Fault Studies In a Power System Network Solar System Incorporated

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Abstract—**This paper present the fault condition analysis to 11kV bus bar when the grid-connected PV system is incorporated with 11kV distribution network system.The project of fault studies in power system network solar system incorporated is conducted at 11kV bus bar to determine the effect of fault by finding out the characteristic of voltage versus time waveform of the grid-connected PV system, 11 kV bus bar and three phase load during fault condition by using Matlab/Simulink. Furthermore, to determine which type of fault that cause most severe damage to this system. Other than that, since the main supply of this system is from PV, one of the objectives is to obtain the behavior of PV module by generating the I-V and P-V characteristics curve based on BPSX510 parameter. Besides that, the grid-connected PV system model with 415Vrms output voltage was model. PV system is interfaced to the distribution network through boost converter, two level three phase inverter and the output voltage is step-up using 0.415/11 kV D11yn transformer. Then, this distribution network is used to supply 415Vrms load through 11k/0.415 kV YNd1 step-down transformer. The type of fault that is being conducted to the 11kV bus bar such as single-line to ground fault, double line to ground fault and line-line fault. The output voltage at grid-connected, 11kV distribution network and load was measured and analyzed. The fault that causes severe damage to system is the double line to ground fault.**

Keywords- single line to ground fault, line to line fault, double line to ground fault, PV (Photovoltaic) module, and simulation.

I. Introduction

Most scientists and researchers believe that the main cause of higher carbon dioxide concentration is from the emission of fossil fuel [1]. This clearly shows that renewable energy has important role in order to stabilize or to decrease the carbon dioxide gas in the atmosphere. There are several types of renewable energy that have been exposed in Malaysia such as hydro energy, biomass energy, solar energy and wind energy. The energy through the effect of PV energy can be one most available and promising renewable energy because the reliability of supply and sustainability of solar radiant energy. In 1839, French Physicist Edmund Becquerel discovered the effect of PV [2]. He had made a copper-cuprous oxide thin-film solar cell [3]. The solar PV is the device that absorbs solar energy from the sun and turns it into electricity.

The main components in fabricating the PV power generation system are solar cells. [4]. Solar cells are basic building blocks that are interconnected together in series to obtain the selected output voltage. A solar module is the combination and designation of solar cell to generate required electric power at particular current rating and voltage. Grid connected PV system is the modules are arranged in array connected in series and parallel to generate electrical energy that transmit to grid through grid inverter. Usually, the grid connected PV system function as distributed generator that supports the main generation systems by supplying power into the grid. The photovoltaic I-V and P-V output characteristics depends on the solar irradiance, the cell temperature and output voltage of PV module.

Commonly, the grid-connected PV system is functioning as distributed generator (DG) that supports the main generation systems by supplying power into grid. In this project, this system may be considered as a distributed generator or solar farm. There are many possibilities of power quality problem need to be noted as to its impact on the distribution network it is connected to. For instance, in TNB grid-interconnection of PV power generation guide, there are many factor need to be measured such as the maximum voltage fluctuation due to solar variation is 6%, total harmonic distortion is less than 5%, flicker, voltage unbalance and short circuit.

This paper focused on the fault condition analysis at 11 kV bus bar of distribution network as the grid-connected PV system incorporated with the 11kV distribution system. There are three most common types of unbalance fault include single line to ground (SLG), double line to ground (DLG) and line to line (LL). These faults are being injected between grid-connected system and distribution network which is at 11kV bus bar. Then, the observation of output voltage will be measured and analyzed during the fault condition. Other than that, the modeling and simulation of grid-connected PV system is elaborated through this paper. This PV module is performed using solar cell. This photovoltaic module is connected to boost chopper and the amplified output voltage from the boost converter supplied to the two level three phase inverter in purpose to obtain 415Vrms. The 415V/11kV of D11-Yn transformer is used to interface the grid-connected PV system to the 11kV bus bar of distribution network. Then, this network is supplied the three phase load through 415V/11kV step-down Yn-D1 transformer.

II. MODELING

The power generated from the PV system transfer through grid-connected PV system to the utility grid. The block diagram of the grid-connected PV system is shown as in Figure 1.

