Investigating and Simulating DGs to Improve Voltage Profile and Reducing Power Loss in Unbalanced Distribution Networks

Hassan BARATI, Abdol Rasool FATTHI

Department of Electrical Engineering, Dezful Branch, Islamic Azad University, Dezful, Iran

barati216@gmail.com, rasool_425@yahoo.com

Abstract. *Development of Distributed generations (DGs) has changed the nature of power networks from passive to active. In order to specify a proper model for DG units, function and connection style of DGs to the network (direct or indirect) must be clarified. In this paper, operation of DGs in an unbalanced condition (due to unbalanced loads) will be studied. A three-phase power flow model is used to confirm the certainty of the proposed model. Generally DG modelling, depend on its type and controlling circuit, is like either PV or PQ bus. In this paper a three-phase unbalanced power flow model using Newton-Raphson method over a 4 buses power system is implemented. Based on the type of bus (PV or PQ), Simulation results show that the DGs can improve voltage profile (NEME and IEEE unbalance factor) and reduce network losses.*

Keywords

DG, network loss, unbalance 3-phase power flow, unbalance factor, voltage profile.

1. Introduction

Increasing in energy consumption and expansion of nonlinear and sensitive loads (like drive systems, heavy single phase loads), continuous variation in network power consumption and unpredicted change in load lead to unbalance in power systems. In most of developed countries evolution of power generation and transmission industry eliminates all technical, academic and commercial requirements. Since operators of power system realized the need of different energy sources, the distributed generation was formed. Distributed generation concept includes small power plants with a capacity between 15 kilowatts to 25 megawatts to supply nearby consumers e.g. small power plants like wind, solar, fuel cells and etc.

Nowadays using distributed generation due to its many advantages like balancing power flow, balancing steady state condition, backup P and Q, reduction of investing in the transmission system, easy installation and startup, from consumers and power companies' point of view is unavoidable. Development of Distributed generations (DGs) has changed the nature of power networks from an active to a reactive one. A distribution company market, which is operated by Distribution System Operator (DSO) is proposed, and Effects of unbalance in power systems has been studied in [1], [2]. In [3], [4], [5], [6], [7], [8], [9], models of generators, transformers, lines and capacitors are presented to study three-phase power flow. Many studies normally focus on finding procedures to introduce DGs as PV and PQ buses in power flow calculations [10], [11], [12], [13], [14], [15], [16], [17]. To indicate a proper model for each DG, function and its connecting style to networks (direct or indirect) different kinds of DG like synchronous and inductive has been studied in [18]. In [19] loads models are presented. To show DG effects in power systems, it is necessary to update most of analyzing tools that used by power system engineers. Probabilistic computer calculations and usual power flow solution to analyze steady state of the network are commonly used. Trustful power flow solution in power networks due to its real and applied nature is challenging. Too many calculating methods have been suggested for this subject, from which the Newton-Raphson method with its converging specification is known as the best method. Also it is a popular method in the industry [19]. In [20], [21], [22], about operation management of DGs power sources connected to distribution networks worked.

As the goal of this paper is the study of DG's impact on voltage profile and power system losses in an unbalanced condition, so despite the DG's type all of DGs' are modeled as PV or PQ and their location is selected randomly based on trial and error method. DG's impact on three-phase power flow in an unbalanced

condition based on the NEMA and IEEE indexes are presented.

2. Voltage Unbalance

2.1. The Definitions of Unbalance

Increase of the nonlinear consumers that are switched by power electronic elements is one of the main reasons for unbalancing. On the other hand, these consumers have taken part in power market sensitive to the unbalance. These factors double the importance of unbalancing phenomenon and emphasize on its control. The definitions of voltage unbalance are stated below:

1) First Definition IEEE Std. 936-1987

The difference between the highest and the lowest rms voltage referred to the average of the three-phase voltages.

2) Second Definition IEEE Std. 112-1991

The maximum deviation from the average phase voltage, referred to the average of the phase voltage.

3) Third Definition NEMA [1], [2]

The definition of voltage unbalance, also known as the line voltage unbalance rate (LVUR), is given by:

$$\%LVUR =$$
$$= \frac{max\ voltage\ deviation\ from\ the\ avg.\ line\ voltage}{avg.\ line\ voltage}. \quad (1)$$

The true definition of voltage unbalance is defined as the ratio of negative sequence voltage component to the positive sequence voltage component. The percentage voltage unbalance factor (%VUF), or the true definition, is given by:

$$\%VUF =$$
$$= \frac{negative\ sequence\ voltage\ component}{positive\ sequence\ voltage\ component} \cdot 100. \quad (2)$$

2.2. Methods of Unbalance Reduction

- Equally distributing single phase loads between all phases.
- Reducing unbalance caused by impedance of the system.
- Using single phase regulators.
- Using passive and active compensators.

