscript pu will indicate a *per-unit* value. The subscript $base$ will indicate a base value, and no subscript will indicate an actual value such as Amperes, Ohms, or Volts.

Per-unit quantities are similar to percent quantities. The ratio in percent is 100 times the ratio in per-unit. For example, a voltage of 70kV on a base of 100kV would be 70% of the base voltage. This is equal to 100 times the per unit value of 0.7 derived above.

The first step in using *per-unit* is to select the base(s) for the system.

S_{base} = power base, in VA. Although in principle S_{base} may be selected arbitrarily, in practice it is typically chosen to be 100 MVA.

V_{base} = voltage base in V. Although in principle V_{base} is also arbitrary, in practice V_{base} is equal to the nominal line-to-line voltage. The term nominal means the value at which the system was designed to operate under normal balanced conditions.

From Eq. (4.5a) it follows that the base power equation for a three-phase system is:

$$S_{3\Phi base} = \sqrt{3} V_{base} I_{base} \tag{5.2}$$

Solving for current:

$$I_{base} = \frac{S_{3\Phi base}}{\sqrt{3} V_{base}}$$

Because $S_{3\Phi \mathrm{base}}$ can be written as kVA or MVA and voltage is usually expressed in kilo-volts, or kV, current can be written as:

$$I_{base} = \frac{kVA_{base}}{\sqrt{3} kV_{base}} amperes \tag{5.3}$$

Solving for base impedance:

$$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V_{base}^2}{S_{base}}$$

$$Z_{base} = \frac{kV_{base}^2 x1000}{kVA_{base}} ohms \tag{5.4a}$$

or

$$Z_{base} = \frac{kV_{base}^2}{MVA_{base}} ohms \tag{5.4b}$$

Given the base values, and the actual values: $V = IZ$, then dividing by the base we are able to calculate the *pu* values

$$\frac{V}{V_{base}} = \frac{IZ}{I_{base}Z_{base}} \Rightarrow V_{pu} = I_{pu}Z_{pu}$$

After the base values have been selected or calculated, then the *per-unit* impedance values for system components can be calculated using Eq. (5.4b)

$$Z_{pu} = \frac{Z(\Omega)}{Z_{base}} = \left(\frac{MVA_{base}}{kV_{base}^2}\right) \cdot Z(\Omega) \qquad (5.5a)$$

or

$$Z_{pu} = \left(\frac{kVA_{base}}{1000 \cdot kV_{base}^2}\right) \cdot Z(\Omega) \qquad (5.5b)$$

It is also a common practice to express *per-unit* values as percentages (i.e. 1 pu = 100%). (Transformer impedances are typically given in % at the transformer MVA rating.) The conversion is simple

$$per-unit = \frac{percent\_value}{100}$$

Then Eq. (5.5a) can be written as

$$\%Z = \frac{100MVA_{base} \cdot Z(\Omega)}{kV_{base}^2} = \frac{kVA_{base}Z(\Omega)}{10kV_{base}^2} \qquad (5.6)$$

It is frequently necessary, particularly for impedance values, to convert from one (old) base to another (new) base. The conversion is accomplished by two successive application of Eq. (5.1), producing:

$$Z_{pu}^{new} = Z_{pu}^{old}\left(\frac{Z_{base}^{old}}{Z_{base}^{new}}\right)$$

Substituting for Z_{base}^{old} and Z_{base}^{new} and re-arranging the new impedance in *per-unit* equals:

$$Z_{pu}^{new} = Z_{pu}^{old}\left(\frac{kVA_{base}^{new}}{kVA_{base}^{old}}\right)\left(\frac{kV_{base}^{old}}{kV_{base}^{new}}\right)^2 \qquad (5.7)$$

In most cases the turns ratio of the transformer is equivalent to the system voltages, and the equipment rated voltages are the same as the system voltages. This means that the voltage-squared ratio is unity. Then Eq. (5.7) reduces to

$$Z_{pu}^{new} = Z_{pu}^{old}\left(\frac{MVA_{base}^{new}}{MVA_{base}^{old}}\right) \tag{5.8}$$

We can quickly change from one impedance value in ohms, to another impedance value in ohms by dividing by the old base voltage and multiplying by the new base voltage in ohms. This is shown in Eq. (5.9)

$$Z_{ohm}^{new} = Z_{ohm}^{old}\cdot\left(\frac{kV_{base}^{new}}{kV_{base}^{old}}\right)^2 \tag{5.9}$$

Example 5.1

A system has S_{base} = 100 MVA, calculate the base current for

a) V_{base} = 230 kV

b) V_{base} = 525 kV

Then using this value, calculate the actual line current and phase voltage where $I = 4.95_{pu}$, and $V = 0.5_{pu}$ at both 230 kV and 525 kV.

Solution

Using Eq. (5.3) $I_{base} = \dfrac{kVA_{base}}{\sqrt{3}kV_{base}} amperes$

a) $I_{base} = \dfrac{1000\times 100}{\sqrt{3}\times 230} amperes = 251A$

b) $I_{base} = \dfrac{1000\times 100}{\sqrt{3}\times 525} amperes = 110.0A$

From Eq. (5.1)

$$I_{actual} = I_{pu}\cdot I_{base} \tag{5.9}$$

$$V_{actual} = V_{pu}\cdot V_{base} \tag{5.10}$$

At 230 kV

c) $I_{actual} = (4.95)\cdot(251A) = 1242A$

d) $V_{actual} = (0.5)\cdot(230kV) = 115kV$

At 525 kV

e) $I_{actual} = (4.95)\cdot(110.0A) = 544A$

f) $V_{actual} = (0.5)\cdot(525kV) = 263kV$

Example 5.2

A 900 MVA 525/241.5 autotransformer has a nameplate impedance of 10.14%

a) Determine the impedance in ohms, referenced to the 525 kV side.

b) Determine the impedance in ohms, referenced to the 241.5 kV side

Solution

First convert from % to *pu.*

$$Zpu = \frac{Z\%}{100} = 0.1014$$

Arranging Eq. (5.5a) and solving for Z_{actual} gives

$$Z(\Omega) = Z_{pu}\frac{kV_{base}^2}{MVA_{base}}\text{; therefore}$$

$$\text{a) } Z_{525kV} = 0.1014 \times \frac{525^2}{900}$$
$$= 31.05\Omega$$

$$\text{b) } Z_{241.5kV} = 0.1014 \times \frac{241.5^2}{900}$$
$$= 6.57\Omega$$

A check can be made to see if the high-side impedance to the low-side impedance equals the turns ratio squared.

$$\frac{31.05}{6.57} = 4.726 \qquad \left(\frac{525}{241.5}\right)^2 = 4.726$$

5.1 Application of per-unit

Appling this to relay settings, a practical example can be shown in calculation of the settings for a relay on a transmission line. For distance relays a common setting for zone 1 is 85% of the line impedance. Zone 2 should be set not less than 125% of the line, with care to not over reach the zone 1 of the next line section. If this does then zone 2 will need to be coordinated with the next line section zone 2.

Referring to Fig. 5.1 the line impedance for the 161 kV line is $Z = 59.3\angle 81^o$ ohms. Using the above criteria of 85% for zone 1 and 125 % for zone 2 the relays would be set at

For zone 1

$$Z_1(\Omega) = 85\%(59.31\angle 81^o)$$
$$Z_1(\Omega) = 50.4\angle 81^o$$

For zone 2

$Z_2(\Omega) = 125\%(59.31\angle 81^o)$

$Z_2(\Omega) = 74.1\angle 81^o$

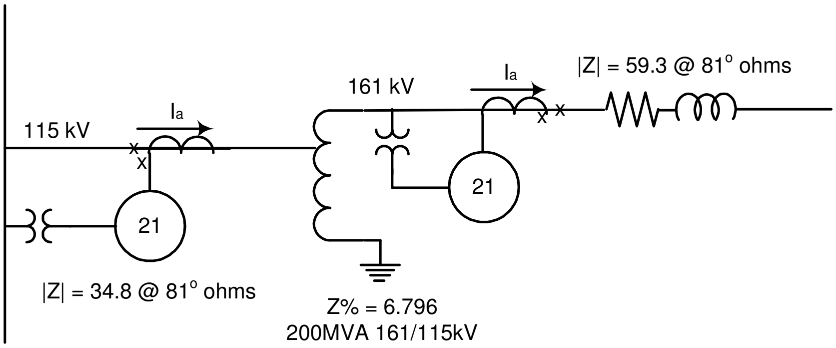


Fig 5.1

For the relays on the 115 kV side of the transformer, the impedance of the transformer needs to be calculated. From example 5.2 we see that

$$Z_{115kV} = 0.06796 \times \frac{115^2}{200}$$
$$= 4.494\Omega$$

Next the line impedance needs referenced to the 115 kV side of the transformer. Using equation 5.9

$$Z_{ohm}^{new} = Z_{ohm}^{old} \cdot \left(\frac{kV_{base}^{new}}{kV_{base}^{old}} \right)^2 \qquad (5.9)$$

Substituting, the line impedance equals

$$Z_{ohm}^{115kV} = 59.3 \cdot \left(\frac{115}{161} \right)^2 = 30.3 ohms$$

Adding this to the transformer, the impedance setting for the relays on the 115 kV side of the transformer is $Z = 34.8\angle 82^o$

Using the same criteria for zone 1 and zone 2 reach.

For zone 1

$Z_1(\Omega) = 85\%(34.8\angle 82^o)$

$Z_1(\Omega) = 29.6\angle 81^o$

For zone 2

$Z_2(\Omega) = 125\%(34.8\angle 81^o)$

$Z_2(\Omega) = 43.5\angle 81^o$

Given these values, one can easily see that by ignoring the base values of the voltages the relay settings would not be adequate. For example if the 161 kV settings were applied to the 115 kV relays, zone 1 would over reach the remote terminal. Conversely, if the 115 kV settings were applied to the 161 kV relays zone 2 would not reach past the remote terminal and would thus not protect the full line.

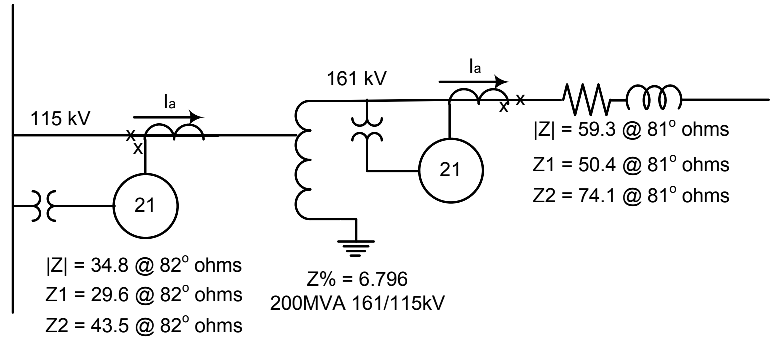


Fig. 5.2

5.2 Calculating actual values from per-unit

In the following sections we will discuss symmetrical faults. The analysis of the faults uses the per-unit. A impedance and voltage of the system is express in per-unit. Then the fault current and fault voltage is solved and that value will be given in per unit. Next we need to convert from per-unit to actual amps and volts by using the base values. Using the above equations it is easy to prove the following equations.

The MVA for a three phase fault is given as

$$MVA_{Fault} = \frac{MVA_{Base}}{Z_{Fault}PU} \tag{5.10}$$

Or

$$MVA_{Fault} = \frac{100}{Z_{Fault}PU} \text{ for a 100 MVA}_{\text{Base}} \tag{5.11 a}$$

$$I_{Fault\_Current} = \frac{I_{Base}}{Z_{Fault}PU} \tag{5.12}$$

Or

$$I_{Fault\_Current} = \frac{100{,}000}{(Z_{Fault}PU)\cdot\sqrt{3}(kV_{Base})} \tag{5.12 a}$$

5.3 Converting per-unit

Before using the per-unit impedance of a transformer from a manufacture nameplate you must first convert it to a per-unit value of your system. Typically the three-phase power base of 100MVA is used. This is done by first converting the per unit impedance to an actual impedance (in ohms) at 525kV and then converting the actual impedance to a per-unit impedance on the new base. Repeat, this time converting the per unit impedance to an actual impedance (in ohms) at 241.5kV and then converting the actual impedance to a per-unit impedance on the new base.

In the problem 3 at the end of this document, the transformer nameplate data is for a ratio of 525/241.5kV or 2.174, whereas BPA's ASPEN model uses nominal voltages of 525kV and 230kV for a ratio of 2.283. Because BPA used a transformer ratio in ASPEN model that was different than the transformer nameplate values, we have a discrepancy in the per-unit impedance values that we obtained. The problem arises because when a transformer is applied to the BPA system the transformer tap used will often be different than the one used in the nameplate calculations.

What is the correct way to convert the per-unit impedance to the BPA base?

Because the actual impedance of the transformer will vary when different taps are used, the most accurate way to model the impedance would be to actually measure the impedance with the transformer on the tap that will normally be used on the BPA system. This impedance would then be converted to a per-unit value on the BPA model base. Since this isn't normally possible, a close approximation can be made by assuming that the per-unit impedance given on the nameplate will remain the same for the different tap positions of the transformer. Find the transformer tap position that most closely matches the ratio of the ASPEN model (2.283 for a 525/230kV transformer), then convert the nameplate per-unit impedance to an actual value based on either the high- or low-side voltage given for that tap position. This actual impedance is then converted to a per-unit value on the BPA model base, using the high-side BPA voltage base if the high-side voltage was used for the conversion to actual impedance, or using the low-side BPA voltage base if the low-side voltage was used for the conversion to actual impedance. See problem 4.

6. Sequence Networks

Refer to the basic three-phase system as shown in Fig. 6.1. There are four conductors to be considered: *a, b, c* and neutral *n*.

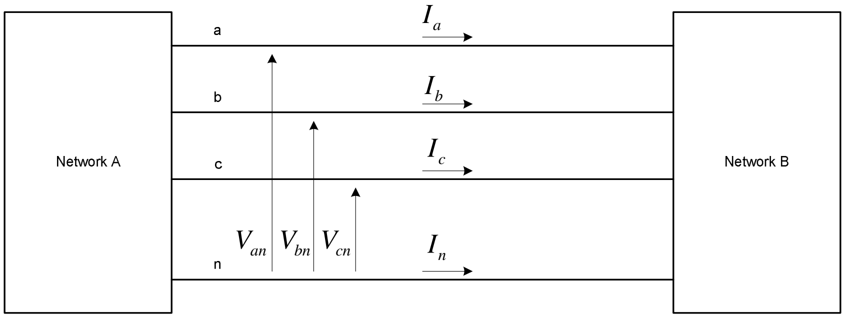


Fig. 6.1

The phase voltages, V_p, for the balanced 3Φ case with a phase sequence *abc* are

$$V_{an} = V_a = V_p\angle 0^o \tag{6.1a}$$

$$V_{bn} = V_b = V_p\angle -120^o \tag{6.1b}$$

$$V_{cn} = V_c = V_p\angle +120^0 = V_p\angle -240^o \tag{6.1c}$$

The phase-phase voltages, V_{LL}, are written as

$$V_{ab} = V_a - V_b = V_{LL}\angle 30^o \tag{6.2a}$$

$$V_{bc} = V_b - V_c = V_{LL}\angle -90^o \tag{6.2b}$$

$$V_{ca} = V_c - V_a = V_{LL}\angle 150^o \tag{6.2c}$$

Equation (6.1) and (6.2) can be shown in phasor form in Fig. 6.2.

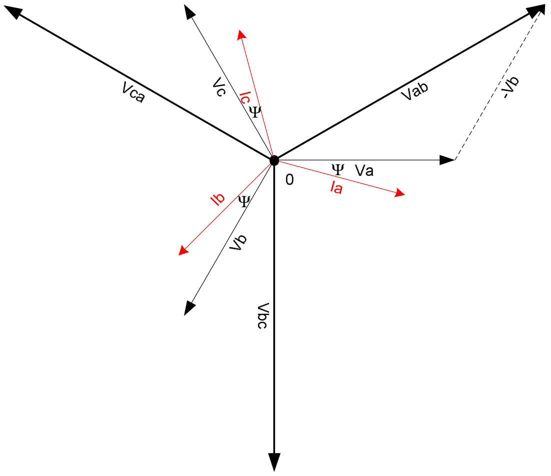


Fig. 6.2

There are two balanced configurations of impedance connections within a power system. For the wye case, as shown in Fig. 4.1, and with an impedance connection of $Z\angle\Psi$, the current can be calculated as

$$I_a = \frac{V}{Z_Y} = \frac{V_P}{Z_Y}\angle 0^o - \psi \tag{6.3}$$

Where Ψ is between -90^o and $+90^o$. For Ψ greater than zero degrees the load would be inductive (I_a lags V_a). For ψ less than zero degrees the load would be capacitive (I_a leads V_a).