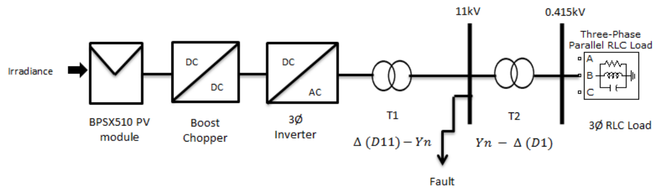


Figure 1 The block diagram of grid-connected PV system

A. Photovoltaic Module (Solar Cell)

First, the PV module for this project is by using of solar cell block from SimElectronics library. It is consist of solar of induced current and temperature dependence. This method is used to obtain the characteristics of a particular photovoltaic cell panel and to plot the I-V curve and P-V characteristics.

The output current, I is given by equation shown in Figure 2 which can be represented by (1).

$$I = Iph - Is.(e^{\frac{V+IRs}{NV_t}} - 1) - I_{s2}.(e^{\frac{V+IRs}{N_2V_t}} - 1) - (V + I.\frac{Rs}{Rp}) \quad (1)$$

Where:

$I_{ph} = I_{pho} . I_r/I_{ro}$ is solar induced current;

I_r is irradiance (light intensity) in W/m^2 falling on the cell;

I_{pho} is measured solar generated current for the irradiance I_{ro};

I_s and I_{s2} is the saturation current of the diode;

$V_t = kT/q$ is the thermal voltage depend on the temperature of the device;

$k = 1.380 \times 10^{-23}$ J/K is the Boltzmann constant;

$q = 1.602 \times 10^{-19}$ C is the electron charge;

N is the quality factor of the first diode;

N_2 is the quality factor of second diode;

V is the terminals of the solar cell;

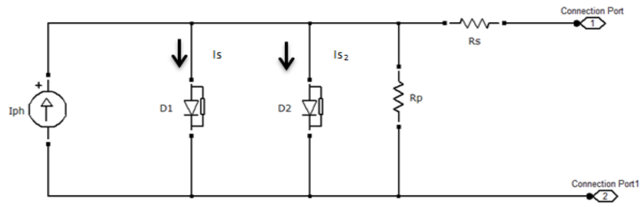


Figure 2 The equivalent circuit of solar cell

In this project there are 72 cells connected in series in order to obtain the particular open-circuit voltage which is 43.5V. For the array subsystem there are six series connected of solar cell as shown in Figure 3.

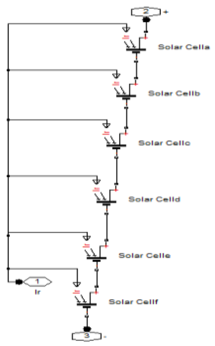


Figure 3 Six series connected of solar cell

. The PV panel model is simulated at a value of 500 W/m^2 of irradiance and a 25˚C of temperature. The parameter for the PV module is shown in Table I. while for the parameter of single solar cell is shown in Table II.

TABLE I. BPSX150 PHOTOVOLTAOC MODULE SPECIFICATION

Open circuit voltage (V_{oc})	43.5 V
Short circuit current (I_{sc})	4.75 A
Maximum power voltage(V_{mp})	34.5 V
Maximum power current(I_{mp})	4.35 A
Maximum power (P_{max})	150 W
Temperature cooefficient of I_{sc} (T1PH1)	-(0.065 ±0.015)%/˚C

TABLE II. THE PARAMETER OF SINGLE SOLAR CELL

Open circuit voltage (V_{oc})	0.6 V
Short circuit current (I_{sc})	4.75 A
Quality Factor, N	1.6
Series resistance, Rs	5.1e-3 Ω
Energy gap, EG	1.12eV
Parameter extraction temperature Tmeas	25 ˚C

B. DC-DC Converter

The boost converter is used to boost up the DC-DC output voltage where the magnitude of output voltage is greater than input voltage. The main DC supply or input voltage of this boost converter is from the PV output voltage, V_{pv} .The circuit of boost converter that been used in this project is shown in Figure 4.

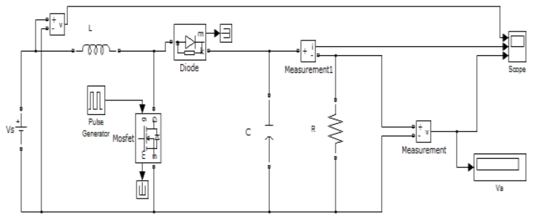


Figure 4: Boost circuit

The input voltage, V_s is 41.01V which is supplied by the PV system. The pulse generator is used to control the switching process for the MOSFET include the period, T and pulse width. The pulse width is 50% of period and this also show that the duty cycle specifies as the percentage of the pulse period that the signal is on if time-based. The resistance, R is used to obtain particular value of output voltage. The output voltage, Va is 511.9 V.