3. DG Model for Power Flow Study

3.1. DG Units Connecting Styles to Power Network are Categorized as Below

1) Wind Turbines

Wind turbines are divided to constant and variable/floating speed. In the first group rotor of an inductive squirrel cage generator is rotated through a gearbox and the generator is directly connected to the power network, but in the second group a synchronic generator or a reference model is used. Output of these units is converted to the proper AC power by means of rectifiers and power electronic inverters for the network.

2) Fuel Cells

Fuel cells directly transform potential energy stored in the fuel to heat and electric energy without any electrical interface machine. Then Produced DC power is converted to AC power adapted to the network using an inverter.

3) Photovoltaic Systems

In photovoltaic systems solar energy is converted to DC current, then like fuel cells their DC output is converted to AC power that is adaptive with the network using an inverter.

4) Internal Combustion Engines

In an internal combustion engine the expansion of the high-temperature and high-pressure gases produced by combustion apply direct force to some component of the engine. The force is applied typically to pistons, turbine blades, or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy. Internal combustion engine driven generators are commonly used to produce electricity.

5) Gas Turbines

These units convert chemical energy stored in fossil fuels into heat and to mechanical energy finally synchronous or inductive generator that is directly connected to the network is rotated.

6)   Microturbine

These units operate the same way as gaseous turbines. The only difference is that a permanent magnet instead of rotating synchronous generator is rotated. So the generator is connected to the network via power electronic interfaces.

Concerning the points above, primary produced energy by DGs (generated by either of synchronous or asynchronous electric machines that are directly or indirectly connected to the network) would be injected to the network, using a combination of electric machines electronic interfaces or only the electronic interfaces may be involved.

3.2.   DG Model and Its Control Circuit Interface Characteristic

DGs model and converter control circuit characteristic are categorized as follow:

1)   Induction Generator Model

Generally, in an induction generator both active and reactive powers are functions of slip.

$$\begin{cases} P = P(V,S) \\ Q = Q(V,S) \end{cases}, \qquad (3)$$

where P and Q active and reactive power respectively, S is the slip of induction generator speed, and V is the bus voltage. Assuming P to be constant and neglecting the very low dependency of reactive power to the slip, the Eq. (3) can be expressed as follows:

$$\begin{cases} P = Ps = \mathrm{Cons\,tan}\,t \\ \quad Q = F(V) \end{cases}. \qquad (4)$$

The expressed model by Eq. (4), which is called SVCM, is an appropriate model of squirrel cage induction generator for power flow studies.

Since the bus voltages are near 1.0 pu in steady-state cases, squirrel cage induction generator can be modeled as a PQ bus for simplicity.

2)   Synchronous Generator Model

Depending on the excitation system, synchronous generators are divided into two categories:

- (a) with adjustable excitation voltage,

- (b) with constant excitation voltage.

The first case can be divided into two separate groups:

- (a1) voltage control mode or constant terminal voltage,

- (a2) power factor control mode or constant power factor.

DGs in subgroup (a1) and (a2) are modeled with PV and PQ buses respectively.

3)   Power Electronic Interface:

Power generated by photovoltaic, fuel cells, microturbines, and some wind farms are injected to network through power electronic converters. In this case power flow depends on controlling scheme that is used in converter control circuit. As a general rule, if the converter control circuit is designed to control P and V independently, the DG model shall be as a PV bus and when it is designed to control P and Q independently, the DG model shall be considered as a PQ bus.

3.3.   Incorporating DG Units in Power Flow Algorithm

The DG units, which are modeled as PQ nodes can be treated as negative PQ loads in power flow studies without any problem. However, handling PV nodes in power flow studies requires some additional processes. It should be noted that the generator terminal voltage is typically controlled by the specification of positive sequence component. So for a PV node, the three-phase active power output and positive sequence voltage of the generator are specified.

4.   Three-Phase Power Flow

Start point for developing node power equations that is suitable for solving three-phase power flow using Newton-Raphson method, describes the relation between injected current to a bus and its voltage. See transmission circuit shown in Fig. 1.

