International Journal of Science and Engineering Applications
Volume 12-Issue 04, 150 – 155, 2023, ISSN:- 2319 - 7560
DOI: 10.7753/IJSEA1204.1050

Quasi-static Power Flow and Fault Analysis of Photovoltaic Farm

Naiqian Zhang
Power and Control Department
South China University of Technology
China

Zhu Peifeng
Power and Control Department
South China University of Technology
China

BAO Zhuo
Power and Control Department
South China University of Technology
China

Abstract: This report first analysis quasi static power flow for photovoltaic power plant. Then, fault analysis for different symmetrical and asymmetrical fault is done. The system used is IEEE 39 bus New England system that a Photovoltaic farm with 500 MW power is connected to bus 24. Newton-Raphson Power flow method is used with Gauss-Jordan elimination method for matrix inversion in this power flow analysis. Different operation condition including faults are also considered for fault at bus 16. The results are validated with simulation in MATLAB software.

Keywords: Quasi static power flow, Gauss-Jordan elimination, IEEE 39 bus New England system, Photovoltaic Farm, Symmetrical and Asymmetrical fault.

1. INTRODUCTION

Renewable energies usages is increased widely in recent years due to their economic and environmental features. In addition, governments encouragements and laws help their increase. Some of renewable energy sources include: Solar Farms, Wind Turbines, Biomass, Geothermal, Fuel cell, and Ocean and tidal. But these sources highly depend to environmental conditions. Then, their different features should to be analysis [1-3].

The solar panel system is designed to receive solar energy and convert it into electricity that can be used for commercial and residential uses. Photovoltaic systems usually include a panel and solar panel modules, an inverter, and sometimes a battery or solar detector and wiring connections. Due to change of solar irradiation, output power of PV will change. It can also come from other factors like passing clouds and accumulative dust on Panels. Then, output power of PV farm will change with respect to time.

These renewable energy sources generations are not dispatchable because their produce energy is free and should be used. Then, a static load flow solution cannot produce a real picture of the system, especially when generations from renewables vary with time [5]. Therefore, a quasi-static or time series analysis is used for power flow analysis of these sources [5-10].

In this paper, first, principle of Photovoltaic (PV) panels is explained. Then, Matrix inversion and Gauss-Jordan elimination method for matrix inversion is explained and implemented. Then, quasi static power flow for a 500 MW panel in IEEE 39 bus New England system is done. Moreover, different type of fault analysis is done including symmetrical and asymmetrical fault. For asymmetrical fault, different line-to-line fault, line-to-ground fault, and double line-to-ground fault are studied.

2. PHOTOVOLTAIC PANEL

Photovoltaic (PV) panels include p-n silicon junctions that produce electrical current by absorbing photons. To show the operation conditions and effected factors on PV panels their models are explained. PV panels can be modeled with single diode [11] or double diode model [12]. The single line model of PV panel that is shown in Fig.1 is:

$$I = I_{pv} - I_0[\exp(\frac{V + R_s I}{V_t a}) - 1] - \frac{V + R_s I}{R_p} \tag{1}$$

Also, double diode model of PV is shown in Fig.2. Its circuit relations is:

$$I = I_{pv} - I_{01}[\exp(\frac{V + R_s I}{V_t a_1}) - 1] - I_{02}[\exp(\frac{V + R_s I}{V_t a_2}) - 1] - \frac{V + R_s I}{R_p} \tag{2}$$

The output voltage and current of PV panels with respect to irradiation and temperature change are shown in Fig. 3 and 4. As it can be concluded in both of this PV models generated output power of PV panels is related to irradiation and temperature. However, effect of temperature is much less than irradiation[13]. Then main factor effecting PV panels output is irradiation that is also considered in this research.

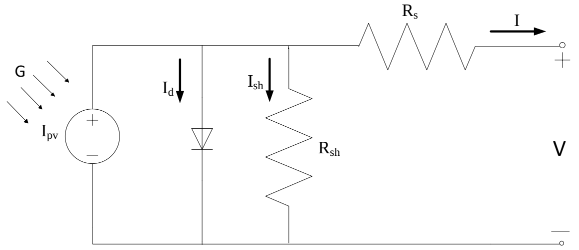

Fig. 1. Single diode model of PV panels.