The output voltage, Va can be calculated using the equation (2). While the equation for duty cycle of the circuit is represented by (3).

$$Va = Vs\left(\frac{1}{1-D}\right) \tag{2}$$

Duty cycle can be calculated using equation (3).The calculated duty cycle is 0.92. The duty cycle is acceptable because it is within the range which is $0 < D < 1$. However, it is high duty cycle and only capable used in the circuit specifically designed for high voltage.

$$D = 1 - \frac{Vs}{Va} \tag{3}$$

C. DC-AC INVERTER

In the grid-connected PV system, the energy converted from solar energy to an inverter which converts the DC voltage to AC sine wave. This two-level three phase inverter is consisting of six transistors (IGBT) and six diodes where each of transistors will conduct for 180˚. Each transistor has a duty cycle 50% of period and switching action takes place for every T/6 time interval of 60 ˚ angle intervals.

There are three modes for the operation of switching include Mode 1 is from 0˚ to 60˚, Mode 2 is from 60˚ to 120˚ and Mode 3 is from 120˚ to 180˚. The sequences of transistor's gating for every mode are shown in the Table III.

TABLE III. THE SEQUENCES OF TRANSISTOR'S GATING FOR EVERY MODE

Mode	Sequence of transistor
Mode 1: $0 \le wt \le \pi/3$	Q1 – Q5-Q6
Mode 2: $\pi/3 \le wt \le 2\pi/3$	Q1-Q2-Q6
Mode 3: $2\pi/3 \le wt \le \pi$	Q1-Q2-Q3

As the switching operation take place for every 60˚, the time delay of the pulse for each transistor is calculated. The calculation of time delay can be seen in Table IV.

TABLE IV. THE TIME DELAY CALCULATION

Transistor	Calculation	Time Delay (ms)
Q1	0	0
Q2	$[(\pi/3)/2\pi]$ x 0.02 = 3.33e-3	3.33
Q3	$[(2\pi/3)/2\pi]$ x 0.02 = 6.67e-3	6.67
Q4	$[(\pi/3)/2\pi]$ x 0.02 = 10e-3	10
Q5	$[[(4\pi/3)/2\pi]$ x 0.02] – 0.02 = -6.667e-3	-6.67
Q6	$[[(5\pi/3)/2\pi]$ x 0.02] – 0.02 = -3.33e-3	-3.33

The output voltage of this two-level three phase inverter is 415 Vrms while the DC input voltage which is supplied from the boost converter is 511.9 Vdc. The circuit of two-level three phase inverter is shown in Figure 5.

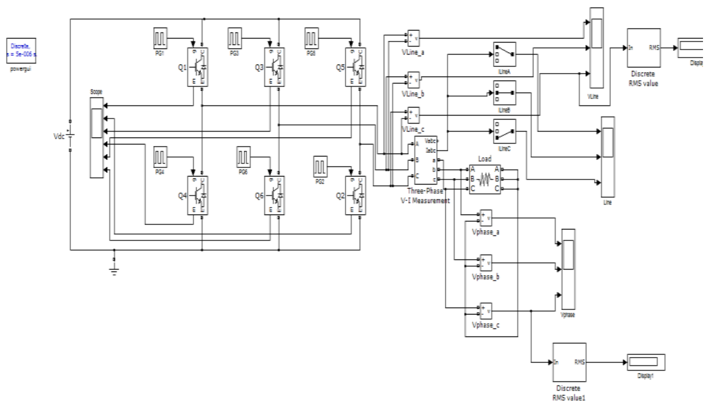


Figure 5: Two-Level Three Phase Inverter

In order to link the grid-connected PV system to the 11kV distribution network, the 10 kVA of step-up three-phase transformer is needed to step up the voltage from 415 V to 11kV. Then, 5kVA of step-down transformer is supplying the three phase parallel load. Then the system supplies to the three phase RLC load with 560 W, 100 var of inductive and 100 var capacitive. Since this system does not have any controller, the load was chosen in order to match the particular measurement value in this distribution network. The connection of utility grid can be seen in Figure 7.

D. *Fault*

The objective of this project is to observe the effect of fault that being applied to the system. Fault can be categorized to two types which are balance fault and unbalanced fault. Though, for this project the type of fault that being used in purpose to observe the effect of fault to the system is the unbalanced fault. This fault is known as unbalanced fault because it is occur when the system is unbalance. There are three types of unbalanced fault on a three phase system such as single line to ground fault (SLG), double line to ground fault (DLG) and line to line fault (LL).