4.1.   Power Flow Equations

Equations for injected active and reactive power to three-phase buses k and m is obtained from following complex power equations:

$$\begin{bmatrix} S_k^{\mathrm{abc}} \\ S_m^{\mathrm{abc}} \end{bmatrix} = \begin{bmatrix} P_k^{\mathrm{abc}} + \mathrm{j}Q_k^{\mathrm{abc}} \\ P_m^{\mathrm{abc}} + \mathrm{j}Q_m^{\mathrm{abc}} \end{bmatrix} = \begin{bmatrix} E_k^{\mathrm{abc}} I_k^{\mathrm{abc}*} \\ E_m^{\mathrm{abc}} I_m^{\mathrm{abc}*} \end{bmatrix}, \qquad (5)$$
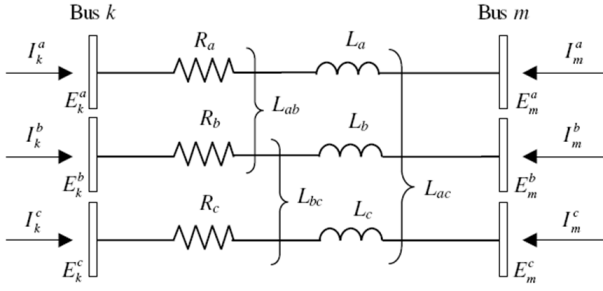
Fig. 1: Transmission lines model for three-phase power flow studies.

Following some complicated algebraic operations, Equations to express injected active and reactive power to phases a, b, c of bus k is acquired by:

$$P_k^\rho = V_k^\rho \left\{ \sum_{i=k,m} \sum_{j=a,b,c} V_i^j \left[G_{\text{ki}}^{\rho j} \cos\left(\theta_k^\rho - \theta_i^j\right) + B_{\text{ki}}^{\rho j} \sin\left(\theta_k^\rho - \theta_i^j\right) \right] \right\}, \quad (6)$$

$$Q_k^\rho = V_k^\rho \left\{ \sum_{i=k,m} \sum_{j=a,b,c} V_i^j \left[G_{\text{ki}}^{\rho j} \sin\left(\theta_k^\rho - \theta_i^j\right) - B_{\text{ki}}^{\rho j} \cos\left(\theta_k^\rho - \theta_i^j\right) \right] \right\}, \quad (7)$$

where ρ represents phases a, b, c.

As predicted phrases that are applied to calculate injected active and reactive power to bus m are like Eq. (6) and Eq. (7) with the difference that m replaces k and vice versa:

$$P_m^\rho = V_m^\rho \left\{ \sum_{i=k,j=a,b,c} V_i^j \left[G_{\text{mi}}^{\rho j} \cos\left(\theta_m^\rho - \theta_i^j\right) + B_{\text{mi}}^{\rho j} \sin\left(\theta_{\text{mk}}^\rho - \theta_i^j\right) \right] \right\}, \quad (8)$$

$$Q_m^\rho = V_m^\rho \left\{ \sum_{i=m,j=a,b,c} V_i^j \left[G_{\text{mi}}^{\rho j} \sin\left(\theta_m^\rho - \theta_i^j\right) - B_{\text{mi}}^{\rho j} \cos\left(\theta_m^\rho - \theta_i^j\right) \right] \right\}. \quad (9)$$

4.2. Newton-Raphson Power Flow Algorithm

Solving three-phase node power equations using Newton-Raphson method presents good certainty in converging.

Power Eq. (6) and Eq. (9) are linearized around a reference working point. In three phases application power difference and state variables are 3×1 vectors and each of them are independent terms of 3×3 Jacobean matrixes. Acquired linear equations that are suitable for solving iterative solution are as below:

$$\begin{bmatrix} \Delta P_l^\rho \\ \Delta Q_l^\rho \end{bmatrix}^{(i)} = \begin{bmatrix} \frac{\partial P_l^\rho}{\partial \theta_j^\rho} & \frac{\partial P_l^\rho}{\partial V_j^\rho} V_j^\rho \\ \frac{\partial Q_l^\rho}{\partial \theta_j^\rho} & \frac{\partial Q_l^\rho}{\partial V_j^\rho} V_j^\rho \end{bmatrix}^{(i)} \begin{bmatrix} \Delta \theta_j^\rho \\ \frac{\Delta V_j^\rho}{V_j^\rho} \end{bmatrix}^{(i)}, \quad (10)$$

where $L = k$, m and $j = k$, m and I is the number of iteration.

