QATAR UNIVERSITY

COLLEGE OF ENGINEERING

DISTANCE POWER SYSTEM PROTECTION IN PRESENCE OF RENEWABLE

ENERGIES (SOLAR AND WIND)

BY

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ABSTRACT

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Renewable energy become widely used in recent years in order to reduce CO_2 emission, which produce from burning oil and gas to generate electrical energy. Solar and wind energies are the main types of renewable energies, as it can be installed near the load, so that it improves power quality that transmitted to load. However, renewable energies can cause mal-operation of distance relay as they can affect the impedance measured by the relay. This Thesis will concern on study of the impact of solar and wind energies on the protection of transmission lines and distance relay. The model of system is simulated by using Matlab/Simulink, while power world simulator is used to perform fault analysis, and detecting fault currents. Single line-to-ground, line-to-line, and double line-to-ground faults will be applied in the transmission lines to verify relay performance in presence of renewable energies. Zones of protection by distance relays is studied in order to detect the impact of renewable energy on fault location seen by the relay.

ACKNOWLEDGMENTS

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CHAPTER 1: INTRODUCTION

1.1 Background:

Power system consists of many parts which are: generation, transmission, distribution, and protection. Protection system plays a vital role in power system, as it protects the system from different types of fault. If the fault stays for a long time in the system it can damage some parts of the system which lead to loss of some expensive equipment. In order to protect the system, a fast response protection system should be used. Protection system includes many devices such as: relays, breakers, and fuses which are the main components of the system. However relay acts as the brain of protection system, as it senses the voltage and current, also it controls the circuit breaker operation. There many types of relays like: overcurrent relay, differential relay, and distance relay. Distance relay is the best type of relays that can provides an accurate protection for long transmission lines, also distance relays can provides backup protection for different lines. In other hand, overcurrent relay can't provides fast protection especially in mesh network, while differential relay needs expensive and accurate communication channels [1]. Distance relay provides a best way of detecting the fault and speed of operation, as it depends on pre-set condition which related to transmission line length, so it can detects the location of fault within the line [2,3]. The operation mechanism of distance relay is different from other types of relays. Distance relay operation not only depend on measuring the voltage only or current but it depends on measuring the ratio of voltage and current to find the value of line impedance depending on ohm's law and compared to the set value of impedance, where the set value of impedance depends on the resistance and reactance of transmission line [4]. The operation of distance relay can be affected by different

factors such as connecting renewable energy to transmission lines because it affects the line impedance.

Renewable energy has a main impact on environment as it produces energy from natural sources compared to normal energy production which rely on burning fossil fuels. Renewable energy produces clean and neat energy which reduce the pressure on CO_2 emission and by default the air pollution will reduce too. For that reason renewable energy can help to achieve environmental sustainability [5]. Renewable energy like solar and wind has other benefits rather than environmental impact such as stabilizing the voltage at the grid. Solar and wind energy can be used as compensators when its connected to grid, as it reduces the voltage drop and reduce the power loss that happen during the transmission from generation side to load side [6]. However, renewable energy has negative impact on protection system especially distance relay. It affects the fault impedance seen by the relay which causes mal-operation of it, moreover renewable energy causes miscoordination of relays [7].

The propose of the thesis is to study the impact of solar and wind energy on distance relay firstly, by applying fault analysis and detect the value of line impedance during different types of fault. Secondly, study the impact of renewable energy on line impedance seen by the relay.

1.2 OBJECTIVES:

The main objective of this thesis is to study the impact of renewable energies including solar and wind energy on the transmission line protection. Investigating the impact of renewable energy on the distance relay operation will be performed through three stages. Firstly, IEEE 9-bus power system is considered and transmission line impedances is calculated. Then different types of faults are applied and sequence impedances of the system will be calculated. Finally, solar and wind energy are added to the IEEE 9-bus system in order to detect their impact on the relay operation in the presence of different types of faults.

CHAPTER 2: LITRATURE REVIEW

Most of power plants are using fossil fuels like petroleum and gas to generate electrical power. However, burning petroleum and gas will produce carbon dioxide gas (CO_2) which has bad effect on environment and human.CO_2 emissions affects earth's atmosphere and lead to global warming issue which causes climate change by increasing weather temperature which has a severe impact on environment. In order to reduce CO_2 emission, alternative sources of electrical energy can be used. Renewable energy like solar and wind are the main alternative recourses can be used to generate neat and safe electricity. However renewable energy has positive and negative impacts on environment and electrical system itself which will be shown in the following studies.

As shown in [8] that renewable energy can produce clean and safe energy which reduce the bad effect of CO_2 emission. Renewable energy includes many technologies to generate electric power such as: biomass energy, nuclear energy, wind energy, and solar energy. Renewable energy can be integrated to electric grid but it has some issues, especially when renewable sources feed the system with high amount of power. The issues of renewable energy integration are: availability of power, location of renewable energy substations and power quality. Availability of power happens because renewable energy depends on natural sources, like solar energy depends on sun radiation to produce electrical power, so during night the output power will be zero as there is no sun radiation. In the same manner for wind energy, that during windy days there is output power, while in other cases the output power will be very low. The location of renewable energy is important like when solar energy used, the location of plant should be specified depends on sun radiation, sometimes the location of plant could be far from grid which can reduce the efficiency

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of transmitted power. Power quality issue happen with renewable energy especially when solar energy is used, the output voltage and frequency are not constant because the solar energy depends on sun radiation which is continuously changing during the day.

In [9] discussed that renewable energy has indirect impact on coast and environment and these effects cannot be measured directly. Some of disadvantages of renewable energy are: firstly, renewable energy equipments are costly especially during production stage like solar energy. Solar energy needs a lot of photovoltaic cells and solar collectors to produce energy, which require a lot of materials to become a substation for electric power generation. Secondly, renewable energy has negative impact on environment during construction stage because of the machines that used increase air pollution with exhaust fumes. Finally, some of renewable energy technologies have low efficiency of converting renewable energy into useful energy for example, solar energy. Solar energy needs 10kwh of sun radiation to produce 1kwh output energy from photovoltaic cells, so the efficiency of PV cells around 10% only.

Also [10] shows the negative impact of renewable energy on environment. During production of photovoltaic cells a lot of chemicals will produce and release to atmosphere causing air pollution. For example, the manufacturing of poly and mono-crystalline modules of photovoltaic cells produce 3.845kg CO_2/KWP and 5.049-5.524 kg SO_2/KWP that will emit to air.

As shown in previous studies that renewable energy has disadvantages on environment and energy quality while the following studies will present the advantages of renewable energy.

[11, 12, 13] show the economic impact of renewable energy. By using input-output method to analyze the impact of renewable energy especially solar and wind energy, it shows that renewable energy has indirect positive impact on economic growth. Where the positive impact of renewable energy can be in terms of offering new jobs and boost employment, so renewable energy can help the economic growth.

While [14] discussed the advantages of renewable energy on electric grid. During transmission of electrical power from generation plant to distribution grids there are some losses will happen because of the transmission line impedance. The losses affect the load as it leads to voltage instability. To enhance voltage stability at load side, compensation methods can be used. One of compensation techniques are using is renewable energy like wind, solar, and mini-hydro are the common renewable sources used to reduce voltage drop at distribution grids because renewable energy can be implemented and integrated near to load. Renewable energy can be used to enhance power system stability and reliability at load side.

As shown in [15] that the output power from renewable energy depends on two factor which are metrological and environmental factors. These factors can affect the output power stability from renewable energy. For example, solar energy has the maximum output power in summer compared to winter depending on that the sun radiations in summer is between three to six time the sun radiations in winter. In order to stabilize the output power from renewable energy sources, combination among different types of renewable energies can be used. However, the best method can be used to determine the best configuration of renewable energy combination is multi-criteria analysis (MCA). MCA is the best method can be used for energy planning.

As renewable energy can be used to reduce the losses in power during transmission and causes voltage drop at buses, sometimes it affects the operation of

protection. The following studies will show the impact of renewable energy on protection system.

Renewable energy has good impact on power system stability and reliability by stabilizing the load voltage near 1 P.U. but it has a negative impact on protection system of transmission lines. Where distance relay and over current relay are used to protect transmission lines against any faults could happen. Protection system is a vital part of power system as it protects the whole system from faults. In case the fault stays for long time in system it causes damage for important and costly part of system and sometimes may causes fire which lead to loss some part of system. During the fault the system voltage reduces which cause generators to loss the synchronisms. The main parts of protection system are circuit breakers, reclosers and relays. Relays are the brain of protection system as it detects the faults and location of it, also it controls the circuit breaker. The main types of relays used to protect transmission lines are distance relays. Distance relays can detect the faults from long distance and by dividing the system into many zones, distance relay can provide protection to more than one zone which can be used to provide a backup protection for other lines. The operation of distance relay depends on measuring the impendence of line by measuring voltage and current and taking the ratio of them, so if the impedance is less than the set impedance the relay will trip in other cases it will not operate, as shown in reference [16,17].

As discussed in [18] that distance relays are using to protect transmission lines connected to wind farms. Wind farms can affect relays trip conditions as the output power from is continuously changing, so that wind farms causes mal-operation of relays. In order to avoid the mal-operation of relays, continuously changing trip conditions of relays are needed. However, fault resistance can affect the trip

conditions and lead the relay to not detect the fault. A new method introduced which is distance-differential protection, that method depending on measuring the current at both ends of line and transmitted to relay through communication channel, so the impact of fault resistance can be eliminated, and using the method of distance relay the location of fault can be detected. By using differential-distance protection the trip conditions of distance relay don't need to be changed when a wind farms connected to line.

As presented in [19] that distance relay detects the faults by measuring the voltage and current of line, also distance relay can provide protection up to 80% of the line length in zone 1 and it can provides protection up to 120% in zone 2. There are two different types of solar power plants which are: T-off connection and Bus connection, where T-off connection is cheaper than Bus connection. However, T-off connection can affects the operation of distance relay by applying high current. T-off connection causes the relay to operate within zone 1 time while the fault happened in zone 2, so it causes a wrong detection of fault location. While Bus-connection type is more reliable and it does not affect the relay operation, where the relay can detect the fault if it happen in zone 1 or in zone 2.

Where [20] shows that the inverter-interfaced renewable energy has a negative impact on distance relays and it cause a mal-operation of relays especially during faults. In order to solve the problem an improved scheme for protection system provided depending on delay and zero-sequence impedance.

In [21, 22] discussed the integration of renewable energy in distribution network as well the integration of it in transmission lines. Overcurrent relays are using for protection in distribution network and the high penetration of renewable energy can affect the operation of relay especially in weak buses. Different methods could be

used in order to reduce the impact of high penetration of renewable energy in distribution network protection, some of these methods are: using distance relays in distribution system especially mho relays as its directional relay with distance relay, so it can distinguish between forward fault and reversed fault. 2- Adding a reclose with relay at the interconnection point with renewable energy, so during the permanent fault the relay will trip and disconnect the renewable energy. However is not proper way because it affects the system reliability. In case the integrating of renewable energy with transmission lines, the high penetration will affect the operation of distance relay. As the induced current from renewable energy is changing because it depends on natural sources causes the impedance seen by the relay to be changed, which causes under/over reach problem to distance relay. To solve that problem two methods can be used: 1- adaptive distance protection 2- artificial intelligence bases differential protection.

While [23] shows that using wind energy with doubly fed induction generator will affect the protection system of transformers. Differential protection is the main protection used for transformer and it's not only protect transformer from fundamental frequency current component, it also protects it from harmonics. While Crowbar protection is used to protect doubly fed induction generator. During short circuit condition crowbar protection causes harmonics in fault current provided from generator to transformer, these harmonics affect the differential protection of transformer, especially second harmonic. In order to prevent differential protection from mal-operation second harmonic locking elements can be used in differential protection of transformer.

By adding photovoltaic generators in centralized model can led to harmful impact on protection elements especially overcurrent relays, reclosers, and circuit

breakers. The impact of high penetration of photovoltaic affects the coordination of overcurrent relays, so to solve that problem, a new setting can be adjusted to relay in order to avoid the miss-coordination of it during faults conditions. As discussed in [24].

The integration of solar photovoltaic has negative impact on distribution network by changing voltage profile and change fault current level which affects the operation of protection system, also high penetration of solar photovoltaic causes thermal issues to transmission line by overloading it. 25% penetration of solar photovoltaic can improve transient stability of bus, as shown in [25].

In [26] studied the impact of renewable energy impact on out-of-step tripping protection with different levels of penetration. The high penetration of renewable energy causes mal-operation of out-of-step tripping relays and it can affect the synchronism of generators due to the variation of output power from renewable energy, also renewable energy can cause variation in system frequency which affects the generators synchronism.

CHAPTER 3: SEQUENCE AND TRANSMISSION LINE IMPEDANCE CALCULATION

This chapter will present the calculation of transmission lines and sequence impedance. Firstly, the calculation of transmission line impedance will be present in terms of line parameters. Secondly, sequence impedance will be calculated in order to be used to perform fault analysis.

3.1 Transmission line impedance

Transmission lines model consists of resistance, inductance, conductance, and capacitance. Where inductance and capacitance are due to the effect of electric and magnetic field. However the conductance represents the leakage current which happen during the current flowing across insulator and the ionized pathways in air, but the leakage current is much smaller than the flowing current in line, so it is neglected [28].

The impedance of transmission line consists of series impedance (or called the self-impedance) and the impedance between transmission lines (or called mutual impedance) which depends on the distance between the lines [27]. The self-impedance can be calculated as:

$$Z_{kk} = R_k + R_{K'} + j\omega 2 \times 10^{-7} ln\frac{D_{kk'}}{D_{kk}}$$ (3.1.1)

And mutual impedance is calculated:

$$Z_{km} = R_{k'} + j\omega 2 * 10^{-7} ln\frac{D_{km'}}{D_{km}}$$ (3.1.2)

Where:

$$D_{kk'} = 658.5\sqrt{\rho/f}$$ (3.1.3)

Where ρ, f are the resistivity and the frequency $\rho = 100\Omega m$ and $f = 50Hz$

D_{kk} is the GMR

D_{km} is the distance between the transmission line

$D_{km'}$ is the GMD and it is calculated by (3.1.4) for completely transposed transmission lines:

$$D_{km'} = \sqrt[3]{D_{12} * D_{23} * D_{31}} \tag{3.1.4}$$

D_{12}, D_{23}, D_{31} is the distance between the transposed lines as shown in figure 1.

R_k is the resistance of transmission line

$R_{k'}$ is the mutual resistance and calculated by using (3.1.5):

$$R_{k'} = 9.869 * 10^{-7} f \tag{3.1.5}$$

Figure 1. Transposed Trasmission Lines [27]
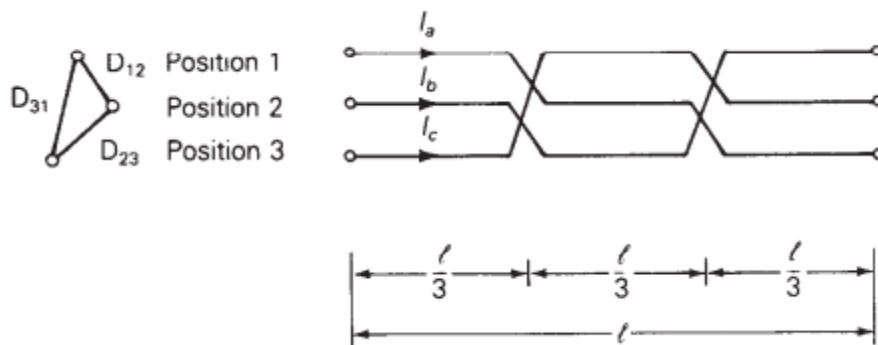
The type of transmission line used in the system is (ACSR) bluebird, where the parameters of the line are shown in Figure 2. The distance between the phases is $7m$ and the distance between phase and ground is $8m$ as the base voltage of the system and frequency is $345KV, 50Hz$. Figure 3 shows the suitable distance between the phases and phase to ground with respect to system voltage.

Code Word	Circular Mils Aluminum	Aluminum			Steel		Outside Diameter (inches)	Copper Equivalent* Circular Mils or A.W.G.	Ultimate Strength (pounds)	Weight (pounds per mile)	Geometric Mean Radius at 60 Hz (feet)	Approx. Current Carrying Capacity† (amps)	r_a Resistance (Ohms per Conductor per Mile)								x_a Inductive Reactance (ohms per conductor per mile at 1 ft spacing all currents) (60 Hz)	x_a' Shunt Capacitive Reactance (megohms per conductor per mile at 1 ft spacing) (60 Hz)
			Strand Diameter (inches)		Strand Diameter (inches)								25°C (77°F) Small Currents				50°C (122°F) Current Approx. 75% Capacity‡					
													dc	25 Hz	50 Hz	60 Hz	dc	25 Hz	50 Hz	60 Hz		
Joree	2515000	76	..	0.1819	19	0.0849	1.880		61700			0.0621									0.0450	0.337	0.0755
Thrasher	2312000	76	..	0.1744	19	0.0814	1.802		57300			0.0595									0.0482	0.342	0.0767
Kiwi	2167000	72	4	0.1735	7	0.1157	1.735		49800			0.0570									0.0511	0.348	0.0778
Bluebird	2156000	84	4	0.1602	19	0.0961	1.762		60300			0.0588									0.0505	0.344	0.0774

Figure 2. Transmission line parameters [27]

Nominal Voltage (kV)	Phase Conductors			Minimum Clearances	
	Number of Conductors per Bundle	Aluminum Cross-Section Area per Conductor (ACSR) (kcmil)*	Bundle Spacing (cm)	Phase-to-Phase (m)	Phase-to-Ground (m)
69	1	—	—	—	—
138	1	300–700	—	4 to 5	—
230	1	400–1000	—	6 to 9	—
345	1	2000–2500	—	6 to 9	7.6 to 11
345	2	800–2200	45.7	6 to 9	7.6 to 11
500	2	2000–2500	45.7	9 to 11	9 to 14
500	3	900–1500	45.7	9 to 11	9 to 14
765	4	900–1300	45.7	13.7	12.2

Figure 3. Spacing between transmission lines [27]

Transmission line configuration assumed to be one bundle per phase as shown in Figure 3. Transmission lines considered to be transposed in order to make phase balancing. The calculation of self and mutual impedance of transmission lines depending on parameters in Figure 1 and Figure 2, also depends on equations (3.1.1)-(3.1.5).

$$D_{kk'} = 685.5 * \sqrt{\frac{100}{50}} = 931.3 \ m \tag{3.1.6}$$

$$R_{k'} = (9.869 * 10^{-7}) * 50 = 4.9345 * 10^{-5} \ \Omega/m \tag{3.1.7}$$

$$D_{kk} = 0.0588 * 0.3048 = 0.0179 \ m \qquad \text{(Depends on figure2)} \tag{3.1.8}$$

$$D_{km'} = \sqrt[3]{8 * 15 * 22} = 13.821 \quad \text{(Depends on distance from phase to ground)} \tag{3.1.7}$$

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$D_{km'} = \sqrt[3]{7 * 7 * 14} = 8.82 \, m$ (Depends on distance between phases)   (3.1.8)

$R_k = 3.138 * 10^{-5} \, \Omega/m$ (Depends on line parameters shown in figure2)   (3.1.9)

After calculating transmission line parameters the impedance of lines can be calculated depending on line length as shown in table 1and the configuration of IEEE 9-bus system considered shown in Figure 4:
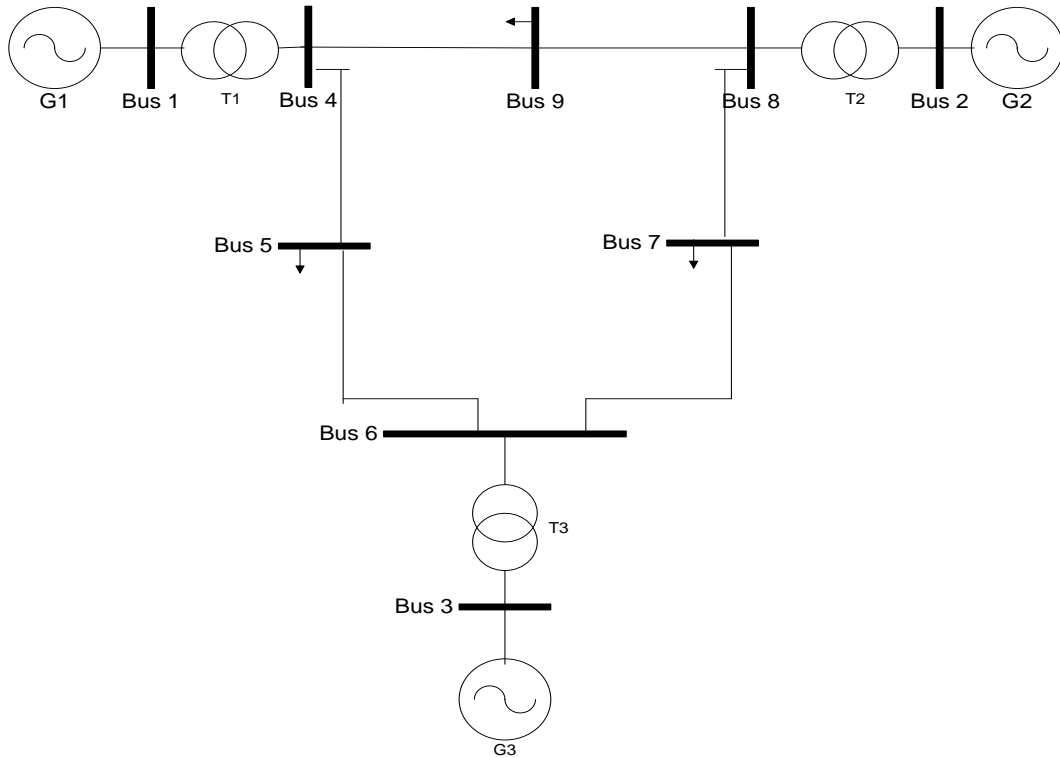
Figure 4. IEEE 9-bus system

Table 1. Transmission Lines Length

Line from bus-to bus	Length (km)
4-5	120
6-7	135
7-8	95
8-9	210
9-4	105
5-6	225

Table 2 shows transmission lines impedance where it is calculated depending on line length shown in table 1:

Table 2. Transmission Lines Impedance

Line from bus-to bus	Impedance (ohm)
4-5	81.78∠87.3
6-7	92.02∠87.3
7-8	64.9∠87.3
8-9	143.4∠87.4
9-4	71.56∠87.4
5-6	153.3∠87.4

As the system base voltage is $345KV$ and the base power is $100MVA$ the base impedance can be calculated as in (3.1.10):

$$Z_{base} = \frac{V_{base}^2}{S_{base}} \qquad (3.1.10)$$

So the base impedance will be:

$$Z_{base} = \frac{345^2}{100} = 1190.25 \ \Omega \qquad (3.1.11)$$

Where the per-unit impedance can be calculated as in (3.1.12)

$$Z_{P.U.} = \frac{Z_{line}}{Z_{base}} \qquad (3.1.12)$$

The per- unit impedance of transmission lines will be calculated depending on the base impedance as shown in (3.1.12). The per-unit impedance of transmission lines shown in table 3.