The phase currents in the balanced three-phase case are

$$I_a = I_p\angle 0^o - \psi \qquad (6.4a)$$

$$I_b = I_p\angle -120^o - \psi \qquad (6.4b)$$

$$I_c = I_p\angle -240^o - \psi \qquad (6.4c)$$

See Fig. 6.2. for the phasor representation of the currents.

7. Symmetrical Components Systems

The electrical power system operates in a balanced three-phase sinusoidal operation. When a tree contacts a line, a lightning bolt strikes a conductor or two conductors swing into each other we call this a fault, or a fault on the line. When this occurs the system goes from a balanced condition to an unbalanced condition. In order to properly set the protective relays, it is necessary to calculate currents and voltages in the system under such unbalanced operating conditions.

In Dr. C. L. Fortescue's paper he described how symmetrical components can transform an unbalanced condition into symmetrical components, compute the system response by straight forward circuit analysis on simple circuit models, and transform the results back into original phase variables. When a short circuit fault occurs the result can be a set of unbalanced voltages and currents. The theory of symmetrical components resolves any set of unbalanced voltages or currents into three sets of symmetrical balanced phasors. These are known as positive, negative and zero-sequence components. Fig. 7.1 shows balanced and unbalanced systems.

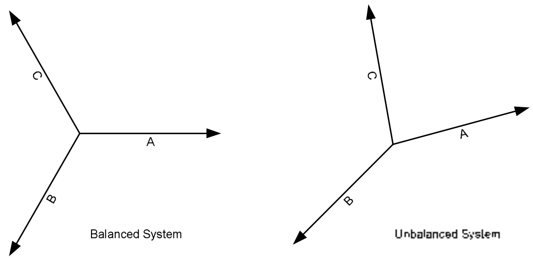


Fig. 7.1

Consider the symmetrical system of phasors in Fig. 7.2. Being balanced, the phasors have equal amplitudes and are displaced 120° relative to each other. By the definition of symmetrical components, $\overline{V}_{b1}$ *always lags* $\overline{V}_{a1}$ by a fixed angle of 120° and always has the same magnitude as $\overline{V}_{a1}$. Similarly $\overline{V}_{c1}$ leads $\overline{V}_{a1}$ by 120°. It follows then that

$$V_{a1} = V_{a1} \qquad (7.1a)$$

$$V_{b1} = (1\angle 240^o)V_{a1} = a^2V_{a1} \qquad (7.1b)$$

$$V_{c1} = (1\angle 120^o)V_{a1} = aV_{a1} \qquad (7.1c)$$

Where the subscript (1) designates the positive-sequence component. The system of phasors is called positive-sequence because the order of the sequence of their maxima occur *abc*.

Similarly, in the negative and zero-sequence components, we deduce

$$V_{a2} = V_{a2} \qquad (7.2a)$$
$$V_{b2} = (1\angle 120^o)V_{a2} = aV_{a2} \qquad (7.2b)$$
$$V_{c2} = (1\angle 240^o)V_{a2} = a^2V_{a2} \qquad (7.2c)$$

$$V_{a0} = V_{a0} \qquad (7.3a)$$
$$V_{b0} = V_{a0} \qquad (7.3b)$$
$$V_{c0} = V_{a0} \qquad (7.3c)$$

Where the subscript (2) designates the negative-sequence component and subscript (0) designates zero-sequence components. For the negative-sequence phasors the order of sequence of the maxima occur *cba*, which is opposite to that of the positive-sequence. The maxima of the instantaneous values for zero-sequence occur simultaneously.

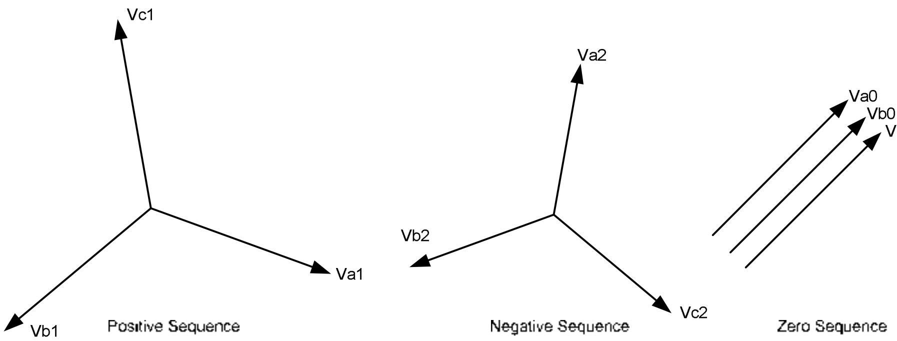


Fig.7.2

In all three systems of the symmetrical components, the subscripts denote the components in the different phases. The total voltage of any phase is then equal to the sum of the corresponding components of the different sequences in that phase. It is now possible to write our symmetrical components in terms of three, namely, those referred to the *a* phase (refer to section 3 for a refresher on the *a* operator).

$$V_a = V_{a0} + V_{a1} + V_{a2} \qquad (7.4a)$$
$$V_b = V_{b0} + V_{b1} + V_{b2} \qquad (7.4b)$$
$$V_c = V_{c0} + V_{c1} + V_{c2} \qquad (7.4c)$$

We may further simplify the notation as follows; define

$$V_0 = V_{a0} \tag{7.5a}$$
$$V_1 = V_{a1} \tag{7.5b}$$
$$V_2 = V_{a2} \tag{7.5c}$$

Substituting their equivalent values

$$V_a = V_0 + V_1 + V_2 \tag{7.6a}$$
$$V_b = V_0 + a^2 V_1 + aV_2 \tag{7.6b}$$
$$V_c = V_0 + aV_1 + a^2 V_2 \tag{7.6c}$$

These equations may be manipulated to solve for V_0, V_1, and V_2 in terms of V_a, V_b, and V_c.

$$V_0 = \frac{1}{3}\left(V_a + V_b + V_c\right) \tag{7.7a}$$
$$V_1 = \frac{1}{3}\left(V_a + aV_b + a^2 V_c\right) \tag{7.7b}$$
$$V_2 = \frac{1}{3}\left(V_a + a^2 V_b + aV_c\right) \tag{7.7c}$$

It follows then that the phase currents are

$$I_a = I_0 + I_1 + I_2 \tag{7.8a}$$
$$I_b = I_0 + a^2 I_1 + aI_2 \tag{7.8b}$$
$$I_c = I_0 + aI_1 + a^2 I_2 \tag{7.8c}$$

The sequence currents are given by

$$I_0 = \frac{1}{3}\left(I_a + I_b + I_c\right) \tag{7.9a}$$
$$I_1 = \frac{1}{3}\left(I_a + aI_b + a^2 I_c\right) \tag{7.9b}$$
$$I_2 = \frac{1}{3}\left(I_a + a^2 I_b + aI_c\right) \tag{7.9c}$$

The unbalanced system is therefore defined in terms of three balanced systems. Eq. (7.6) may be used to convert phase voltages (or currents) to symmetrical component voltages (or currents) and vice versa [Eq. (7.7)].

Example 7.1

Given $V_a = 5\angle 53^o$, $V_b = 7\angle -164^o$, $V_c = 7\angle 105^o$, find the symmetrical components. The phase components are shown in the phasor form in Fig. 7.3

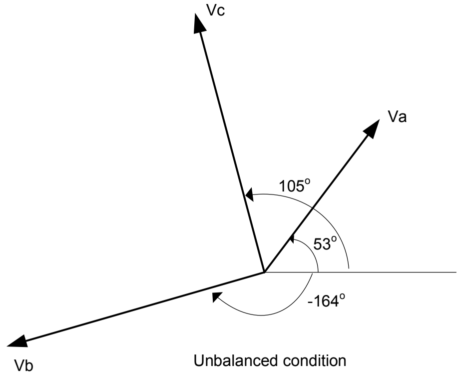


Fig. 7.3

Solution

Using Eq. (7.7a)

Solve for the zero-sequence component:

$$V_{a0} = \frac{1}{3}(V_a + V_b + V_c)$$
$$= \frac{1}{3}(5\angle 53^o + 7\angle -164^o + 7\angle 105^o)$$
$$= 3.5\angle 122^o$$

From Eq. (7.3b) and (7.3c)

$$V_{b0} = 3.5\angle 122^o$$
$$V_{c0} = 3.5\angle 122^o$$

Solve for the positive-sequence component:

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2V_c)$$
$$= \frac{1}{3}(5\angle 53^o + (1\angle 120^o \cdot 7\angle -164^o) + (1\angle 240^o \cdot 7\angle 105^o))$$
$$= 5.0\angle -10^o$$

From Eq. (7.1b) and (7.1c)

$$V_{b1} = 5.0\angle -130^o$$
$$V_{c1} = 5.0\angle 110^o$$

Solve for the negative-sequence component:

$$V_{a2} = \frac{1}{3}(V_a + a^2V_b + aV_c)$$

$$= \frac{1}{3}\left(5\angle 53^o + \left(1\angle 240^o \cdot 7\angle -164^o\right) + \left(1\angle 120^o \cdot 7\angle 105^o\right)\right)$$
$$= 1.9\angle 92^o$$

From Eq. (7.2b) and (7.2c)

$$V_{b2} = 1.9\angle -148^o$$
$$V_{c2} = 1.9\angle -28^o$$

The sequence components can be shown in phasor form in Fig. 7.4.

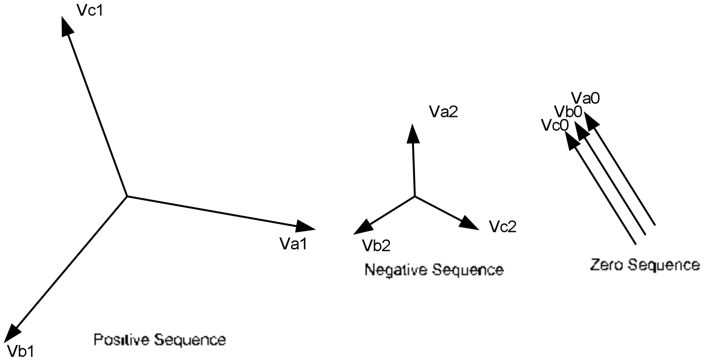


Fig. 7.4

Using Eq. (7.6) the phase voltages can be reconstructed from the sequence components.

Example 7.2

Given $V_0 = 3.5\angle 122^o$, $V_1 = 5.0\angle -10^o$, $V_2 = 1.9\angle 92^o$, find the phase sequence components. Shown in the phasor form in Fig. 7.4

Solution

Using Eq. (7.6)

Solve for the A-phase sequence component:

$$V_a = V_0 + V_1 + V_2$$
$$= 3.5\angle 122^o + 5.0\angle -10^o + 1.9\angle 92^o$$
$$= 5.0\angle 53^o$$

Solve for the B-phase sequence component:

$$V_b = V_0 + a^2 V_1 + aV_2$$
$$= 3.5\angle 122^o + 5.0\angle -130^o + 1.9\angle -148^o$$
$$= 7.0\angle -164^o$$

Solve for the C-phase sequence component:

$$
\begin{aligned}
V_c &= V_0 + aV_1 + a^2V_2 \\
&= 3.5\angle 122^o + 5.0\angle 110^o + 1.9\angle -28^o \\
&= 7.0\angle 105^o
\end{aligned}
$$

This returns the original values given in Example 5.2.

This can be shown in phasor form in Fig. 7.5.

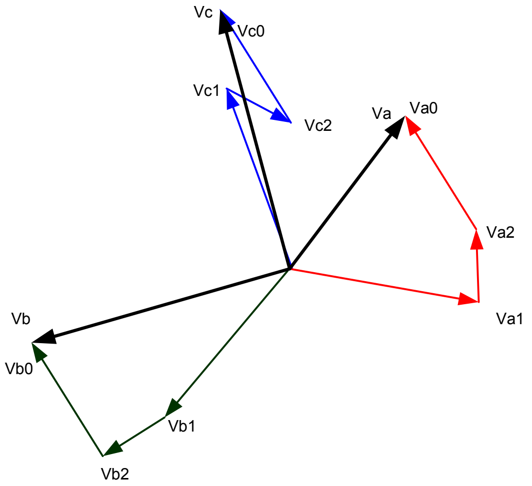


Fig. 7.5

Notice in Fig. 7.5 that by adding up the phasors from Fig. 7.4, that the original phase, Fig. 7.3 quantities are reconstructed.

8. Balanced and Unbalanced Fault analysis

Let’s tie it together. Symmetrical components are used extensively for fault study calculations. In these calculations the positive, negative and zero-sequence impedance networks are either given by the manufacturer or are calculated by the user using base voltages and base power for their system. Each of the sequence networks are then connected together in various ways to calculate fault currents and voltages depending upon the type of fault.

Given a system, represented in Fig. 8.1, we can construct general sequence equivalent circuits for the system. Such circuits are indicated in Fig. 8.2.

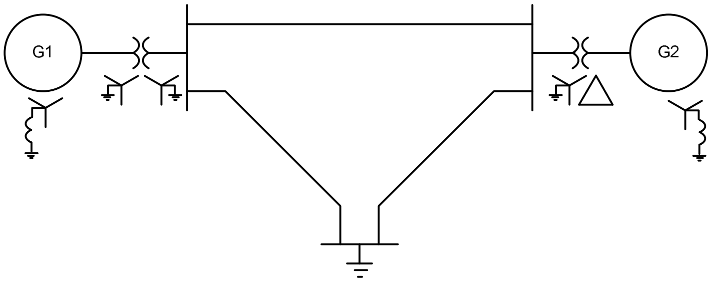


Fig. 8.1

The positive-sequence impedance system data for this example in per-unit is shown in Fig. 8.2.

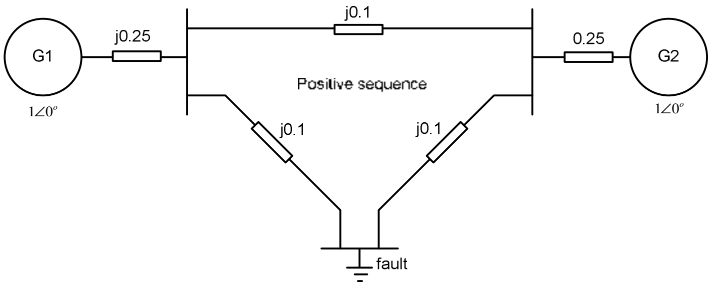


Fig. 8.2

Assuming the negative-sequence equals the positive-sequence, then the negative-sequence is shown in Fig 8.3

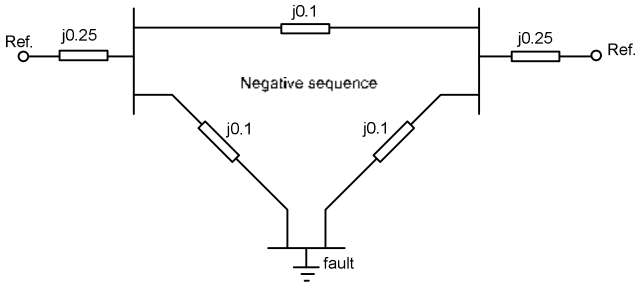


Fig. 8.3

The zero-sequence impedance is greater then the positive and for our purpose is assumed to be three times greater. Also because of the wye-delta transformer, zero-sequence from the generator will not pass through the transformer. This will be shown in section 10.2. Zero-sequence is shown in Fig 8.4

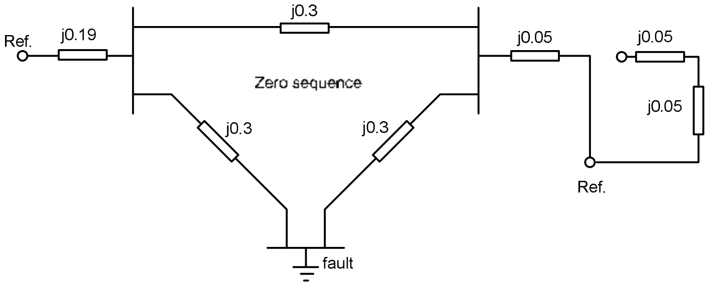


Fig. 8.4

The Thevenin equivalents for each circuit is reduced and shown in Fig. 8.5

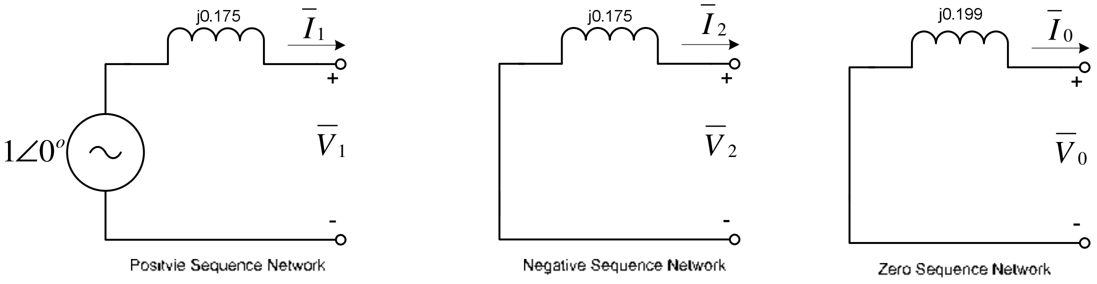


Fig. 8.5

Each of the individual sequence may be considered independently. Since each of the sequence networks involves symmetrical currents, voltages and impedances in the three phases, each of the sequence networks may be solved by the single-phase method. After converting the power system to the sequence networks, the next step is to determine the type of fault desired and the connection of the impedance sequence network for that fault. The network connections are listed in Table 8.1

<u>Table 8.1 - Network Connection</u>

- Three-phase fault - The positive-sequence impedance network is only used in three-phase faults. Fig. 8.3
- Single Line-to-Ground fault - The positive, negative and zero-sequence impedance networks are connected in series. Fig. 8.5
- Line-to-line fault - The positive and negative-sequence impedance networks are connected in parallel. Fig. 8.7
- Double Line-to-Ground fault - All three impedance networks are connected in parallel. Fig. 8.9

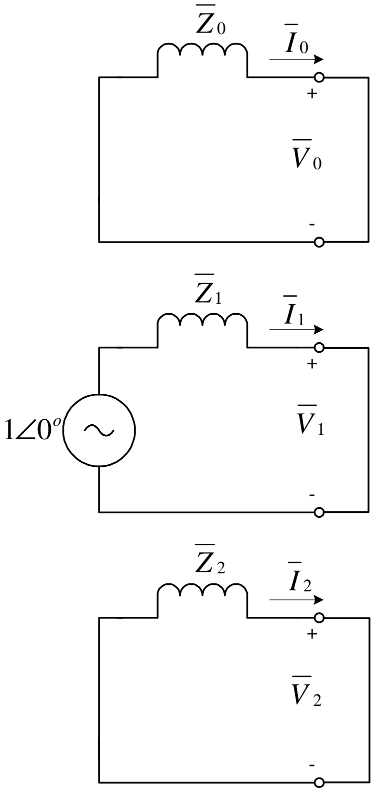
The system shown in Fig. 8.1 and simplified to the sequence network in Fig. 8.5 and will be used throughout this section.