In this project, the fault are being injected between the D11-Yn, 415 V/ 11kV step-up three phase transformer and Yn-D1, 11kV/ 415 V step-down three phase transformer which is at 11kV bus bar.

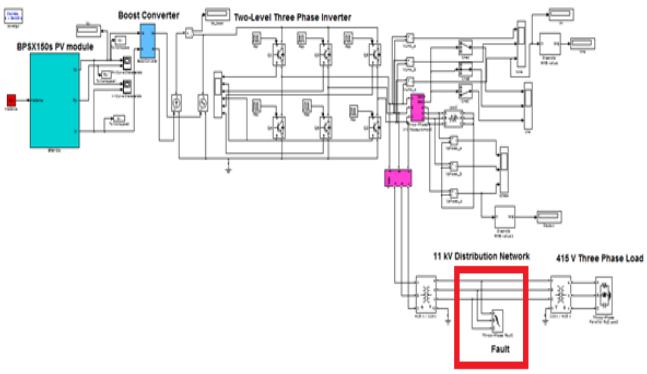


Figure 6: Completed circuit of Grid-connected PV system and location with fault applied

In Figure 6 show the completed circuit of grid-connected PV system and the location of fault that is being injected to the system.

III. SIMULATION RESULT AND DISCUSSION

A. *Simulation Results of PV Module*

The PV module is simulated and the behavior of PV module is obtained. This model was simulated with 500 W/m^2 of irradiance and 25˚C of cell temperature. The irradiance of 500 W/m ^{2} was chosen because it is the standard average solar irradiation in Malaysia. The objective in implementing this module is to obtain the similar characteristic of I-V and P-V curve characteristic with the curve characteristic given in the manufacturer's datasheet. Hence for this case, the I-V curve and PV curve obtained in this simulation is similar with the curve characteristic in the manufacturer's datasheet. The I-V curve characteristic shown in Figure 7 and P-V curve characteristic of the PV module in Figure 8.

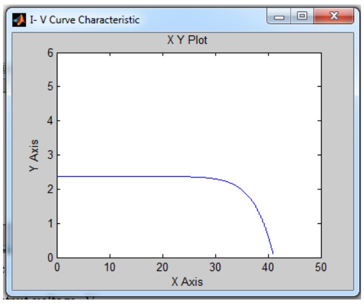


Figure 7: I-V Curve Characteristic

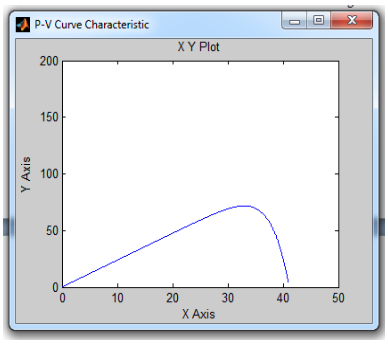


Figure 8: P-V Curve Characteristic

In Figure 7; the X-axis represents the output voltage, V_{pv} while the Y-axis represents the output current, I_{pv}. Then, in Figure 8; the x-axis represent the output voltage, V_{pv} while the Y-axis represent the output power of PV module, P_{pv}.

B. *Simulation Results on Normal Operating Condition.*

This normal operation condition is the condition where there is no fault being applied to the system. The sinusoidal waveform of voltage versus time in second shown which consist of phase a, phase b and phase c. in Figure 9 is the waveform measured at 11kV distribution network.

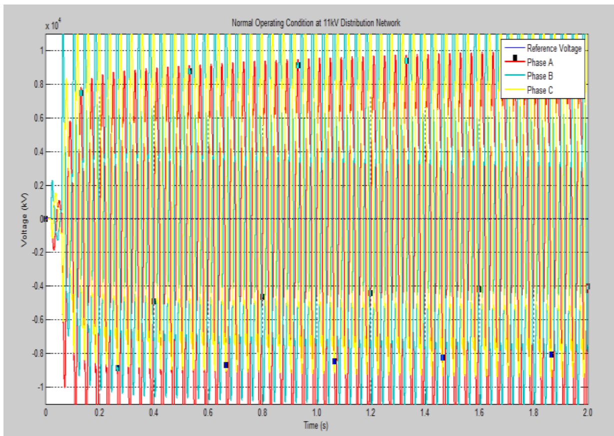


Figure 9: Waveform of normal condition at 11kV distribution line.

The sinusoidal waveform shown which consist of phase a, phase b and phase c. in Figure 10 is the waveform measured at three phase load. The output voltage is 415Vrms.