Table 3. Per-Unit Impedance Of Transmission Lines

Line from bus-to bus	Impedance (ohm)
4-5	0.069∠87.3
6-7	0.0773∠87.3
7-8	0.0545∠87.3
8-9	0.1205∠87.4
9-4	0.0601∠87.4
5-6	0.1288∠87.4

Depending on impedance values in table 3 the sequence impedance will calculated in next section.

3.2 Sequence impedance:

Sequence impedance can be calculated for all parts of power system such as: generators, transmission lines, transformers, and loads. Sequence impedance can be used to analyze power system in case phase unbalance and faults. However, to convert the system from phase to sequence, symmetrical components can be used.

3.2.1 Symmetrical Components;

Symmetrical components is a powerful method which used to analyze unbalanced three phase system. The method introduced by C.L. Fortescue in 1918 [27]. The main principle of symmetrical components is to convert three phase system into three uncoupled systems called sequence network. The sequence networks will be connected to unbalanced point of three phase system in order to analyze the system. The sequence networks are: zero, positive, and negative sequence.

As discussed before that the sequence networks connected to point of unbalancing, while each network has specific feature as follows:

1- Zero sequence: the three phases have the same magnitude with zero phase shift.

2- Positive sequence: three phases have the same magnitude with $\pm 120°$ phase shift between phases.

3- Negative sequence: three phases have the same magnitude with $\pm 120°$ phase shift between phases.

The sequence voltage can be calculated as in (3.2.1.1):

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}^{-1} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (3.2.1.1)$$

Where V_0, V_1, V_2 are the sequence voltages, V_a, V_b, V_c are the phase voltage, a is defined in (3.2.1.2):

$$a = 1 \angle 120 \qquad (3.2.1.2)$$

In the same manner the sequence current can be calculated as in (3.2.1.3)

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}^{-1} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (3.2.1.3)$$

Where I_0, I_1, I_2 and I_a, I_b, I_c are the sequence and phase currents.

Although the sequence network can be calculated to loads, generators , transmission lines, and transformers in terms of impedance.

3.2.2 Sequence impedance of generator:

Sequence impedance of generator can be determined by applying short circuit on the terminal of unloaded generator. However, the sequence impedance of generator provided by the manufacture of generator as shown in Figure 5

Constant (units)	Type	Symbol	Turbo-Generator (solid rotor)	Water-Wheel Generator (with dampers)	Synchro-nous Condenser	Synchro-nous Motor
Reactances (per unit)	Synchronous	X_d	1.1	1.15	1.80	1.20
		X_q	1.08	0.75	1.15	0.90
	Transient	X'_d	0.23	0.37	0.40	0.35
		X'_q	0.23	0.75	1.15	0.90
	Subtransient	X''_d	0.12	0.24	0.25	0.30
		X''_q	0.15	0.34	0.30	0.40
	Negative-sequence	X_2	0.13	0.29	0.27	0.35
	Zero-sequence	X_0	0.05	0.11	0.09	0.16
Resistances (per unit)	Positive-sequence	R (dc)	0.003	0.012	0.008	0.01
		R (ac)	0.005	0.012	0.008	0.01
	Negative-sequence	R_2	0.035	0.10	0.05	0.06
Time constants (seconds)	Transient	T'_{d0}	5.6	5.6	9.0	6.0
		T'_d	1.1	1.8	2.0	1.4
	Subtransient	$T''_d = T''_q$	0.035	0.035	0.035	0.036
	Armature	T_a	0.16	0.15	0.17	0.15

Figure 5. Sequence impedance of generator [27]

The subtransient reactance presents the positive sequence impedance which will be used to perform the fault analysis with zero and negative sequence impedance [27]. The type of generator and sequence parameters listed in table 4.

Table 4. Generator Data

Type of generator	Zero sequence(P.U)	Positive sequence(P.U)	Negative sequence(P.U)
Turbo –Generator (solid rotor)	0.05	0.15	0.13

3.2.3 Transformer sequence impedance

In per-unit system the transformer presents in terms of leakage reactance. While the reactance of zero, positive, and negative sequence are equal. However, the difference in per-unit sequence depends on transformer configuration and depends on the neutral line impedance in case the neutral is grounded or not as shown in Figure 6 [27].
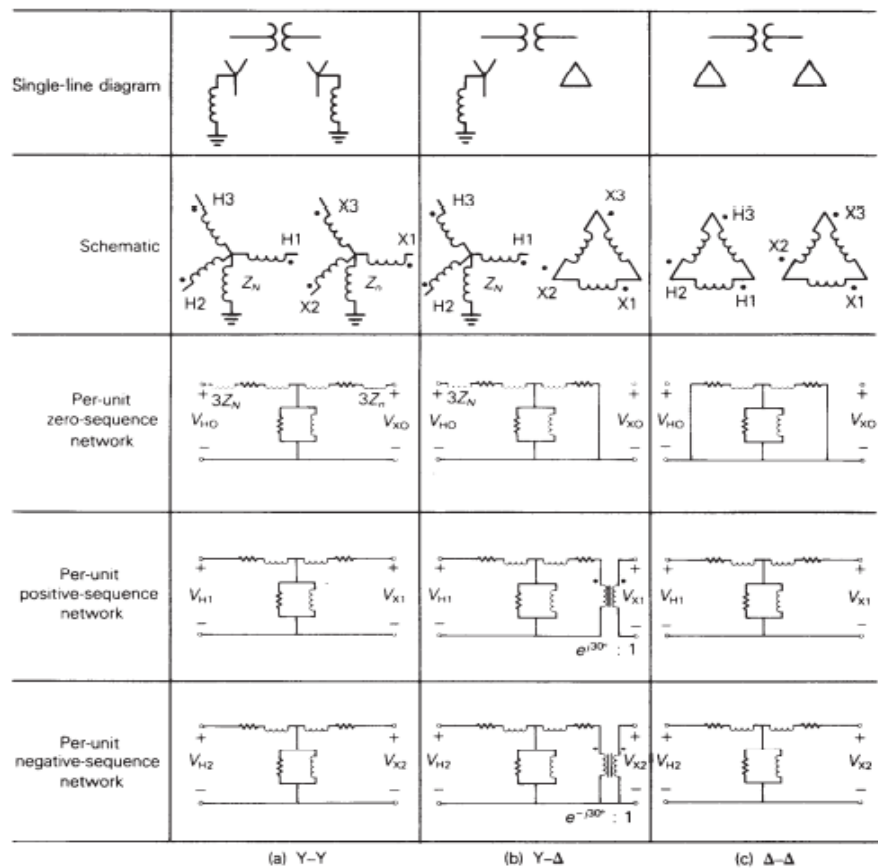

Figure 6. Transformer sequence network [27]

The neutral line impedance has important role when the line is grounded. The neutral impedance has main impact especially in zero sequence as it is $3 * Z_n$ [28].

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3.2.4 Sequence impedance of three phase transmission lines

As discussed in section 3.1 that the transmission lines considered to be completely transposed. While the sequence impedance of transposed transmission lines can be calculated as in (3.2.4.1):

$$\hat{Z}_s = A^{-1} * \hat{Z}_p * A = \begin{bmatrix} \hat{Z}_0 & 0 & 0 \\ 0 & \hat{Z}_1 & 0 \\ 0 & 0 & \hat{Z}_0 \end{bmatrix} \qquad (3.2.4.1)$$

Where the zero, positive, and negative sequence can be calculated as:

$$\hat{Z}_0 = \hat{Z}_{aaeq} + 2 * \hat{Z}_{abeq} \qquad (3.2.4.2)$$

$$\hat{Z}_1 = \hat{Z}_2 = \hat{Z}_{aaeq} - \hat{Z}_{abeq} \qquad (3.2.4.3)$$

Where $\hat{Z}_{aaeq}$ and $\hat{Z}_{abeq}$ are the self and mutual impedance

By using the values of transmission lines impedance found in section3.1 and equations (3.2.4.1)-(3.2.4.3) the sequence impedance of transmission lines can be calculated, where sequence impedance of transmission lines presented in table 5 and table 6:

Table 5. Sequence Impedance Of Transmission Lines In Ohm

	Zero sequence (Ω)	Positive sequence(Ω)
4-5	85.84∠75.57	81.78∠87.3
6-7	96.6∠75.6	92.02∠87.3
7-8	68.1∠75.6	64.9∠87.3
8-9	148.56∠75.4	143.4∠87.4
9-4	75.13∠75.6	71.56∠87.4
5-6	161∠75.56	153.3∠87.4

Table 6. Sequence Impedance Of Transmission Lines In P.U

Line from bus-to bus	Zero sequence (P.U)	Positive sequence(P.U)
4-5	0.072∠75.57	0.069∠87.3
6-7	0.081∠75.6	0.077∠87.3
7-8	0.057∠75.6	0.0545∠87.3
8-9	0.125∠75.4	0.120∠87.4
9-4	0.063∠75.6	0.060∠87.4
5-6	0.135∠75.56	0.128∠87.4

As shown in the chapter that the impedance of transmission line calculated depending on the system voltage, where the voltage used to specify the distance between the phases and phases to ground, also the calculation of impedance depends on transmission line configuration which considered to be transposed transmission lines. Sequence impedance of generators, transformer, and transmission line calculated by using symmetrical components. Symmetrical components used to convert the system from phase domain to sequence domain. Later on the sequence impedance will be used in the next chapter in order to calculate the fault current.

CHAPTER 4: FAULT ANALYSIS

In three phase power system there are two major types of faults happened which are symmetrical and unsymmetrical fault. While unsymmetrical fault includes three types of fault and these types are: single line-to-ground, line-to-line, and double line-to-ground as shown in Figure 7 [27].
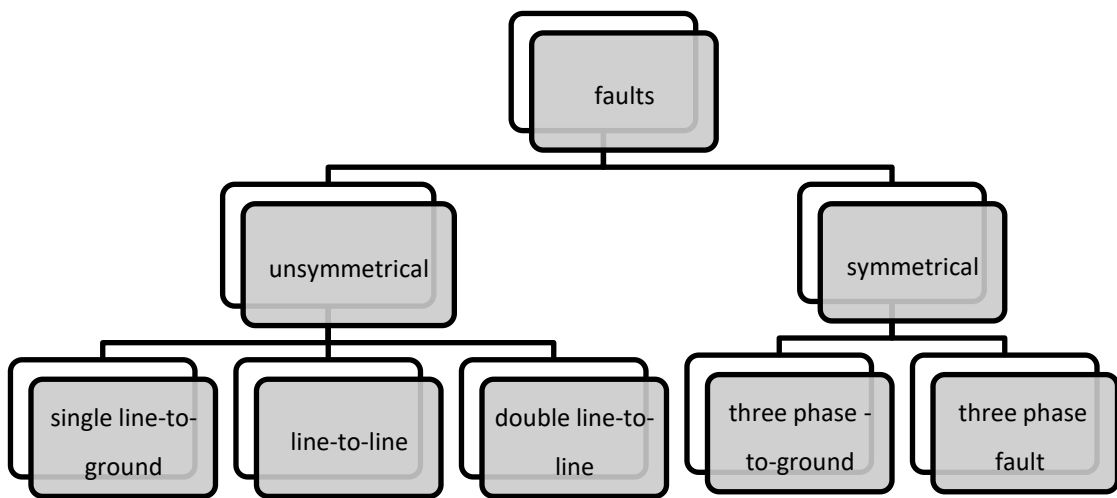
Figure 7. Fault types

4.1 Symmetrical fault:

Symmetrical faults mean the three phases are shorted together. This type of fault is infrequent, while 2%-5% of faults are symmetrical fault [29]. However, symmetrical fault is the most sever one as the network is balanced. Symmetrical faults can be solved by Thevenin method. Where the Thevenin impedance calculated from the faulted point and the fault current calculated by:

$$\mathbf{I_f} = \frac{\mathbf{V_F}}{\mathbf{Z_{Th}}} \tag{4.1.1}$$

Where $\mathbf{V_f}$ and $\mathbf{Z_{Th}}$ are the prefault voltage and thevenin impedance seen from the faulted point.

4.2 Unsymmetrical faults:

Unsymmetrical faults are more frequent to occur more than the symmetrical faults and include three types of fault which are: single line-to-ground, line-to-line, and double line-to-ground fault. However, single line-to-ground fault is the highest occurrence, then double-to-ground fault and line-to-line fault is the lowest occurrence [29]. In order to calculate the fault current of unsymmetrical faults, zero, positive, and negative sequence network interconnected to point where the fault happens. The following sections will present the calculation of fault current for each type of unsymmetrical faults in details.

4.2.1 Single line-to-ground fault (L-G)

Single line-to-ground fault means one of the three phases connected to ground through fault impedance $\mathbf{Z_F}$ as shown in Figure 8. However, in case of bolted fault the fault impedance will be zero $\mathbf{Z_F = 0}$, where fault impedance $\mathbf{Z_F}$ in case of transmission lines represents the total fault impedance between the line and ground which includes the impedance of arc and transmission tower.
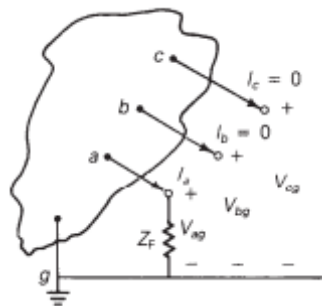

Figure 8. Single line-to-ground fault [27]

As shown in Figure 10 that only phase a is connected to ground, so the fault condition in phase domain that:

$$I_b = I_c = 0 \qquad\qquad (4.2.1.1)$$

$$V_{ag} = Z_F I_a \qquad\qquad (4.2.1.2)$$

In order to calculate the fault current of phase a the sequence network will be connected in series as in Figure 9.
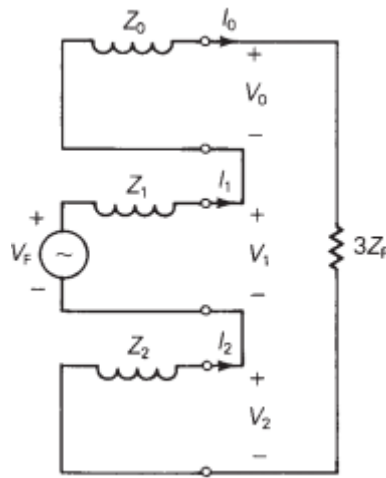
Figure 9. Interconnected sequence [27]

As the sequence network connected in series, so the sequence currents will be equal as in (4.2.1.3):

$$I_0 = I_1 = I_2 = \frac{V_F}{Z_0 + Z_1 + Z_2 + 3Z_F} \qquad\qquad (4.2.1.3)$$

By transforming (4.2.1.3) to phase domain it will produce:

$$I_a = I_0 + I_1 + I_2 = 3I_1 = \frac{3V_F}{Z_0 + Z_1 + Z_2 + 3Z_F} \qquad\qquad (4.2.1.4)$$

As shown in (4.2.1.4) that the fault current in phase domain it is three times the positive sequence current [27].

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4.2.2 Line-to-line fault (L-L):

Figure 10 represent line-to-line fault, where the fault happens between phase b and phase c through fault impedance Z_F.
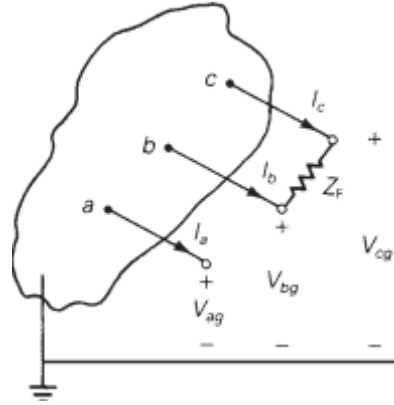
Figure 10. Line-to-line fault [27]

In order to calculate the fault current, specific conditions for line-to-line fault should be considered which are:

$$I_a = 0 \qquad\qquad (4.2.2.1)$$

$$I_c = -I_b \qquad\qquad (4.2.2.2)$$

$$V_{bg} - V_{cg} = Z_F I_b \qquad\qquad (4.2.2.3)$$

However the fault current can be calculated by transforming the system to sequence domain as follows:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} \qquad\qquad (4.2.2.4)$$

And the sequence voltage can be calculated as:

$$(V_0 + a^2 V_1 + a V_2) - (V_0 + a V_1 + a^2 V_2) = Z_F(I_0 + a^2 I_1 + a I_2) \qquad (4.2.2.5)$$

By simplifying (4.2.2.5):

$$V_1 - V_2 = Z_F I_1 \qquad\qquad (4.2.2.6)$$

By applying the same fault conditions in phase domain to sequence domain the fault

current will be:

$$I_1 = -I_2 = \frac{V_F}{(Z_1 + Z_2 + Z_F)} \qquad\qquad (4.2.2.7)$$

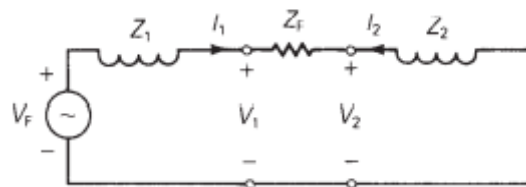By using (4.2.2.4)-(4.2.2.7) the sequence network can be implemented as in

Figure 11.

Figure 11. Sequence network of line-to-line fault [27]

4.2.3 Double Line-to-Ground fault (LLG)

   Double line-to-ground fault happen by connecting two phases through fault

impedance to ground as shown in Figure 12.
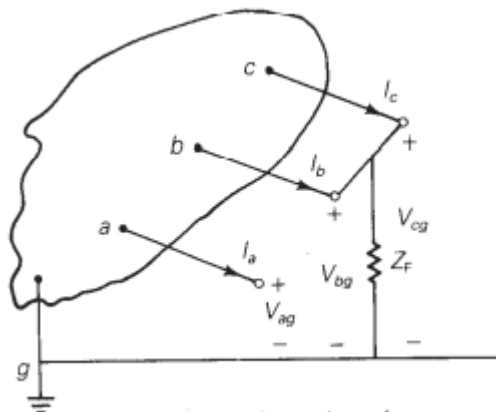
Figure 12. Double line-to-ground fault [27]

Where the fault conditions in phase domain that:

$$I_a = 0 \tag{4.2.3.1}$$

$$V_{cg} = V_{bg} \tag{4.2.3.2}$$

$$V_{bg} = Z_F(I_b + I_c) \tag{4.2.3.3}$$

By transforming the system to sequence network by using symmetrical components the fault conditions will be:

$$I_0 + I_1 + I_2 = 0 \tag{4.2.3.4}$$

$$V_0 - V_1 = (3Z_F)I_0 \tag{4.2.3.5}$$

$$V_1 = V_2 \tag{4.2.3.6}$$

Equations (4.2.3.4)-(4.2.3.6) are satisfied when the zero, positive, and negative sequence networks connected in parallel as shown in Figure 13.
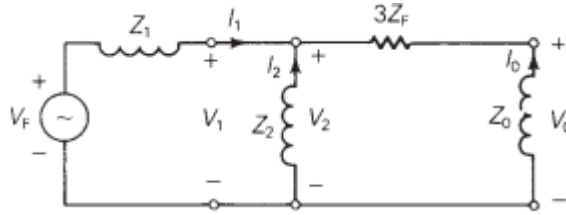
Figure 13. Sequence network of double line-to-ground fault [27]

So the sequence currents will be:

$$I_1 = \frac{V_F}{Z_1 + \left[\frac{Z_2(Z_0 + 3Z_F)}{Z_2 + Z_0 + 3Z_F}\right]} \tag{4.2.3.7}$$

$$I_2 = (-I_1)\left(\frac{Z_0 + 3Z_F}{Z_2 + Z_0 + 3Z_F}\right) \tag{4.2.3.8}$$

$$I_0 = (-I_1)\left(\frac{Z_2}{Z_2 + Z_0 + 3Z_F}\right) \tag{4.2.3.9}$$

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4.3 Bus Impedance Matrix

Bus impedance matrix can be used to calculate the fault current especially in systems include huge number of buses. Bus impedance matrix can be found by firstly finding the sequence bus admittance matrix then taking the inverse of it.

$$Z_{bus} = Y_{bus}{}^{-1} \qquad\qquad (4.3.1)$$

Figure 14 to Figure 17 show the equivalent bus impedance matrix (rake equivalent) for each sequence network of faulted system.
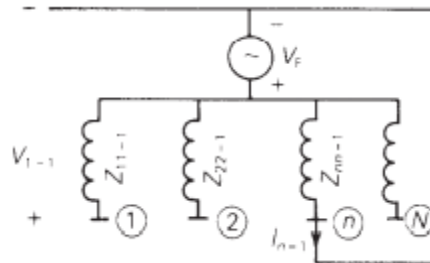
Figure 14. Three phase fault [27]
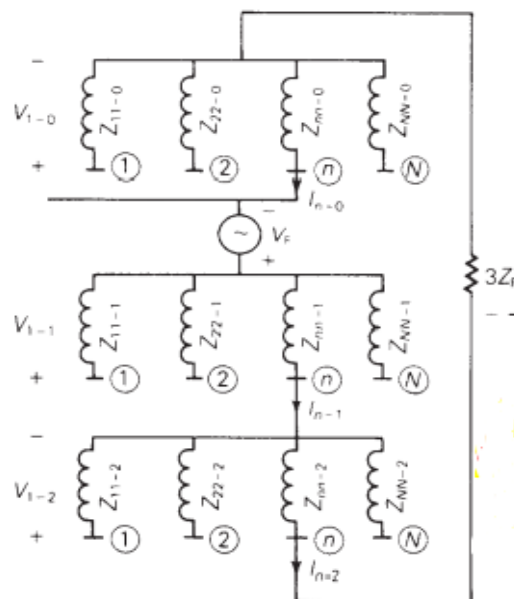
Figure 15. Single line-to-ground fault [27]
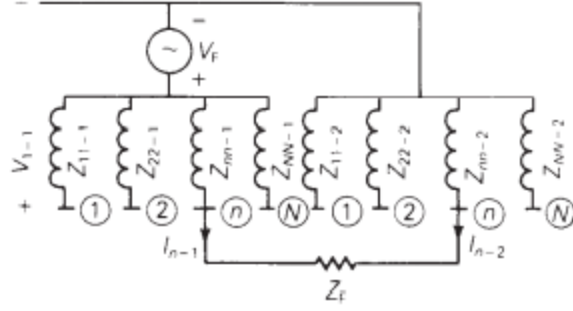
Figure 16. Line-to-line fault [27]
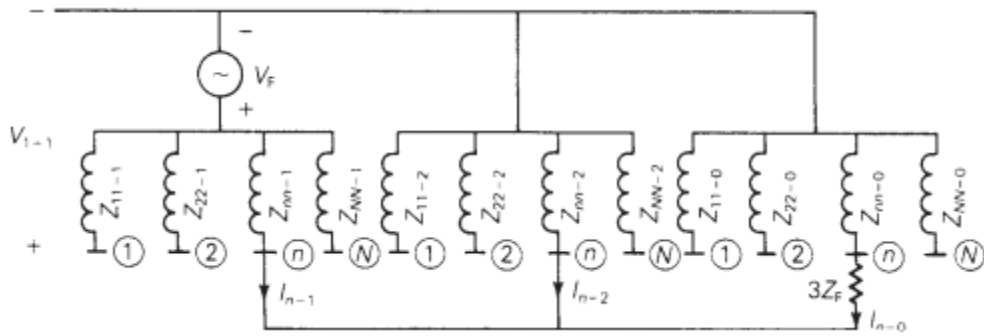
Figure 17. Double line-to-ground fault [27]

Depending on sequence network shown in Figure 14 to Figure 17, the fault current of

each fault type can be calculated as follows:

(a) Three phase fault:

$$I_{n-1} = \frac{V_F}{Z_{nn-1}} \tag{4.3.2}$$

$$I_{n-0} = I_{n-2} = 0 \tag{4.3.3}$$

(b) Single line-to-ground fault:

$$I_{n-0} = I_{n-1} = I_{n-2} = \frac{V_F}{Z_{nn-0} + Z_{nn-1} + Z_{nn-2} + 3Z_F} \tag{4.3.4}$$

(c) Line-to-line fault:

$$I_{n-1} = -I_{n-2} = \frac{V_F}{Z_{nn-1} + Z_{nn-2} + Z_F} \tag{4.3.5}$$

(d) Double line-to-ground fault:

$$I_{n-1} = \frac{V_F}{Z_{nn-1}+\left[\frac{Z_{nn-2}(Z_{nn-0}+3Z_F)}{Z_{nn-2}+Z_{nn-0}+3Z_F}\right]} \tag{4.3.6}$$

$$I_{n-2} = (-I_{n-1})\left(\frac{Z_{nn-0}+3Z_F}{Z_{nn-0}+3Z_F+Z_{nn-2}}\right) \tag{4.3.7}$$

$$I_{n-0} = (-I_{n-1})\left(\frac{Z_{nn-2}}{Z_{nn-0}+3Z_F+Z_{nn-2}}\right) \tag{4.3.8}$$

Where n represent the number of faulted bus.