Example 8.1

Given $Z_0 = 0.199\angle 90^o\ pu$, $Z_1 = 0.175\angle 90^o\ pu$, $Z_2 = 0.175\angle 90^o\ pu$, compute the fault current and voltages for a Three-phase fault. Note that the sequence impedances are in *per-unit*. This means that the solution for current and voltage will be in *per-unit*.

Solution

The sequence networks are interconnected, and shown



Note that for a three phase fault, there are no negative or zero-sequence voltages.

$$V_0 = V_2 = 0$$
$$I_0 = I_2 = 0$$

The current I_1 is the voltage drop across Z_1

$$I_1 = \frac{V_1}{Z_1}$$
$$I_1 = \frac{1\angle 0^o}{j0.175}$$
$$= -j5.71$$

The phase current is converted from the sequence value using Eq. (7.8).

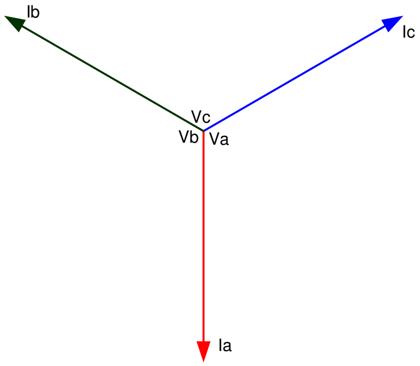
$$I_a = 0 - j5.71 + 0 = 5.71\angle -90^o\ pu$$
$$I_b = 0 + a^2(-j5.71) + a(0) = 5.71\angle 150^o\ pu$$
$$I_c = 0 + a(-j5.71) + a^2(0) = 5.71\angle 30^o\ pu$$

Calculating the voltage drop, the sequence voltages are

$$V_0 = V_2 = 0$$
$$V_1 = 1\angle 0^o - Z_1 I_1$$
$$V_1 = 1 - j0.175(-j5.71) = 0.0$$
$$= 0.0 pu$$

The phase voltages are converted from the sequence value using Eq. (7.6).

$$V_a = 0.0 + 0.0 + 0.0 = 0.0\,pu$$
$$V_b = 0.0 + a^2(0.0) + a(0.0) = 0.0\,pu$$
$$V_c = 0.0 + a(0.0) + a^2(0.0) = 0.0\,pu$$



The *per-unit* value for the current and voltage would now be converted to actual values using Eq. (5.9) and Eq. (5.10) and knowing the base power and voltage for the given system. See example 5.1 for a reference.

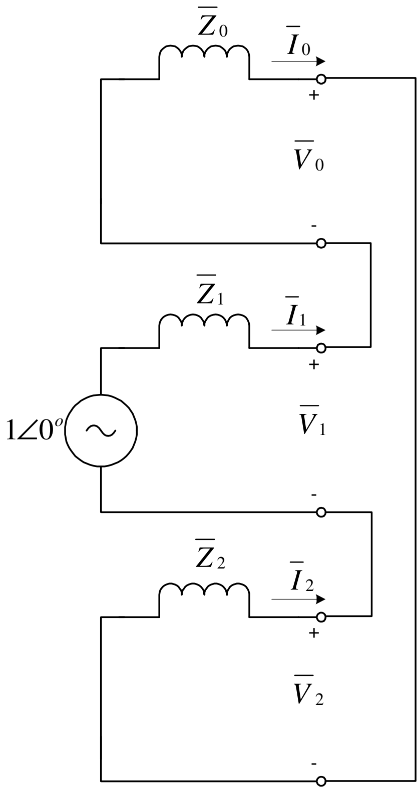
The currents and voltages can be shown in phasor form.

Example 8.2

Given $Z_0 = 0.199\angle 90^o\ pu$, $Z_1 = 0.175\angle 90^o\ pu$, $Z_2 = 0.175\angle 90^o\ pu$, compute the fault current and voltages for a Single line-to-ground fault. Note that the sequence impedances are in *per-unit*. This means that the results for current and voltage will be in *per-unit*.

Solution

The sequence networks are interconnected in series, as shown.



Because the sequence currents are in series, and using ohms law.

$$I_0 = I_1 = I_2$$
$$I_0 = \frac{V_1}{(Z_0 + Z_1 + Z_2)}$$

$$I_0 = \frac{1\angle 0^o}{(j0.199 + j0.175 + j0.175)}$$
$$= -j1.82\,pu$$

The phase currents are converted from the sequence value using Eq. (7.8). Substituting $I_0 = I_1 = I_2$ into

Eq. (7.8) gives

$$I_a = I_0 + I_0 + I_0 = 3I_0$$
$$I_b = I_0 + a^2 I_0 + aI_0 = 0$$
$$I_c = I_0 + aI_0 + a^2 I_0 = 0$$

Refer to Table 3.2: $\left(1 + a + a^2 = 0\right)$

Note that $I_a = 3I_0$. This is the quantity that the relay "see's" for a Single Line-to-Ground fault.

Substituting $I_0 = -j1.82\,pu$

$$I_a = 3I0 = 3(-j1.82)$$
$$= -j5.46\,pu$$

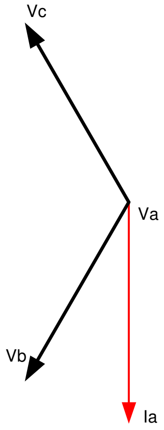
Calculating the voltage drop, the sequence voltages are

$$V_0 = -Z_0 I_0$$
$$V_1 = V - Z_1 I_1$$
$$V_2 = -Z_2 I_2$$

Substituting in the impedance and current from above

$$V_0 = -j0.199(-j1.82) = -0.362$$
$$V_1 = 1 - j0.175\left(-j1.82\right) = 0.681$$
$$V_2 = -j0.175\left(-j1.82\right) = -0.319$$

The phase voltages are converted from the sequence value using Eq. (7.6).



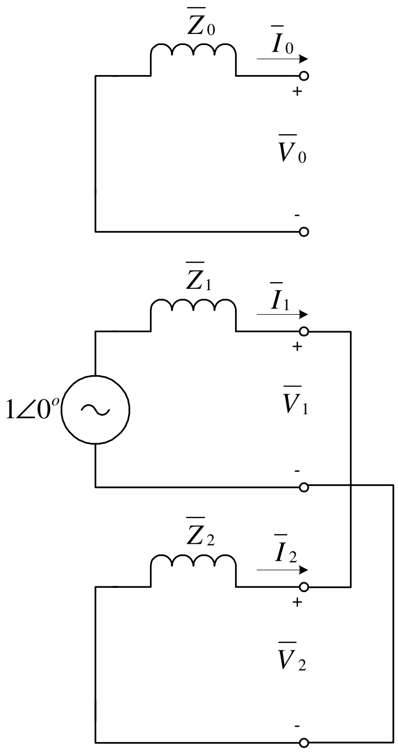
$$V_a = -0.362 + 0.681 - 0.319 = 0$$
$$V_b = -0.362 + a^2(0.681) + a(-0.319) = 1.022\angle 238^o\ pu$$
$$V_c = -0.362 + a(0.681) + a^2(-0.319) = 1.022\angle 122^o\ pu$$

The *per-unit* value for the current and voltage would now be converted to actual values using Eq. (5.9) and Eq. (5.10) and knowing the base power and voltage for the given system. See example 5.1 for a reference.

The currents and voltages can be shown in phasor form.

Example 8.3

Given $Z_0 = 0.199\angle 90^o\, pu$, $Z_1 = 0.175\angle 90^o\, pu$, $Z_2 = 0.175\angle 90^o\, pu$, compute the fault current and voltages for a Line-to-Line fault. Note that the sequence impedances are in *per-unit*. This means that the solution for current and voltage will be in *per-unit*.



Solution

The sequence networks are interconnected, as shown.

Because the sequence currents sum to one node, it follows that

$$I_1 = -I_2$$

The current I_1 is the voltage drop across Z_1 in series with Z_2

$$I_1 = \frac{V_1}{Z_1 + Z_2}$$

$$I_1 = \frac{1\angle 0^o}{j0.175 + j0.175}$$
$$= -j2.86pu$$

$$I_2 = +j2.86pu$$
$$I_0 = 0$$

The phase current is converted from the sequence value using Eq. (7.8).

$$I_a = 0 - j2.86 + j2.86 = 0pu$$
$$I_b = 0 + a^2(-j2.86) + a(j2.86) = -4.95pu$$
$$I_c = 0 + a(-j2.86) + a^2(j2.86) = 4.95pu$$

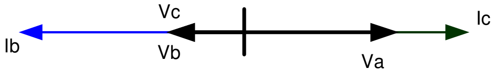
Calculating the voltage drop, and referring to Fig. 8.7, the sequence voltages are

$$V_1 = V_2$$
$$V_2 = -Z_2 I_2$$
$$= -(j1.75)(j2.86)$$
$$= 0.5pu$$
$$V_0 = 0$$

The phase voltages are converted from the sequence value using Eq. (7.6).

$$V_a = 0.0 + 0.5 + 0.5 = 1.0\,pu$$
$$V_b = 0.0 + a^2(0.5) + a(0.5) = -0.5\,pu$$
$$V_c = 0.0 + a(0.5) + a^2(0.5) = -0.5\,pu$$

The *per-unit* value for the current and voltage would now be converted to actual values using Eq. (5.9) and Eq. (5.10) and knowing the base power and voltage for the given system. See example 5.1 for a reference.



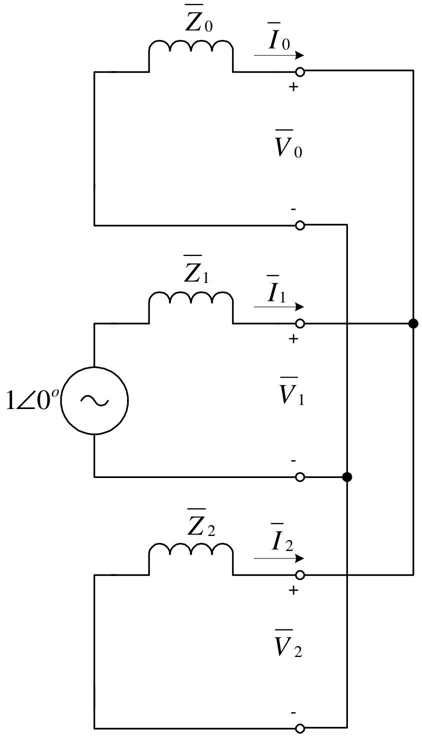
The currents and voltages can be shown in phasor form.

Example 8.4

Given $Z_0 = 0.199\angle 90^o\ pu$, $Z_1 = 0.175\angle 90^o\ pu$, $Z_2 = 0.175\angle 90^o\ pu$, compute the fault current and voltages for a Double Line-to-Ground fault. Note that the sequence impedances are in *per-unit*. This means that the solution for current and voltage will be in *per-unit*.

Solution

The sequence networks are interconnected, as shown in Fig. 8.9



Because the sequence currents sum to one node, it follows that

$$I_1 = -(I_0 + I_2)$$

The current I_1 is the voltage drop across Z_1 in series with the parallel combination of Z_0 and Z_2

$$I_1 = \frac{V_1}{Z_1 + \left(\dfrac{Z_0 Z_2}{Z_0 + Z_2}\right)}$$

Substituting in $V_1 = 1\angle 0^o$, and Z_0, Z_1, and Z_2, then solving for I_1

$$I_1 = -j3.73 pu$$
$$I_0 = \frac{Z_2}{(Z_0 + Z_2)} I_1$$
$$= +j1.75$$
$$I_2 = \frac{Z_0}{(Z_0 + Z_2)} I_1$$
$$= +j1.99$$

The phase current is converted from the sequence value using Eq. (7.8).

$$I_a = j1.75 - j3.73 + j1.99 = 0 pu$$
$$I_b = j1.75 + a^2(-j3.73) + a(j1.99) = 5.60\angle 152.1^o\ pu$$
$$I_c = j1.75 + a(-j3.73) + a^2(j1.99) = 5.60\angle 27.9^o\ pu$$

Calculating the voltage drop, and referring to Fig. 8.9, the sequence voltages are

$$V_0 = V_1 = V_2$$
$$V_0 = -Z_0 I_0$$
$$= -(j1.75)(j0.199)$$
$$= 0.348 pu$$

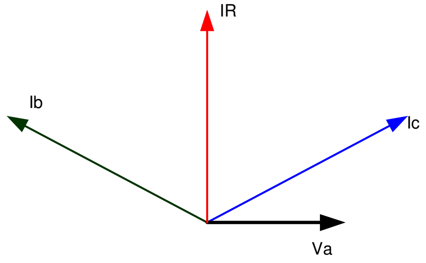
The phase voltages are converted from the sequence value using Eq. (7.6).

$$V_a = 0.348 + 0.348 + 0.348 = 1.044 pu$$
$$V_b = 0.348 + a^2(0.348) + a(0.348) = 0 pu$$
$$V_c = 0.348 + a(0.348) + a^2(0.348) = 0 pu$$

Refer to Table 3.2: $\left(1 + a + a^2 = 0\right)$

The *per-unit* value for the current and voltage would now be converted to actual values using Eq. (5.9) and Eq. (5.10) and knowing the base power and voltage for the given system. See example 5.1 for a reference.

The currents and voltages can be shown in phasor form.



9. Oscillograms and Phasors

Attached are four faults that were inputted into a relay and then captured using the relay software.