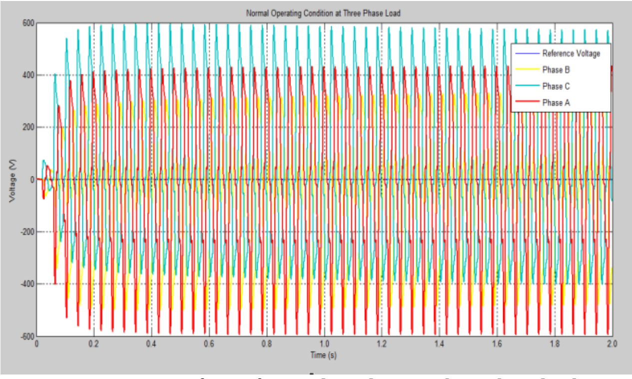
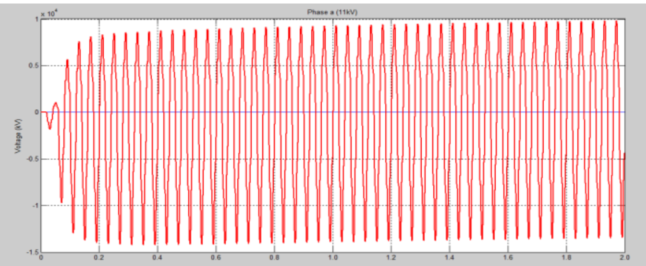


Figure 10: Waveform of normal condition at three phase load.

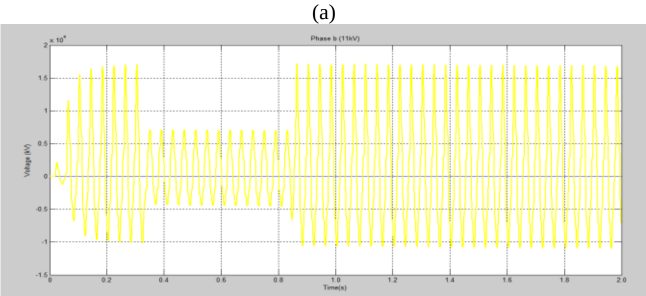
C. SimulationResult for Single Line to ground Fault

The parameter used in the three phase fault block in Matlab/Simulink in order to accomplish this fault analysis in this project such as fault resistance is 0.001ohm, the ground resistance is 0.001ohm and the transition time is 10/60 to 25/60. The parameter is common for all the cases.

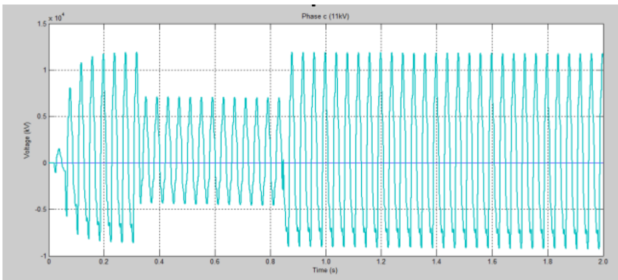
For this case, single line will be grounded with 0.001 ohm of ground resistance. The single line to ground fault will be applied to phase c. The waveform of phase a, phase b and phase c measured at 11kV distribution line during fault is shown in Figure 11.The waveform of phase b in Figure 11(b) shown the voltage to drop from 11kV at 0.38s to 0.711 kV during the fault occurs. At 0.8s, the fault cleared the voltage back to steady-state and this same goes with phase c as shown in Figure 11(c). This show that this single line to ground faults only affected phase b and c. While in phase a shown in Figure 11(a), the waveform is in normal condition but the voltage measured is slightly drop and the value of voltage for phase a is 0.845kV.



(a)



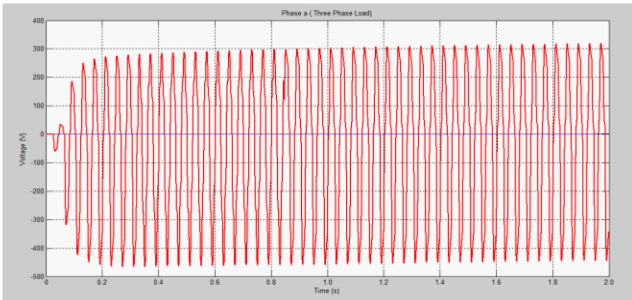
(b)