4.4 Fault current calculation of IEEE 9-bus system

The previous sections presented the way of calculating the fault current of three types of fault and how to construct bus impedance matrix which used to calculate the sequence impedance of system. However, in this section the calculation of bus impedance matrix and fault current will be applied on IEEE 9-bus system.

First of all in order to calculate bus impedance matrix, the sequence network configuration should be constructed first, where it depends on the sequence impedance of generators, transmission lines and the reactance of transformer which provided in chapter three. While the sequence impedance of loads not considered for simplicity. By considering the three transformers are delta-wye configuration and the values of transformer reactance present in table 7, the zero sequence network will be as shown in Figure 18.

Table 7. Transformer Reactance

Transformer	T1	T2	T3
Reactance (P.U)	j0.0576	j0.0625	j0.0586
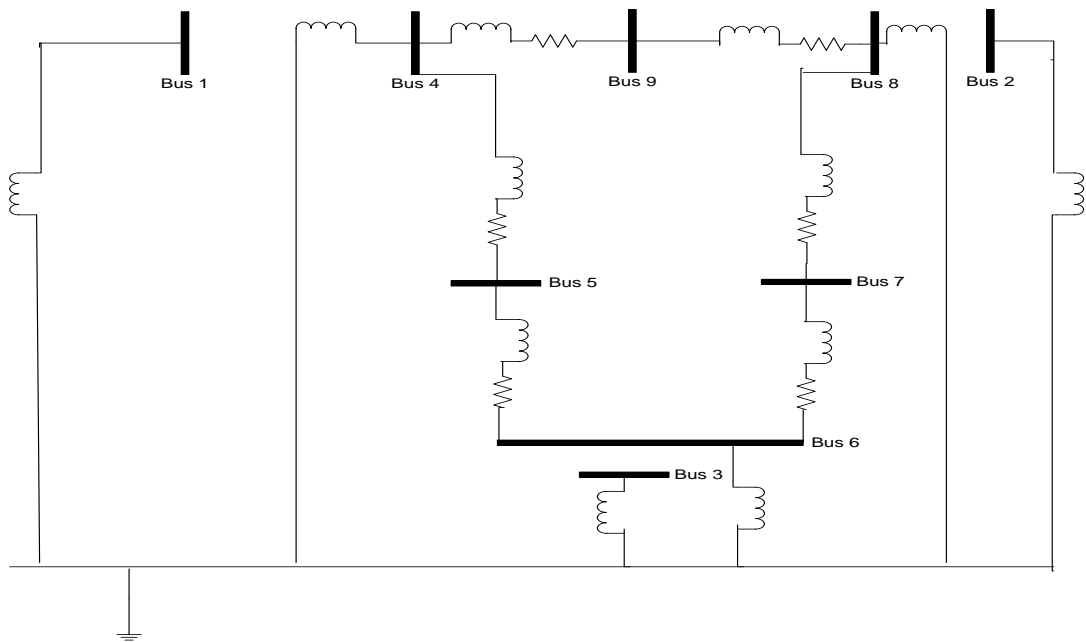
Figure 18. Zero sequence network

Where positive sequence network of the system is different from zero sequence as it includes the source and transformer configuration does not affect the circuit as in zero sequence. Figure 19 shows the configuration of positive sequence network.
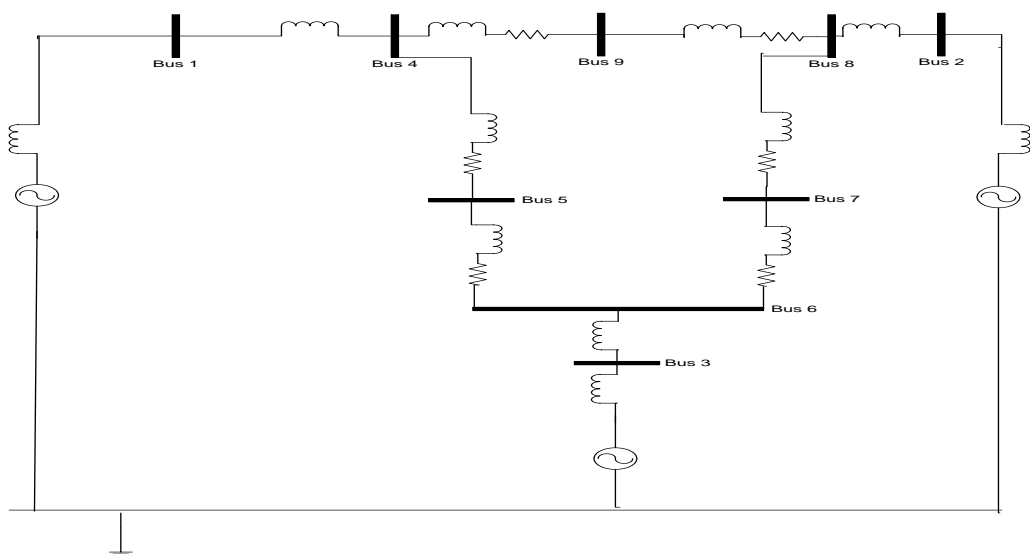
Figure 19. Positive sequence network

Negative sequence network is similar to positive sequence except that the source is not included as shown in Figure 20.
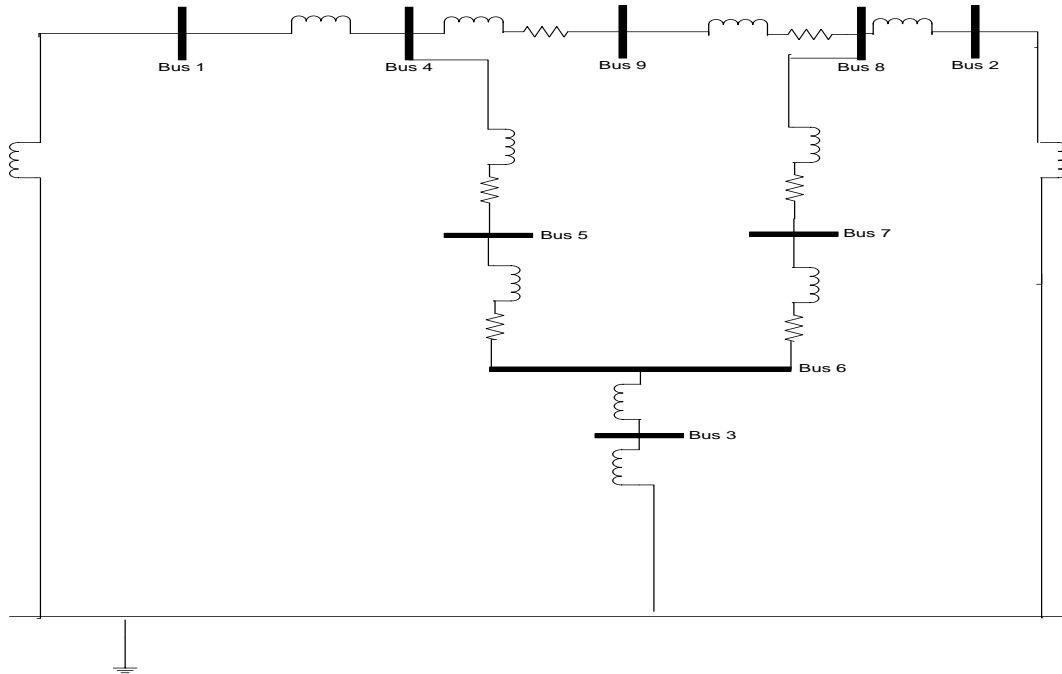
Figure 20. Negative sequence network

Figure 18-20 shows the general configuration of sequence network without specifying the fault location. However, in order to find sequence impedance of the system, bus impedance matrix can be used. Where bus impedance matrix can be found by calculating bus admittance matrix of each sequence network then taking the inverse of it as shown in the following:

1- Zero- sequence:

Admittance matrix can be constructed for zero-sequence network depending on Figure 18 and it will:

$Y_{bus(0)(P.U)} =$

$$\begin{bmatrix} -j20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -j20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -j20 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7.47-j46.4 & -3.45+j13.4 & 0 & 0 & 0 & -4.02+j15.34 \\ 0 & 0 & 0 & -3.45+j13.4 & 5.33-j20.6 & -1.88+j7.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1.88+j7.2 & 4.8-j36.03 & -2.94+11.8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -2.94+j11.8 & 7.3-j28.8 & -4.35+j17.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -4.35+j17.1 & 6.28-j40.9 & -1.93+j7.8 \\ 0 & 0 & 0 & -4.02+j15.34 & 0 & 0 & 0 & -1.93+j7.8 & 5.95-j23.12 \end{bmatrix}$$

and by taking the inverse of admittance matrix, bus impedance matrix can be found.

$Z_{bus(0)(P.U)}$

$$=\begin{bmatrix} j0.05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & j0.05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & j0.05 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0023+j0.0394 & 0.0011+j0.0287 & -0.0013+0.0089i & -0.0012+j0.0094 & -0.0012+j0.0096 & 0.0010+j0.0294 \\ 0 & 0 & 0 & 0.0011+j0.0287 & 0.0125+j0.0709 & j0.0194 & -0.0007+j0.0140 & -0.001+j\,0.0103 & 0.0003+j0.0226 \\ 0 & 0 & 0 & -0.0013+j0.0089 & j0.0194 & 0.0024+j0.0388 & 0.0003+j0.0227 & -0.0012+j0.0115 & -0.0012+j0.0098 \\ 0 & 0 & 0 & -0.0012+j0.0094 & -0.0007+j0.0140 & 0.0003+j0.0227 & 0.0091+j0.0588 & 0.0011+j0.0284 & -0.0004+j0.0158 \\ 0 & 0 & 0 & -0.0012+j0.0096 & -0.0012+j0.0103 & -0.0012+j0.0115 & 0.0011+j0.0284 & 0.0026+0.0398j & 0.0002+j0.0198 \\ 0 & 0 & 0 & 0.0010+j0.0294 & 0.0003+j0.0226 & -0.0012+j0.0098 & -0.0004+j0.0158 & 0.0002+j0.0198 & 0.0112+j0.0668 \end{bmatrix}$$

By referring to appendix A where the code used to calculate the bus impedance matrix

2- Positive - sequence:

In the same manner bus admittance constructed for positive sequence depending on sequence network shown in Figure 19.

$$Y_{bus(1)(P.U)} = \begin{bmatrix} -j24.02 & 0 & 0 & j17.4 & 0 & 0 & 0 & 0 & 0 \\ 0 & -j22.7 & 0 & 0 & 0 & 0 & 0 & j16 & 0 \\ 0 & 0 & -j23.7 & 0 & 0 & j17.1 & 0 & 0 & 0 \\ j17.4 & 0 & 0 & 1.42-j48.4 & -0.67+j14.5 & 0 & 0 & 0 & -0.75+j16.6 \\ 0 & 0 & 0 & -0.67+j14.5 & 1.01-j22.14 & -0.34+j7.68 & 0 & 0 & 0 \\ 0 & 0 & j17.1 & 0 & -0.34+j7.68 & 0.95-j37.7 & -0.61+j13 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.61+j13 & 1.48-j31.3 & -0.87+j18.3 & 0 \\ 0 & j16 & 0 & 0 & 0 & 0 & -0.87+j18.3 & 1.25-j42.6 & -0.38+j8.32 \\ 0 & 0 & 0 & -0.75+j16.6 & 0 & 0 & 0 & -0.38+j8.32 & 1.13-j24.9 \end{bmatrix}$$

So bus impedance matrix will be:

$Z_{bus(1)(P.U)}$

$$=\begin{bmatrix} j0.0955 & j0.0280 & j0.0281 & j0.0743 & j0.0622 & j0.0389 & j0.0394 & j0.0397 & j0.0628 \\ j0.0280 & j0.0928 & j0.0299 & j0.0386 & j0.0397 & j0.0415 & j0.0576 & j0.0691 & j0.0489 \\ j0.0279 & j0.0297 & j0.0933 & j0.0385 & j0.0498 & j0.0709 & j0.0541 & j0.0422 & j0.0398 \\ j0.0743 & j0.0386 & j0.0388 & 0.0011+j0.1026 & j0.0858 & j0.0537 & j0.0544 & j0.0548 & j0.0867 \\ j0.0622 & j0.0397 & j0.0501 & j0.0858 & 0.0024+j0.1254 & j0.0695 & j0.0618 & j0.0563 & j0.0760 \\ j0.0389 & j0.0415 & j0.0713 & j0.0537 & j0.0695 & 0.0010+j\,0.0988 & j0.0754 & j0.0588 & j0.0555 \\ j0.0394 & j0.0576 & j0.0544 & j0.0544 & j0.0618 & j0.0754j & 0.0018+j\,0.1110 & j0.0818 & j0.0636 \\ j0.0397 & j0.0691 & j0.0424 & j0.0548 & j0.0563 & j0.0588 & j0.0818 & 0.0010+j0.0981 & j0.0693 \\ j0.0628 & j0.0489 & j0.0400 & j0.0867 & j0.0760 & j0.0555 & j0.0636 & j0.0693 & 0.0022+j\,0.1211 \end{bmatrix}$$

3- Negative – sequence

Negative sequence admittance matrix can be constructed depending on Figure 20

$Y_{bus(2)(P.U)}$

$$
=\begin{bmatrix}
-j25.05 & 0 & 0 & j17.4 & 0 & 0 & 0 & 0 & 0 \\
0 & -j23.7 & 0 & 0 & 0 & 0 & 0 & j16 & 0 \\
0 & 0 & -j24.76 & 0 & 0 & j17.1 & 0 & 0 & 0 \\
j17.4 & 0 & 0 & 1.42-j48.4 & -0.67+j14.5 & 0 & 0 & 0 & -0.75+j16.6 \\
0 & 0 & 0 & -0.67+j14.5 & 1.01-j22.1 & -0.34+j7.7 & 0 & 0 & 0 \\
0 & 0 & j17.1 & 0 & -0.34+j7.7 & 0.95-j37.7 & -0.61+j13 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -0.61+j13 & 1.48-j31.3 & -0.87+j18.3 & 0 \\
0 & j16 & 0 & 0 & 0 & 0 & -0.87+j18.3 & 1.25-j42.6 & -0.38+j8.32 \\
0 & 0 & 0 & -0.75+j16.6 & 0 & 0 & 0 & -0.38+j8.32 & 1.13-j25
\end{bmatrix}
$$

$Z_{bus(2)(P.U)}$

$$
=\begin{bmatrix}
j0.0863 & j0.0232 & j0.0232 & j0.0668 & j0.0556 & j0.0337 & j0.0341 & j0.0344 & j0.0558 \\
j0.0230 & j0.0840 & j0.0248 & j0.0332 & j0.0342 & j0.0358 & j0.0511 & j0.0619 & j0.0426 \\
j0.0232 & j0.0248 & j0.0845 & j0.0333 & j0.0441 & j0.0639 & j0.0480 & j0.0367 & j0.0344 \\
j0.0668 & j0.0334 & j0.0335 & 0.0011+j0.0962 & j0.0800 & j0.0485 & j0.0491 & j0.0495 & j0.0804 \\
j0.0555 & j0.0345 & j0.0442 & j0.0799 & 0.0024+j0.1199 & j0.0640 & j0.0564 & j0.0510 & j0.0701 \\
j0.0335 & j0.0359 & j0.0639 & j0.0639 & j0.0639 & 0.0010+j0.0925 & j0.0695 & j0.0532 & j0.0498 \\
j0.0339 & j0.0511 & j0.0480 & j0.0488 & j0.0562 & j0.0695i & 0.0018+j0.1050 & j0.0757 & j0.0576 \\
j0.0341 & j0.0619 & j0.0367 & j0.0491 & j0.0507 & j0.0531 & j0.0756 & 0.0010+j0.0917 & j0.0631 \\
j0.0559 & j0.0431 & j0.0346 & j0.0804 & j0.0702 & j0.0501 & j0.0581 & j0.0638 & 0.0021+j\,0.1145
\end{bmatrix}
$$

By calculating bus impedance matrix, sequence impedance of the system can be

found by specifying fault location. For case study two cases of fault location applied

to system:

- Case 1: Applying fault at bus 5

By applying the fault at bus 5 the sequence impedance of the system can be taken

from bus impedance matrix of zero, positive, and negative matrix

as $(Z_{55-0}, Z_{55-1}, Z_{55-2})$, where the values shown Table 8. See Appendix A for

code.

Table 8. Sequence Impedance of Fault at Bus 5

Sequence Impedance (P.U)	Z0	Z1	Z2
	$0.0125+j0.0709$	$0.0024+j0.1254$	$0.0024+j0.1199$

By referring to equations (4.3.4) – (4.3.8) and consider fault impedance $Z_F = 0$, fault

current can be calculated for different types of fault as shown in Table 9.

See appendix B for code.

Table 9. Fault Current at Bus 5

Type of Fault	L-G	L-L	LLG
Current (P.U)	9.5709	7.1613	11.0165

- Case 2: applying fault at bus 7

By applying the fault at bus 7, the sequence impedance will

be $(Z_{77-0}, Z_{77-1}, Z_{77-2})$, as shown in table 10. See Appendix A for code.

Table 10. Sequence Impedance of Bus 7

Sequence impedance (P.U)	Z0	Z1	Z2
	$0.0091 + 0.0588i$	$0.0018 + 0.1110i$	$0.0018 + 0.1050i$

In the same manner as did in case 1 the fault current at bus 7 will be calculated, where

table 11 shows the fault current that results from applying different types of fault at

bus 7. See Appendix B for code.

Table 11. Fault Current at Bus 7

Type of Fault	L-G	L-L	LLG
Current (P.U)	10.9894	8.0852	12.9145

As presented in the chapter that single line-to-ground, line-to-line, and double line-to-ground fault consider to be applied to two different buses in IEEE 9-bus system and the buses are bus 5 and bus 7. Bus impedance matrix method used to calculate the sequence impedance of the system seen from faulted bus, where it is applied to find the sequence impedance of the system when the fault happened at bus 5 and bus 7. After the sequence impedance calculated, the fault current during the three types of fault calculated depending on it .

CHAPTER 5: RENEWABLE ENERGY

Renewable energy has positive impact especially on environment, as it produces electric energy from natural and clean resources which leads to reduce CO2 emissions and by default the air pollution will reduce. Renewable energy contains many natural sources to produce energy, however sun and wind are the most two types of energy sources are widely used. The following chapter will concern on solar and wind energy.

5.1 Solar energy:

Photovoltaic system is one of systems depends on converting solar power into electric energy. The name of photovoltaic comes from the ability of material to convert the energy stored in light photons into voltage and current [30]. The equivalent circuit of photovoltaic cell shown in Figure 21.
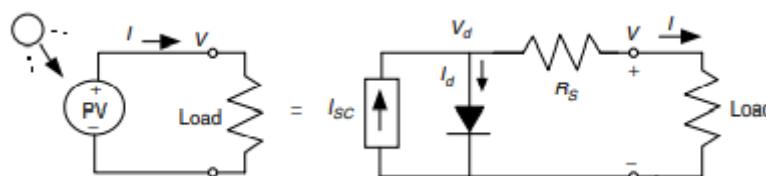
Figure 21. Equivelent circuit of PV cell [30]

The output voltage of each cell is around $0.5\,V$ which is very low voltage for application, so that modules can be used. Modules are connection of cells in series, where the typical modules contain 36 cells per module. However the typical modules become 72, 92, and 128 cell per module [30]. Where the output voltage of module can be calculated as:

$$V_{module} = n(V_d - IR_s) \tag{5.1.1}$$

In order to generate high power the modules will be connected which form array. There many ways for array connection like the series connection will increase the voltage but with equal current, the other way of connection is parallel connection which the current can increase but the voltage will be the same for all arrays. The best connection of arrays to achieve max output power by making series and parallel connection of arrays as shown in Figure 22 [30].
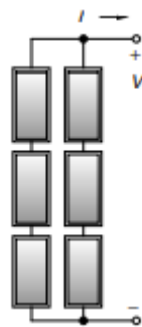
Figure 22. Series and parallel connection of arrays [30]

Photovoltaic output is DC, so that it needs to be converted to AC before connected to load. However, converter can be used in order to control the output from photovoltaic and there many types of converters, but the main type used with photovoltaic is boost converter which will be discussed in next section.