Three-phase fault. Compare to example (8.1)

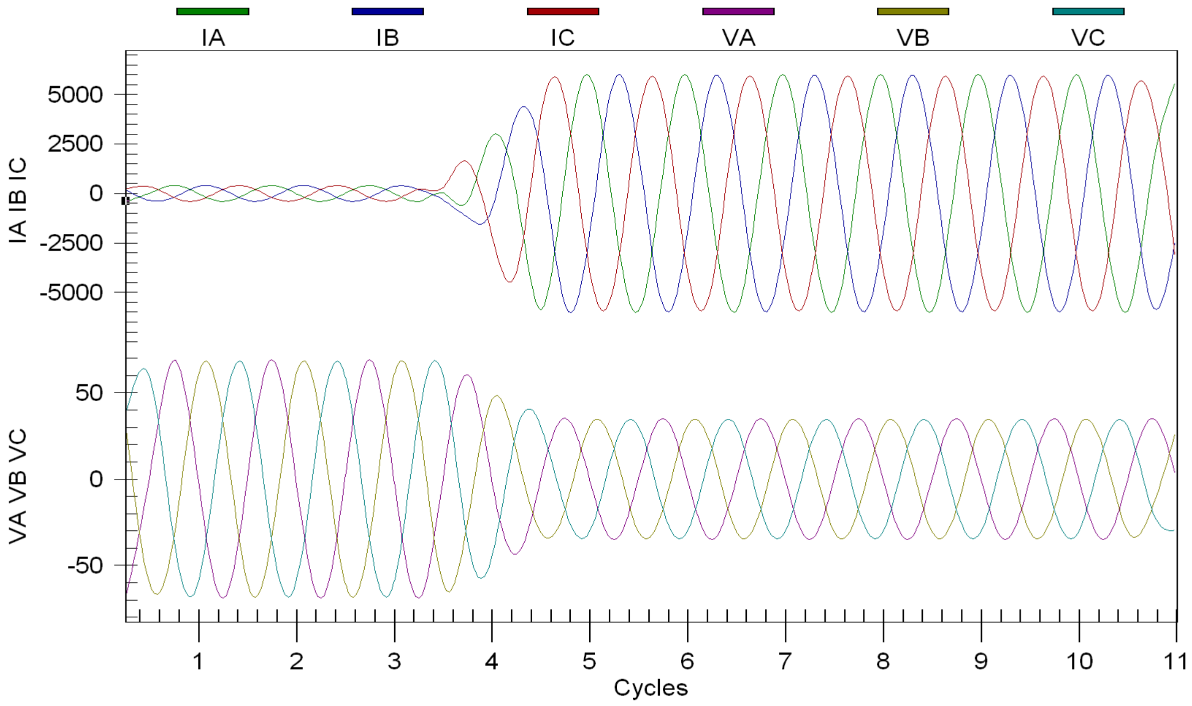


Fig 9.1a

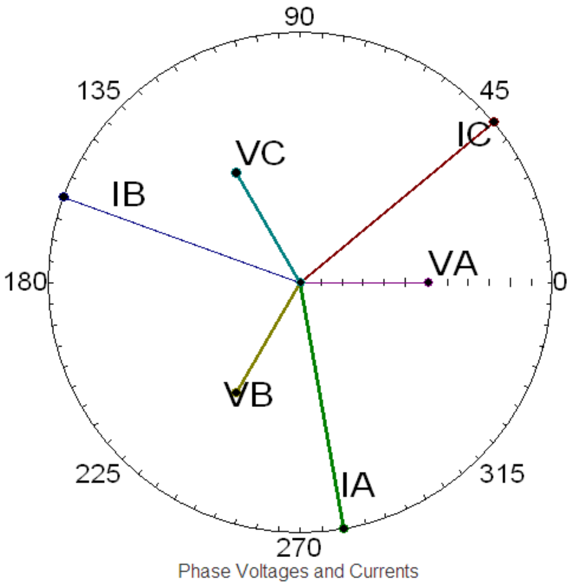


Fig 9.1b

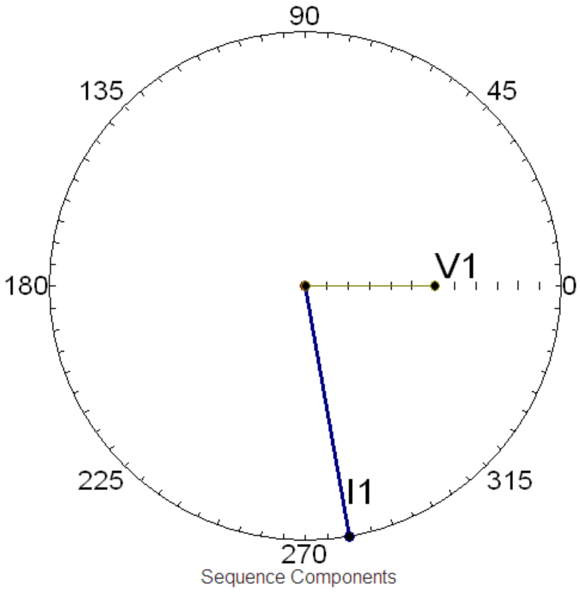


Fig 9.1c

Single Line-to-Ground fault. Compare to example (8.2)

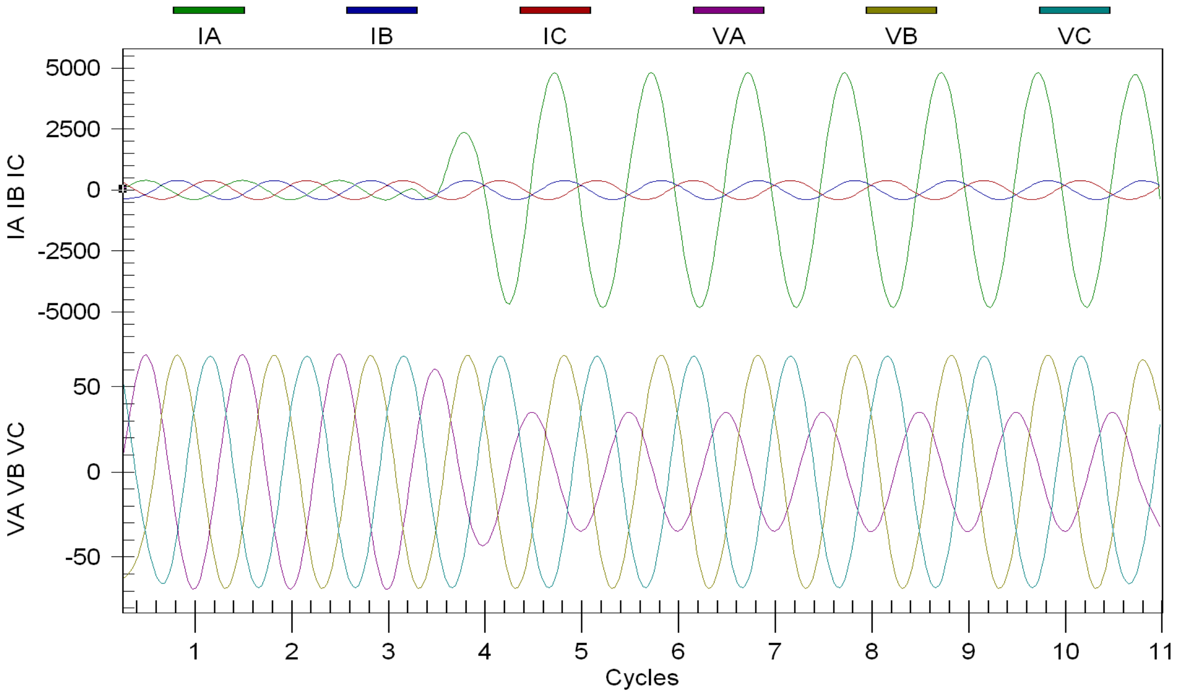
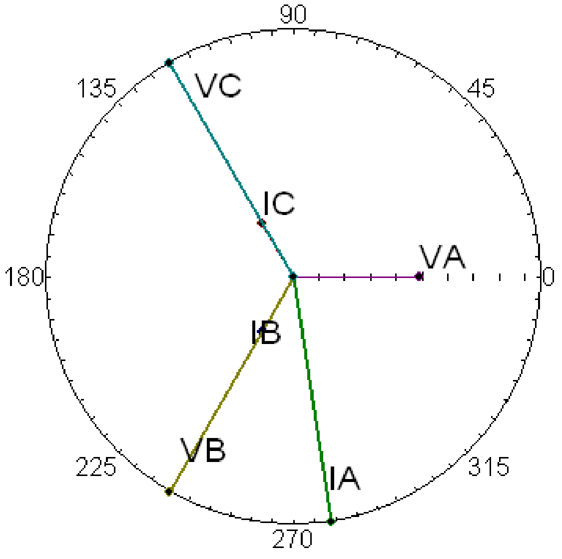
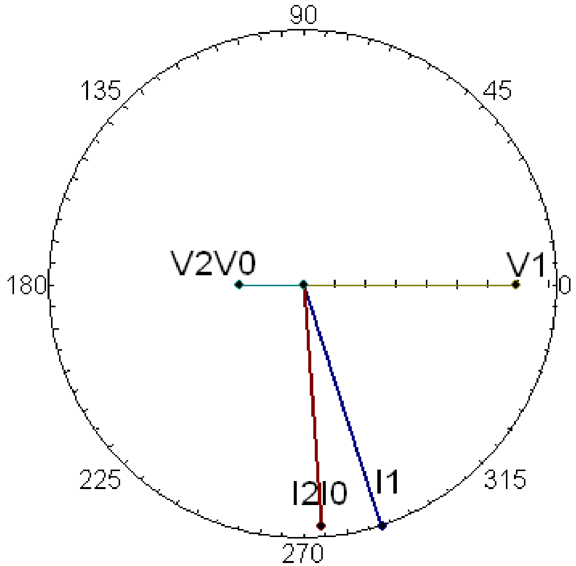


Fig 9.2a



Phase Voltages and Currents

Fig 9.2b



Sequence Components

Fig 9.2c

Line-to-Line fault. Compare to example (8.3)

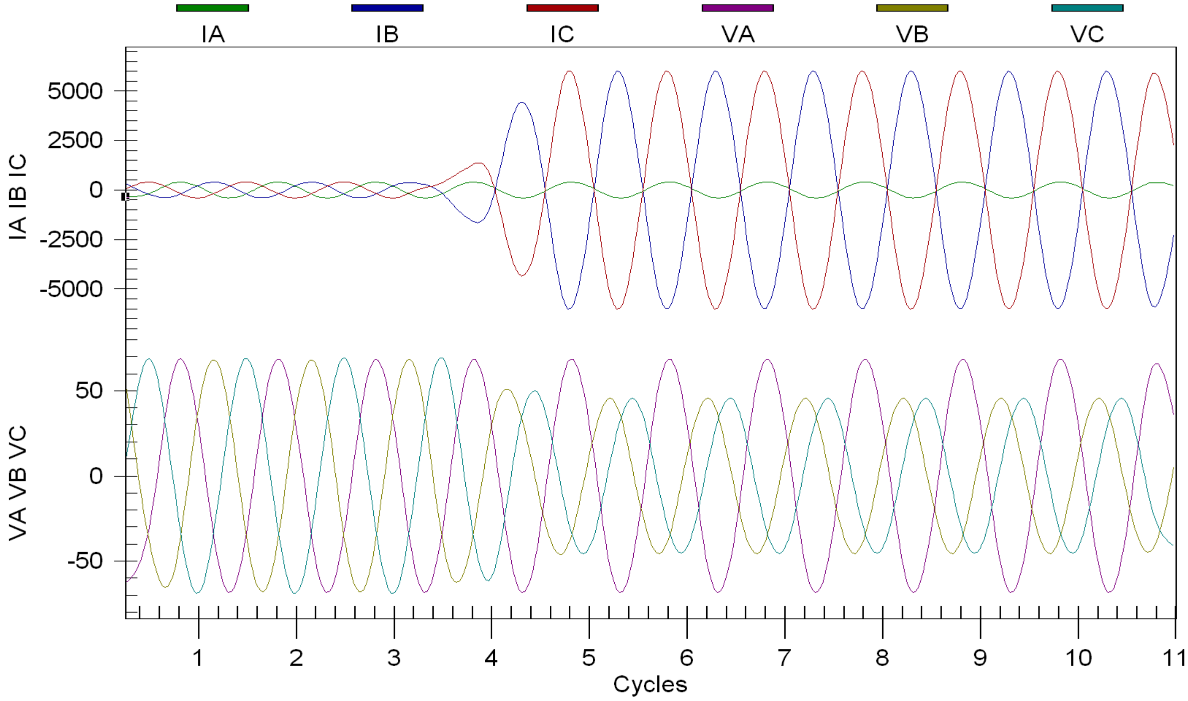


Fig 9.3a

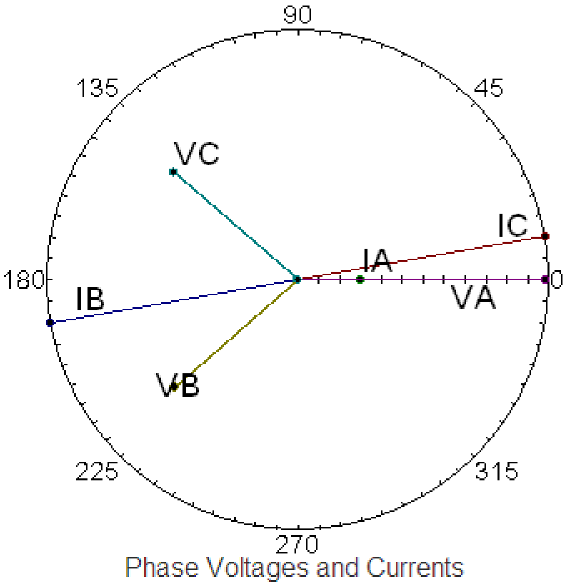


Fig 9.3b

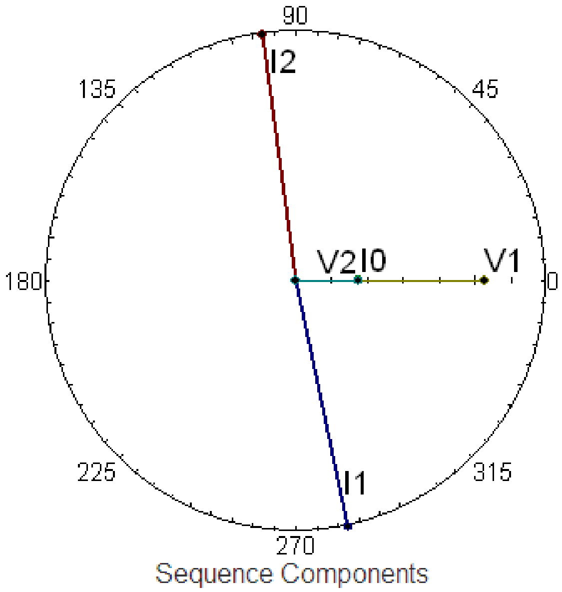


Fig 9.3c

Double Line-to-Ground fault. Compare to example (8.4)

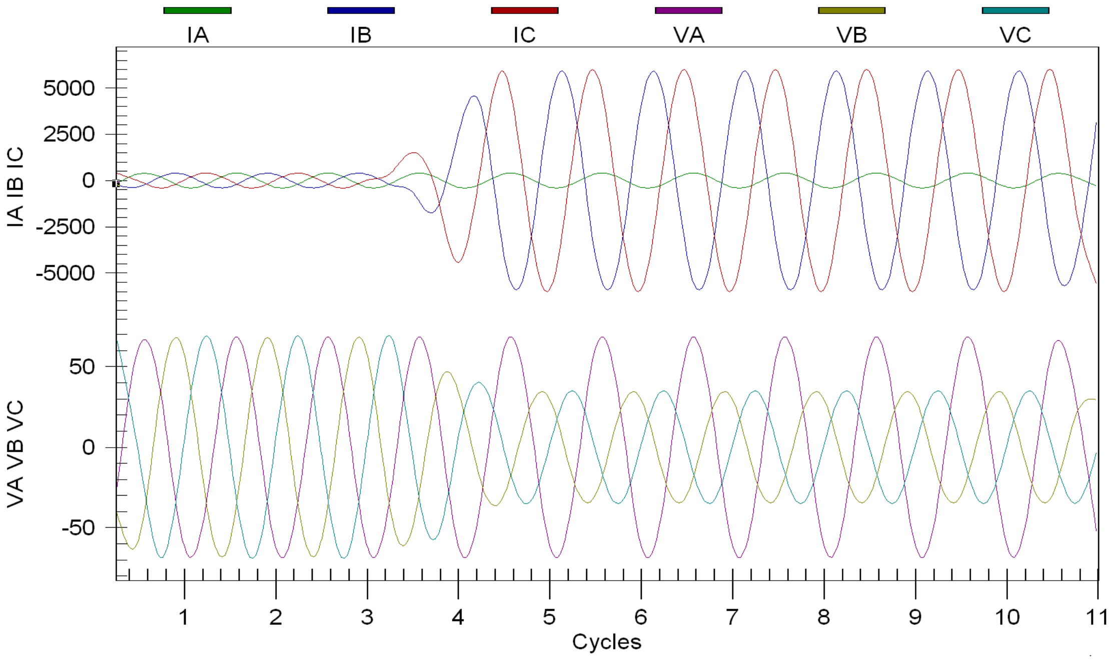
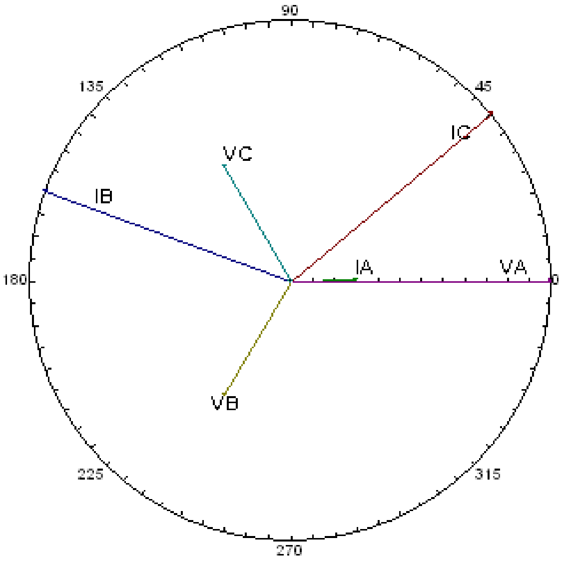
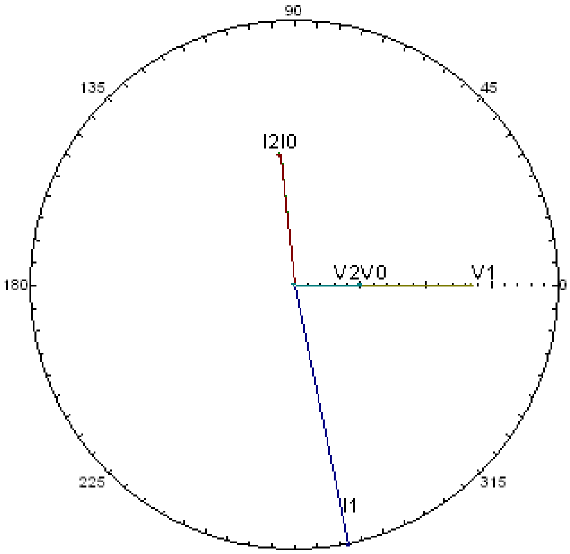