Vector statement is supposes like the below one:

$$\Delta P_l^\rho = \begin{bmatrix} \Delta P_k^a & \Delta P_k^b & \Delta P_k^c & \Delta P_m^a & \Delta P_m^b & \Delta P_m^c \end{bmatrix}^t, \quad (11)$$

$$\Delta Q_l^\rho = \begin{bmatrix} \Delta Q_k^a & \Delta Q_k^b & \Delta Q_k^c & \Delta Q_m^a & \Delta Q_m^b & \Delta Q_m^c \end{bmatrix}^t, \quad (12)$$

$$\Delta \theta_i^\rho = \begin{bmatrix} \Delta \theta_k^a & \Delta \theta_k^b & \Delta \theta_k^c & \Delta \theta_m^a & \Delta \theta_m^b & \Delta \theta_m^c \end{bmatrix}^t, \quad (13)$$

$$\frac{\Delta V_j^\rho}{V_j^\rho} = \begin{bmatrix} \frac{\Delta V_k^a}{V_k^a} & \frac{\Delta V_k^b}{V_k^b} & \frac{\Delta V_k^c}{V_k^c} & \frac{\Delta V_m^a}{V_m^a} & \frac{\Delta V_m^b}{V_m^b} & \frac{\Delta V_m^c}{V_m^c} \end{bmatrix}^t. \quad (14)$$

Jacobean array comprises:

$$\frac{\partial P_l^\rho}{\partial \theta_j^\rho} = \begin{bmatrix} \frac{\partial P_l^a}{\partial \theta_j^a} & \frac{\partial P_l^a}{\partial \theta_j^b} & \frac{\partial P_l^a}{\partial \theta_j^c} \\ \frac{\partial P_l^b}{\partial \theta_j^a} & \frac{\partial P_l^b}{\partial \theta_j^b} & \frac{\partial P_l^b}{\partial \theta_j^c} \\ \frac{\partial P_l^c}{\partial \theta_j^a} & \frac{\partial P_l^c}{\partial \theta_j^b} & \frac{\partial P_l^c}{\partial \theta_j^c} \end{bmatrix}, \quad (15)$$

$$\frac{\partial P_l^\rho}{\partial V_j^\rho} V_j^\rho = \begin{bmatrix} \frac{\partial P_l^a}{\partial V_j^a} V_j^a & \frac{\partial P_l^a}{\partial V_j^b} V_j^b & \frac{\partial P_l^a}{\partial V_j^c} V_j^c \\ \frac{\partial P_l^b}{\partial V_j^a} V_j^a & \frac{\partial P_l^b}{\partial V_j^b} V_j^b & \frac{\partial P_l^b}{\partial V_j^c} V_j^c \\ \frac{\partial P_l^c}{\partial V_j^a} V_j^a & \frac{\partial P_l^c}{\partial V_j^b} V_j^b & \frac{\partial P_l^c}{\partial V_j^c} V_j^c \end{bmatrix}, \quad (16)$$

$$\frac{\partial Q_l^\rho}{\partial \theta_j^\rho} = \begin{bmatrix} \frac{\partial Q_l^a}{\partial \theta_j^a} & \frac{\partial Q_l^a}{\partial \theta_j^b} & \frac{\partial Q_l^a}{\partial \theta_j^c} \\ \frac{\partial Q_l^b}{\partial \theta_j^a} & \frac{\partial Q_l^b}{\partial \theta_j^b} & \frac{\partial Q_l^b}{\partial \theta_j^c} \\ \frac{\partial Q_l^c}{\partial \theta_j^a} & \frac{\partial Q_l^c}{\partial \theta_j^b} & \frac{\partial Q_l^c}{\partial \theta_j^c} \end{bmatrix}, \quad (17)$$

$$\frac{\partial Q_l^\rho}{\partial V_j^\rho} V_j^\rho = \begin{bmatrix} \frac{\partial Q_l^a}{\partial V_j^a} V_j^a & \frac{\partial Q_l^a}{\partial V_j^b} V_j^b & \frac{\partial Q_l^a}{\partial V_j^c} V_j^c \\ \frac{\partial Q_l^b}{\partial V_j^a} V_j^a & \frac{\partial Q_l^b}{\partial V_j^b} V_j^b & \frac{\partial Q_l^b}{\partial V_j^c} V_j^c \\ \frac{\partial Q_l^c}{\partial V_j^a} V_j^a & \frac{\partial Q_l^c}{\partial V_j^b} V_j^b & \frac{\partial Q_l^c}{\partial V_j^c} V_j^c \end{bmatrix}. \quad (18)$$