5.2 Boost Converter

Boost converter is one of power electronics DC-to-DC converter that used to step up the voltage. The circuit configuration of boost converter shown in Figure 23.
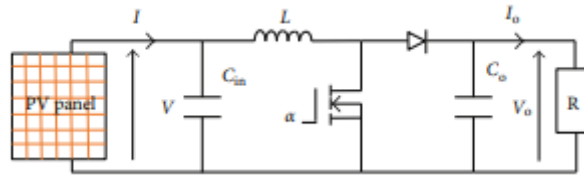
Figure 23. Boost converter [31]

The input-output voltage relationship of boost converter depends on duty cycle and the output voltage can be calculated as:

$$V_o = \frac{1}{1-D} * V_{in} \tag{5.2.1}$$

Where D is the duty cycle.

The design of boost converter depends on calculating the values of inductor, input capacitor, and the output capacitor. The following equations present the calculation of converter parameters:

- Inductor calculation:

Inductor value can be calculated as:

$$L_{min} \geq \frac{D(1-D)^2 R_L}{2F} \tag{5.2.2}$$

Where R_L, F are the load resistance and the switching frequency.

- Input capacitor:

Input capacitor is used to reduce the voltage ripple [31]. The input capacitor can be calculated as:

$$C_{in} \geq \frac{D}{8 F^2 L \Delta V} \tag{5.2.3}$$

- Output capacitor:

The output capacitor to specify the output voltage ripple. The output capacitor can be calculated:

$$C_o \geq \frac{D}{R \, F \, \Delta V} \qquad (5.2.4)$$

Depending on equations (5.2.2)-(5.2.4) the parameters of boost converter found as presented in Table 13 and the calculation of parameters made depending on the output power from solar and the output voltage, also the design of converter depends on the duty cycle and ripple voltage where the assumed values are presented in Table 12.

Table 12. Assumed Parameters For Boost Converter

$P_o(MW)$	$V_o(V)$	D	ΔV_o
2	6000	0.5	1%

Table 13. Boost Converter

L (H)	$C_o(F)$	$C_{in}(F)$	$R_L(\Omega)$
2.25×10^{-4}	5.56×10^{-4}	1.11×10^{-3}	18

Where the model of solar energy can be build depending on the parameters of boost converter found. The simulation model of solar energy shown in Figure 24. The simulation parameters shown in Table 14.

Table 14. Solar Model Prameters

Temperature (℃)	Sun irrandance (W/m^2)	$V_{oc}(V)$	$I_{sc}(A)$
25	$500 - 100$	36.3	7.35
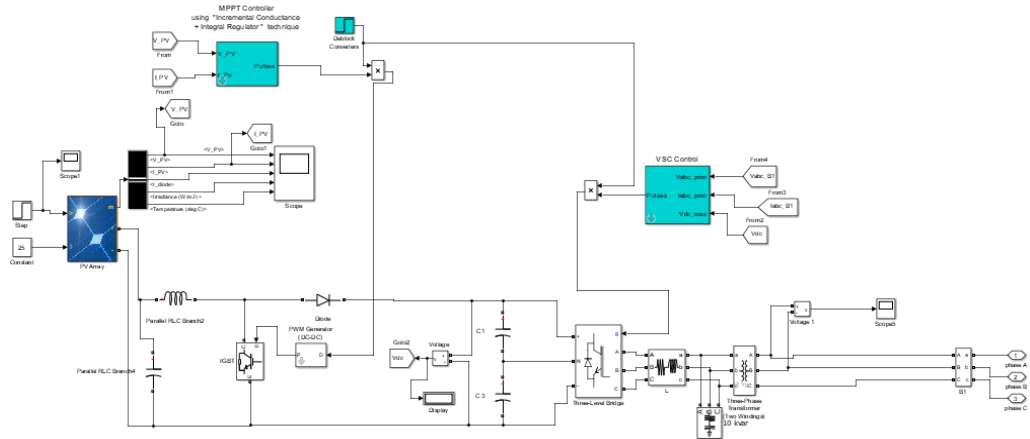
Figure 24. Solar energy model

5.3 Wind Energy

Wind energy is type of renewable energy as it produces the power from wind. The output power increased as the height and blades diameter of wind tower became bigger. Figure 25 shows how the output power increased as the height and blades diameter increased [30].

Figure 25. Output power Vs wind turbine size [30]

However the output power delivered by wind turbine depends on the speed of wind, so if the wind speed increase the output power will increase too, which present a direct relation between wind speed and output power [30].

Wind energy system can be categorized into two types depending on generation system connected to wind turbine, where the two types are:
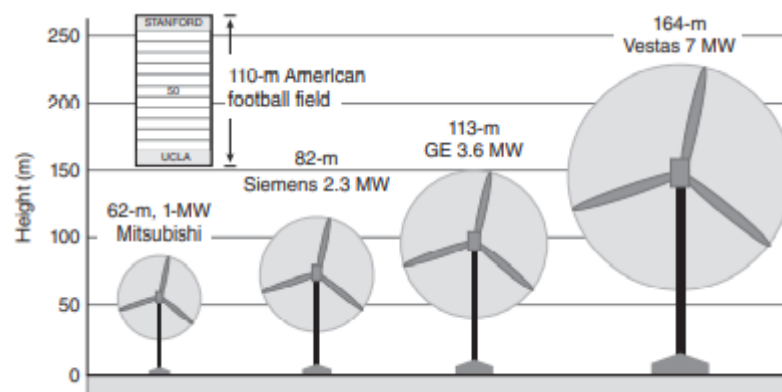
1- Fixed speed

2- Variable speed

However, variable speed wind energy type especially, doubly-feed induction generator will concern on it.

5.3.1 Doubly-Fed Induction Generator

DFIG is one of the most popular wind turbine configurations used and Figure 26 shows circuit configuration of DFIG.
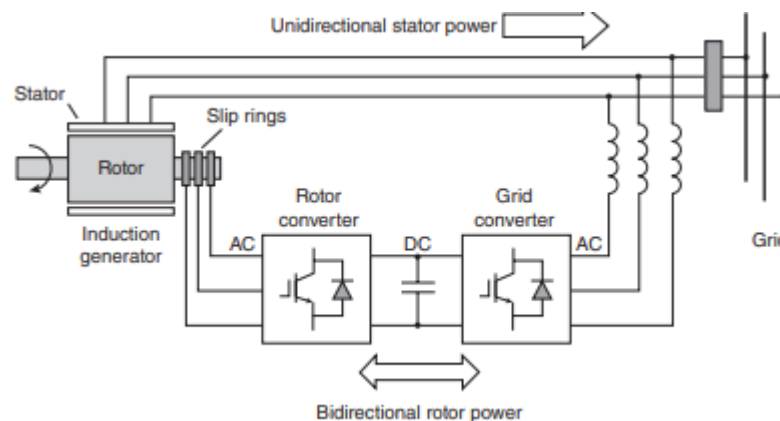
Figure 26. Configuration of DFIG [30]

As shown in Figure 26 that grid connected to stator in order to provide stator magnetic field and the power generated in stator will feed back to grid. However, the difference that the rotor allows bidirectional power flow between rotor and grid. When the rotor rotates less than the synchronous speed the machine acts as motor which slowing down the turbine speed and absorb the power from the grid. In the other hand when the machine rotates at speed higher than the synchronous speed, the

power generated in rotor give it back to grid. Where the back-back voltage converter allow the bidirectional power flow between the rotor and grid [30].Where the simulation model of doubly-fed induction generator shown in Figure 27. The simulation parameters presented in Table 15.

Table 15. Model Prameters of Wind Model

Wind speed(m/s)	Turbine power(W)	$V_{LL}(V)$	$F(HZ)$
15	1.5	575	50
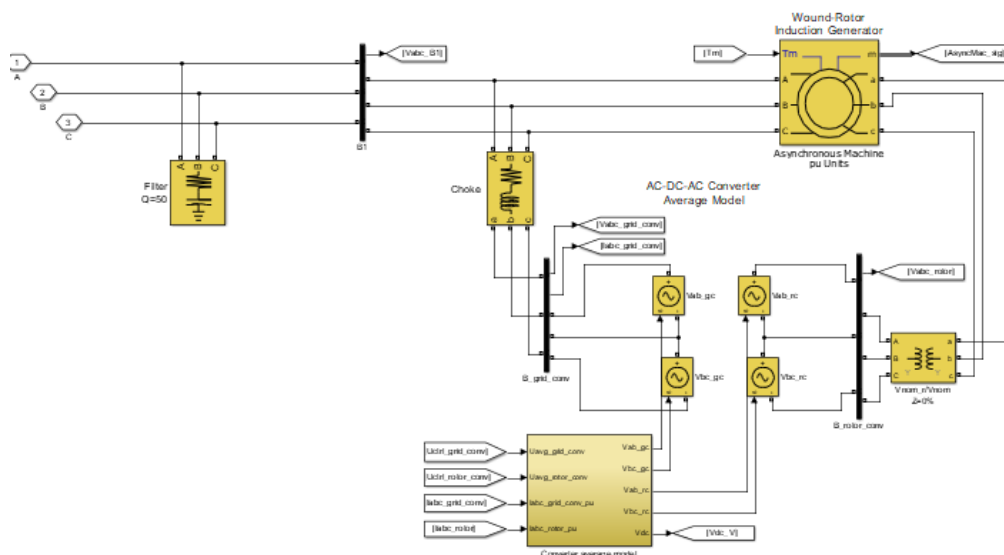
Figure 27. Wind energy model

Solar and wind energies are the two types of renewable energies discussed in the chapter. For solar energy, the design of boost converter depends on the duty cycle, input voltage, and the output voltage. However, incremental conduction mode used for maximum power tracking. In the same manner, doubly-fed induction generator type used as it is the main type widely used. However, this chapter shows the types and design of renewable energy but not discussed the impact of renewable energy on

distance relay operation, but the impact of renewable energy on distance relay will be present in chapter 7.

CHAPTER 6: DISTANCE RELAY

Protection system is important part of power system, as it protects the system from sever faults which can cause permanent damage in power system equipments. Protection system includes many devices used for protection and one of these devices is relay. Where the main function of relay is detecting the fault and control circuit breaker operation. There are many types of relays and each type protect specific equipment, while this project concerns on distance relay as it is used to protect transmission lines. The following sections will present the operation of distance relay, model of relay and zones of protection.

6.1 Operation of Distance Relay

Distance relay operation is unlike the other types of relays which only measure the voltage or current. Distance relay measure the voltage and current of bus and taking the ratio of voltage to current in order to calculate the positive sequence impedance of transmission line.

$$Z = \frac{V_{bus}}{I_{bus}}$$
(6.1.1)

The relay compares the measured impedance of line with the setting impedance Z_r , where the action of relay will depends on two conditions as follows:

$Z < |Z_r|$ (Relay considered fault and trip)
(6.1.2)

$Z > |Z_r|$ (normal condition and relay will not trip)
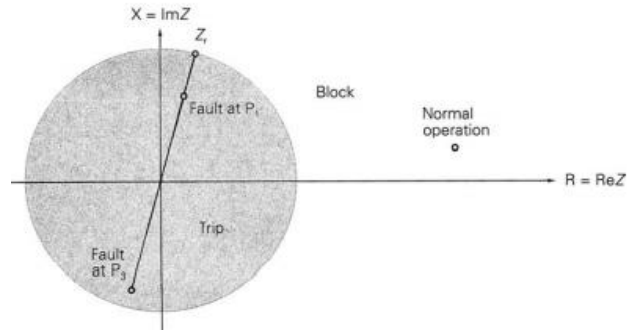(6.1.3)

Figure 28 shows relay trip condition.

Figure 28. Impedance relay operation [27]

6.2 Relay model

Distance relay model implemented by using Matlab/ Simulink, where relay model depends on symmetrical components equations that developed in chapter 4. In addition to symmetrical components equations, the following equations used for detecting transmission lines impedance which presented in [32].

$$Z_{A-G} = Z_1 \times \frac{V_0+V_1+V_2}{Z_1 I_1 + Z_1 I_2 + Z_0 I_0} = Z_1 \times \frac{V_{A-G}}{Z_1 I_1 + Z_1 I_2 + Z_0 I_0} \tag{7.3.1}$$

$$Z_{A-B} = \frac{V_1 - aV_2}{I_1 - aI_2} = \frac{V_1 - aV_2}{I_{A-B}} \tag{7.3.2}$$

As presented in [32] that relay model starts by taking three phase bus voltage and current, then will pass through discrete fourier in order to extract the magnitude and phase for voltage and current which will used to find the sequence components which later will used to calculate line impedance as shown in Figure 29.
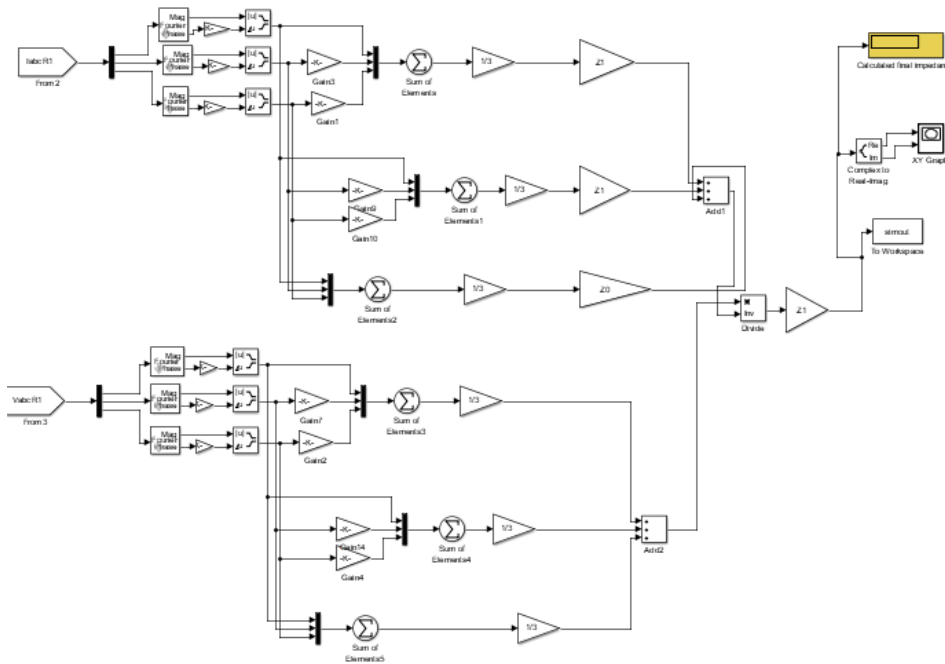
Figure 29. Distance relay model for L-G fault

6.3 Zones of Protection

Zones of protection applied for huge and complicated power system. The main principle of zones is, dividing the system into many zones (parts) in order to perform highest protection level for whole system. In case of fault, the only zone contains the fault will be isolated by circuit breaker. However, the zones will be overlapped to make sure that all areas protected [27]. In the same manner zones applied to distance relay, where the relay has three zones of protection and the zones specified depending on line impedance. The main benefits of zones that it specifies the trip condition of the relay and provides backup protection for other relays. Where zone 1 is set to reach 80% of transmission line length, zone 2 is set to reach 120% of line length which mean the relay can cover protection for 100% of line length and 20% of second line. Where zone 3 is to cover 100% of first line and 120% of second line [27].

Figure 30 and Figure 31 show the zones of protection applied to IEEE 9-bus system where Table 16 and Table 17 present the impedance values for zones at bus 5 and bus 7.
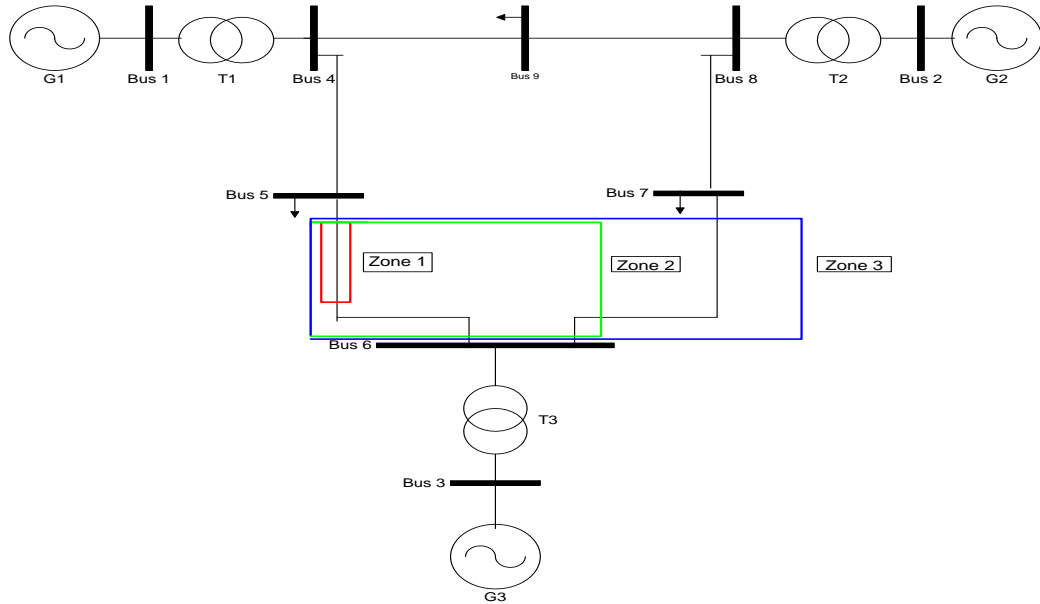

Figure 30. Zones of protection at bus 5

Table 16. Zones Protection at Bus 5

Zone	1	2	3
Impedance (Ω)	5.568+122.56i	8.352+183.84i	12.2+263.5i
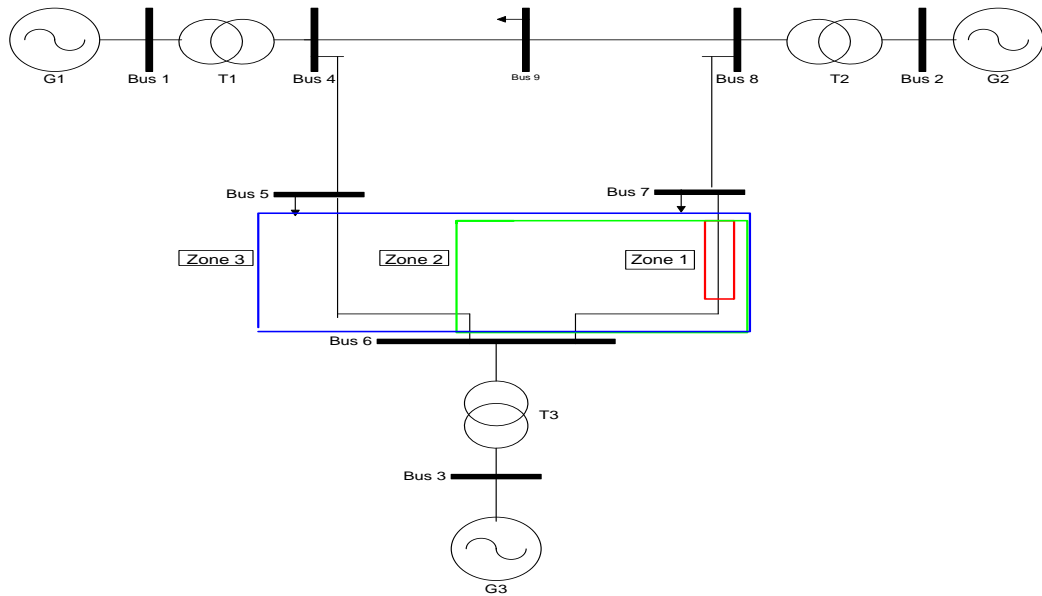
Figure 31. Zones of protection at bus 7

Table 17. Zones Of Protection at Bus 7

Zone	1	2	3
Impedance (Ω)	3.464+73.5i	5.196+110.3i	12.68+275.76i

As discussed in the chapter that distance relay is the main type of relays used for transmission line protection. The operation of distance relay depends on measuring the ratio of voltage and current and compared to set value to take the action. Distance relay can cover three zones of protection in order to provided backup protection where zone cover 80% of line length and zone 2 cover 100% of line plus 20% of other line. However, zone 3 cover 100% of line and 120% of other line. The impact of renewable energy on distance relay can be detected by the zones which will be discussed in chapter 7.

CHAPTER 7: RESULTS AND DISSCUASION

The following chapter will present the simulation of IEEE 9-bus system in normal condition and fault condition, while the simulation of system will consider the impact of renewable energy on distance relay. By the end of this chapter the impact of renewable energy solar and wind on distance relay can be detected depending on the output power that specified for solar and wind if it can cause mal-operation of relay or the relay operation will not be affected and relay settings will not change.

7.1 IEEE 9-bus System

Figure 4 in chapter 3 shows the configuration of IEEE 9-bus system. Where the system consists of three generators, three transformers, six transmission lines, and three loads distributed on bus9, bus5, and bus7. The parameters of transmission lines and generators, also the way of calculation was shown in chapter 3.Where the three loads data shown Table 18.