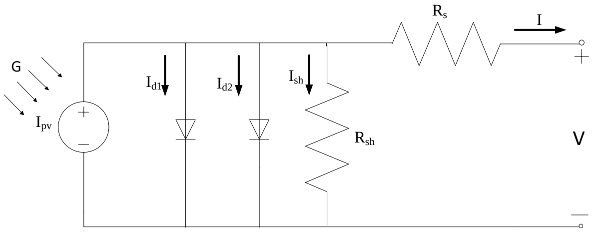

Fig. 2. Double diode model of PV panels

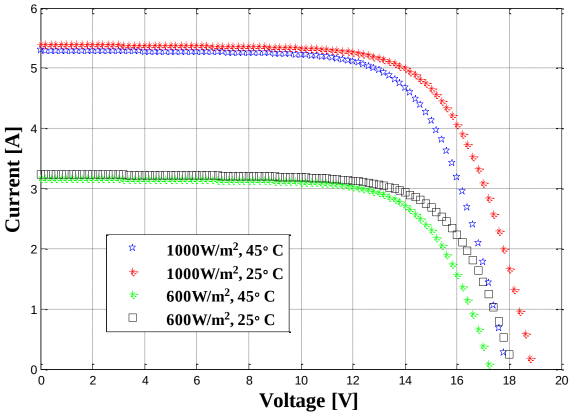

Fig. 3. PV panels charectirsits

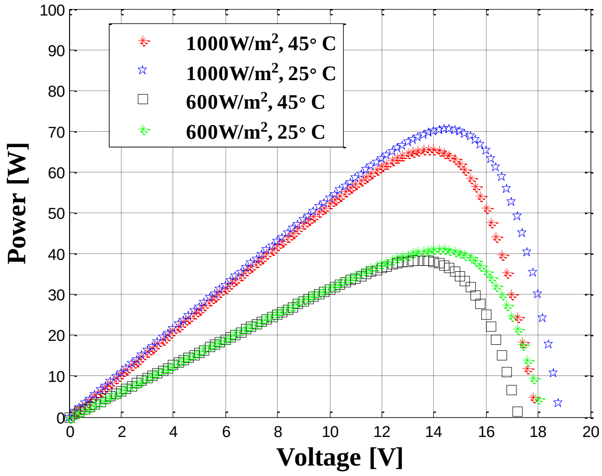

Fig. 4. PV panels charectirsits

Matrices cannot be divided. In fact, there is no concept as the division of a matrix, but we can multiply its matrix in its inverse. Matrix inversion can be difficult for matrix that their determinant is zero. Then the conventional methods cannot be used[14].

Matrix inversion is important for calculation in different problems include the obvious one that is linear equation solving and so many other fields. It is used at almost all mathematical and statistical software [15]. For example, with considering matrix equation, to find answer of an equation:

$$A.X = B \tag{2}$$

If matrix A has an inversion, A^{-1} then answer of this equation will be:

$$X = A^{-1}.B \tag{3}$$

Some methods of matrix inversion include Gauss-Jordan elimination, Gaussian elimination, LU decomposition, Strassen-Newton, Coppersmith and Winograd, Cholesky decomposition, QR decomposition, RRQR factorization and so on. These methods used for different applications with different features. In this research Gauss-Jordan elimination is used [15].