It should be noted that linear Eq. (10) is only applied to one three-phase transmission line between m and k buses. However, the result can simply be generalized to a more practical one than includes nl transmission lines between nb buses l and j where $l = 1, \ldots, k, m, \ldots n_b - 1$ and $j = 1, \ldots k, m, \ldots n_b - 1$, Also when slack bus is not stated in linear equations, there will be only $n_b - 1$ buses. It is supposed that element number l in Eq. (10) is connected between k and m buses. Self and mutual Jacobean statement are simply calculated as below, where $\rho1 = \rho2$ are used for phases a, b, c respectively.

For $k = m$ and $\rho1 = \rho2$:

$$\frac{\partial P_{k,l}^{\rho 1}}{\partial \theta_{k,l}^{\rho 1}} = -Q_k^{\rho 1 \text{cal}} - \left(V_k^{\rho 1}\right)^2 B_{\text{kk}}^{\rho 1 \rho 1}, \quad (19)$$

$$\frac{\partial P_{k,l}^{\rho 1}}{\partial V_{k,l}^{\rho 1}} V_k^{\rho 1} = P_k^{\rho 1 \text{cal}} + \left(V_k^{\rho 1}\right)^2 G_{\text{kk}}^{\rho 1 \rho 1}, \quad (20)$$

$$\frac{\partial Q_{k,l}^{\rho 1}}{\partial \theta_{k,l}^{\rho 1}} = P_k^{\rho 1 \text{cal}} - \left(V_k^{\rho 1}\right)^2 G_{\text{kk}}^{\rho 1 \rho 1}, \quad (21)$$

$$\frac{\partial Q_{k,l}^{\rho 1}}{\partial V_{k,l}^{\rho 1}} V_{k,l}^{\rho 1} = Q_k^{\rho 1\,\mathrm{cal}} - \left(V_k^{\rho 1}\right)^2 B_{kk}^{\rho 1 \rho 1}. \qquad (22)$$

For $k = m$ and $\rho 1 \neq \rho 2$:

$$\frac{\partial P_{k,l}^{\rho 1}}{\partial \theta_{k,l}^{\rho 2}} = V_k^{\rho 1} V_k^{\rho 2} \left[G_{kk}^{\rho 1 \rho 2} \sin\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right) - B_{kk}^{\rho 1 \rho 1} \cos\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right)\right], \quad (23)$$

$$\frac{\partial P_{k,l}^{\rho 1}}{\partial V_{k,l}^{\rho 2}} V_{k,l}^{\rho 2} = V_k^{\rho 1} V_k^{\rho 2} \left[G_{kk}^{\rho 1 \rho 2} \cos\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right) + B_{kk}^{\rho 1 \rho 1} \sin\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right)\right], \quad (24)$$

$$\frac{\partial Q_{k,l}^{\rho 1}}{\partial \theta_{k,l}^{\rho 2}} = -V_k^{\rho 1} V_k^{\rho 2} \left[G_{kk}^{\rho 1 \rho 2} \cos\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right) + B_{kk}^{\rho 1 \rho 1} \sin\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right)\right], \quad (25)$$

$$\frac{\partial Q_{k,l}^{\rho 1}}{\partial V_{k,l}^{\rho 2}} V_{k,l}^{\rho 2} = V_k^{\rho 1} V_k^{\rho 2} \left[G_{kk}^{\rho 1 \rho 2} \sin\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right) - B_{kk}^{\rho 1 \rho 1} \cos\left(\theta_k^{\rho 1} - \theta_k^{\rho 2}\right)\right], \quad (26)$$