Fig 9.4a



Phase Voltages and Currents
Fig 9.4b



Sequence Components
Fig 9.4c

10. Addition Symmetrical Components considerations

10.1 Symmetrical Components into a Relay

Using a directional ground distance relay it will be demonstrated how sequential components are used in the line protection. To determine the direction of a fault, a directional relay requires a reference against which the line current can be compared. This reference is known as the polarizing quantity. Zero-sequence line current can be referenced to either zero-sequence current or zero-sequence voltage, or both may be used. The zero-sequence line current is obtained by summing the three-phase currents. See Fig. 10.1

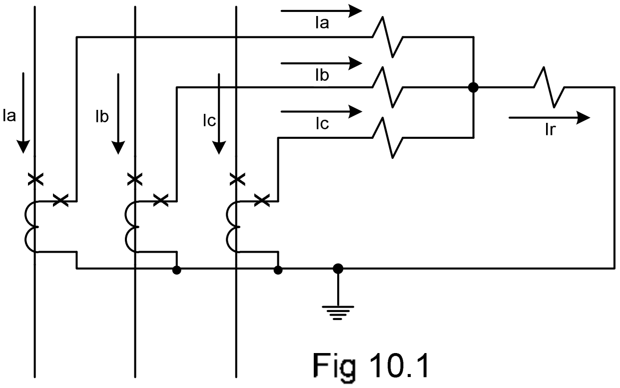


Fig 10.1

From Eq. (7.9)

$$\left(I_a + I_b + I_c\right) = 3I_0 = I_r \qquad (10.1)$$

This is known as the residual current or simply $3I_0$.

The zero-sequence voltage at or near the bus can be used for directional polarization. The polarizing zero-sequence voltage is obtained by adding an auxiliary potential transformer to the secondary voltage. The auxiliary transformer is wired as a broken-delta and the secondary inputted to the relay. See Fig 10.2

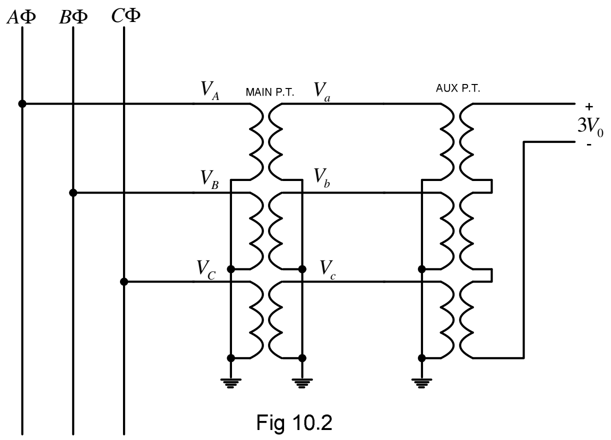


Fig 10.2

From Eq. (7.7a) the zero-sequence voltage equals

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \tag{10.2a}$$

$$3V_0 = (V_a + V_b + V_c) \tag{10.2a}$$

Example 10.1

Using the values obtained from example 8.2, calculate $3V_0$.

Solution

$$V_a = 0$$

$$V_b = 1.022\angle 238^o\ pu$$

$$V_c = 1.022\angle 122^o\ pu$$

$$3V_0 = 0 + 1.022\angle 238^o + 1.022\angle 122^o$$

$$= 1.08\angle 180^o\ pu$$

The zero-sequence voltage is $1.08\angle 180^o\ pu$. By connecting the value in the reverse gives $-3V_0$ which equals $1.08\angle 0^o\ pu$. Plotting this, we can show in phasor form what the relay see's, Ia lagging $-3V_0$ by the line angle. In this case resistance is neglected, therefore Ia lags by 90^o. (see Fig 10.3).

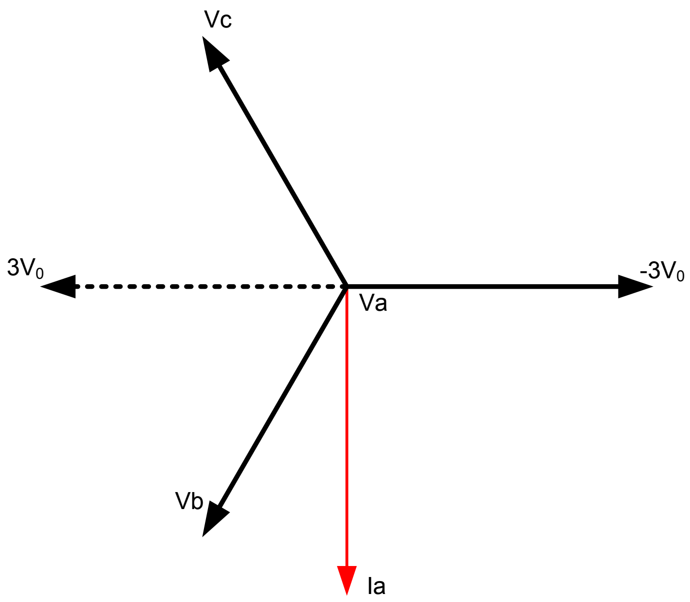


Fig 10.3

10.2 Symmetrical Components through a Transformer

This section will look at current flow through a wye-delta transformer bank. It will be shown in the next chapter that for faults that include ground that zero-sequence quantities will be generated. It can be shown using symmetrical components that zero-sequence components cannot pass through delta-wye transformer banks. If zero-sequence is flowing on the wye side, the currents will be reflected to the other side, but circulate within the delta. Fig 10.4 The current on the left side is

$$I_a = \frac{1}{n}(I_A - I_B)$$

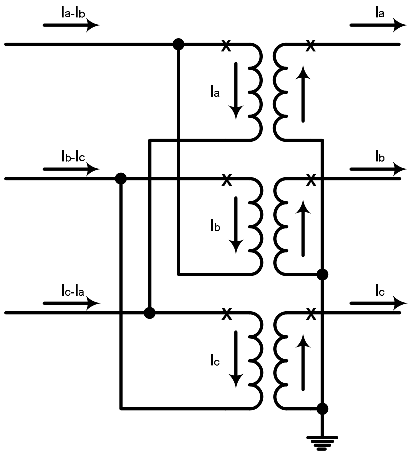


Fig 10.4

From equation 7.2 we have

$$I_A = I_{A0} + I_{A1} + I_{A2} \qquad (10.3\ a)$$
$$I_B = I_{B0} + I_{B1} + I_{B2} \qquad (10.3\ b)$$

Substituting on the right side of the equation 8.1 gives

$$(I_A - I_B) = (I_{A0} - I_{B0}) + (I_{A1} - I_{B1}) + (I_{A2} - I_{B2}) \qquad (10.4)$$

The zero-sequence currents are in-phase, therefore equation 10.3 simplifies to

$$(I_A - I_B) = (I_{A1} - I_{B1}) + (I_{A2} - I_{B2}) \qquad (10.5)$$

Where $(I_{A1} - I_{B1}) = \sqrt{3} I_{A1} \angle 30^o$ and $(I_{A2} - I_{B2}) = \sqrt{3} I_{B2} \angle -30^o$

$$I_a = \frac{1}{n}(\sqrt{3} I_{A1} \angle 30^o) + (\sqrt{3} I_{B2} \angle -30^o)$$
$$I_a = \frac{\sqrt{3}}{n}(I_{A1} \angle 30^o + I_{B2} \angle -30^o) \qquad (10.6)$$

In a balanced system where there is no negative or zero-sequence current then equation 10.6 reduces to

$$I_a = \frac{\sqrt{3}}{n}(I_A \angle 30^o) \qquad (10.7)$$

As can be seen the current will shift by 30^o when transferring through a transformer connected delta-wye. The same can be prove when looking at the voltages.

Now consider the connection in Fig 10.5.

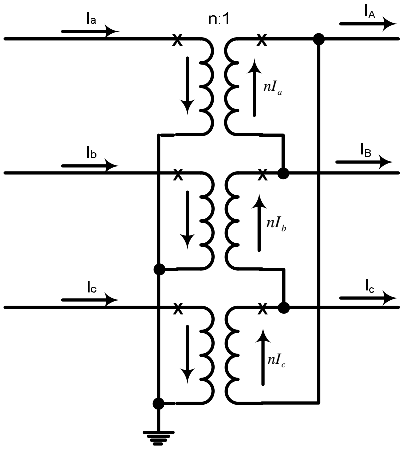


Fig 10.5

$$I_A = n(I_a - I_c)$$

Substituting equation 7.2 and reducing gives

$$(I_A - I_C) = (I_{A0} - I_{C0}) + (I_{A1} - I_{C1}) + (I_{A2} - I_{C2}) \tag{10.8}$$

$$I_a = n(\sqrt{3}I_{A1}\angle -30^o) + (\sqrt{3}I_{C2}\angle 30^o)$$

$$I_a = n\sqrt{3}(I_{A1}\angle -30^o + I_{C2}\angle 30^o) \tag{10.9}$$

As seen from the prior example equation 10.9 will reduce to

$$I_a = n\sqrt{3}(I_A\angle -30^o)$$

if there is no negative or zero-sequence current, which is the case for a balanced system.

By inspection of the equations above for ANSI standard connected delta-wye transformer banks if the positive-sequence current on one side leads the positive current on the other side by 30^o, the negative-sequence current correspondingly will lag by 30^o. Similarly if the positive-sequence current lags in passing through the bank, the negative-sequence quantities will lead 30^o.

The direction of the phase shifts between the delta-connected winding and the wye-connected winding depends on the winding connections of the transformer.

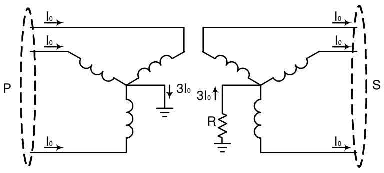
The winding configurations of a transformer will determine whether or not zero-sequence currents can be transformed between windings. Because zero-sequence currents do not add up to zero at a neutral point, they cannot flow in a neutral without a neutral conductor or a ground connection. If the neutral has a neutral conductor or if it is grounded, the zero-sequence currents from the phases will add together to equal 3I0 at the neutral point and then flow through the neutral conductor or ground to make a complete path.

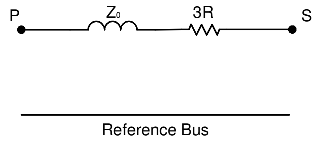
Following are some different transformer winding configurations and their effect on zero-sequence currents

1. **Transformers with at least two grounded wye windings**

   When a transformer has at least two grounded-wye windings, zero-sequence current can be transformed between the grounded-wye windings. The I0 currents will add up to 3I0 in the neutral and return through ground or the neutral conductor. The I0 currents will be transformed into the secondary windings and flow in the secondary circuit. Any impedance between the transformer neutral points and ground must be represented in the zero-sequence network as three times its value to correctly account for the zero-sequence voltage drop across it.

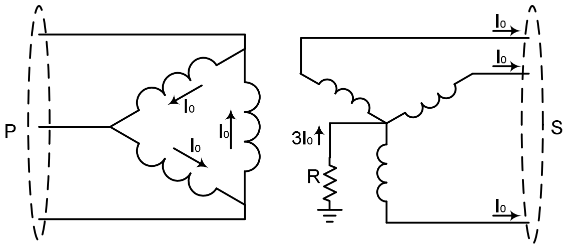
   Below on the left is a three-phase diagram of a grounded-wye, grounded-wye transformer connection with its zero-sequence network model on the right. Notice the resistance in the neutral of the secondary winding is modeled by 3R in the zero-sequence network model.

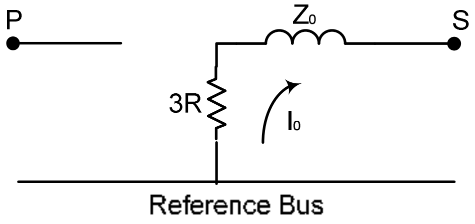




2. **Transformers with a grounded-wye winding and a delta winding**

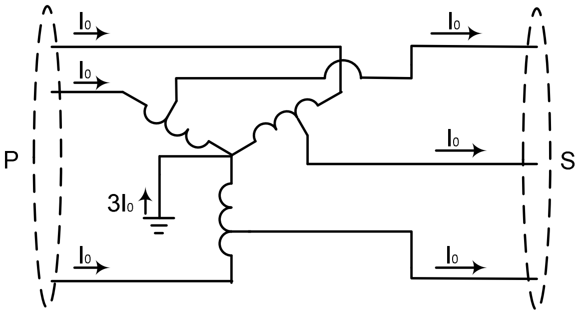
   When a transformer has a grounded-wye winding and a delta winding, zero-sequence currents will be able to flow through the grounded-wye winding of the transformer. The zero-sequence currents will be transformed into the delta winding where they will circulate in the delta without leaving the terminals of the transformer. Because the zero-sequence current in each phase of the delta winding is equal and in phase, current does not need to enter or exit the delta winding. Below on the left is a three-phase diagram of a grounded-wye-delta transformer connection with its zero-sequence network model on the right.

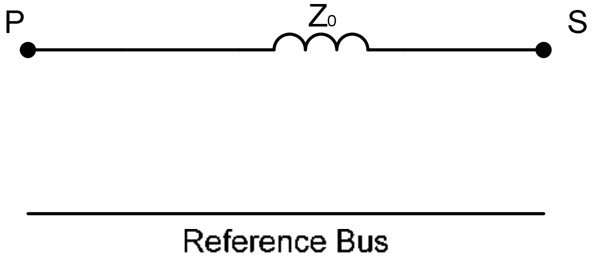




3. **Autotransformers with a grounded neutral**

   Autotransformers can transform zero-sequence currents between the primary and secondary windings if the neutral is grounded. Zero-sequence current will flow through both windings and the neutral ground connection. Below on the left is a three-phase diagram of a grounded neutral autotransformer with its zero-sequence network model on the right.

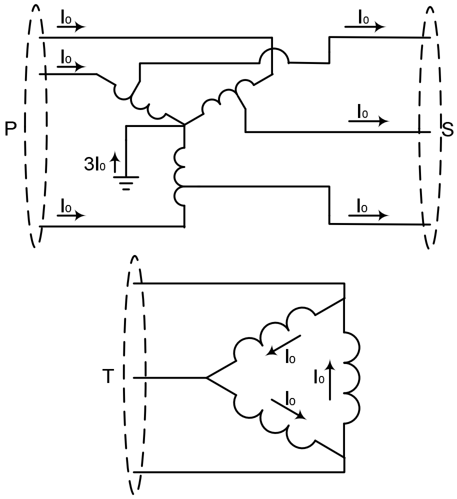


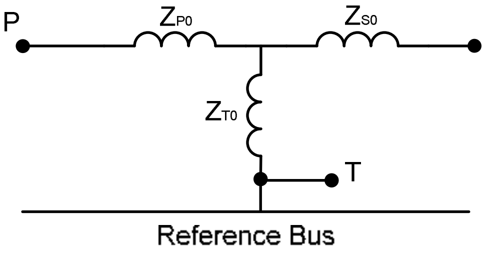


4. **Autotransformers with a delta tertiary**

   If an autotransformer has a delta tertiary, zero-sequence current can flow through either the primary or secondary winding even if the other winding is open circuited in the same manner that zero-sequence current can flow in a grounded-wye-delta transformer. If the ground is removed from the neutral, zero-sequence current can still flow between the primary and secondary windings, although there will not be any transformation of currents between the primary and secondary windings—only between the partial winding between the primary and secondary terminals and the delta tertiary. This is not a normal condition though, so it will not be analyzed here.