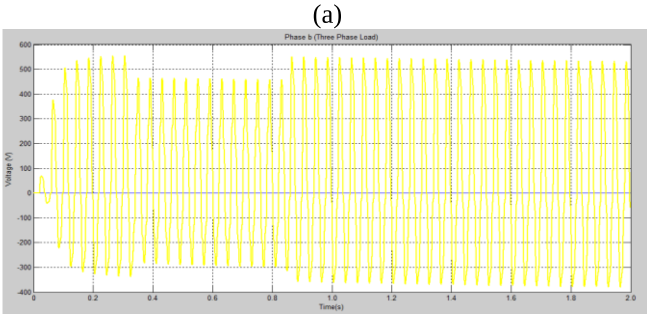
(c)

Figure 11: The waveform at 11kV at distribution network during fault condition. (a) Phase a. (b) Phase b (c) Phase c.

Besides that, this effect of single line to ground fault to the three phase load can be observed in Figure 12. The voltage waveform in phase a as shown in Figure 12(a) is in sinusoidal- state but the voltage drop to 306.6V from the actual voltage which is 415V. Figure 12(a) show the voltage waveform measured at phase b, the voltage about 15 % from the actual waveform. This fault cause severe damage to phase c in three phase load since the fault is applied to phase c. The voltage measured at phase c of three phase load show that the voltage is zero during the fault condition but after 0.8s, the fault cleared and the waveform back to steady – state.



(a)



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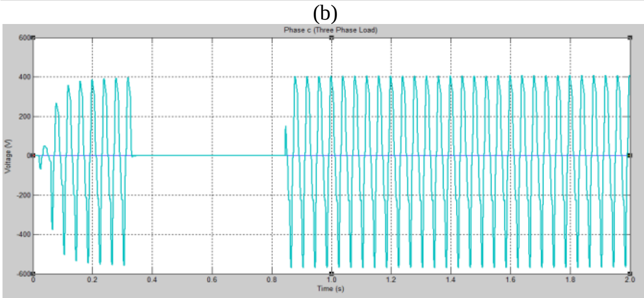


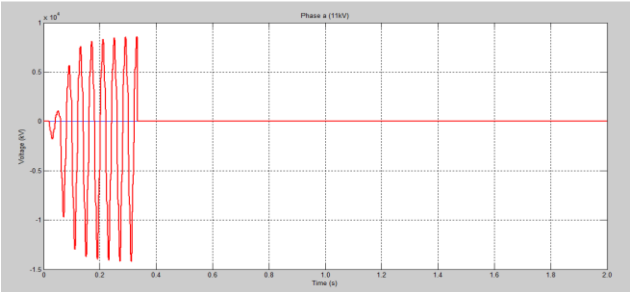
(c)

Figure 12: The waveform at three phase load during fault condition. (a) Phase a. (b) Phase b. (c) Phase c

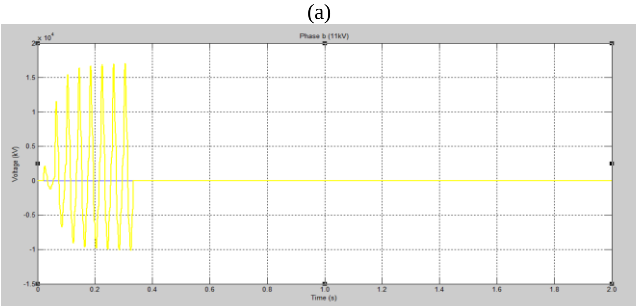
D. SimulationResult for Double Line to ground Fault

The parameter used in the three phase fault block in Matlab/Simulink in order to accomplish this fault analysis in this project is common as the first case. Meanwhile for this case, two lines of phases are grounded with 0.001 ohm. Phase a and b of 11kV bus bar was chosen in purpose to accomplish this type of fault analysis.

This fault analysis cause the most severe damage to 11kV distribution network and three phase load compare to others fault analysis. The waveform for all phases of 11kV distribution network can be observed in Figure 13. The waveforms show that steady-state waveform start to distort at 0.35s and the waveform continuously at 0 V until the end of simulation time.