For $k \neq m$:

$$\frac{\partial P_{k,l}^{\rho 1}}{\partial \theta_m^{\rho 2}} = V_k^{\rho 1} V_m^{\rho 2} \left[G_{km}^{\rho 1 \rho 2} \sin\left(\theta_k^{\rho 1} - \theta_m^{\rho 2}\right) - B_{km}^{\rho 1 \rho 1} \cos\left(\theta_k^{\rho 1} - \theta_m^{\rho 2}\right)\right], \quad (27)$$

$$\frac{\partial P_{k,l}^{\rho 1}}{\partial V_{m,l}^{\rho 2}} V_{m,l}^{\rho 2} = V_k^{\rho 1} V_m^{\rho 2} \left[G_{km}^{\rho 1 \rho 2} \cos\left(\theta_k^{\rho 1} - \theta_m^{\rho 2}\right) + B_{km}^{\rho 1 \rho 1} \sin\left(\theta_k^{\rho 1} - \theta_m^{\rho 2}\right)\right], \quad (28)$$

$$\frac{\partial Q_{k,l}^{\rho 1}}{\partial \theta_m^{\rho 2}} = -V_k^{\rho 1} V_m^{\rho 2} \left[G_{km}^{\rho 1 \rho 2} \cos\left(\theta_k^{\rho 1} - \theta_m^{\rho 2}\right) + B_{km}^{\rho 1 \rho 1} \sin\left(\theta_k^{\rho 1} - \theta_{mk}^{\rho 2}\right)\right], \quad (29)$$

$$\frac{\partial Q_{k,l}^{\rho 1}}{\partial V_{m,l}^{\rho 2}} V_{m,l}^{\rho 2} = V_k^{\rho 1} V_m^{\rho 2} \left[G_{km}^{\rho 1 \rho 2} \sin\left(\theta_k^{\rho 1} - \theta_m^{\rho 2}\right) - B_{km}^{\rho 1 \rho 1} \cos\left(\theta_k^{\rho 1} - \theta_m^{\rho 2}\right)\right], \quad (30)$$

Iterative power flow solution using Newton-Raphson method needs observation of points applied for positive sequence solutions i.e. specify primary value to the state variable and checking required reactive power for the generator. In three-phase application voltages a, b, c primary phase angles are valued 0, $-2\pi/3$ and $2\pi/3$ respectively.

5. Three-phase Power Flow Computer Simulation Results of a 4 Buses IEEE Distribution Network

IEEE 4 buses distribution network includes an infinite bus, load, a transformer and two lines that its single line diagram is illustrated in Fig. 2 and its data is collected in [20]. In the next section, outputs resulted from Newton-Raphson method for three-phase power flow in an unbalanced condition with and without DG are presented. As the goal of this paper is the study of DG's impact on voltage profile and power system losses in an unbalanced condition, so despite the DG's type all of DGs' are modeled as PV or PQ and their location is selected randomly based on trial and error method.
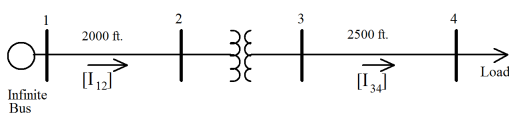
Fig. 2: IEEE four buses single line diagram.

5.1. Three-phase Power Flow Without DG

To evaluate the certainty of the computer program and algorithm, results of some of three-phase power flow with different transformer connections are added and are compared with results of reference [9] as shown in Tab. 1.

Tab. 1: Comparison between three-phase power flow and reference network.

Transformer Connection		Gr Y − Gr Y		Gr Y − D	
		Suggested Algorithm Result	IEEE [9]	Suggested Algorithm Result	IEEE [9]
Bus Voltage 2					
Va	**(V)**	7108.2	7107	7115.8	7113
	deg	−0.34	−0.3	−0.32	−0.3
Vb	**(V)**	7143.3	7140	7129.6	7132
	deg.	−120.33	−120.3	−120.31	−120.3
Vc	**(V)**	7121.4	7121	7130.6	7123
	deg.	119.65	119.6	119.61	119.6
Bus Voltage 4					
Va	**(V)**	1919.4	1918	3534.4	3437
	deg.	−9.19	−9.1	−5.8	−7.8
Vb	**(V)**	2073	2061	3269.8	3497
	deg.	−128.16	−128.3	−128.97	−129.3
Vc	**(V)**	1977.9	1981	3566	3388
	deg.	111	110.9	108.55	110.6

Table 1 represent voltage magnitude and phase angle in buses of distribution network. For example in bus four; voltage amplitude and phase angle of phase a are 1919.4 volts and −9.19°, these values have been recorded 1918 volts with −9.1° in reference [9]; comparison between these two validate suggested algorithm. Voltage profile and network losses will be studied. In Fig. 3 voltages magnitudes are shown, and it is observed that bus four has the worst condition from phase's voltage profile point of view.