3.1 Gauss-Jordan elimination

Gauss-Jordan elimination is a method in linear algebra for calculating matrix inversion and solving linear equations. This method is also used to find the order of a matrix. To do inversion of matrix considering matrix A:

3. MATRIX INVERSION

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{5}$$

Then with considering identify matrix I:

$$I = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix} \tag{6}$$

Then it can be written as:

$$[A\,I] = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} & 1 & 0 & \cdots & 0 \\ a_{21} & a_{22} & \cdots & a_{2n} & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{7}$$

This method is performed continuously on matrices of coefficients. The name of this method is taken from the German mathematician Karl Friedrich Gaus. To perform surface-level operations in a matrix, a series of basic operations are used on matrix rows. To the maximum, the maximum possible size of the underlying matrix index is zero. There are three types of base operations on the matrix rows: 1- change of Two rows of Matrix 2-Multiplying a row of matrices in a non-zero number 3- adding a row with another multiple of another row. By doing this, the matrix becomes a diagonal matrix (stack form). When all effective coefficients (the leftmost data in each row) are equal to one, the rest of the columns in the columns are zero. The matrix becomes a reduced bridging matrix. This method can be used for inversion of a matrix or solving linear equations of a matrix. For computational reasons, it is sometimes preferred to stop operations on rows before conversion[14, 17].

And using operations to convert that to:

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & b_{11} & b_{12} & \cdots & b_{1n} \\ 0 & 1 & \cdots & 0 & b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \tag{8}$$

Then matrix:

$$B = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \tag{9}$$

is inversion of matrix A. In this report a simple code is used by adding each row by multiple of another row by their proportional coefficient.

4. Quasi-STATIC OR TIME SERIES POWER FLOW ANALYSIS

Use of renewable energy sources increase in modern power system grids. Then dynamic power flow is not applicable in these systems. So, static power flow based on time should be used. Then, a static load flow solution cannot produce a real picture of the system, especially when generations from renewables vary with time [4]. Therefore, a quasi-static or time series analysis is used for power flow analysis of these sources[5-10].

In conventional ICs, where there is no galvanic isolation between the DC and AC subgrids, the high-frequency common mode (CM) voltage across the parasitic capacitance produces a strong flow of ground leakage current [2] and [16].

Therefore, a quasi-static or time series analysis is used for power flow analysis of these sources like photovoltaic farms [5-10]. It depends to daily produced power of photovoltaic system and also load in different conditions by time. Then this power flow includes probability features of PV panel in power flow.

In this research, different irradiation conditions is considered with PV produced power. In the future work effect of temperature and other environmental factors and geographical effects can be considered. Moreover, load change specially for distributed loads can be considered in this method.

4.1 Power Flow Analysis

The studies of power flow analysis are the key to the analysis and design of power systems, and their implementation is essential for exploiting and scheduling economic times between electricity companies. Also, the analysis of the load distribution is a precondition for studies of the transient and eventual occurrence of network events.

In the study of power systems, the study of system analysis, which aims to determine the important parameters of the system in normal or emergency situations, are called load propagation. The studied parameters of load distribution include voltages, currents, active and reactive power, power losses, power exchange between different power systems, production and consumption balance in the system, transmission power, calculation of reactive power requirements of the system and other characteristics that can be used[17]. Since these power flow equations are non-linear, they must be solved with numerical and repetitive methods. Two common methods for solving these equations are Gaussian-Seidel and Newton-Raphson methods [17].

Newton Raphson Power flow is used in this research because of its good convergence [15]. With considering current:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{4}$$

And we have:

$$I_i = \sum_{j=1}^{n} \left|Y_{ij}\right| \left|V_j\right| \angle \theta_{ij} + \delta_j \tag{5}$$

Then complex power of bus *i* will be:

$$P_j - jQ_i = V_i^* I_i \tag{6}$$

That is expended to:

$$P_j - jQ_i = \left|V_i\right| \angle -\delta_j \sum_{j=1}^{n} \left|Y_{ij}\right| \left|V_j\right| \angle \theta_{ij} + \delta_j \tag{7}$$

Then finally we have these equations that should be solved with Newton-Raphson methods:

$$P_i = \sum_{j=1}^{n} \left|V_i\right| \left|V_j\right| \left|Y_{ij}\right| Cos(\theta_{ij} - \delta_i + \delta_j) \tag{8}$$

$$Q_i = -\sum_{j=1}^{n} \left|V_i\right| \left|V_j\right| \left|Y_{ij}\right| \mathrm{Sin}(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

But in the power flow analysis conventional power plant are modeled as PV bus and loads as PQ bus in addition to one generator as slack bus. At these PV buses voltage is constant, but Photovoltaic is modeled as current source that its voltage is not constant. Then to model Photovoltaic Power plant in the system it should be modeled as a PV bus with variable voltage. Another method is to model Photovoltaic system as a PQ bus with negative produced power. Then its reactive power will be constant and its voltage can be changed.