   Note that when modeling three-winding transformers the impedance needs to be broken into the impedance of the individual windings.

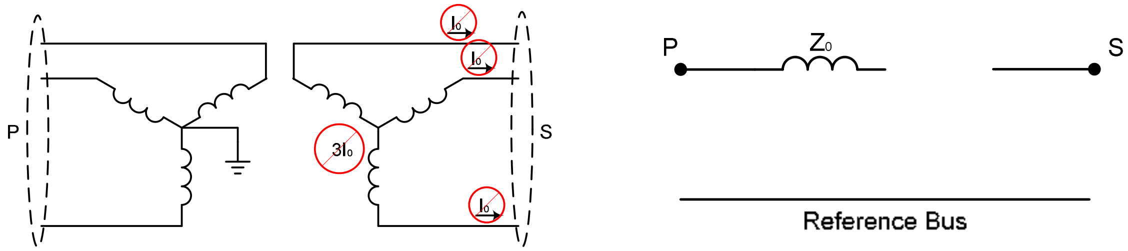




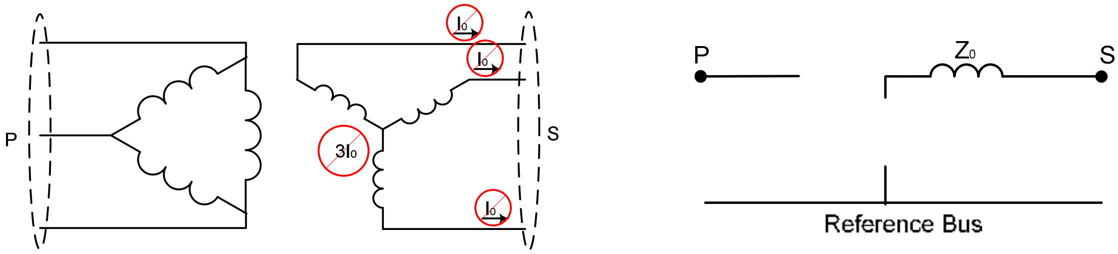
5. Other transformers

Other transformer configurations, such as ungrounded wye-ungrounded wye, grounded wye-ungrounded wye, ungrounded wye-delta, and delta-delta will not allow zero-sequence currents to flow and will have an open path in the zero-sequence network model. Some of these configurations are shown below with their zero-sequence network models.

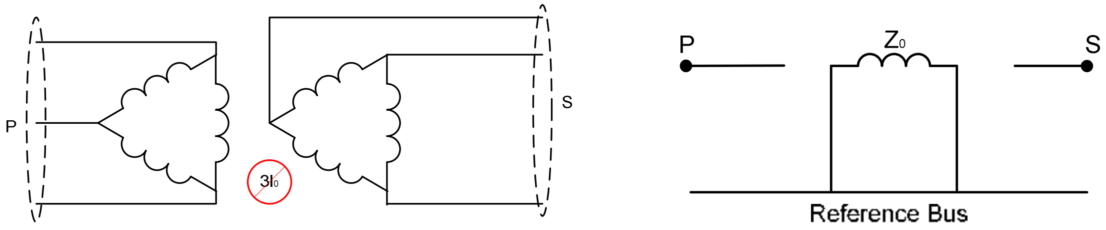
Grounded wye-ungrounded wye



Delta-Ungrounded Wye



Delta-Delta



In the preceding transformer connection diagrams the values of I0 at the terminals of the primary and secondary windings will be equal on a per-unit basis. They will also have the same per-unit values within the wye and delta windings; however, the per-unit values of current within the windings of an autotransformer are somewhat more difficult to determine because part of the winding carries both primary and secondary currents. If the magnitude of current within the winding of an autotransformer needs to be known, it can be determined by equating the ampere turns of the primary winding to those of the secondary winding and solving. If a tertiary is involved, it will need to be included in the equation also.

Magnitude of transformer zero-sequence impedance

The zero-sequence impedance of a single-phase transformer is equal to the positive-sequence impedance. When three single-phase units are connected as a three-phase unit in a configuration that will transform zero-sequence currents (grounded wye-grounded wye, grounded wye-delta, etc.), the zero-sequence impedance of the three-phase unit will normally be equal to the positive-sequence impedance.

In transformers built as three-phase units, i.e. with a three-phase core, in a configuration capable of transforming zero-sequence currents, the zero-sequence impedance will be the same as the positive-sequence impedance if the transformer core is of the shell type. If the core is of the core type, the zero-sequence impedance will be different than the positive-sequence impedance. This is because the zero-sequence excitation flux does not sum to zero where the three legs of the core come together and is forced to travel outside of the iron core, through the oil or the transformer tank where the magnetic permeability is much less than the iron core. This results in a low impedance (high conductance) in the magnetizing branch of the transformer model. The larger zero-sequence magnetizing current results in a lower apparent zero-sequence impedance. Using a lower value of zero-sequence impedance in the transformer zero-sequence model is sufficient for most fault studies, but to obtain a highly accurate zero-sequence model of a three-phase core-form transformer, the magnetizing branch can not be neglected.

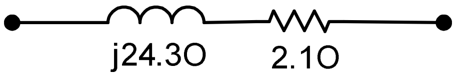
11. System Modeling

11.1 System Modeling: Transmission Lines

Transmission lines are represented on a one-line diagram as a simple line connecting busses or other circuit elements such as generators, transformers etc.

Transmission lines are also represented by a simple line on impedance diagrams, but the diagram will include the impedance of the line, in either ohm or per-unit values. Sometimes the resistive element of the impedance is omitted because it is small compared to the reactive element.

Here is an example of how a transmission line would be represented on an impedance diagram with impedances shown in ohms:



In a balanced three-phase system the impedance of the lines and loads are the same, and the source voltages are equal in magnitude. We can calculate the single-phase current, but must take into account the voltage drop across the mutual impedance caused by the other phase currents. From Fig 11.1, the voltage drop in A-phase is

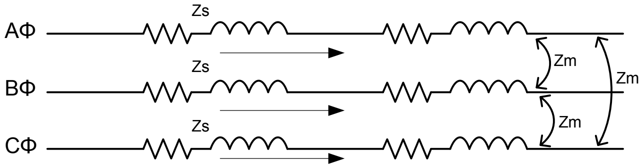


Fig 11.1

$$V_a = Z_S I_A + Z_m I_B + Z_m I_C \qquad (11.1a)$$

For the case of a balanced three-phase current $(I_B + I_C) = -I_A$. Thefore:

$$V_a = (Z_S - Z_m)I_A \qquad (11.1b)$$

Dividing by I_A shows the positive-sequence impedance of the line equals the self impedance minus the mutual impedance.

$$Z_{a1} = \frac{V_{A0}}{I_{A0}} = (Z_S - Z_m) \qquad (11.2)$$

The negative-sequence current encounters a negative-sequence impedance which is equal to the positive-sequence impedance

$$Z_{a2} = \frac{V_A}{I_A} = (Z_S - Z_m) \qquad (11.3)$$

For the zero-sequence impedance, because I_{a0}, I_{b0} and I_{c0} are in phase with each other,

$$I_{A0} = I_{B0} = I_{C0}$$

then zero-sequence voltage drop is given in equation 11.4

$$V_{a0} = Z_S I_{A0} + Z_m I_{B0} + Z_m I_{C0} = Z_S I_{A0} + (Z_m + Z_m)I_{A0} \qquad (11.4a)$$
$$V_{a0} = (Z_S + 2Z_m)I_{A0} \qquad (11.4b)$$

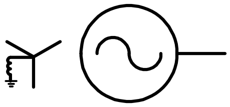
Dividing each side by I_{A0} give the zero-sequence impedance:

$$Z_{a0} = \frac{V_{A0}}{I_{A0}} = (Z_S - Z_m) \qquad (11.5)$$

The result gives the zero-sequence impedance as function of the self and mutual impedance of the line. The zero-sequence impedance is always larger than the positive-sequence because we are adding two times the mutual impedance to the self impedance, instead of subtracting the mutual impedance from the self impedance.

11.2 System Modeling: Subtransient, Transient, and Synchronous Reactance of Synchronous Generators

A synchronous generator is modeled by an internal voltage source in series with an internal impedance.
Below is a typical one-line diagram symbol for a generator.



The circle represents the internal voltage source. The symbol to the left of the circle indicates that the three phases of the generator are wye-connected and grounded through a reactance. The symbol for a synchronous motor is the same as a synchronous generator.

A typical impedance diagram representation of a synchronous generator is shown in Fig. 11.2.

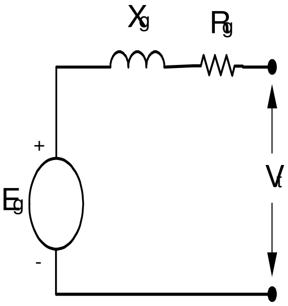


Fig. 11.2

When modeling the impedance of a synchronous generator (or motor), the resistive component is usually omitted because it is small compared to the reactive component.

When a fault is applied to a power system supplied by a synchronous generator, the initial current supplied by the generator will start at a larger value, and over a period of several cycles it will decrease from its initial value to a steady state value.

The initial value of current is called the subtransient current or the initial symmetrical rms current. Subtransient current decreases rapidly during the first few cycles after a fault is initiated, but its value is defined as the maximum value that occurs at fault inception.

After the first few cycles of subtransient current, the current will continue to decrease for several cycles, but at a slower rate. This current is called the transient current. Although, like the subtransient current, it is continually changing, the transient current is defined as its maximum value, which occurs after the first few cycles of subtransient current.

After several cycles of transient current, the current will reach a final steady state value. This is called the steady state current or the synchronous current.

The reason why the current supplied by the synchronous generator is changing after a fault is because the increased current through the armature of the generator creates a flux that counteracts the flux produced by the rotor. This results in a reduced flux through the armature and therefore a reduced generated voltage. However, because the decrease in flux takes time, the generator voltage will be initially higher and decrease over time.

We account for the changing generator voltage in our model by using different values of reactance in series with the internal generator voltage.

We use three values of reactance to model the generator during the period after fault inception: the subtransient reactance (Xd'') is used during the initial few cycles; the transient reactance (Xd') is used for the period following the initial few cycles until a steady state value is reached; the synchronous reactance (Xd) is used for the steady state period.

The impedance diagrams for a synchronous generator (or motor) during the subtransient, transient, and synchronous periods are shown in Fig. 11.3.

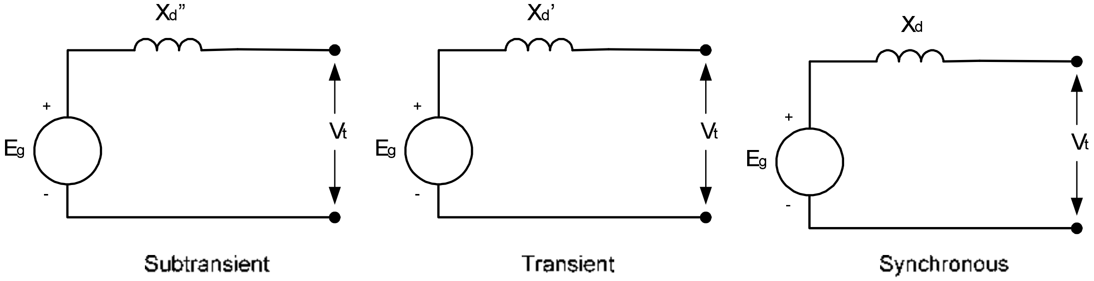
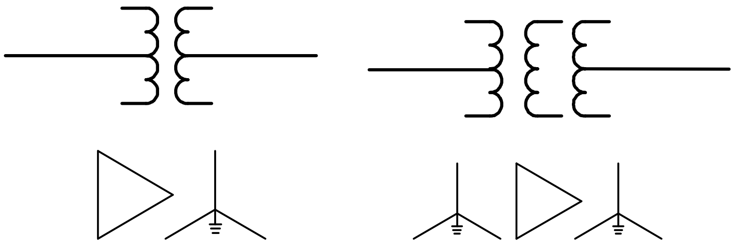


Fig. 11.3

The reactance of synchronous motors are the same as for synchronous generators. If the line to a synchronous motor develops a three-phase fault, the motor will no longer receive electrical energy from the system, but its field remains energized and the inertia of its rotor and connected load will keep the rotor turning for some time. The motor is then acting like a generator and contributes current to the fault

11.3 System Modeling: Transformers

Transformers are represented in one-line diagrams by several symbols. Below are some typical ones.



The first is a two-winding transformer connected delta- grounded wye, and the second is a three-winding transformer connected grounded wye-delta-grounded wye.

An impedance model of a practical two-winding transformer is shown in Fig. 11.4.

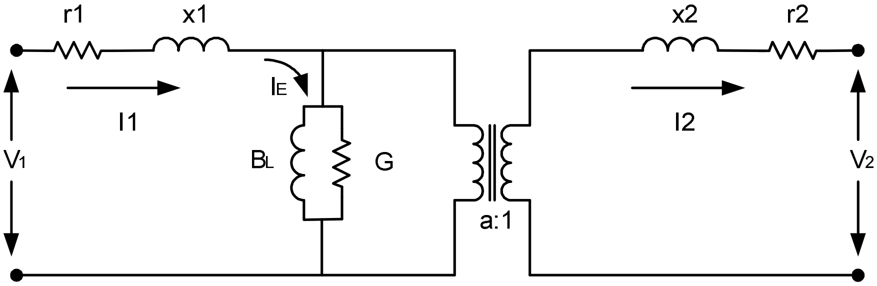
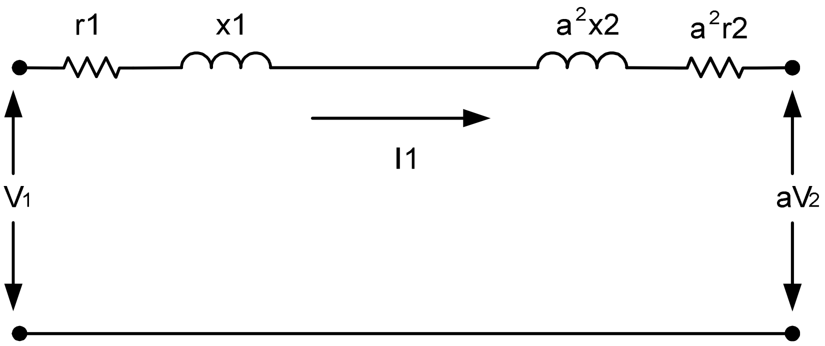


Fig. 11.4

In the model, a:1 represents the winding ratio of the ideal transformer shown by the two coupled coils, BL in parallel with G represents the magnetizing susceptance and conductance which make up the magnetizing branch, IE represents the excitation current, r1 and x1 represent the leakage impedance of winding 1,r2 and x2 represent the leakage impedance of winding 2, V1 and I1 represents the primary voltage and current respectively, and V2 and I2 represent the secondary voltage and current respectively.

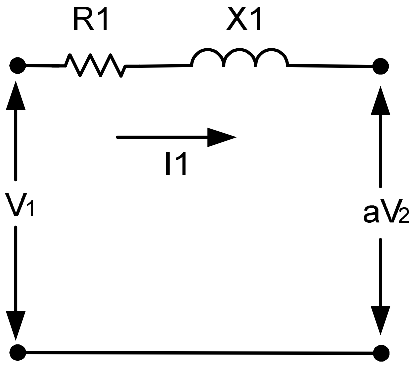
Because normal fault and load currents are very much larger than the magnetizing current, IE, we can omit the magnetizing branch from our model. We can also omit the ideal transformer if we refer the leakage impedances to either the primary- or secondary-side of the transformer. The leakage impedance of one side of the transformer can be referred to the other side of the transformer by multiplying it by the square of the turns ratio. Below is the simplified impedance diagram with the magnetizing branch removed and the leakage impedance of the secondary winding referred to the primary side of the transformer.



Our impedance model can be further simplified by letting

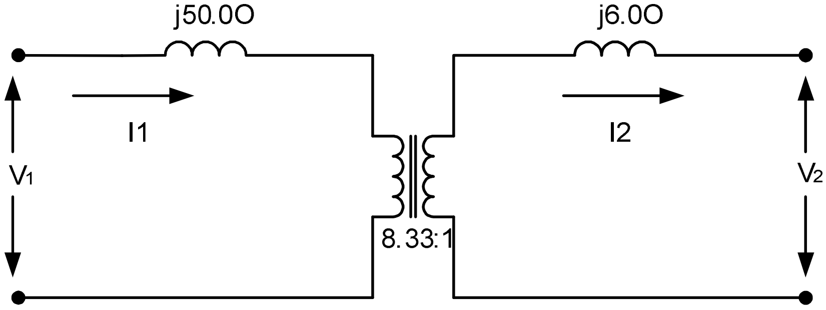
$R1 = r1 + a^2 r^2$

$X1 = x1 + a^2 x^2$



When using this simplified model, any impedances and voltages connected to the secondary side of the circuit must now be referred to the primary side.