(a)



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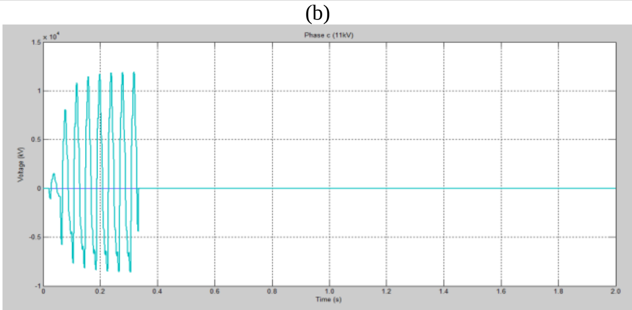
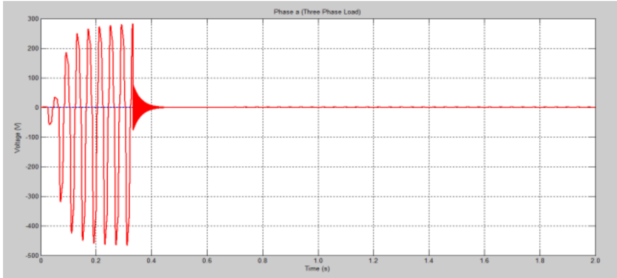


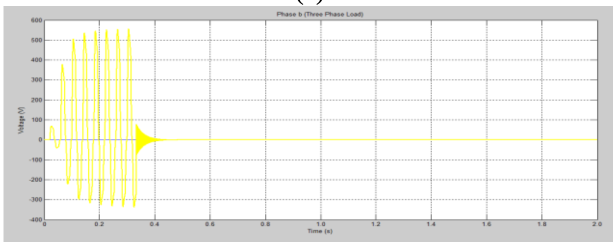
(c)

Figure 13: The waveform at 11kV distribution network during fault condition. (a) Phase a (b) Phase b (c) Phase c.

Similar with 11 kV distribution network results, the double line to ground fault cause most severe damage to three phase load. The waveforms of voltage versus time for three phase load are shown in Figure 14. This show that, supply for the three phase load is cut-off because of this fault. This clearly shows that, double line to ground fault give high impact to the distribution network and three phase load. This also may lead instability voltage in this system.



(a)



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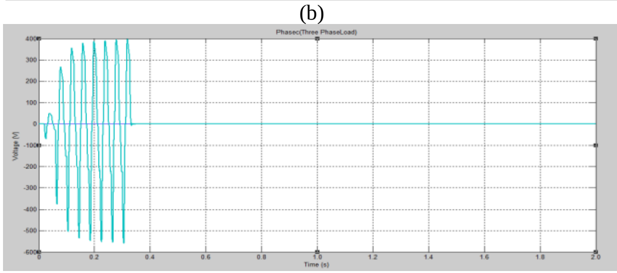


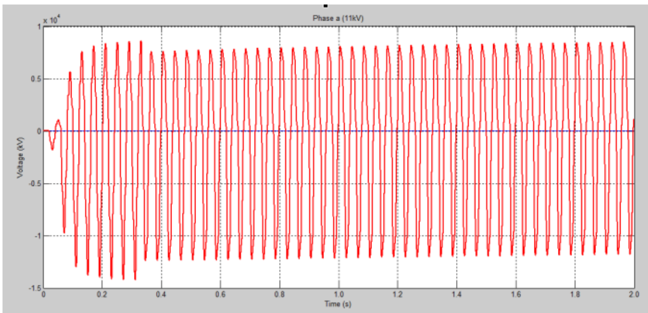
(c)

Figure 14: The waveform at three phase load during fault condition. (a)Phase a (b) Phase b (c) Phase c.

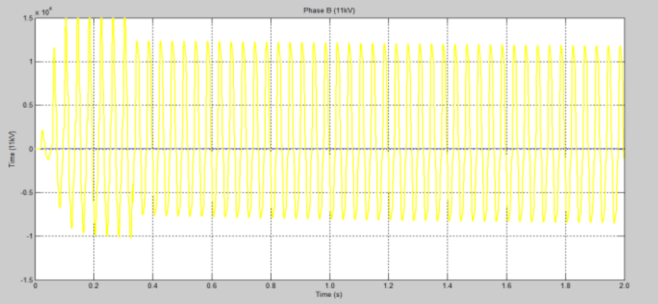
E. SimulationResult for Line to Line Fault

The line to line fault is a short circuit fault in a grounded system [5]. The line to line fault is applied to phase a and phase c at 11 kV busbar. The parameter used in this fault test is similar with others case.

Figure 15 show the waveform measured at 11 kV distribution network was obtained. The most affected line is in phase c shown in Figure 15(c), the voltage drop from 11kV to 0 V at 0.35s. While in phase a shown in Figure 15(a), the waveforms start to distort at 0.38s, the voltage start to drop to 0.783 kV and continuously maintain 0.783kV until the simulation time stop. In phase b shown in Figure 15(b) , the voltage increase to 1.6 kV but then it starts to decrease to 1.2kV at 0.38s instantly after the fault occurs.