Table 18. Load Data

Load at bus	Bus 9	Bus 7	Bus 5
P+jO (Mw)+j(Mvar)	125+j50	100+j35	90+j30

By using the values of transformer reactances, load, and transmission line impedance, which calculated previously in chapter three depending on the type of transmission line and line length, the simulation of system can done by using Matlab/Smulink program. Figure 32 shows the simulation of IEEE 9-bus system.
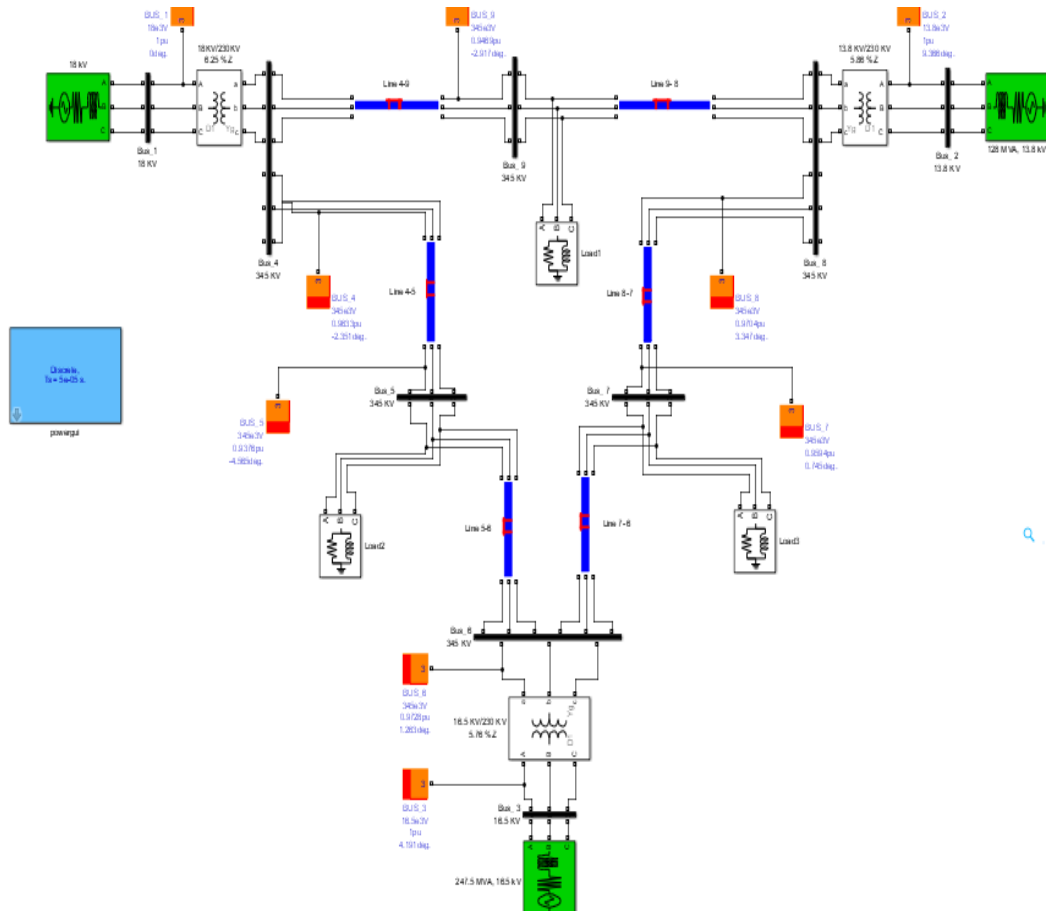
Figure 32. IEEE 9-bus simulation

The simulation shows the normal condition of the system. The study will concern on applying renewable energy on two buses which are bus 5 and bus 7. However, two cases in normal condition of system will be discussed which are:

- Case 1: normal condition without renewable energy

In this case the results of bus voltage and current will be presented in addition to impedance seen by the bus, where the impedance calculated by dividing bus voltage over bus current. Figure 33 and Figure 34 show the results at bus 5 and bus 7.
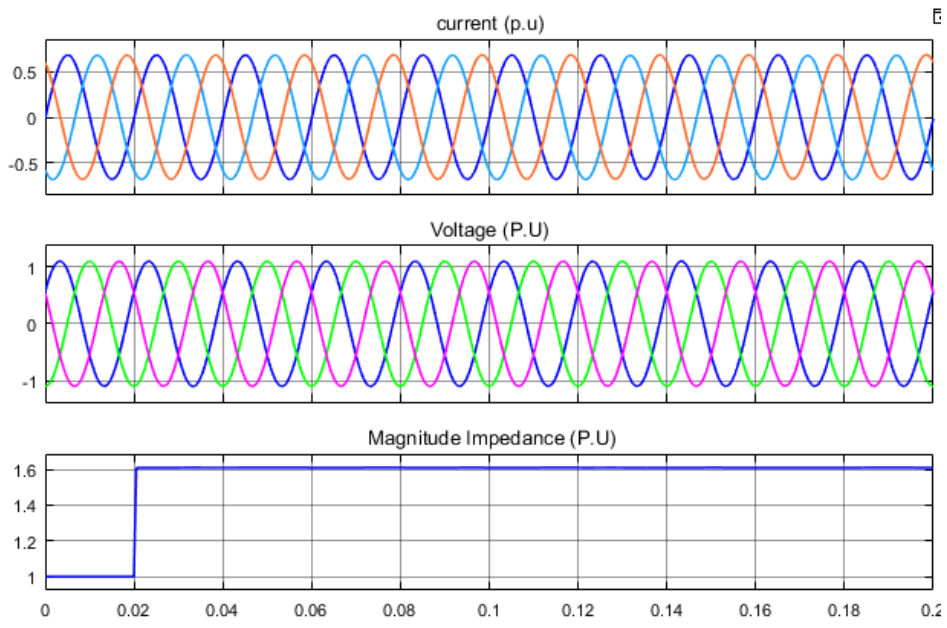
Figure 33. Voltage ,current and impedance seen from bus 5
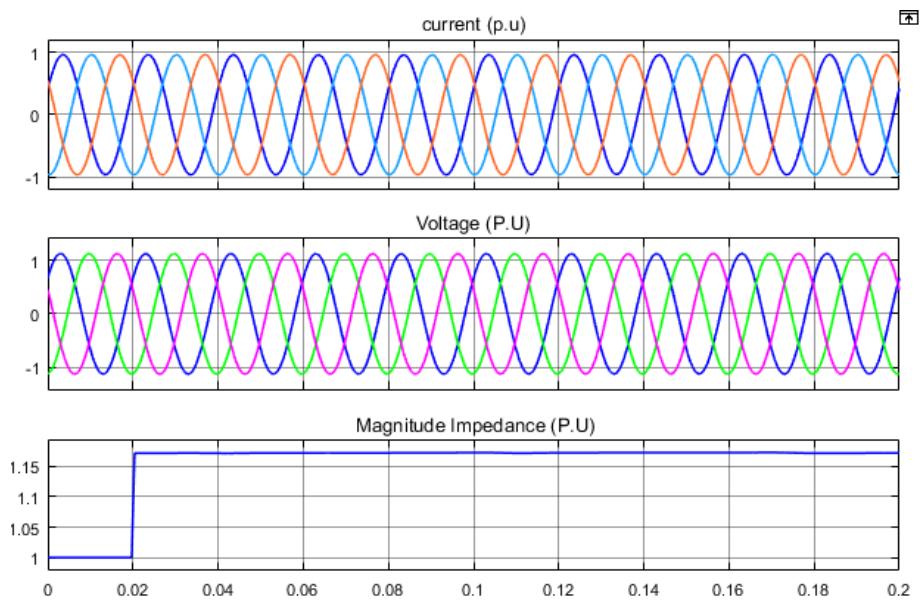
Figure 34. Voltage ,current and impedance seen from bus 7

- Case 2: normal condition with renewable energy:

    1- 2MW solar energy source added to bus 5

As shown in Figure 35 that the bus voltage, current , and impedance is slightly change which mean the solar energy has low impact on bus 5.
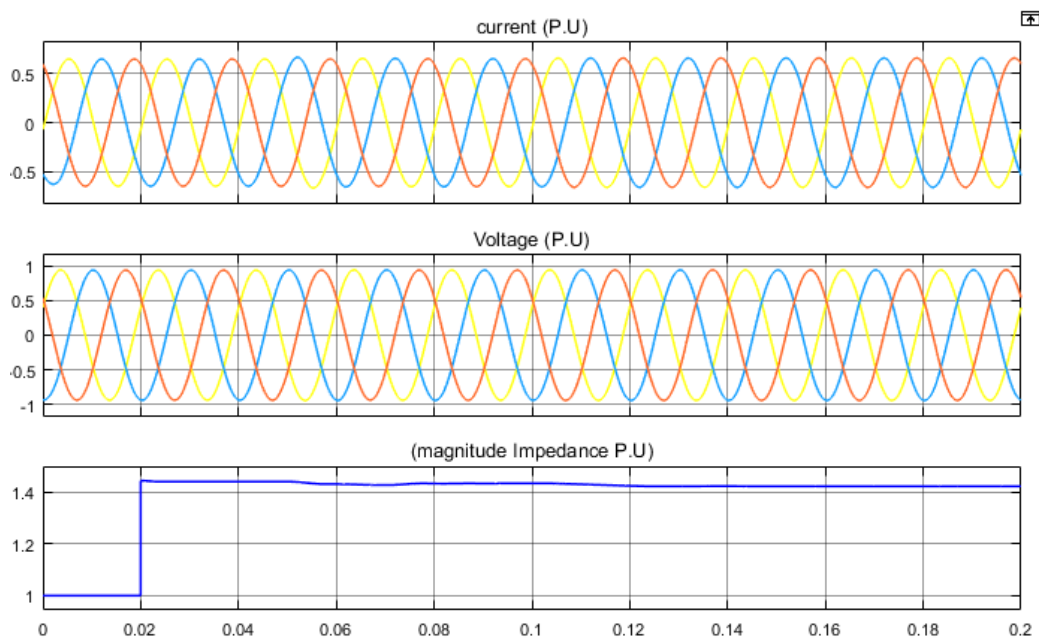
Figure 35**.** Adding solar energy on bus 5

    2- Adding 9MW DFIG wind energy on bus 7.

By adding 9MW wind energy on bus 7 causes small variation on bus voltage and current, also it only causes 0.05 P.U change in line impedance which mean that the variation in impedance is not that much. The results of adding wind energy illustrated in Figure 36.
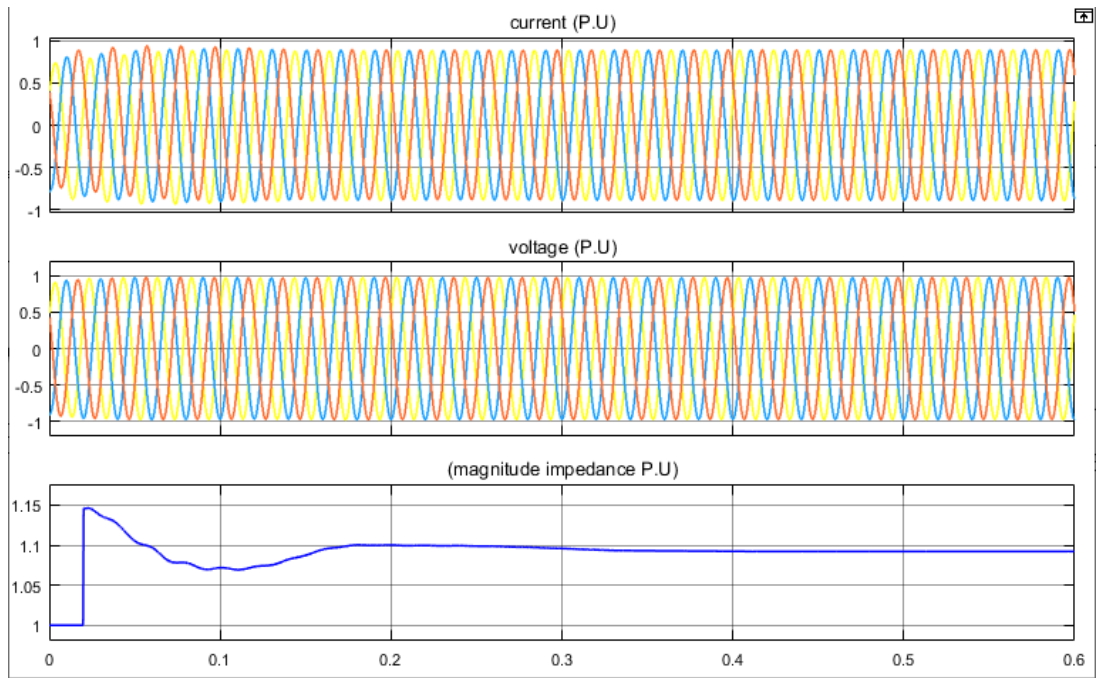
Figure 36. 9MW Wind energy effect on bus 7

3- 15MW wind energy added in bus 7

In same manner by increasing the capacity of wind energy to 15MW the impedance changed much compared to 9MW wind energy, as illustrated in

Figure 37.
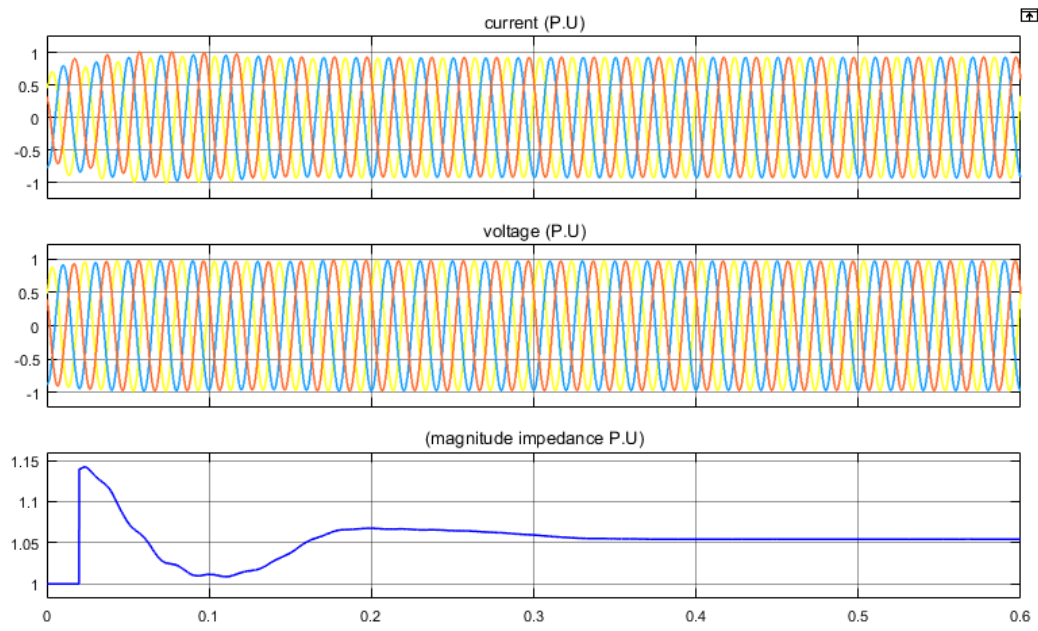
Figure 37. 15MW Wind energy impact on bus 7

As shown in Figure 35 to Figure 37 that 2MW solar energy causes small deviation in impedance at bus 5 compared to 9MW and 15MW wind energy that causes much deviation in measured impedance at bus 7. The impact of solar and wind energy until now studied when the system in normal condition without any fault. However in next section a fault condition of the system will be discussed.

7.2 IEEE 9-bus system with fault

Previous section shows the normal condition of the system. However, this section will presents the fault condition in two buses which are bus 5 and bus 7. By applying the fault to simulation model, fault currents were similar to manual calculation which presented in chapter 4. In order to test the results, the fault applied to model by using two different programs which are Matlab/Simulink and power world simulator, where the results of three types of fault current at bus 5 from Matlab/Simulink shown in Figure 38 to Figure 40 .

Figure 38. Fault current of Matlab/Simulink at bus 5 for L-G Fault

Figure 39. Fault current of Matlab/Simulink at bus 5 for L-L fault

Figure 40. Fault current of Matlab/Simulink at bus 5 for LLG fault

In the same manner the faults applied to model in power world simulator program, where the model shown in Figure 41.
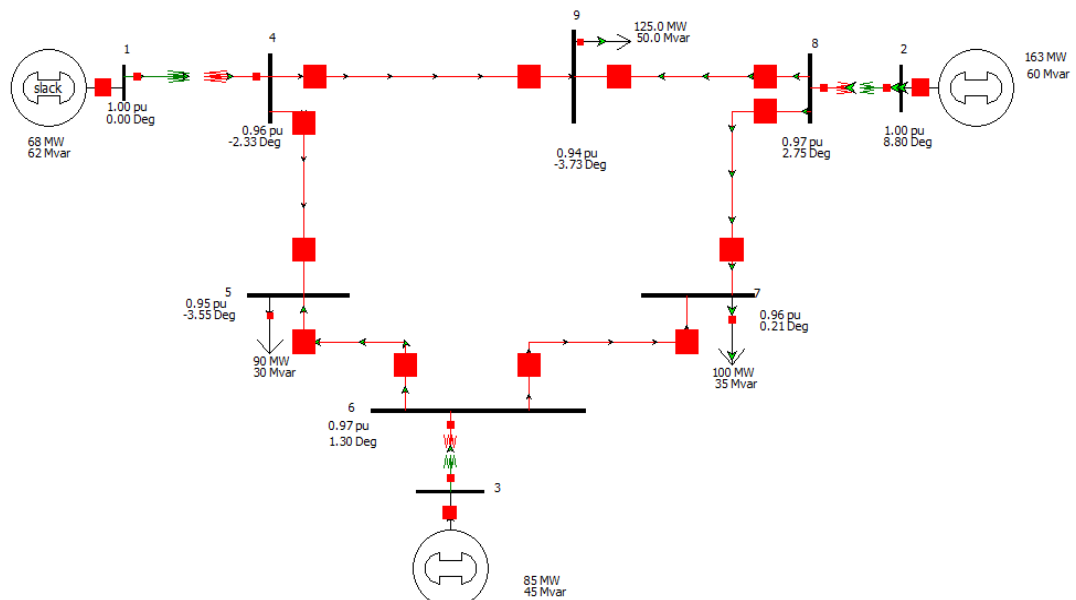
Figure 41. Power world simulator model

Different types of fault applied at bus 5 and the values of fault currents shown in Table19.

Table 19. Fault Current at Bus 5 From Power World Simulator

Type of Fault	L-G	L-L	LLG
Current (P.U)	9.783	7.505	10.972

By applying L-G, L-L, LLG fault at bus 5, the results from Matlab/Simulink, power world simulator, and manual calculation show that the values of fault currents are close to each other, however the difference of fault current values among three methods is less than 0.5 P.U.

- Case 2: applying faults at bus 7

By applying three types of fault at bus 7 in Matlab/Simulink model, the results of fault currents shown in Figure 42.
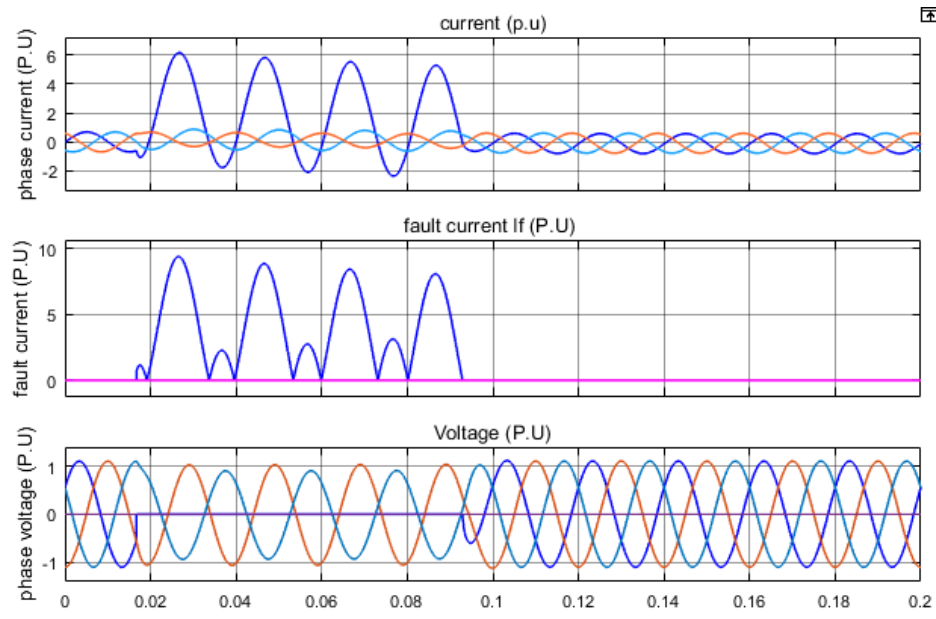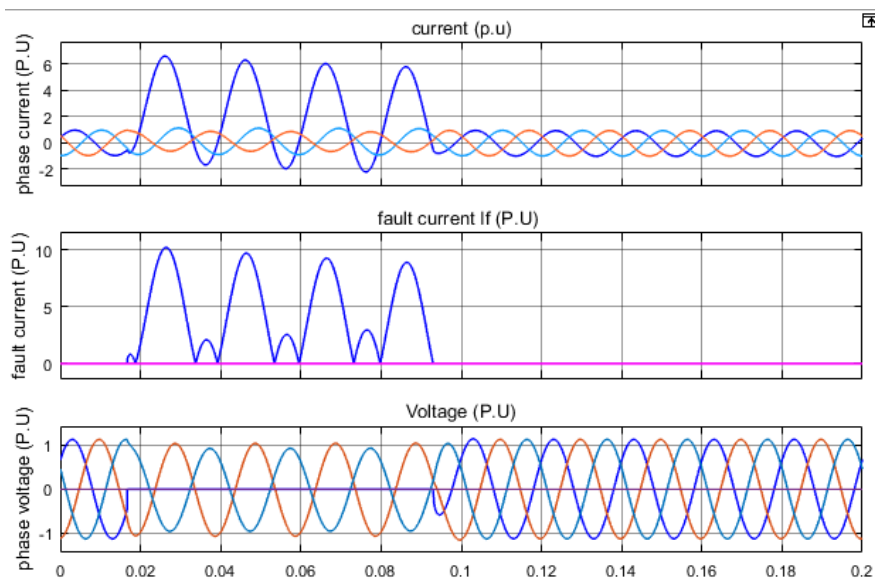