Figure 4 demonstrates active power losses in phases A, B, C of lines 1-2, transformer and lines 3-4 as well as total network active and reactive power losses which are 0.32157 and 0.88962 respectively.
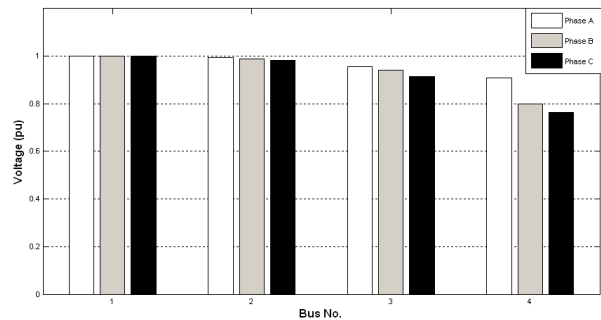
Fig. 3: Voltage magnitude in absence of DG.

In Tab. 2, four buses simulation results without DG are shown. By observing Tab. 2, it can be seen that NEMA and IEEE unbalance factor in bus 4 has the
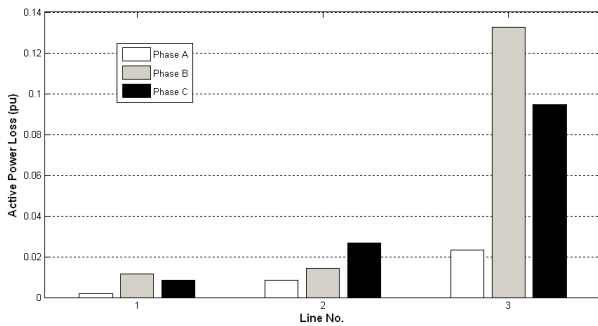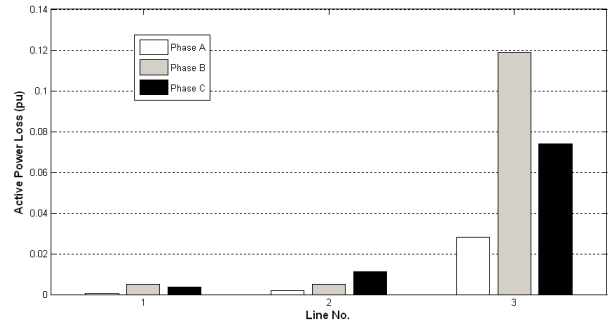
Fig. 4: Power losses in absence of DG.

most value; that means voltage unbalance in the worst case is 0.10124 and 0.064413 respectively.

Tab. 2: 4 buses network results – without DG.

Bus Number	1	2	3	4
Phase 'A' Voltage Mag. (pu)	1	0.99562	0.95604	0.90742
Phase 'B' Voltage Mag. (pu)	1	0.98735	0.94217	0.80043
Phase 'C' Voltage Mag. (pu)	1	0.98377	0.91608	0.76415
Phase 'A' Voltage Angle (Deg)	0.0	−0.12	−2.40	−4.04
Phase 'B' Voltage Angle (Deg)	−120	−120.13	−123.52	101.83
Phase 'C' Voltage Angle (Deg)	120	119.21	114.81	111
Zero Sequence	1.67×10^{-16}	0.0066923	0.016967	0.093352
Neg. Sequence	1.11×10^{-16}	0.0030186	0.018371	0.052771
NEMA Unbala. Factor	0	0.0067791	0.023472	0.10124
IEEE Unbala. Factor	1.11×10^{-16}	0.0030525	0.019588	0.064413

5.2. Three-phase Power Flow with PQ Model of DG

If DG is modeled like PQ and installed in bus 3 with the value of $0.3 + j0.4$ pu for each phase, implementing three-phase power flow will lead to results shown in Fig. 5 for bus voltage amplitude in phases A, B, C. In compare to previous scheme phases voltage unbalance specially in bus four has been reduced and voltage profile has been improved in the entire network.
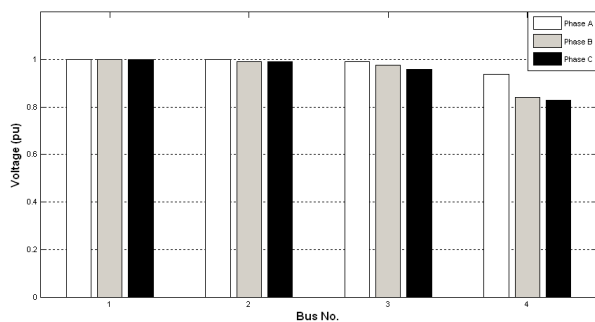

Fig. 5: Voltage amplitude with PQ model of DG.