(a)



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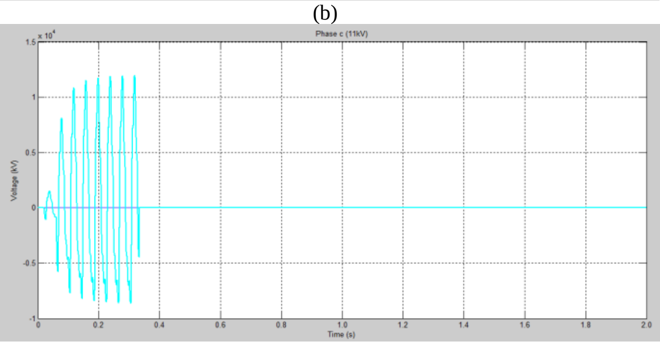
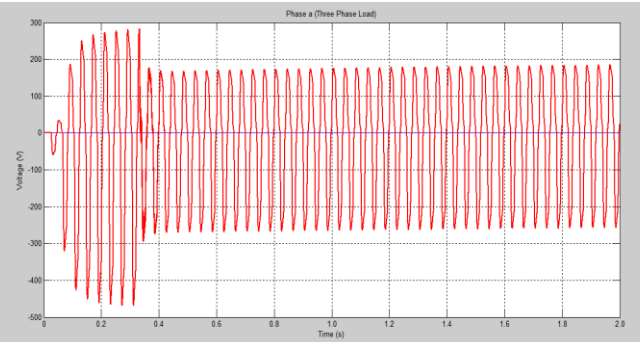


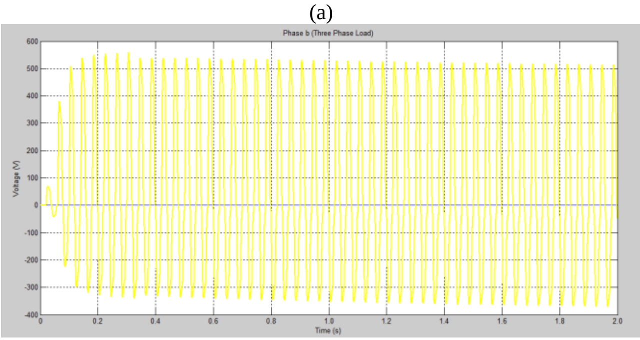
(c)

Figure 15: The waveform at 11kV distribution network during fault. (a) Phase a (b) Phase b (c) Phase c

The line to line fault also cause the waveform in phase a phase b and phase c in three phases load to distort. The waveform in three phase load is shown in Figure 17. In phase a shown in Figure 16(a), the fault occurs at 0.38s and this cause the voltage drop to 168 V from the actual voltage which is 415 V. In phase b shown in Figure 16(b), the voltage increase to 539 V. Finally in phase c shown in Figure 16(c) , the voltage also drops to 168 V at 0.38s.



(a)



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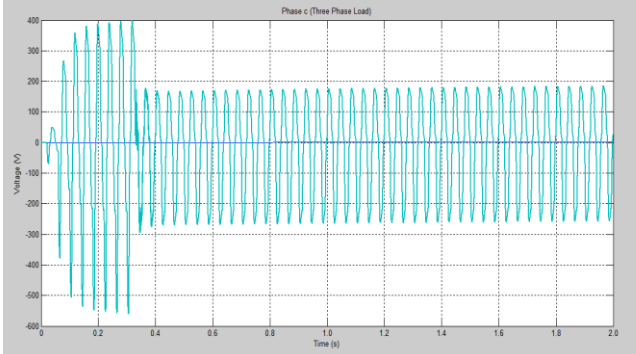

(c)

Figure 16: The waveform at Three Phase Load (a) Phase a (b) Phase b (c) Phase c

IV. CONCLUSION

As a conclusion, all the objectives of this project are successfully achieved. The modeling and simulation of grid-connected PV system with 11 kV distribution network and three phase load was modeled and simulated using Matlab/Simulink. The behavior of I-V and P-V curve were generated. The effect of single line to ground fault, double line to ground fault and line to line fault were analyzed. Through this simulation, the type of fault which cause most severe damage to 11kV distribution network and three phase load is double line to ground fault compare to others fault. From this simulation also show that, this fault condition does not give effect to the grid-connected PV system. However, it needs to be concern in future because this fault may lead to others unexpected instability condition.

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