Figure 42. Fault current of Matlab/Simulink at bus 7 for L-G fault

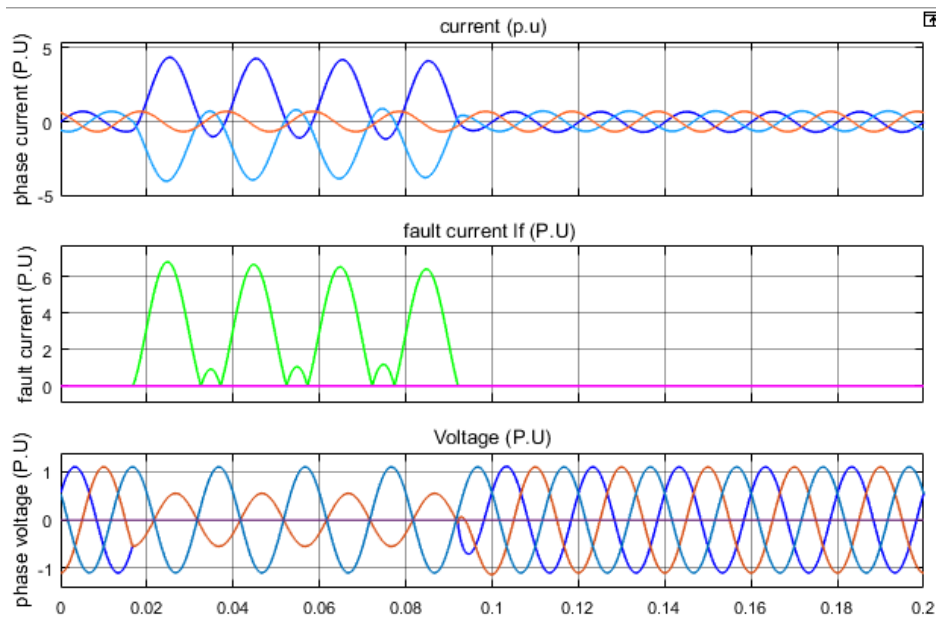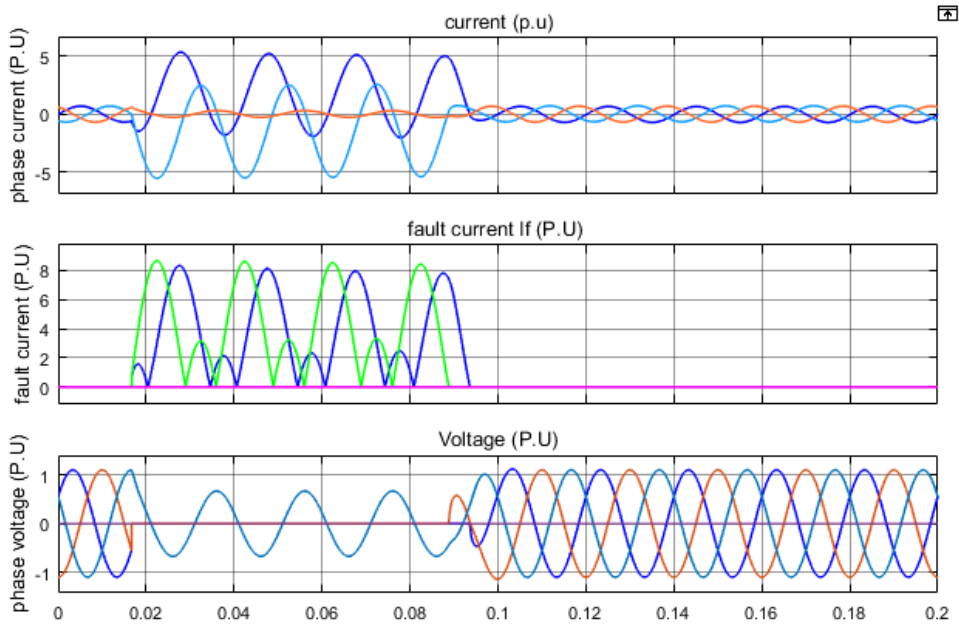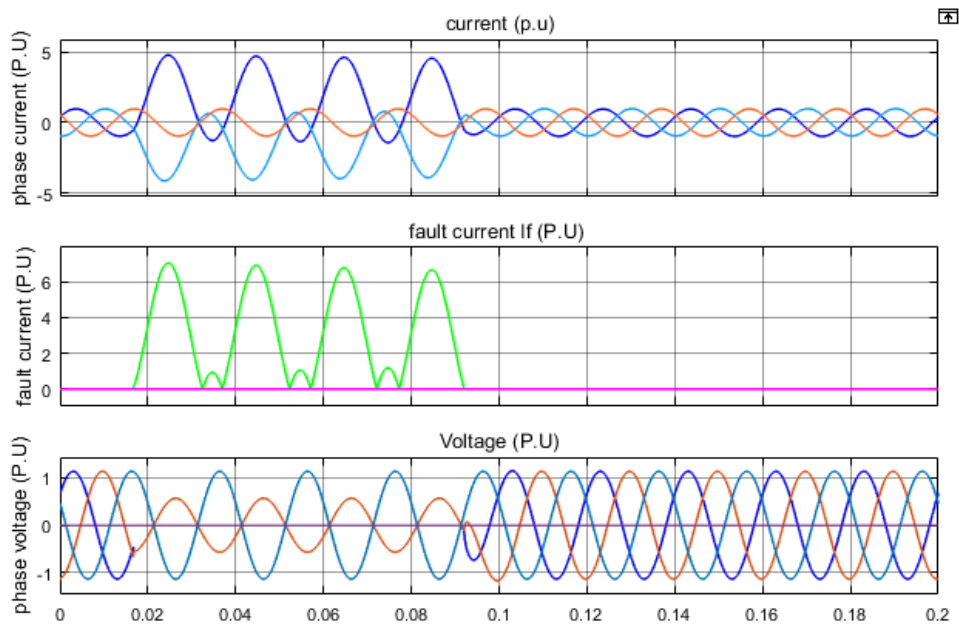Figure 43. Fault current of Matlab/Simulink at bus 7 for L-L fault
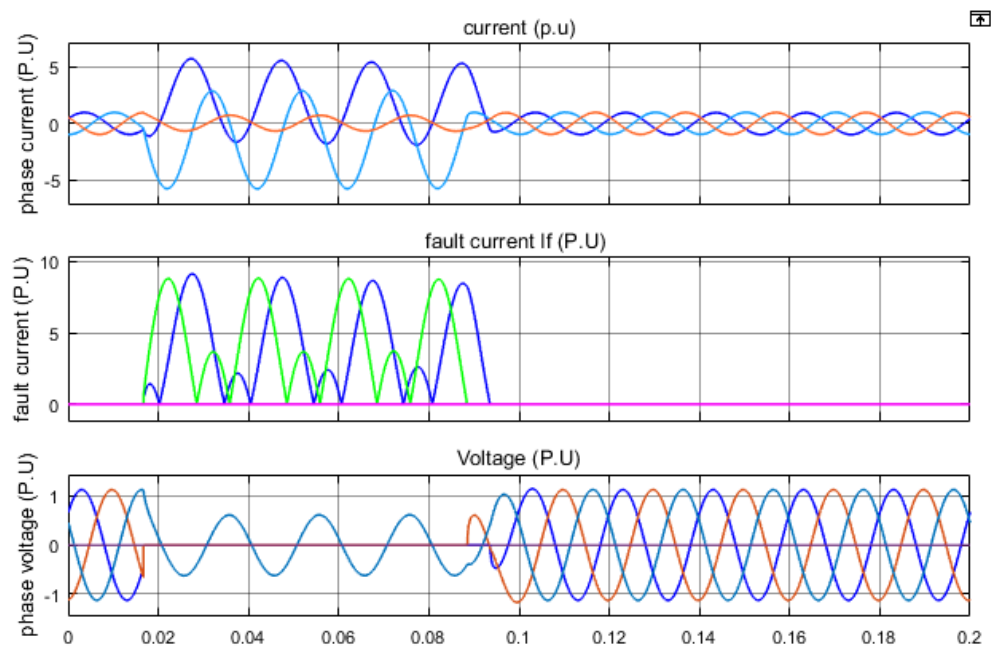
Figure 44. Fault current of Matlab/Simulink at bus 7 for LLG

Where the results of fault currents by using power world simulator shown in

Table 20.

Table 20. Fault Current at Bus 7 Using Power World Simulator

Type of Fault	L-G	L-L	LLG
Current (P.U)	11.266	8.467	12.936

By applying L-G, L-L, and LLG fault to bus 7, the results from Matlab/Simulink, power world simulator, and manual calculation shows that the fault current are close to each other with small difference less than 0.5 P.U.

The previous results show the fault currents without distance relay, however the following results will present the impedance of line measured by the relay during the fault. In order to detect the impact of renewable energy on distance relay two cases will be applied.

- Case 1 applied fault at bus 5 and bus 7 without renewable energy.

By applying L-G fault to bus 5 the result from relay will be as in Figure 45 and Figure 46. Where phase A is consider where the fault happen.
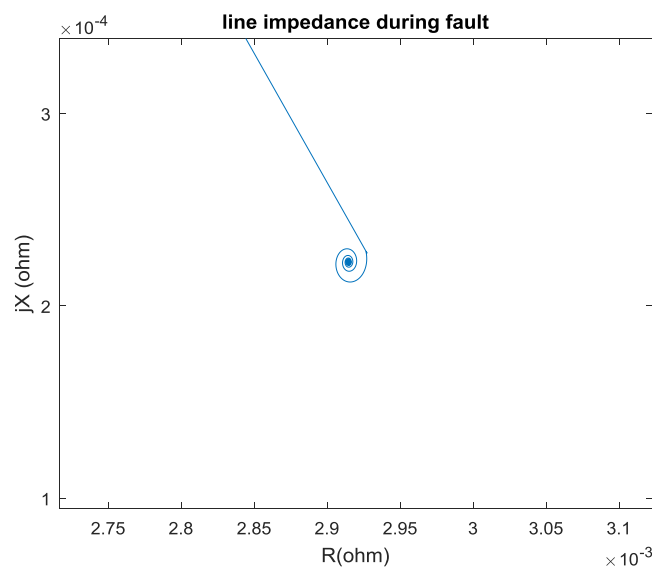
Figure 45. L-G fault impedance at the bus 5
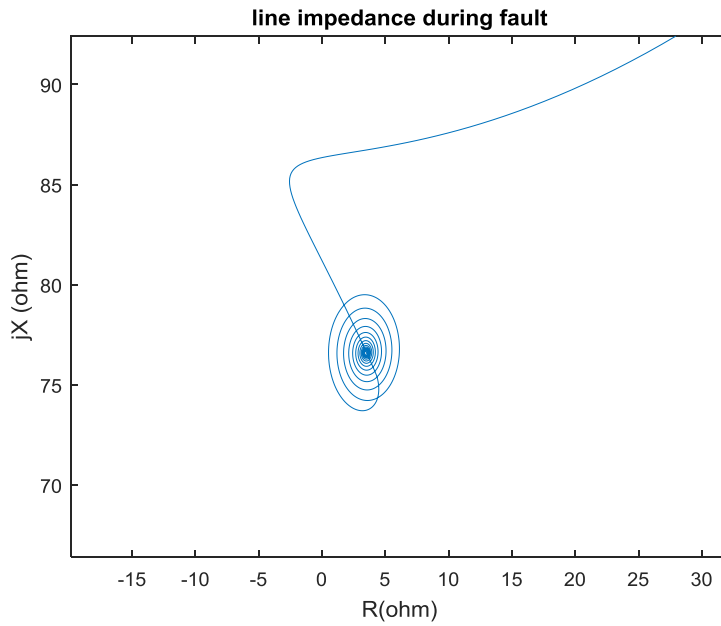
Figure 46. L-G fault impedance at the middle of line

As shown in Figure 45 when the fault applied at the bus 5 the impedance reduced to very small value which almost zero as the bus voltage reduces. However, by applying the fault at the middle of line the impedance measured is higher than the impedance when the fault at bus as shown in Figure 46.

In the same manner by applying L-L fault at bus 5, where phases A and phase B considered where the fault happen. The results of applying the fault in different location shown in Figure 47 and Figure 48.
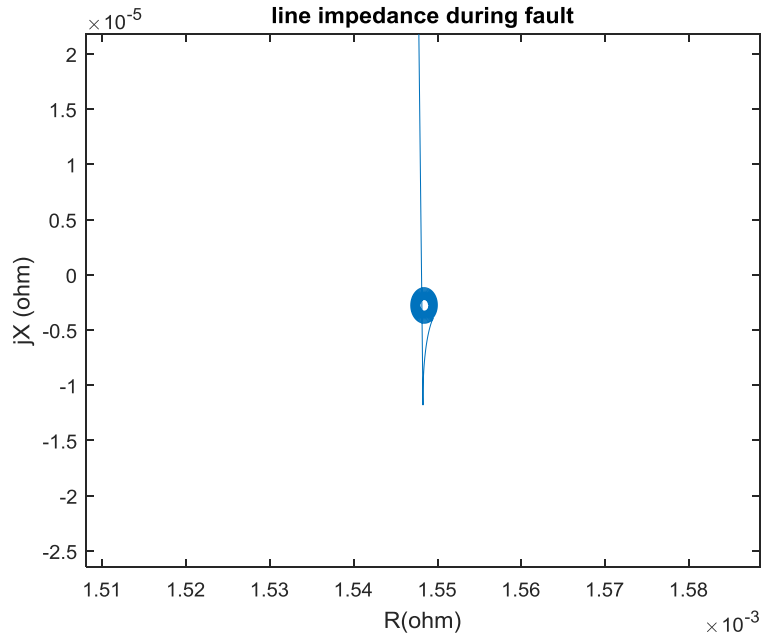
Figure 47. L-L fault at bus 5
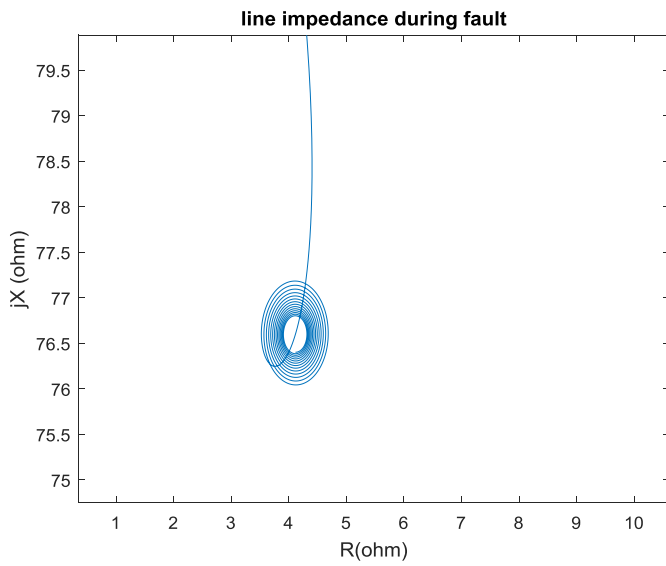
Figure 48. L-L fault in middel of line between bus 5 and bus 6

By comparing the values of impedance in Figure 47 and Figure 48 it obvious that when the fault happen in the middle of line the measured impedance by the relay will be higher.

In same manner by applying the fault at bus 7 the result of L-G fault will be presented in Figure 49 and Figure 50 with different locations

.
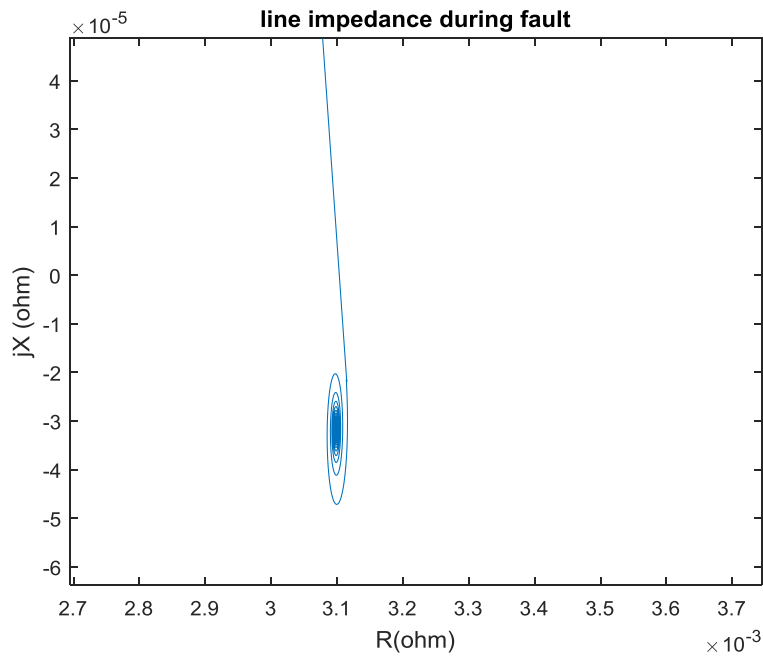
Figure 49. L-G fault at bus 7
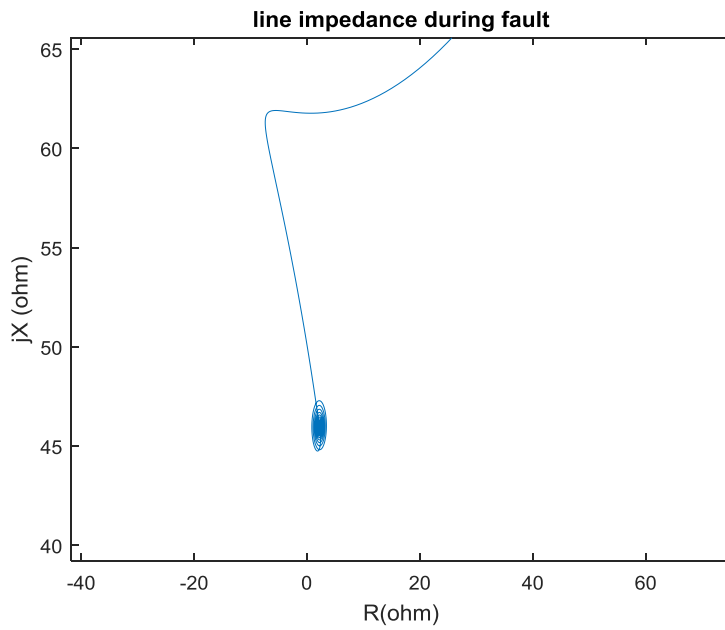
Figure 50. L-G fault in the middle of Line between bus 6 and bus 7

In same manner by applying L-L fault at bus 7, the results of fault locations presented in Figure 51 and Figure 52.
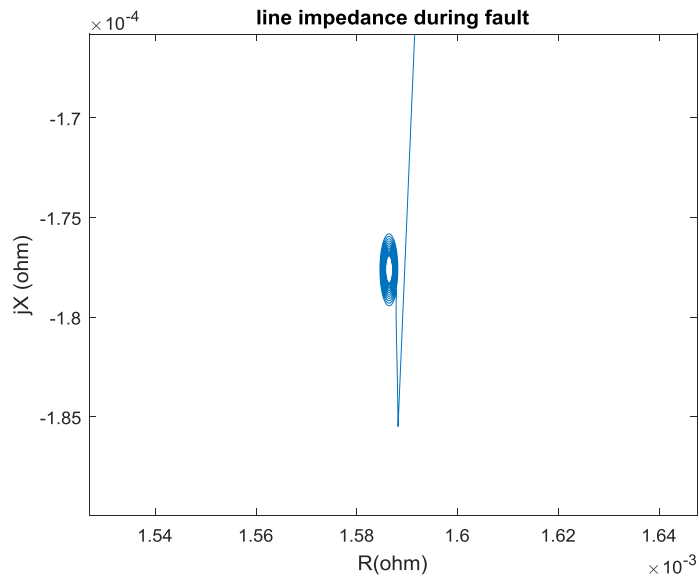
Figure 51. L-L Fault at bus 7
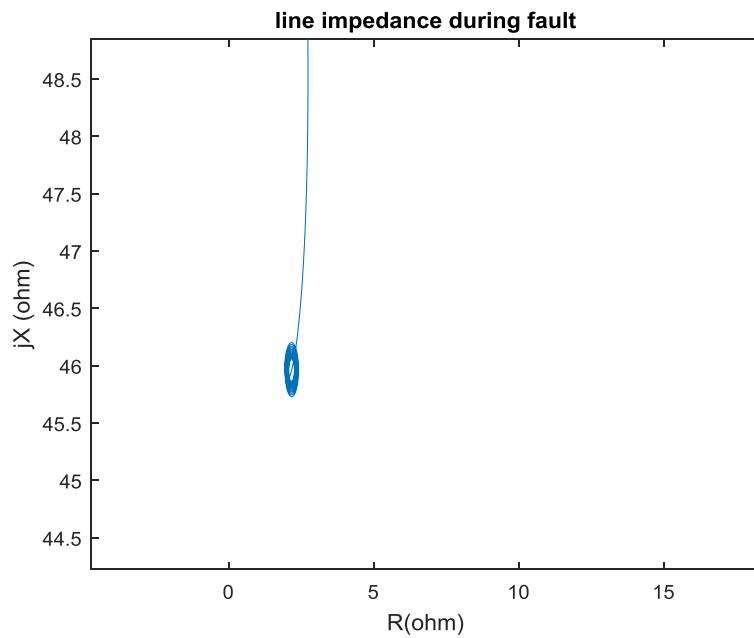
Figure 52. L-L Fault in the middle of line between bus 6 and bus 7

- Case 2: impact of renewable energy on relay operation

In case 1 faults applied without adding renewable in order to detect impedance value seen by the relay during fault, while case 2 will presents faults at bus 5 and bus 7 with renewable energy

.

1- Adding 2MW solar energy on bus 5 which the results of single line-to-ground illustrated in Figure 53 and Figure 54.
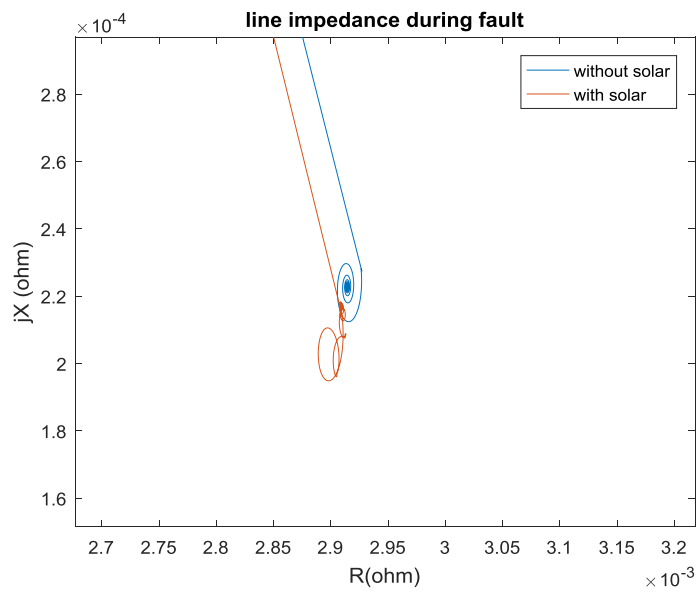
Figure 53. L-G Fault with solar at bus 5
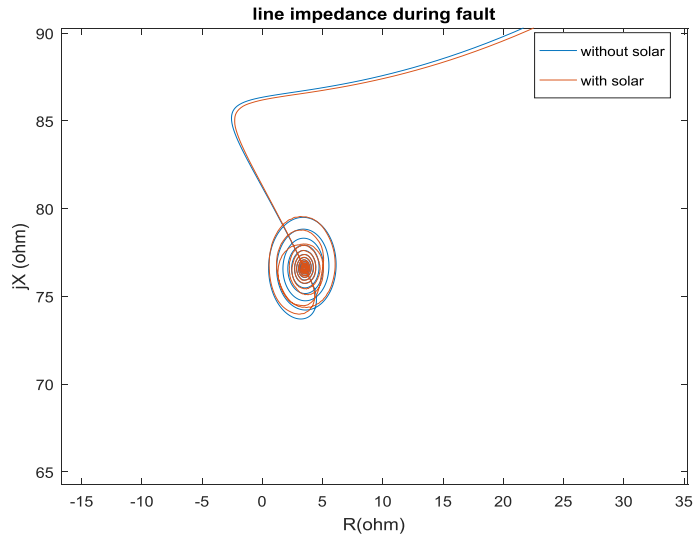
Figure 54. L-G Fault with solar at the middle of line

As shown in Figure 53 and Figure 54 that applying L-G fault at bus 5 and in the middle of line between bus 5 and bus 6; solar will causes very small deviation on measured impedance.