5. IMPLEMENTED SYSTEM

In all the systems there are some benchmark systems to analysis proposed ideas and compare the results. Then, there will be standard results for comparison that enables the better conclusion. In power system also there are some benchmark systems that A. IEEE 39 bus New England system is one of the popular one.

5.1 IEEE 39 Bus New England System

The system used in this research for analyze is IEEE 39 bus New England system or the 10-machine New-England Power System [17]. IEEE 39 bus New England system is a simple presentation of 345 kV system in New England. It includes 10 generators, 21 loads, and 46 lines. The base of system is based on 100 MVA. For this base condition, active power is 6254.2 MW and reactive power is 1387.1 Mar [18]. single-line diagram of system is shown in Fig. 10 [19-24].

5.2 500 MW PV Farm

Using of renewable energy specially wind farms and solar farms increase in the last decades. In this research a PV farm with maximum 500 MW output power at 1000 $\mathrm{W/m^2}$ or 1 sun is determined. The irradiation output and its generated power with respect of this conditions are shown in Figs. 6 and 7.

6. SIMULATION

Several case studies are considered in this research. First case is just PV farm in IEEE 39 bus New England system as shown in Fig. 11.

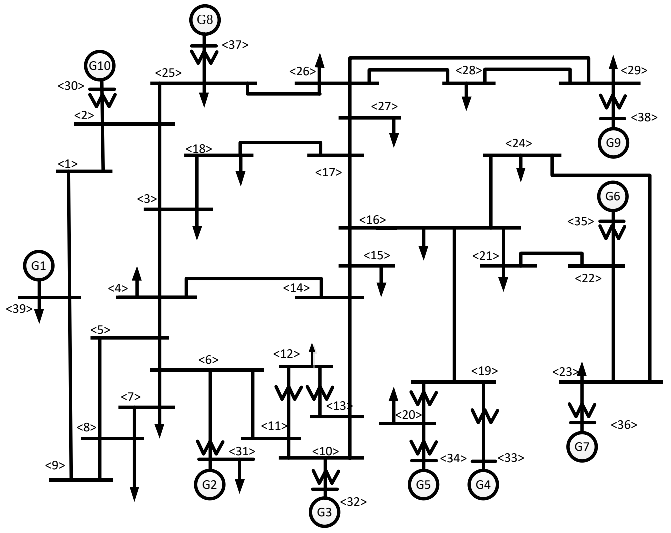

Fig. 5. IEEE 39 bus New England system.

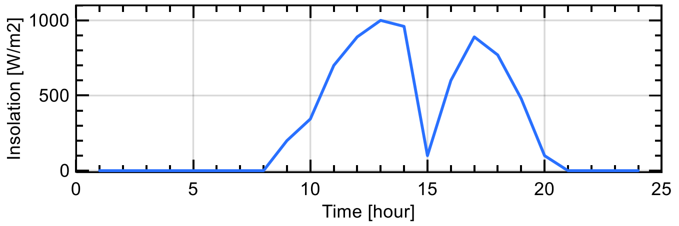

Fig. 6. Irradiation data.

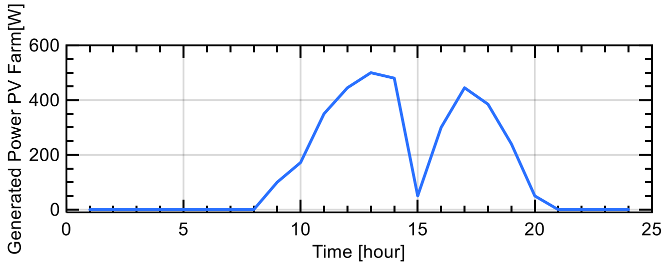

Fig. 7. PV produced power.