As an example, the following transformer model will be converted to the simplified impedance model. The magnetizing branch and the leakage resistances have been omitted to simplify the problem.



The secondary-side impedance is multiplied by the square of the turns ratio before being transferred to the primary side.

j6.0 * 8.332 = j416.3Ω

This is added to the high side to get an impedance of j50Ω + j416.3Ω = j466.3Ω

The simplified model is shown in Fig. 11.5

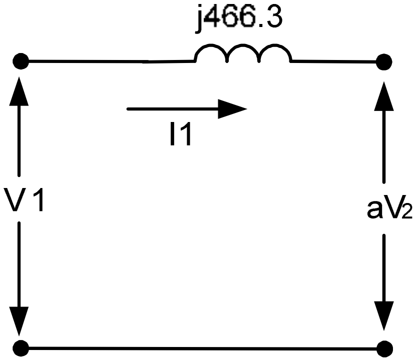
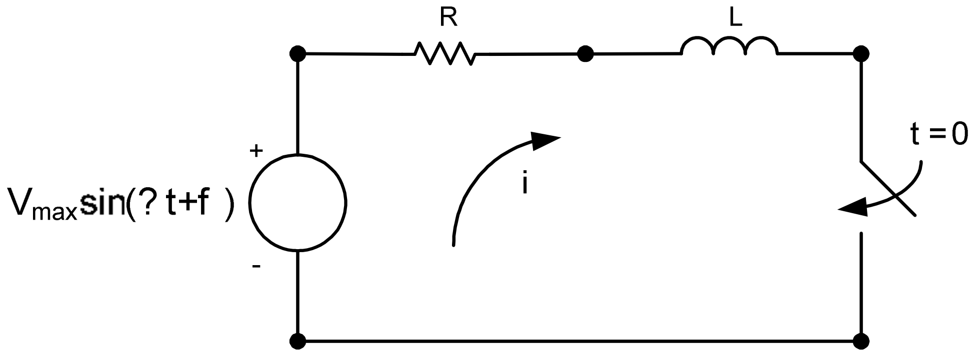


Fig. 11.5

11.4 Some additional points – DC Offset

In a transmission network, the sudden occurrence of a short circuit will result in a sinusoidal current that is initially larger and decreases due to the changing air gap flux in the synchronous generators. We've seen that this is modeled by subtransient, transient, and synchronous reactances in our generator model. In a circuit containing resistance and inductance (RL circuit), such as in a transmission network, the sudden occurrence of a short circuit will also result in DC offset in the current that occurs after a fault is applied. Consider the RL circuit below:



If the switch is closed at time t=0, the voltage around the circuit is
Vmaxsin(ωt+φ) = Ri + Ldi/dt

Solving this differential equation for the instantaneous current, i, gives
i = Vmax [sin(ωt+φ-θ) – e-Rt/Lsin(φ-θ)] / │Z│

Where │Z│= √(R2 + (ωL)2 and θ = tan-1(ωL/R)

The important thing to note from the solution is that there is a sinusoidal component that represents the steady-state solution for the current ($Vmax \sin(\omega t+\varphi-\theta) / |Z|$) and a exponentially decaying component ($-Vmax\ e-Rt/L\sin(\varphi-\theta) / |Z|$).

Some points to note about the exponentially decaying—or DC offset—component:

The initial value of the DC offset is determined by what point in the cycle the voltage waveform is at when the fault occurs (the value of φ) and will range from 0 up to the value of the steady state component.

The dc component will decrease with a time constant of L/R. The larger the ratio of inductance to resistance in the circuit, the larger the time constant, and the slower the dc component will decay.

Three time constants after the switch is closed, the dc offset will have decayed to 5% of its initial value.

DC offset is an important consideration in sizing breakers.

Most modern microprocessor-based relays are immune to DC offset because after the analog signals are converted to digital signals, they can be mathematically filtered to remove the DC component. Therefore the DC component doesn’t need to be considered in the relay settings.

Some electromechanical relays are immune to DC offset, and some aren’t. Clapper and plunger type units are generally not immune, and DC offset will have to be allowed for in the relay settings (one guideline is to set pickup at 160% of the desired ac pickup current). Cylinder type units, used in distance relays, are immune to DC offset.

The different values of the AC fault current should be considered in the relay settings. The subtransient fault current should be used in setting instantaneous current elements, whereas the synchronous fault current should be used in current elements with long time delays.

Problems

Problem 1

BPA's system model uses a three-phase power base of 100MVA. The line-to-line voltage base is 525kV for the 500 system, 230kV for the 230 system, and 115kV for the 115 system.

a) An undervoltage relay on the 115 system is set to pick up at 0.85 pu (per unit) of the phase-to-ground voltage. What is the phase-to-ground voltage that the undervoltage relay will pick up at?

b) A three-phase fault on the 500 system results in a fault current of 2750A. What is the per unit value of this current?

c) What is the base impedance for the 500 system?

d) What is the base impedance for the 230 system?

e) What is the base impedance for the 115 system?

Problem 2

From our example 5.2, the percent impedance of a 525/241.5kV autotransformer is 10.14% based on its nameplate value of 900MVA. Suppose we need to model this transformer in BPA's ASPEN model which uses a 100MVA power base. What would the per-unit impedance be?

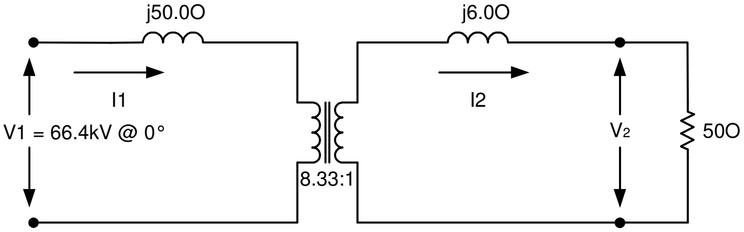
Problem 3

From our example in 5.2, convert the per-unit impedance to a per-unit value in a three-phase power base of 100MVA.
a) First convert the per unit impedance to an actual impedance (in ohms) at 525kV and then convert the actual impedance to a per-unit impedance on the new base.
b) Repeat, this time converting the per unit impedance to an actual impedance (in ohms) at 241.5kV and then converting the actual impedance to a per-unit impedance on the new base

Problem 4

Convert the per-unit impedance of the transformer in the example to a per-unit value in the BPA model with a three-phase power base of 100MVA by first converting the per unit impedance to an actual impedance (in ohms) at 230 kV and then converting the actual impedance to a per-unit impedance on the new base.

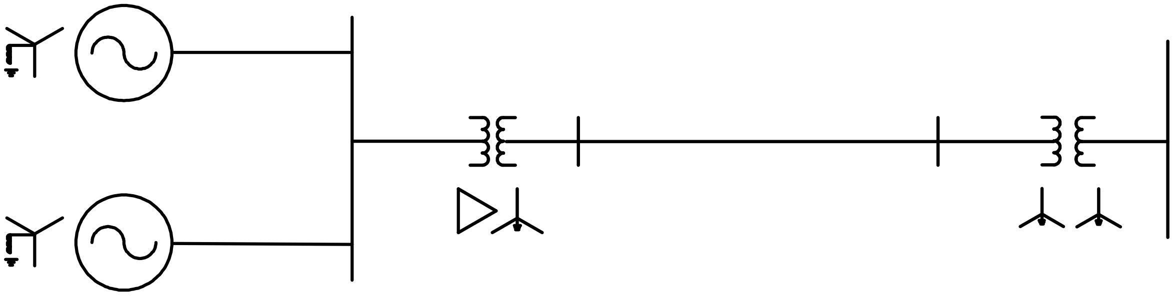
Problem 5



Using the transformer model convert from ohms to per-unit.
The voltage base for the primary side will be 115kV, and the voltage base for the secondary side will be 13.8kV. The power base for both sides is 100MVA.

Problem 6

Below is a one line diagram of a partial power system.
The two generators are identical, each rated 13.8kV and 50MVA with a subtransient reactance of X_d'' = 15%. The two generators are tied to a common bus which is connected to a transmission line with a delta-grounded wye transformer rated at 150MVA, 13.8kV/115kV and an impedance of 9.7%. The transmission line is 30 miles long and has an impedance of 5.43 + j22.5Ω. At the end of the transmission line is a grounded wye-grounded wye transformer, rated 225MVA, 115kV/230kV with an impedance of 7.4% that connects the line to a 230kV bus. The remaining power system connected to the 230kV bus is not shown.

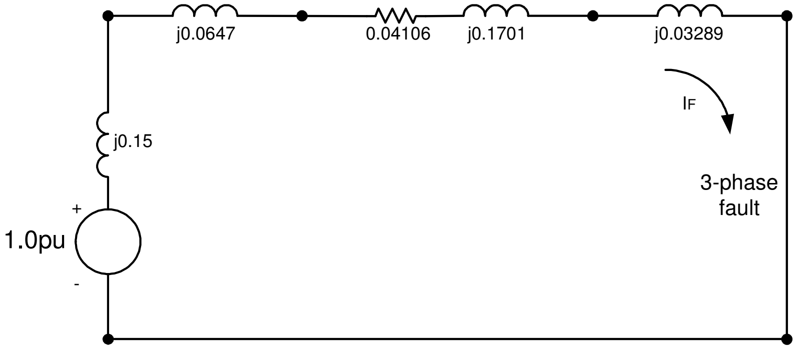


From the above information, draw the impedance diagram with impedances shown in their per-unit values. Use voltage bases of 13.8kV, 115kV, and 230kV for the corresponding parts of the system, and use a power base of 100MVA for the whole system.

Problem 7

From the impedance diagram, determine the per-unit and ampere values of subtransient current in each generator and at the fault for a three-phase fault applied on the 230kV bus with both generators operating at 1.0pu voltage.

The generators can be combined into their Thevenin equivalent as shown below.



Problem 8

From the one line diagram of a partial power system that we used in problem 6.

From the above information, we drew the positive-sequence impedance diagram using subtransient impedances for the generators and with impedances shown in their per-unit values. Normally the positive-sequence network is drawn with the reference bus (which is the neutral point) shown at the top instead of the bottom.

The negative-sequence reactance of the generators is equal to their positive-sequence subtransient reactance. Draw the positive and negative-sequence networks for the power system with impedances shown in their per-unit values.

Problem 9

Each generator has a zero-sequence reactance of 5% and is grounded through a reactance of 2Ω. The transmission line has a zero-sequence impedance of 12.9 + j75.9Ω. The grounded wye-grounded wye transformer has a zero-sequence reactance of 4.8%. Draw the zero-sequence impedance diagram.

Solutions

Problem 1

a) $V_{BL\text{-}G} = V_{BL\text{-}L} / \sqrt{3}$
$V_{BL\text{-}G} = 115\text{kV} / \sqrt{3} = 66.4\text{kV}$

$Z_{PU} = Z_A / Z_B$
$Z_A = Z_{PU} * Z_B$
$Z_A = 0.85*66.4\text{kV}$
$Z_A = 56.4\text{kV}$

b) $I_B = P_{B3\Phi} / \sqrt{3}*V_{BL\text{-}L}$
$I_B = 100\text{x}10^6 / \sqrt{3}*525\text{x}10^3$
$I_B = 110.0 \text{ A}$

$I_{PU} = I_A / I_B$
$I_{PU} = 2750 \text{ A} / 110 \text{ A}$
$I_{PU} = 25.0 \text{ pu}$

c) $Z_B = V_{BL\text{-}L2} / P_{B3\Phi}$
$Z_B = (525\text{x}10^3)^2 / 100\text{x}10^6$
$Z_B = 2756.25\Omega$

d) $Z_B = V_{BL\text{-}L2} / P_{B3\Phi}$
$Z_B = (230\text{x}10^3)^2 / 100\text{x}10^6$
$Z_B = 529.0\Omega$

e) $Z_B = V_{BL\text{-}L2} / P_{B3\Phi}$
$Z_B = (115\text{x}10^3)^2 / 100\text{x}10^6$
$Z_B = 132.25\Omega$

Problem 2

$Z_{pu\ new} = Z_{pu\ old} *(V_{BL\text{-}L\ old} / V_{BL\text{-}L\ new})^2 * (P_{B3\Phi\ new} / P_{B3\Phi\ old})$

$Z_{pu\ old} = 10.14 / 100 = 0.1014$
$V_{BL\text{-}L\ old} = 525\text{kV}$, $P_{B3\Phi\ old} = 900\text{MVA}$
$V_{BL\text{-}L\ new} = 525\text{kV}$, $P_{B3\Phi\ new} = 100\text{MVA}$

$Z_{pu\ new} = 0.1014 *(525\text{kV} / 525\text{kV})^2 * (100\text{MVA} / 900\text{MVA})$
$Z_{pu\ new} = 0.1014 *1* (100 / 900)$
$Z_{pu\ new} = 0.01127 \text{ pu}$

Problem 3

$Z_{PU} = Z_A / Z_B$
$Z_A = Z_{PU} * Z_B$

$Z_B = V_{BL\text{-}L}{}^2 / P_{B3\Phi}$

a) Using the high-side voltage:
$Z_{B\ old} = 525{,}000^2 / 900x10^6$
$Z_{B\ old} = 306.25\Omega$

$Z_A = 0.1014 * 306.25$
$Z_A = 31.05\Omega$

Converting to the 100MVA base:
$Z_{B\ new} = V_{BL\text{-}L\ new}{}^2 / P_{B3\Phi\ new}$
$Z_{B\ new} = 525{,}000^2 / 100x10^6$
$Z_{B\ new} = 2756.25\Omega$

$Z_{PU\ new} = Z_A / Z_{B\ new}$
$Z_{PU\ new} = 31.05\Omega / 2756.25\Omega$
$Z_{PU\ new} = 0.01127$ pu

b) Using the low-side voltage:
$Z_{B\ old} = \mathbf{241{,}500}^2 / 900x10^6$
$Z_{B\ old} = 64.80\Omega$

$Z_A = 0.1014 * 64.80$
$Z_A = 6.57\Omega$

Converting to the 100MVA base:
$Z_{B\ new} = V_{BL\text{-}L\ new}{}^2 / P_{B3\Phi\ new}$
$Z_{B\ new} = \mathbf{230{,}000}^2 / 100x10^6$
$Z_{B\ new} = 529.0\Omega$

Z_{PU} new $= Z_A / Z_{B\ new}$
Z_{PU} new $= 6.57\Omega / 529.0\Omega$
Z_{PU} new $= 0.01242$ pu

Problem 4

Repeat problem 3 assuming the transformer has a tap with a ratio of 525 /230 kV and using the low side voltage.

Problem 5

Answer:

The base impedance of the secondary side is $Z_B = V_{BL\text{-}L2} / P_{B3\Phi}$

$Z_B = (13.8*10^3)2 / 100*10^6$
$Z_B = 1.904\Omega$

The per-unit impedance of the secondary leakage reactance is
X2 = j6.0 / 1.094 = j3.151 pu
The per-unit value of the load resistance is R_L = 50 / 1.904 = 26.26 pu

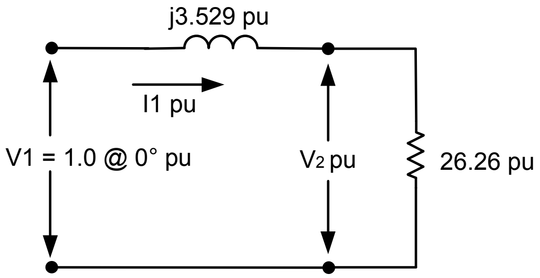
The base impedance of the primary side is $Z_B = V_{BL\text{-}L2} / P_{B3\Phi}$

$Z_B = (115*10^3)2 / 100*10^6$
$Z_B = 132.25\Omega$

The per-unit impedance of the primary leakage reactance is
X1 = j50.0 / 132.25 = j0.3781 pu

The total per-unit impedance of our model can be obtained by simply adding together the per-unit values of the primary and secondary impedances.