However by applying line-to-line fault the results with solar energy shown in Figure 55 and Figure 56.
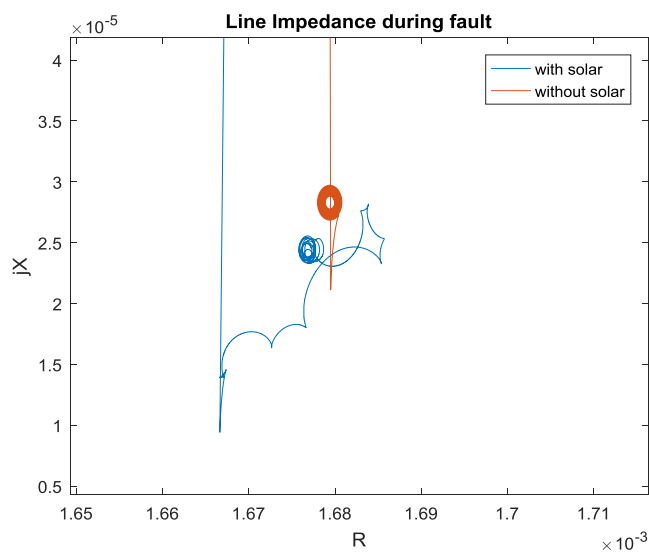
Figure 55. L-L Fault with solar at bus 5
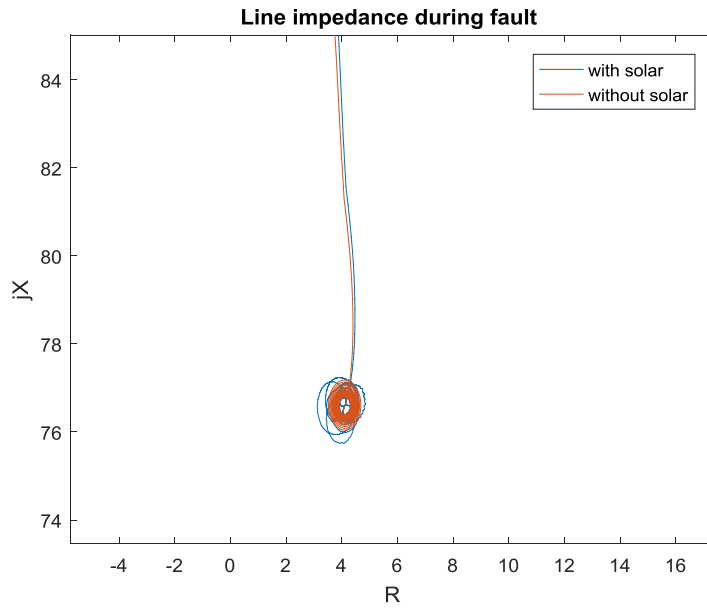
Figure 56. L-L Fault with solar at the middle of line

Figure 54 and Figure 56 shows that applying L-L fault in two location with presence of solar energy causes changing in impedance.

2- Wind energy:

For wind energy two case will be examined which are 9MW and 15MW.

- Case1: 9MW wind energy

Figure 57 and Figure 58 shows the result of L-G Fault with the presence of 9MW wind energy at bus 7.
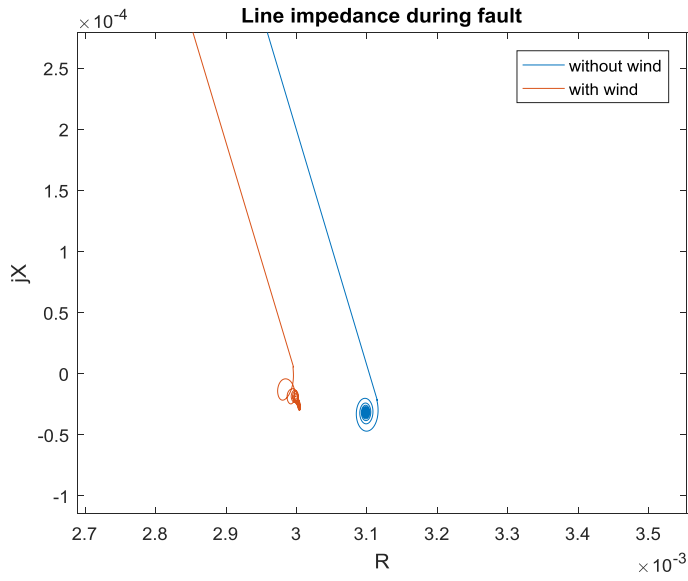
Figure 57. L-G fault with 9MW Wind at bus 7
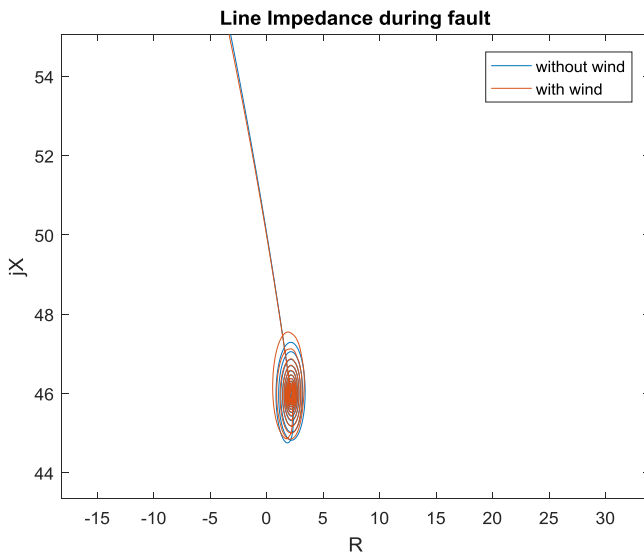
Figure 58. L-G fault with 9MW Wind at the middle of line

Where Figure 59 and Figure 60 present the L-L fault with 9MW wind energy at bus 7.
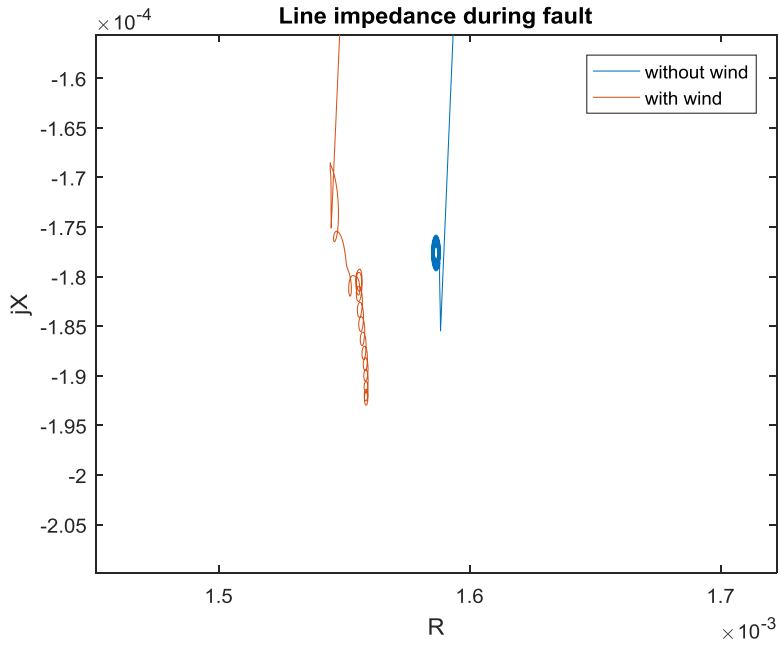
Figure 59. L-L fault with 9MW Wind at bus 7
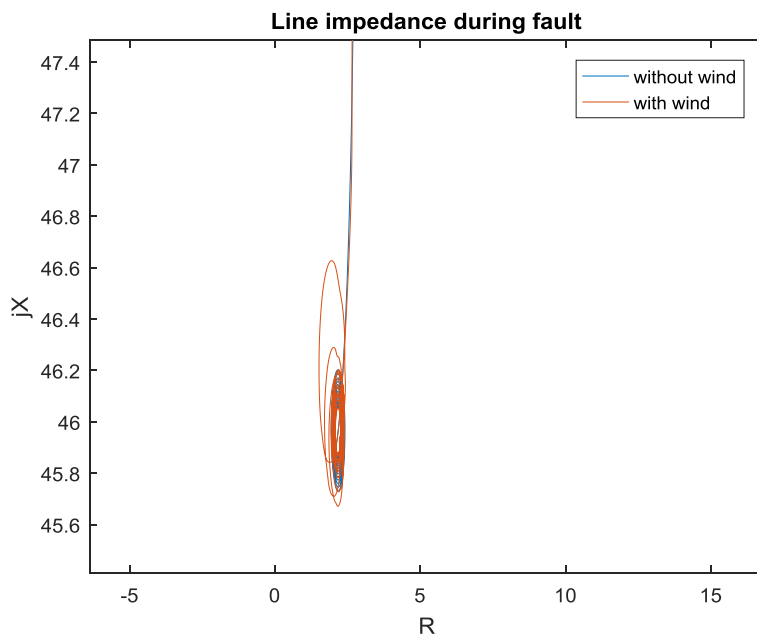
Figure 60. L-L fault with 9MW Wind at the middle of line

Figure 58 to Figure 60 showed L-G and L-L fault in two locations with 9MW wind energy, where wind energy causes deviation in measured impedance especially when the fault happened at the bus where the impact of wind energy reduced when the fault at the middle of line.

- Case 2: adding 15MW wind energy.

By adding 15MW wind energy on bus 7 the result of L-G Fault illustrated in Figure 61 and Figure 62.
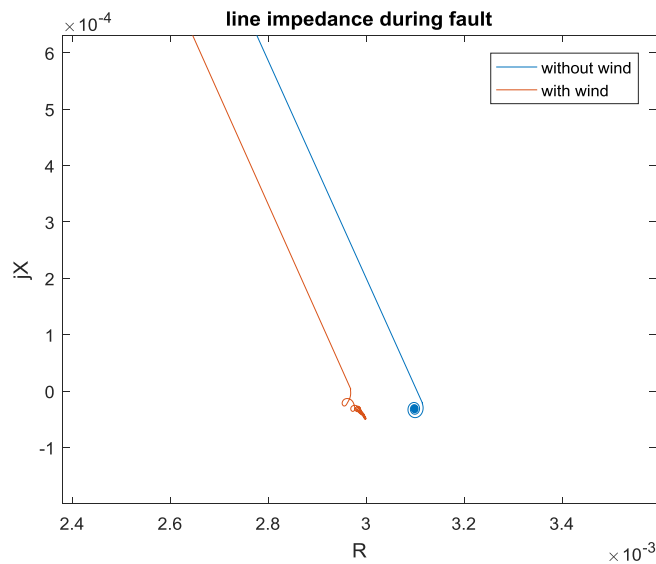
Figure 61. L-G fault with 15MW Wind at bus 7
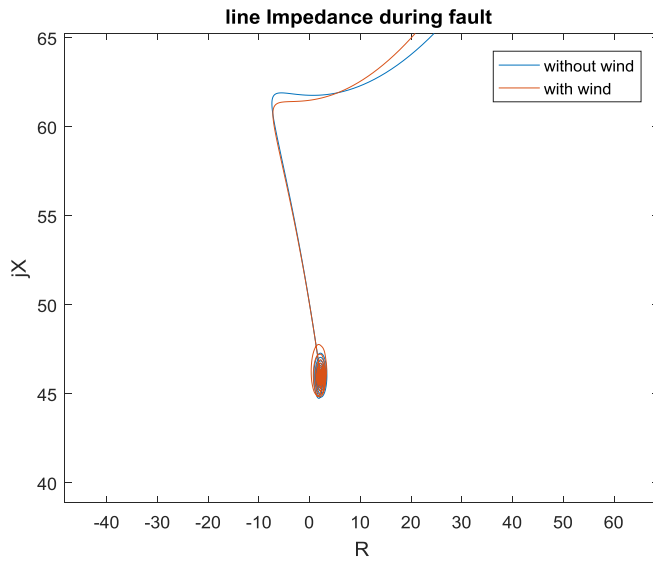
Figure 62. L-G fault with 15MW Wind at the middle of line

Where Figure 63 and Figure 64 present the L-L fault at bus 7 with 15MW wind energy.
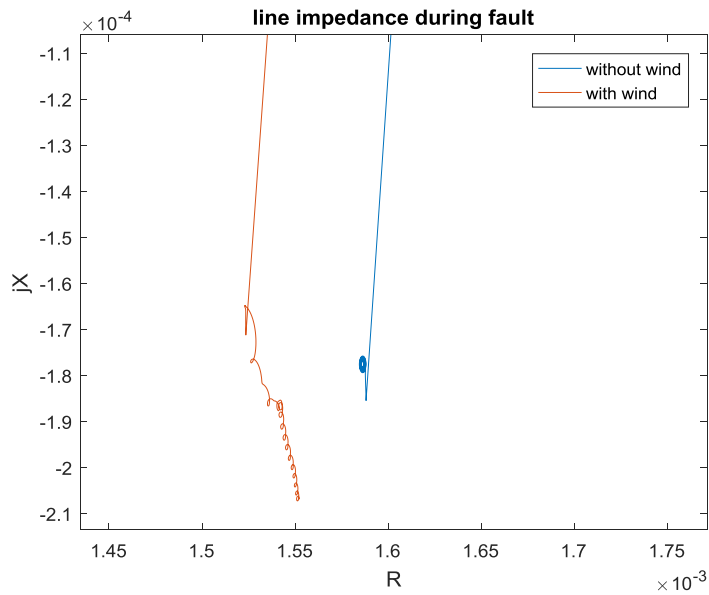
Figure 63. L-L fault with 15MW Wind at bus 7
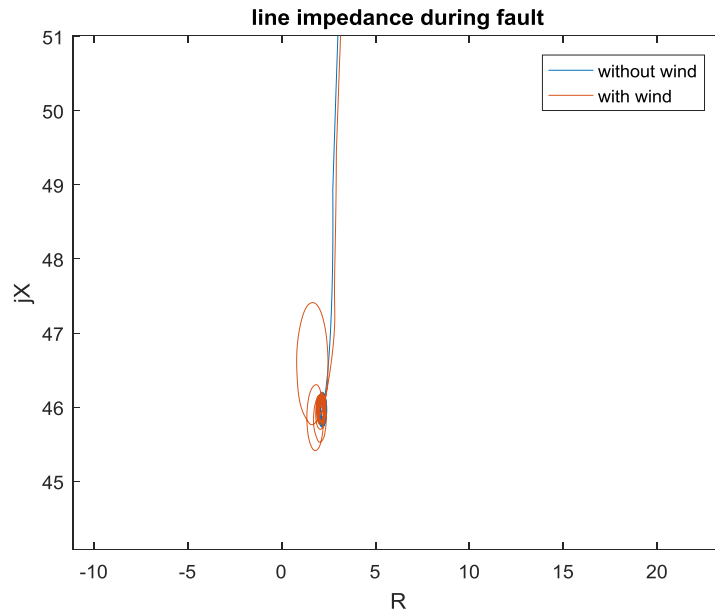
Figure 64. L-L fault with 15MW Wind at the middle of line

By comparing the results obtained from applying faults at bus 5 and bus 7 before and after adding renewable energy the results showed:

Firstly, by adding 2MW solar energy at bus 5 causes a small deviation in impedance measured by distance relay but the deviation in impedance is not that much and the relay not affected by adding solar energy as the impedance measured by relay when fault at bus 5 and in middle of line is within the range of impedance of zone 1.

Secondly, by adding 9MW wind energy at bus 7 the impedance measured by relay when fault at bus 7 and in middle of line is within range of zone 1 impedance. In the same manner, that increasing the size of wind energy to 15MW increases the deviation of impedance seen by relay during fault at bus 7 and in middle of line.

Depending on results obtained it is obvious that adding 2MW solar energy, 9MW and 15MW wind energy will not cause mal-operation of distance relay and the current relay settings can handle adding renewable energy with sizes mentioned without causing wrong detection of fault location.

CHAPTER 8: CONCLUSION AND FUTURE WORK

8.1 Conclusion

IEEE 9-bus system used in thesis in order to study the impact of renewable energy especially solar and wind on the protection system of transmission lines. Where two conditions were applied on system which are normal condition and fault condition to detect the impact of renewable energies on distance relay of transmission lines.

Firstly, the impedance of transmission lines calculated depending on system voltage as the spacing between transmission lines depending on voltage. The impedance of transmission lines used to detect the voltages and currents of buses before faults happened. The results show that bus 5 and bus 7 have the highest voltage drop compared to other buses. For that reason, renewable energies added to bus 5 and bus 7.

Secondly, the sequence impedance of transmission lines, transformer, and generator found in order to perform fault analysis. Bus impedance matrix method used in order to calculate zero, positive, and negative sequence impedance of system seen from fault point, where single line-to-ground, line-to-line, double line-to-ground fault applied to system. Matlab/Simulink, power world simulator, and manual calculation by using code applied to calculate fault current, where the results from three ways were similar with very small difference.

The model of distance relay was build depending on symmetrical components equation in order to measure the value of voltage and current of bus during the fault. The impact of renewable energy on distance relay detected through two steps. the first step was applying different type of fault and detect the value of line impedance seen by the relay, the second step was applying faults with renewable energy in order to

detect the impedance of line seen by relay during the fault. The results showed that adding 2MW solar energy on bus 5 slightly affects the impedance of transmission line seen by distance relay especially when the fault applied to the bus. In same manner adding 9MW wind energy causes small deviation on impedance measured by the relay and by increasing the size of wind energy to 15MW the changing of line impedance increased. However, by adding three protection zones of distance relay on bus 5 and bus 7 the results showed that when the fault happen exactly at the bus and in middle of line with renewable energies, the relay still can see the fault in zone 1, which mean the deviation in line impedance happened does not have huge impact on the operation of distance relay.

The main idea concludes from the study that adding 2MW solar energy, 9MW and 15MW wind energy on bus 5 and bus 7 causes changing in line impedance, however the changing of line impedance does not affect the relay settings and the relay operation not affected.

Finally, the values of renewable energies used in this thesis do not have high impact on distance relay settings. However, by increasing the penetration level of renewable energy to higher values the impact of solar and wind energies on distance relay will be obvious.

8.2 Future work

For the future work, many point can be done for studying the impact of renewable energy on distance relay however, the main points that will be done in future as follows:

1- Study the impact of renewable energy on distance relay by using real-time-digital simulator (RTDS) as it can gives real and practical results.

2- Changing the location of renewable energy to be in the middle of transmission line and integrate it to different buses in order to detect the impact of it on distance relay.

3- Apply the study of renewable energy impact on distance by using real systems like KAHRMAA system.

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APPENDIX A: MATLAB CODE FOR BUS IMPEDANCE MATRIX

```
%% zero sequence impedance
ybus0=[-20i 0 0 0 0 0 0 0 0;
    0 -20i 0 0 0 0 0 0 0;
    0 0 -20i 0 0 0 0 0 0;
    0 0 0 7.47-46.4i -3.45+13.4i 0 0 0 -4.02+15.34i;
    0 0 0 -3.45+13.4i 5.33-20.6i -1.88+7.2i 0 0 0;
    0 0 0 0 -1.88+7.2i 4.8-36.03i -2.94+11.8i 0 0;
    0 0 0 0 0 -2.94+11.8i 7.3-28.8i -4.35+17.1i 0;
    0 0 0 0 0 0 -4.35+17.1i 6.28-40.9i -1.93+7.8i;
    0 0 0 -4.02+15.34i 0 0 0 -1.93+7.8i 5.95-23.12i]
zbus0=inv(ybus0)
%% positive sequence impedance
ybus1=[-24.02i 0 0 17.4i 0 0 0 0 0;
    0 -22.7i 0 0 0 0 0 16i 0;
    0 0 -23.7i 0 0 17.i 0 0 0;
    17.4i 0 0 1.42-48.5i -0.67+14.5i 0 0 0 -0.75+16.6i;
    0 0 0 -0.67+14.5i 1.01-22.14i -0.34+7.68i 0 0 0;
    0 0 17.1i 0 -0.34+7.68i 0.95-37.7i -0.61+13i 0 0;
    0 0 0 0 0 -0.61+13i 1.48-31.3i -0.87+18.3i 0;
    0 16i 0 0 0 0 -0.87+18.3i 1.25-42.6i -0.38+8.32i;
    0 0 0 -0.75+16.6i 0 0 0 -0.38+8.32i 1.13-24.9i]
zbus1=inv(ybus1)
 %% negative sequence
 ybus2=[-25.05i 0 0 17.4i 0 0 0 0 0;
    0 -23.7i 0 0 0 0 0 16i 0;
    0 0 -24.76i 0 0 17.1i 0 0 0;
    17.4i 0 0 1.42-48.4i -0.67+14.5i 0 0 0 -0.75+16.6i;
    0 0 0 -0.67+14.5i 1.01-22.1i -0.34+7.7i 0 0 0;
    0 0 17.1i 0 -0.34+7.7i 0.95-37.7i -0.61+13i 0 0;
    0 0 0 0 0 -0.61+13i 1.48-31.3i -0.87+18.3i 0;
    0 16i 0 0 0 0 -0.87+18.3i 1.25-42.6i -0.38+8.32i;
    0 0 0 -0.75+16.6i 0 0 0 -0.38+8.42i 1.13-25i]
zbus2=inv(ybus2)
```