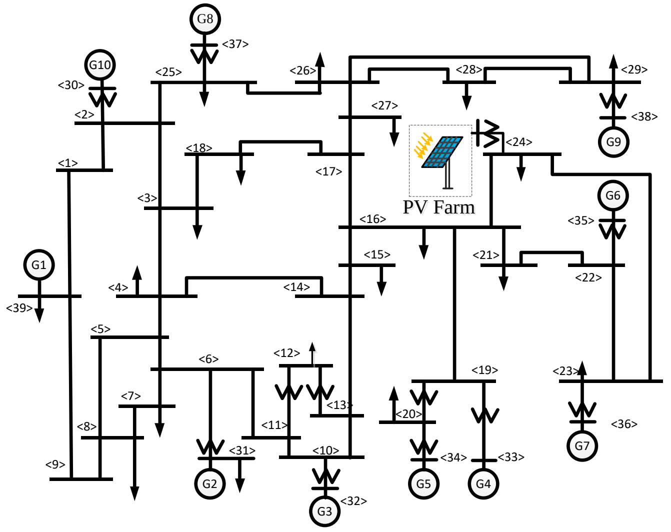

Fig. 8. IEEE 39 bus New England system with PV farm.

6.1 PV Farm

IEEE is shown in Fig.11. PV farm is located at bus 24. A new 500 MW PV (at 1 sun or 1000 W/m2) farm is being added to the IEEE 39 bus New England system and will be connected

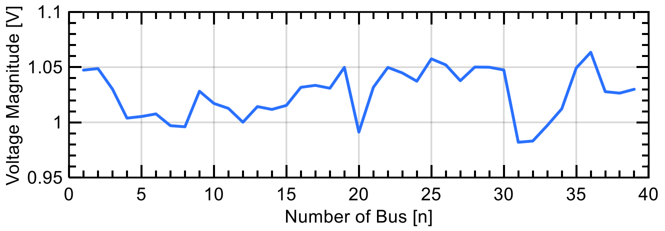

Fig. 10. Voltage Magnitude.

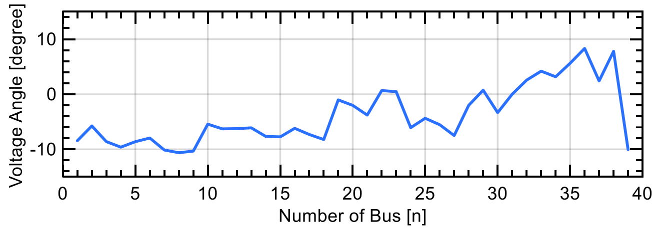

Fig. 11. Voltage Angle.

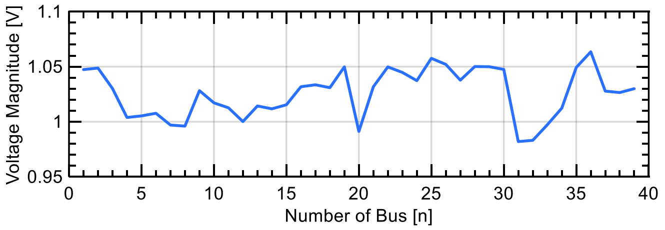

Fig. 12. Voltage Magnitude.

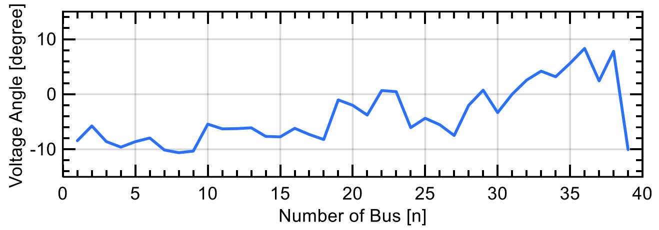

Fig. 13. Voltage Angle.