X = X1 + X2 = j0.3781 + j3.151 = j3.529 pu



Problem 6

Answer:

Converting the impedances to per-unit on a 100MVA base using
$Z_{pu\ new} = Z_{pu\ old} *(V_{BL\text{-}L\ old} / V_{BL\text{-}L\ new})^2 * (P_{B3\Phi\ new} / P_{B3\Phi\ old})$

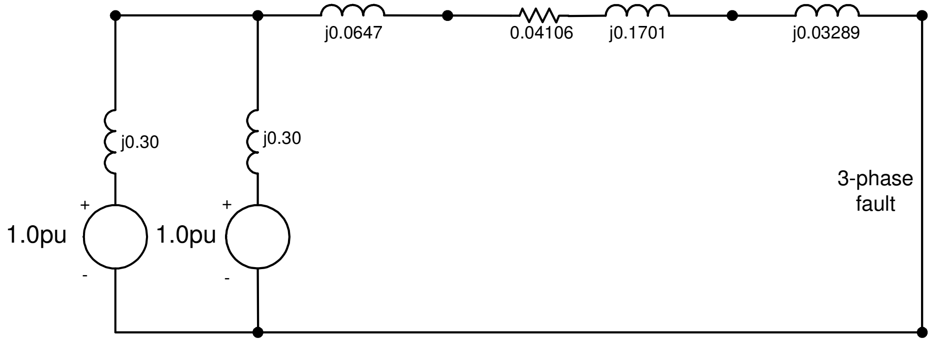
Each generator subtransient reactance is $X_d'' = j0.15 * (13.8kV / 13.8kV)^2 * (100MVA / 50MVA)$
$X_d'' = j0.30$ pu

The 13.8kV / 115kV transformer impedance is $X = 0.097 * (13.8kV / 13.8kV)^2 * (100MVA / 150MVA)$
X = j0.06467 pu

The base impedance for the 115kV line is $Z_B = V_{BL\text{-}L2} / P_{B3\Phi}$
$Z_B = (115x10^3)^2 / 100x10^6 = 132.25\Omega$
The per-unit impedance of the 115kV transmission line is (5.43+j22.5) / 132.25 = 0.04106+j0.1701 pu

The 115kV / 230kV transformer impedance is $X = 0.074 * (115kV / 115kV)^2 * (100MVA / 225MVA)$
X = j0.03289 pu

The impedance diagram with the per-unit values of the impedances is shown below.



Problem 7

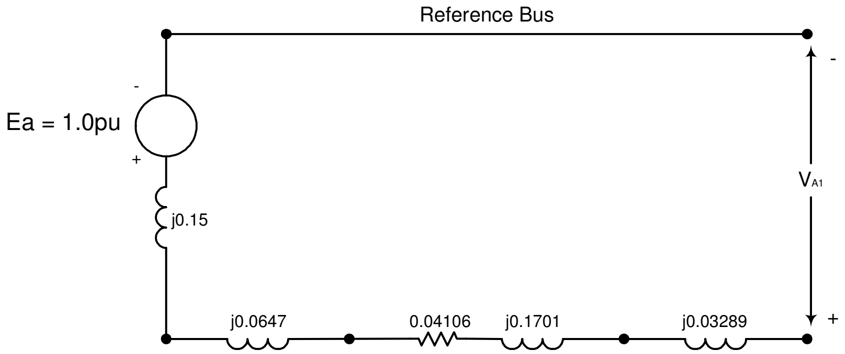
Answer:

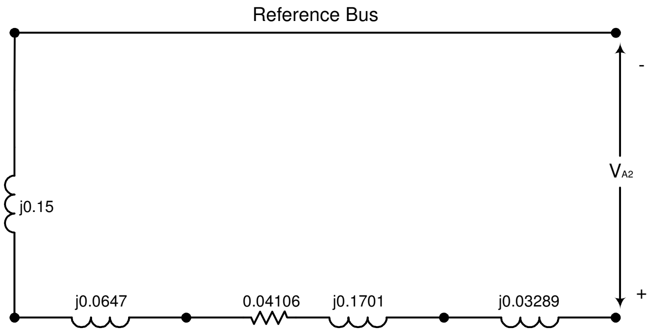
The fault current is
$I_F = 1.0 / (0.04106 + j0.15 + j0.0647 + j0.1701 + j0.03289)$
$I_F = 1.0 / (0.04106 + j0.41769)$
$I_F = 2.382$ @ $-84.4°$ pu

At the generators, the total fault current is $I_{FGT} = 2.382 * I_B$
$I_B = P_{B3\Phi} / \sqrt{3}*V_{BL-L} = 100x10^6 / \sqrt{3}*13.8x10^3 = 4184$ A
$I_{FGT} = 2.382 * 4184 = 9966$ A
Each generator contributes half of this current
$I_{FG} = 9966 / 2 = 4983$ A

At the fault, the total fault current is $I_F = 2.382 * I_B$
$I_B = P_{B3\Phi} / \sqrt{3}*V_{BL-L} = 100x10^6 / \sqrt{3}*230x10^3 = 251.0$ A
$I_F = 2.382 * 251.0 = 597.9$ A

Problem 8





Problem 9

Answer:

The zero-sequence reactance of each generator is 5%, or 0.05pu on a 13.8kV, 50MVA base. Converting this to a 100MVA base gives

$Z_{pu\ new}$ = j0.05 * (100 / 50) = j0.10 pu

Each generator is grounded through a reactance of 2Ω. The base impedance at 13.8kV, 100MVA is ZB = (13.8x103)2 / (100x106) = 1.9044Ω. The per-unit impedance of each grounding reactor is Zpu = j2.0 / 1.9044 = j1.05pu. The grounding reactances will need to be multiplied by three for the zero-sequence network, giving a value of 3 * j1.05 = j3.15pu.

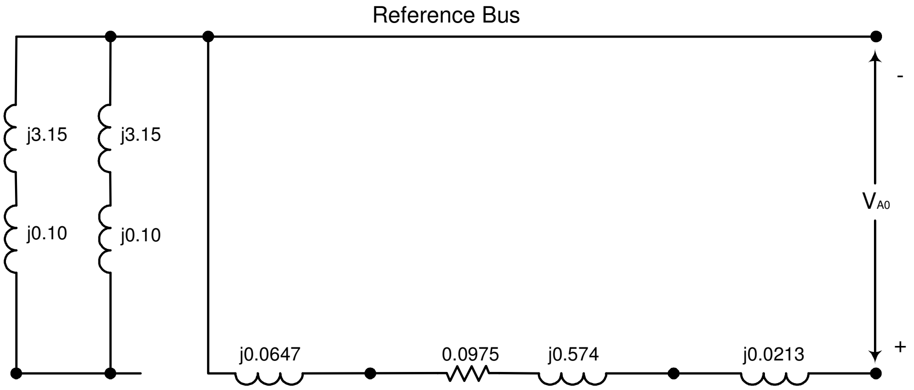
Because a value is not given for the zero-sequence impedance of the delta-grounded wye transformer, it can be assumed that the zero-sequence impedance is the same as the positive-sequence impedance.

The zero-sequence impedance of the transmission line is 12.9 + j75.9Ω. The base impedance at 115kV, 100MVA is Z_B = $(115x103)^2$ / $(100x10^6)$ = 132.25Ω. Converting the zero-sequence line impedance to a per-unit value gives Z_{L0} = (12.9 + j75.9) / 132.25 = 0.0975 + j0.574pu.

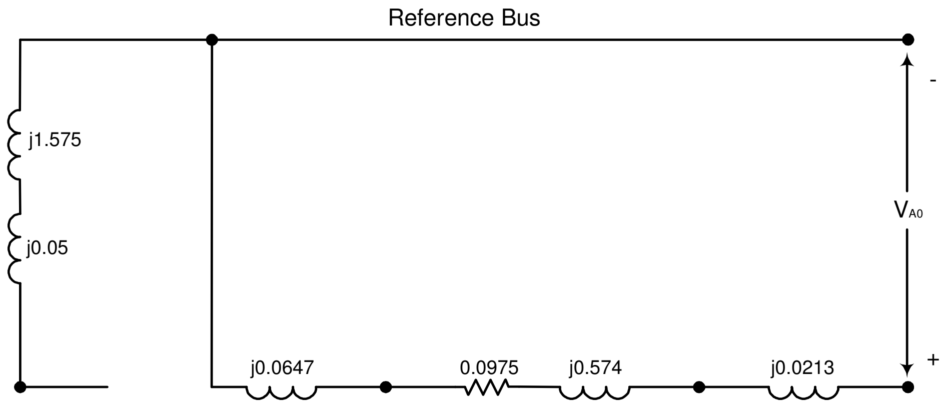
The zero-sequence impedance of the grounded wye-grounded wye transformer is 4.8%, or j0.048pu on a base of 115kV, 225MVA. Converting to a 115kV, 100MVA base gives

$Z_{pu\ new}$ = j0.048 * (100 / 225) = j0.0213 pu

The zero-sequence network is shown below. Notice the interruption in the path caused by the delta-wye transformer.



Here is a simplified version of the zero-sequence network with the two generator branches combined into an equivalent branch.


Reference Bus
j1.575
j0.05
-
V_{A0}
+
j0.0647
0.0975
j0.574
j0.0213

Appendix

Three Phase System

$S = \sqrt{3}V_{LL}I_L$, $P = \sqrt{3}V_{LL}I_L \cos\Theta$, $Q = \sqrt{3}V_{LL}I_L \sin\Theta$

Per-Unit

First step in using *per-unit* is to select the base(s) for the system.

Sbase = Power base, in VA	Sbase = 100 MVA
Vbase = voltage base in V	Vbase = Nominal voltage rated line-to-line

$$per-unit = \frac{actual\_value}{base\_value}$$

$$per-unit = \frac{percent\_value}{100}$$

$$\frac{V}{V_{base}} = \frac{IZ}{I_{base}Z_{base}}$$

$$V_{pu} = I_{pu}Z_{pu}$$

$$I_{base} = \frac{kVA_{base}}{\sqrt{3}kV_{base}} amperes$$

$$\boxed{I_{base} = \frac{100kVA_{base}}{\sqrt{3}(230)V_{base}} amperes = 251A}$$

Ex: 230kV base, 100MVA base

$$MVA_{Fault} = \frac{MVA_{Base}}{Z_{Fault}PU}$$

$$I_{Fault\_Current} = \frac{I_{Base}}{Z_{Fault}PU}$$

$$Z_{base} = \frac{kV_{base}^2 x1000}{kVA_{base}} ohms \text{ (in kVA)}$$

$$Z_{base} = \frac{kV_{base}^2}{MVA_{base}} ohms \text{ (in MVA)}$$

$$Z_{base} = \frac{V_{base}^2}{100} \text{ (for a 100 MVA base)}$$

$$Z_{pu} = \frac{Z(\Omega)}{Z_{base}}$$

$$Z_{pu} = \left(\frac{MVA_{base}}{kV_{base}^2}\right) \cdot Z(\Omega) \text{ (in MVA)}$$

$$\%Z = \frac{100MVA_{base} \cdot Z(\Omega)}{kV_{base}^2} \text{ (percent in MVA)}$$

$$Z_{ohm}^{new} = Z_{ohm}^{old} \cdot \left(\frac{kV_{base}^{new}}{kV_{base}^{old}}\right)^2 \text{ (new impedance reflective through a transformer)}$$

$$\boxed{Z_{ohm}^{new} = 7.2 \cdot \left(\frac{115}{230}\right)^2 = 1.8ohms}$$

Ex: 115kV line impedance on the 115kV side of a 230/115kV transformer

Symmetrical Components

a Operator

$$a = 1\angle 120^o$$
$$a^2 = 1\angle 240^o$$
$$a^3 = 1$$

$$V_a = V_0 + V_1 + V_2$$
$$V_b = V_0 + a^2V_1 + aV_2$$
$$V_c = V_0 + aV_1 + a^2V_2$$

$$V_0 = \frac{1}{3}\left(V_a + V_b + V_c\right)$$
$$V_1 = \frac{1}{3}\left(V_a + aV_b + a^2V_c\right)$$
$$V_2 = \frac{1}{3}\left(V_a + a^2V_b + aV_c\right)$$

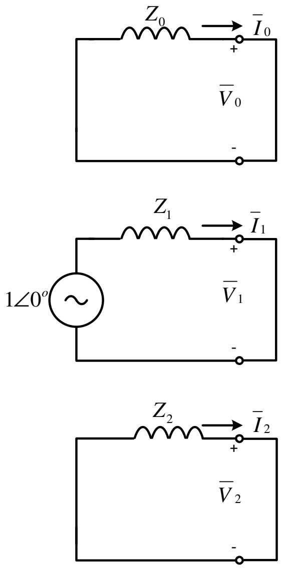
$$I_a = I_0 + I_1 + I_2$$
$$I_b = I_0 + a^2I_1 + aI_2$$
$$I_c = I_0 + aI_1 + a^2I_2$$

$$I_0 = \frac{1}{3}\left(I_a + I_b + I_c\right)$$
$$I_1 = \frac{1}{3}\left(I_a + aI_b + a^2I_c\right)$$
$$I_2 = \frac{1}{3}\left(I_a + a^2I_b + aI_c\right)$$

$3I_0 = \left(I_a + I_b + I_c\right)$ (residual currents or sum of the three phase currents)

Three-Phase fault

$$MVA_{Fault} = \frac{MVA_{Base}}{Z_{Fault}\,pu}$$



$$I_1 = \frac{E_a}{Z_1}$$

$$I_2 = I_0 = 0$$

$$I_A = I_1 = \left(\frac{1}{Z_1}\right)\left(\frac{100kVA}{\sqrt{3}\cdot kV}\right)$$

$$I_B = a^2 I_A$$

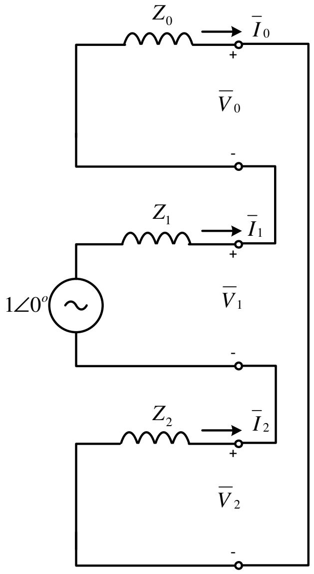
$$I_B = aI_A$$

$$E_1 = 1 - I_1 Z_1$$

$$E_2 = E_0 = 0$$

0ne-line to ground fault

$$MVA_{Fault} = \frac{3\cdot MVA_{Base}}{Z_1 + Z_2 + Z_0\,pu}$$



$$I_0 = I_1 = I_2 = \frac{1}{Z_1 + Z_2 + Z_0}$$

$$I_A = I_0 + I_1 + I_2 = 3I_0$$

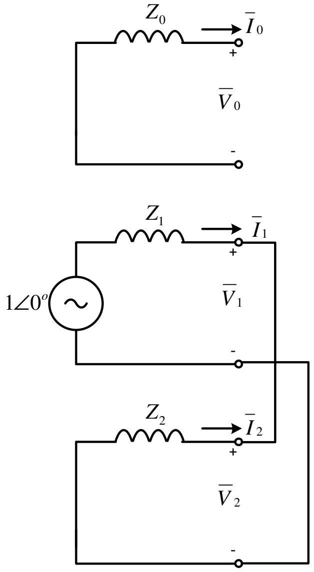
$$I_B = I_c = 0$$

$$E_1 = 1 - I_1 Z_1$$

$$E_2 = -I_2 Z_2$$

$$E_0 = -I_0 Z_0$$

Line-Line fault, or Phase-to-phase fault



$$I_1 = -I_2 = \frac{1}{Z_1 + Z_2} = \frac{1}{2Z_1}$$

$$I_0 = 0$$

$$I_A = 0$$

$$I_B = I_0 + a^2 I_1 + aI_2 = a^2 I_1 + aI_2 = a^2 I_1 + aI_1$$

$$I_B = \frac{\left(a^2 - a\right)E}{Z_1 + Z_2}$$

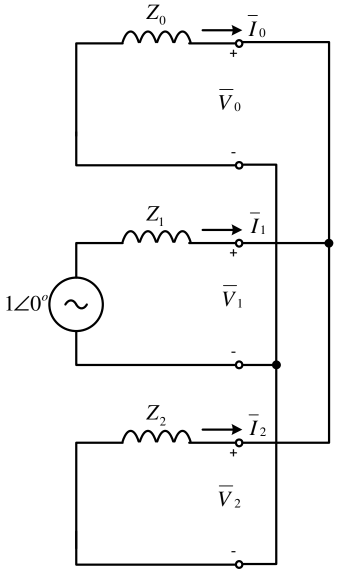
$$I_C = -I_B \text{ when } Z_1 = Z_2$$

$$E_1 = 1 - I_1 Z_1$$

$$E_2 = -I_2 Z_2 = E_1$$

$$E_0 = 0$$

Double Line-Line fault, or Two phase to Ground fault



$$I_1 = \frac{1}{Z_1 + \left(\frac{Z_0 Z_2}{Z_0 + Z_2}\right)}$$

$$I_2 + I_0 = -I_1$$

$$I_2 = \frac{Z_0 I_1}{Z_0 + Z_2}$$

$$I_0 = \frac{Z_2 I_1}{Z_0 + Z_2}$$

$$E_1 = 1 - I_1 Z_1$$

$$E_2 = -I_2 Z_2 = E_1$$

$$E_0 - I_0 Z_0 = E_1$$

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