APPENDIX B: MATLAB CODE FOR FAULT CURRENT CALCULATION

```
zdata1 = [ 0     1     0.00     0.15
           0     2     0.00     0.15
           0     3     0.00     0.15
           1     4     0.00     0.0576
           2     8     0.00     0.06252
           8     9     0.0055   0.12
           4     9     0.0027   0.06
           4     5     0.0032   0.069
           3     6     0.00     0.0586
           5     6     0.0058   0.13
           6     7     0.0036   0.077
           7     8     0.0026   0.0545];


zdata0 = [ 0     1     0.00     0.05
           0     2     0.00     0.05
           0     3     0.00     0.05
           1     4     inf      inf
           2     8     inf      inf
           3     6     inf      inf
           0     8     0.00     0.0625
           0     4     0.00     0.0576
           0     6     0.00     0.0586
           4     9     0.016    0.061
           4     5     0.018    0.07
           5     6     0.034    0.13
           6     7     0.02     0.08
           7     8     0.014    0.055
           8     9     0.03     0.121];


zdata2=  [ 0     1     0.00     0.13
           0     2     0.00     0.13
           0     3     0.00     0.13
           1     4     0.00     0.0576
           2     8     0.00     0.06252
           8     9     0.0055   0.12
           4     9     0.0027   0.06
           4     5     0.0032   0.069
           3     6     0.00     0.0586
           5     6     0.0058   0.13
           6     7     0.0036   0.077
           7     8     0.0026   0.0545];
Zbus0 = zbuild(zdata0)
Zbus1 = zbuild(zdata1)
Zbus2 = zbuild(zdata2)
lgfault(zdata0, Zbus0, zdata1, Zbus1, zdata2, Zbus2)
llfault(zdata1, Zbus1,zdata2, Zbus2)
dlgfault(zdata0, Zbus0, zdata1, Zbus1, zdata2, Zbus2)
```

```matlab
% This program forms the complex bus impedance matrix by the method
% of building algorithm.  Bus zero is taken as reference.
%  Copyright (c) 1998-2013  by H. Saadat

function [Zbus] = zbuild(linedata)
nl = linedata(:,1); nr = linedata(:,2); R = linedata(:,3);
X = linedata(:,4);
nbr=length(linedata(:,1)); nbus = max(max(nl), max(nr));
for k=1:nbr
    if R(k) == inf || X(k) ==inf
    R(k) = 99999999; X(k) = 99999999;
    else, end
end

ZB = R + j*X;
Zbus = zeros(nbus, nbus);
tree=0;  %%%%new
% Adding a branch from a new bus to reference bus 0
  for I = 1:nbr
  ntree(I) = 1;
      if nl(I) == 0 || nr(I) == 0
          if nl(I) == 0
              n = nr(I);
          elseif nr(I) == 0
              n = nl(I);
          end
              if abs(Zbus(n, n)) == 0
                  Zbus(n,n) = ZB(I);tree=tree+1; %%new
              else Zbus(n,n) = Zbus(n,n)*ZB(I)/(Zbus(n,n) + ZB(I));
              end
              ntree(I) = 2;
      else,end
  end

% Adding a branch from new bus to an existing bus
while tree < nbus  %%% new

  for n = 1:nbus
     nadd = 1;
     if abs(Zbus(n,n)) == 0
        for I = 1:nbr
            if nadd == 1;
                if nl(I) == n || nr(I) == n
                    if nl(I) == n
                        k = nr(I);
                    elseif nr(I) == n
                        k = nl(I);
                    end
                      if abs(Zbus(k,k))  ~= 0
                            for m = 1:nbus
                                if m ~= n
                                Zbus(m,n) = Zbus(m,k);
                                Zbus(n,m) = Zbus(m,k);
                                else, end
                            end
                            Zbus(n,n) = Zbus(k,k) + ZB(I); tree=tree+1;
%%new
                            nadd = 2;  ntree(I) = 2;
                      else, end
                else, end
```

```matlab
            else, end
         end
      else, end
end


end   %%%%%new

% Adding a link between two old buses
  for n = 1:nbus
      for I = 1:nbr
          if ntree(I) == 1
             if nl(I) == n || nr(I) == n
                if nl(I) == n
                   k = nr(I);
                elseif nr(I) == n
                   k = nl(I);
                end
             DM = Zbus(n,n) + Zbus(k,k) + ZB(I) - 2*Zbus(n,k);
                for jj = 1:nbus
                AP = Zbus(jj,n) - Zbus(jj,k);
                   for kk = 1:nbus
                   AT = Zbus(n,kk) - Zbus(k, kk);
                   DELZ(jj,kk) = AP*AT/DM;
                   end
                end
                Zbus = Zbus - DELZ;
                ntree(I) = 2;
             else,end
          else,end
      end
  end

% The program llfault is designed for the line-to-line
% fault analysis of a power system network. The program requires
% the positive- and negative-sequence bus impedance matrices,
% Zbus1, and Zbus2.The bus impedances matrices may be defined
% by the user, obtained by the inversion of Ybus or it may be
% determined either from the function Zbus = zbuild(zdata)
% or the function Zbus = zbuildpi(linedata, gendata, yload).
% The program prompts the user to enter the faulted bus number
% and the fault impedance Zf. The prefault bus voltages are
% defined by the reserved Vector V. The array V may be defined or
% it is returned from the power flow programs lfgauss, lfnewton,
% decouple or perturb. If V does not exist the prefault bus voltages
% are automatically set to 1.0 per unit. The program obtains the
% total fault current, bus voltages and line currents during the
fault.
%
% Copyright (C) 1998-2013 Hadi Saadat

function llfault(zdata1, Zbus1, zdata2, Zbus2, V)
if exist('zdata2') ~= 1
zdata2=zdata1;
else, end
if exist('Zbus2') ~= 1
Zbus2=Zbus1;
else, end

nl = zdata1(:,1); nr = zdata1(:,2);
```

```matlab
R1 = zdata1(:,3); X1 = zdata1(:,4);
R2 = zdata2(:,3); X2 = zdata2(:,4);
ZB1 = R1 + j*X1;  ZB2 = R2 + j*X2;
nbr=length(zdata1(:,1)); nbus = max(max(nl), max(nr));
if exist('V') == 1
    if length(V) == nbus
    V0 = V;
    else, end
else,  V0 = ones(nbus, 1) + j*zeros(nbus, 1);
end
fprintf('\nLine-to-line fault analysis \n')
ff = 999;
while ff > 0
nf = input('Enter Faulted Bus No. -> ');
rtn=isempty(nf);
    if rtn==1; nf=-1; end
        while nf <= 0 || nf > nbus
    fprintf('Faulted bus No. must be between 1 & %g \n', nbus)
    nf = input('Enter Faulted Bus No. -> ');
    rtn=isempty(nf);
    if rtn==1; nf=-1; end
    end
rtz=1;
    while rtz==1
  fprintf('\nEnter Fault Impedance Zf = R + j*X in ')
    Zf = input('complex form (for bolted fault enter 0). Zf = ');
  rtz=isempty(Zf);
  end
fprintf('  \n')
fprintf('Line-to-line fault at bus No. %g\n', nf)
a =cos(2*pi/3)+j*sin(2*pi/3);
sctm = [1   1   1; 1 a^2  a; 1 a  a^2];
Ia0=0;
Ia1 = V0(nf)/(Zbus1(nf,nf)+Zbus2(nf, nf)+Zf); Ia2=-Ia1;
I012=[Ia0; Ia1; Ia2];
Ifabc = sctm*I012;
Ifabcm = abs(Ifabc);
fprintf('Total fault current = %9.4f per unit\n\n', Ifabcm(2))
fprintf('Bus Voltages during the fault in per unit \n\n')
fprintf('     Bus    -------Voltage Magnitude-------  \n')
fprintf('     No.    Phase a     Phase b     Phase c  \n')

for n = 1:nbus
Vf0(n)= 0;
Vf1(n)= V0(n) - Zbus1(n, nf)*Ia1;
Vf2(n)= 0 - Zbus2(n, nf)*Ia2;
Vabc = sctm*[Vf0(n); Vf1(n); Vf2(n)];
Va(n)=Vabc(1); Vb(n)=Vabc(2); Vc(n)=Vabc(3);
fprintf(' %5g',n)
fprintf(' %11.4f', abs(Va(n))),fprintf(' %11.4f', abs(Vb(n)))
fprintf(' %11.4f\n', abs(Vc(n)))
end
fprintf('  \n')
fprintf('Line currents for fault at bus No.  %g\n\n', nf)
fprintf('     From      To      -----Line Current Magnitude----  \n')
fprintf('     Bus       Bus     Phase a     Phase b     Phase c  \n')

for n= 1:nbus
   for I = 1:nbr
      if nl(I) == n || nr(I) == n
         if nl(I) ==n
```

```matlab
                    k = nr(I);
            elseif nr(I) == n
                k = nl(I);
            end
                if k ~= 0
                Ink0(n, k) = 0;
                Ink1(n, k) = (Vf1(n) - Vf1(k))/ZB1(I);
                Ink2(n, k) =  (Vf2(n) - Vf2(k))/ZB2(I);

                Inkabc = sctm*[Ink0(n, k); Ink1(n, k); Ink2(n, k)];
                Inkabcm = abs(Inkabc); th=angle(Inkabc);
                    if real(Inkabc(2)) < 0

                fprintf('%7g', n), fprintf('%10g', k),
                 fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f',
abs(Inkabc(2)))
                fprintf(' %11.4f\n', abs(Inkabc(3)))
                elseif real(Inkabc(2)) ==0 && imag(Inkabc(2)) > 0
                fprintf('%7g', n), fprintf('%10g', k),
                fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f',
abs(Inkabc(2)))
                fprintf(' %11.4f\n', abs(Inkabc(3)))
                else, end
            else, end
        else, end
    end
    if n==nf
    fprintf('%7g',n), fprintf('          F'),
    fprintf(' %11.4f', Ifabcm(1)),fprintf(' %11.4f', Ifabcm(2))
    fprintf(' %11.4f\n', Ifabcm(3))
    else, end
end
resp=0;
   while strcmp(resp, 'n')~=1 && strcmp(resp, 'N')~=1 && strcmp(resp,
'y')~=1 && strcmp(resp, 'Y')~=1
   resp = input('Another fault location? Enter ''y'' or ''n'' within
single quote -> ');
   if strcmp(resp, 'n')~=1 && strcmp(resp, 'N')~=1 && strcmp(resp,
'y')~=1 && strcmp(resp, 'Y')~=1
   fprintf('\n Incorrect reply, try again \n\n'), end
   end
   if resp == 'y' || resp == 'Y'
   nf = 999;
   else ff = 0; end
end   % end for while

% The program lgfault is designed for the single line-to-ground
% fault analysis of a power system network. The program requires
% the positive-, negative- and zero-sequence bus impedance matrices,
% Zbus1 Zbus2,and Zbus0.The bus impedances matrices may be defined
% by the user, obtained by the inversion of Ybus or it may be
% determined either from the function Zbus = zbuild(zdata)
% or the function Zbus = zbuildpi(linedata, gendata, yload).
% The program prompts the user to enter the faulted bus number
% and the fault impedance Zf. The prefault bus voltages are
% defined by the reserved Vector V. The array V may be defined or
% it is returned from the power flow programs lfgauss, lfnewton,
% decouple or perturb. If V does not exist the prefault bus voltages
% are automatically set to 1.0 per unit. The program obtains the
% total fault current, bus voltages and line currents during the
fault.
```

```matlab
%
% Copyright (C) 1998-2013 H. Saadat

function lgfault(zdata0, Zbus0, zdata1, Zbus1, zdata2, Zbus2, V)
if exist('zdata2') ~= 1
zdata2=zdata1;
else, end
if exist('Zbus2') ~= 1
Zbus2=Zbus1;
else, end
nl = zdata1(:,1); nr = zdata1(:,2);
nl0 = zdata0(:,1); nr0 = zdata0(:,2);
nbr=length(zdata1(:,1)); nbus = max(max(nl), max(nr));
nbr0=length(zdata0(:,1));
R0 = zdata0(:,3); X0 = zdata0(:,4);
R1 = zdata1(:,3); X1 = zdata1(:,4);
R2 = zdata1(:,3); X2 = zdata1(:,4);

for k=1:nbr0
    if R0(k)==inf || X0(k) ==inf
    R0(k) = 99999999;  X0(k) = 99999999;
    else, end
end
ZB1 = R1 + j*X1;  ZB0 = R0 + j*X0;
ZB2 = R2 + j*X2;

if exist('V') == 1
    if length(V) == nbus
    V0 = V;
    else, end
else,  V0 = ones(nbus, 1) + j*zeros(nbus, 1);
end
fprintf('\nLine-to-ground fault analysis \n')
ff = 999;
while ff > 0
nf = input('Enter Faulted Bus No. -> ');
rtn=isempty(nf);
    if rtn==1; nf=-1; end
        while nf <= 0 || nf > nbus
    fprintf('Faulted bus No. must be between 1 & %g \n', nbus)
    nf = input('Enter Faulted Bus No. -> ');
    rtn=isempty(nf);
    if rtn==1; nf=-1; end
    end
rtz=1;
    while rtz==1
  fprintf('\nEnter Fault Impedance Zf = R + j*X in ')
    Zf = input('complex form (for bolted fault enter 0). Zf = ');
  rtz=isempty(Zf);
  end
fprintf('  \n')
fprintf('Single line to-ground fault at bus No. %g\n', nf)
a =cos(2*pi/3)+j*sin(2*pi/3);
sctm = [1   1   1; 1 a^2  a; 1 a  a^2];
Ia0 = V0(nf)/(Zbus1(nf,nf)+Zbus2(nf, nf)+ Zbus0(nf, nf)+3*Zf);
Ia1=Ia0; Ia2=Ia0;
I012=[Ia0; Ia1; Ia2];
Ifabc = sctm*I012;
Ifabcm = abs(Ifabc);
fprintf('Total fault current = %9.4f per unit\n\n', Ifabcm(1))
fprintf('Bus Voltages during the fault in per unit \n\n')
```

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```
fprintf('      Bus      -------Voltage Magnitude-------  \n')
fprintf('      No.     Phase a      Phase b      Phase c  \n')

for n = 1:nbus
Vf0(n)= 0 - Zbus0(n, nf)*Ia0;
Vf1(n)= V0(n) - Zbus1(n, nf)*Ia1;
Vf2(n)= 0 - Zbus2(n, nf)*Ia2;
Vabc = sctm*[Vf0(n); Vf1(n); Vf2(n)];
Va(n)=Vabc(1); Vb(n)=Vabc(2); Vc(n)=Vabc(3);
fprintf(' %5g',n)
fprintf(' %11.4f', abs(Va(n))),fprintf(' %11.4f', abs(Vb(n)))
fprintf(' %11.4f\n', abs(Vc(n)))
end
fprintf('  \n')
fprintf('Line currents for fault at bus No.  %g\n\n', nf)
fprintf('      From      To      -----Line Current Magnitude----  \n')
fprintf('      Bus      Bus      Phase a      Phase b      Phase c  \n')
for n= 1:nbus
   for I = 1:nbr
      if nl(I) == n || nr(I) == n
         if nl(I) ==n
            k = nr(I);
         elseif nr(I) == n
            k = nl(I);
         end
            if k ~= 0
            Ink1(n, k) = (Vf1(n) - Vf1(k))/ZB1(I);
            Ink2(n, k) =  (Vf2(n) - Vf2(k))/ZB2(I);
            else, end
      else, end
   end
   for I = 1:nbr0
      if nl0(I) == n || nr0(I) == n
         if nl0(I) ==n
            k = nr0(I);
         elseif nr0(I) == n
            k = nl0(I);
         end
            if k ~= 0
            Ink0(n, k) =  (Vf0(n) - Vf0(k))/ZB0(I);
            else, end
      else, end
   end
   for I = 1:nbr
      if nl(I) == n || nr(I) == n
         if nl(I) ==n
            k = nr(I);
         elseif nr(I) == n
            k = nl(I);
         end
            if k ~= 0
            Inkabc = sctm*[Ink0(n, k); Ink1(n, k); Ink2(n, k)];
            Inkabcm = abs(Inkabc); th=angle(Inkabc);
               if real(Inkabc(1)) > 0
               fprintf('%7g', n), fprintf('%10g', k),
               fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f',
abs(Inkabc(2)))
               fprintf(' %11.4f\n', abs(Inkabc(3)))
               elseif real(Inkabc(1)) ==0 && imag(Inkabc(1)) < 0
               fprintf('%7g', n), fprintf('%10g', k),
```

```matlab
                fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f',
abs(Inkabc(2)))
                fprintf(' %11.4f\n', abs(Inkabc(3)))
                else, end
            else, end
        else, end
    end
    if n==nf
    fprintf('%7g',n), fprintf('            F'),
    fprintf(' %11.4f', Ifabcm(1)),fprintf(' %11.4f', Ifabcm(2))
    fprintf(' %11.4f\n', Ifabcm(3))
    else, end
end
resp=0;
    while strcmp(resp, 'n')~=1 && strcmp(resp, 'N')~=1 && strcmp(resp,
'y')~=1 && strcmp(resp, 'Y')~=1
    resp = input('Another fault location? Enter ''y'' or ''n'' within
single quote -> ');
    if strcmp(resp, 'n')~=1 && strcmp(resp, 'N')~=1 && strcmp(resp,
'y')~=1 && strcmp(resp, 'Y')~=1
    fprintf('\n Incorrect reply, try again \n\n'), end
    end
    if resp == 'y' || resp == 'Y'
    nf = 999;
    else ff = 0; end
end    % end for while
%Ink0
%Ink1
%Ink2


% The program dlgfault is designed for the double line-to-ground
% fault analysis of a power system network. The program requires
% the positive-, negative- or zero-sequence bus impedance matrices,
% Zbus1 Zbus2,and Zbus0. The bus impedances matrices may be defined
% by the user, obtained by the inversion of Ybus or it may be
% determined either from the function Zbus = zbuild(zdata)
% or the function Zbus = zbuildpi(linedata, gendata, yload).
% The program prompts the user to enter the faulted bus number
% and the fault impedance Zf. The prefault bus voltages are
% defined by the reserved Vector V. The array V may be defined or
% it is returned from the power flow programs lfgauss, lfnewton,
% decouple or perturb. If V does not exist the prefault bus voltages
% are automatically set to 1.0 per unit. The program obtains the
% total fault current, bus voltages and line currents during the
% fault.
%
% Copyright (C) 1998-2013 Hadi Saadat

function dlgfault(zdata0, Zbus0, zdata1, Zbus1, zdata2, Zbus2, V)

if exist('zdata2') ~= 1
zdata2=zdata1;
else
end
if exist('Zbus2') ~= 1
Zbus2=Zbus1;
else
end


nl = zdata1(:,1); nr = zdata1(:,2);
```

```matlab
nl0 = zdata0(:,1); nr0 = zdata0(:,2);
nbr=length(zdata1(:,1)); nbus = max(max(nl), max(nr));
nbr0=length(zdata0(:,1));
R0 = zdata0(:,3); X0 = zdata0(:,4);
R1 = zdata1(:,3); X1 = zdata1(:,4);
R2 = zdata2(:,3); X2 = zdata2(:,4);

for k = 1:nbr0
    if R0(k) == inf || X0(k) == inf
    R0(k) = 99999999; X0(k) = 999999999;
    else
    end
end
ZB1 = R1 + j*X1;  ZB0 = R0 + j*X0;
ZB2 = R2 + j*X2;

if exist('V') == 1
    if length(V) == nbus
    V0 = V;
    else
    end
else
    V0 = ones(nbus, 1) + j*zeros(nbus, 1);
end

fprintf('\nDouble line-to-ground fault analysis \n')
ff = 999;
while ff > 0
nf = input('Enter Faulted Bus No. -> ');
rtn=isempty(nf);
    if rtn==1; nf=-1; end
while nf <= 0 || nf > nbus
    fprintf('Faulted bus No. must be between 1 & %g \n', nbus)
    nf = input('Enter Faulted Bus No. -> ');
    rtn=isempty(nf);
        if rtn==1; nf=-1;
        end
end
rtz=1;
    while rtz==1
  fprintf('\nEnter Fault Impedance Zf = R + j*X in ')
    Zf = input('complex form (for bolted fault enter 0). Zf = ');
  rtz=isempty(Zf);
    end
fprintf('  \n')
fprintf('Double line-to-ground fault at bus No. %g\n', nf)
a =cos(2*pi/3)+j*sin(2*pi/3);
sctm = [1   1   1; 1 a^2  a; 1 a   a^2];

Z11 = Zbus2(nf, nf)*(Zbus0(nf, nf)+ 3*Zf)/(Zbus2(nf, nf)+Zbus0(nf,
nf)+3*Zf);
Ia1 = V0(nf)/(Zbus1(nf,nf)+Z11);
Ia2 =-(V0(nf) - Zbus1(nf, nf)*Ia1)/Zbus2(nf,nf);
Ia0 =-(V0(nf) - Zbus1(nf, nf)*Ia1)/(Zbus0(nf,nf)+3*Zf);
I012=[Ia0; Ia1; Ia2];
Ifabc = sctm*I012; Ifabcm=abs(Ifabc);
Ift = Ifabc(2)+Ifabc(3);
Iftm = abs(Ift);

fprintf('Total fault current = %9.4f per unit\n\n', Iftm)
```

```
fprintf('Bus Voltages during the fault in per unit \n\n')
fprintf('     Bus    -------Voltage Magnitude------  \n')
fprintf('     No.    Phase a      Phase b     Phase c  \n')

for n = 1:nbus
Vf0(n)= 0 - Zbus0(n, nf)*Ia0;
Vf1(n)= V0(n) - Zbus1(n, nf)*Ia1;
Vf2(n)= 0 - Zbus2(n, nf)*Ia2;
Vabc = sctm*[Vf0(n); Vf1(n); Vf2(n)];
Va(n)=Vabc(1); Vb(n)=Vabc(2); Vc(n)=Vabc(3);
fprintf(' %5g',n)
fprintf(' %11.4f', abs(Va(n))),fprintf(' %11.4f', abs(Vb(n)))
fprintf(' %11.4f\n', abs(Vc(n)))
end
fprintf('  \n')
fprintf('Line currents for fault at bus No.  %g\n\n', nf)
fprintf('     From      To      ----Line Current Magnitude----  \n')
fprintf('     Bus       Bus      Phase a      Phase b     Phase c  \n')
for n= 1:nbus
   for I = 1:nbr
      if nl(I) == n || nr(I) == n
         if nl(I) ==n
            k = nr(I);
         elseif nr(I) == n
            k = nl(I);
         end
            if k ~= 0
            Ink1(n, k) = (Vf1(n) - Vf1(k))/ZB1(I);
            Ink2(n, k) =  (Vf2(n) - Vf2(k))/ZB2(I);
            else
            end
      else
      end
   end
   for I = 1:nbr0
      if nl0(I) == n || nr0(I) == n
         if nl0(I) ==n
            k = nr0(I);
         elseif nr0(I) == n
            k = nl0(I);
         end
            if k ~= 0
            Ink0(n, k) =  (Vf0(n) - Vf0(k))/ZB0(I);
            else
            end
      else
      end
   end
   for I = 1:nbr
      if nl(I) == n || nr(I) == n
         if nl(I) ==n
            k = nr(I);
         elseif nr(I) == n
            k = nl(I);
         end
            if k ~= 0
            Inkabc = sctm*[Ink0(n, k); Ink1(n, k); Ink2(n, k)];
            Inkabcm = abs(Inkabc); th=angle(Inkabc);
               if real(Inkabc(2)) < 0
               fprintf('%7g', n), fprintf('%10g', k),
```

```matlab
                    fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f',
abs(Inkabc(2)))
                    fprintf(' %11.4f\n', abs(Inkabc(3)))
                    elseif real(Inkabc(2)) ==0 && imag(Inkabc(2)) > 0
                    fprintf('%7g', n), fprintf('%10g', k),
                    fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f',
abs(Inkabc(2)))
                    fprintf(' %11.4f\n', abs(Inkabc(3)))
                    else
                    end
                else
                end
        else
        end
    end
    if n==nf
    fprintf('%7g',n), fprintf('           F'),
    fprintf(' %11.4f', Ifabcm(1)),fprintf(' %11.4f', Ifabcm(2))
    fprintf(' %11.4f\n', Ifabcm(3))
    else
    end
end
resp=0;
    while strcmp(resp, 'n')~=1 && strcmp(resp, 'N')~=1 && strcmp(resp,
'y')~=1 && strcmp(resp, 'Y')~=1
    resp = input('Another fault location? Enter ''y'' or ''n'' within
single quote -> ');
    if strcmp(resp, 'n')~=1 && strcmp(resp, 'N')~=1 && strcmp(resp,
'y')~=1 && strcmp(resp, 'Y')~=1
    fprintf('\n Incorrect reply, try again \n\n'), end
    end
    if resp == 'y' || resp == 'Y'
    nf = 999;
    else ff = 0;
    end
end   % end for while
```