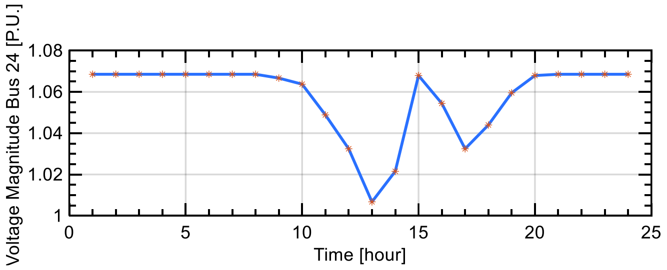

Fig. 14. Voltage Magnitude Bus 24.

to bus 24 through a new standard transformer with 0.1 pu impedance to a new bus (40). The hourly insolation data for a typical day is provided that used linearly at the simulation.

6.2 PV Farm with Fault in Bus 16

Conduct a series of fault studies (4) for load bus 16 in the network at t=3:00 pm. Examine both symmetrical and asymmetrical faults to determine the minimum and maximum fault currents. Mention in the report how you are considering fault current contribution from the PV plant.

7. FAULTS

When the fault occurs, voltages of some lines and buses reaches values lower than its voltage threshold. The area includes of these lines and buses is considered as the area of

Table I. Fault analysis with PV at bus No. 16

Fault condition	Total fault current
Balanced three-phase fault	74.5829 per unit
Line-to-line fault	64.5907 per unit
Double line-to-ground fault	65.2595 per unit
Single line to-ground fault	69.6191 per unit

Table II. Fault analysis without PV at bus No. 16

Fault condition	Total fault current
Balanced three-phase fault	65.9024 per unit
Line-to-line fault	57.0732 per unit
Double line-to-ground fault	62.8437 per unit
Single line to-ground fault	64.3427 per unit

vulnerability related to voltage sag [25]. Results of fault analysis for line to line fault is shown in Table I and Table II. For this analysis llfault function is used from [14]. Line to line fault current. in this case for bus 16 is 64.5907 per unit.

Also, this study has been done without present of PV farm. Without PV farm line to line current is 57.0732 per unit that is 11% less than previous case with PV farm. This also shows that PV farm increase fault current in grid.

8. RESULTS

First to test power flow with Gauss-Jordan elimination PV farm is not considered. Then first power flow with conventional Power flow and inversion code of MATLAB is done. The results for voltage magnitude and power angle are shown in Fig. 10,11. At next step, invented Gauss-Jordan elimination method is used for inversion of Matrix. The results are shown in Fig. 12 and 13. As it is shown the results are the same. Then Performed Gauss-Jordan elimination is correct. Next power flow with existing of PV farm at bus 24 is done. For this aim quasi static power flow is considered for 24-hour operation of PV farm. As explained Photovoltaic farm is considered as PQ bus with negative generation in power flow analysis and 24 power flow is run for this system as quasi static or time series power flow. First it is observed that voltage of PV change with change of radiation. Then it can be concluded that with change of radiation that led to change of produced power pf PV farm, voltage magnitude of buses change. If Irradiation increase that power will also increase, load profile of bus will decrease.

More importantly it is shown in Fig. 14 that voltage magnitude is decreased with present of PV farm. Then, PV farm will reduce bus voltage profile. Then a capacitor bank should be added to increase bus voltage especially at day time that output power of PV increase.

9. CONCLUSION

In this report effect of Photovoltaic farm on power system grid and power flow studied have been evaluated. Static power flow or time series power flow is used. The results are discussed using MATLAB simulations. It is shown that adding PV farm to grid will reduce bus voltage profile. Then a capacitor bank should be added to increase bus voltage especially at day time that output power of PV increase. As future work and research in this area can be done with modifying quasi-static or time series power flow with smaller time step that give more accurate results. Then other renewable energy generations also can be used. Moreover, other factors effected PV farms like temperature can be added. In addition, effect of variable loads can be studied to have better analysis.

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