Fig. 6: Active power losses with PQ model of DG.

Tab. 3: 4 buses network results with PQ model of DG.

Bus Number	1	2	3	4
Phase 'A' Voltage Mag. (pu)	1	1.0006	0.99033	0.93808
Phase 'B' Voltage Mag. (pu)	1	0.9922	0.97733	0.83997
Phase 'C' Voltage Mag. (pu)	1	0.99153	0.96025	0.82803
Phase 'A' Voltage Angle (Deg)	0.0	−0.07	−1.48	−2.72
Phase 'B' Voltage Angle (Deg)	−120	−120.13	−122.51	−125.27
Phase 'C' Voltage Angle (Deg)	120	119.29	116.01	104.68
Zero Sequence	1.67×10^{-16}	0.0061001	0.015253	0.08411
Neg. Sequence	1.11×10^{-16}	0.0022112	0.015113	0.045399
NEMA Unbala. Factor	0	0.0058741	0.016107	0.079875
IEEE Unbala. Factor	1.11×10^{-16}	0.0022228	0.015488	0.052495

Figure 6 shows phases A, B, C active power losses in lines 1-2, transformer and lines 3-4 as well as total active and reactive network losses which are 0.24673 and 0.60588 respectively.

In Tab. 3, four buses simulation results with the PQ model of DG are shown. By observing Tab. 4, it can be seen that NEMA and IEEE unbalance factors in all buses are improved; that means voltage unbalance in the worst case is 0.079875 and 0.052495 respectively. These are better factors in compared to without DG condition.

5.3. Three-phase Power Flow in Presence of PV Model of DG

If DG is modeled like PV, installed in bus 3 and its active power for each phase and voltage amplitude set to 0.3 pu and 1 pu respectively a better improvement will be observed in voltage profile in compare to that for the PQ model. Buses voltage amplitude in phases A, B, C is plotted in Fig. 7.

Figure 8 shows active power losses in phases a, b, c in lines 1-2, transformer and lines 3-4. Network total active and reactive power losses are 0.22577 and 0.55086 respectively.

In Tab. 4, four buses simulation results with PV model of DG are shown. By observing Tab. 5, it can be seen that NEMA and IEEE unbalance factors in all buses are improved; that means voltage unbalance in the worst case is 0.050001 and 0.0444418 respectively. These factors in comparison to the case without DG are better.
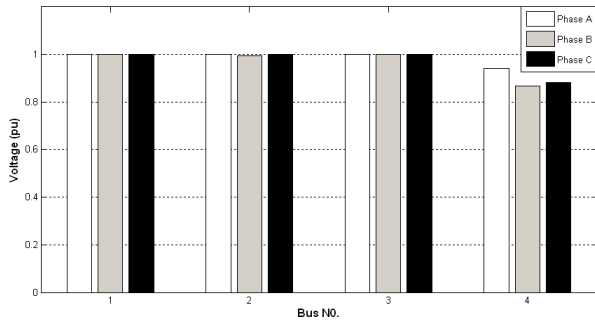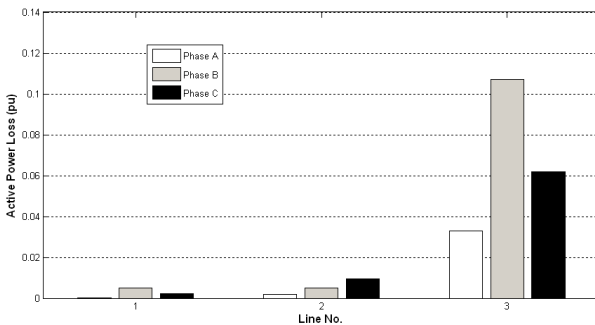

Fig. 7: Voltage amplitude with PV model of DG.

Fig. 8: Active power loses with PV model of DG.

Tab. 4: 4 buses network results with PQ model of DG.

Bus Number	1	2	3	4
Phase 'A' Voltage Mag. (pu)	1	0.99967	1	0.94178
Phase 'B' Voltage Mag. (pu)	1	0.9947	1	0.8678
Phase 'C' Voltage Mag. (pu)	1	0.99945	1	0.88119
Phase 'A' Voltage Angle (Deg)	0.0	−0.04	−1.55	−2.70
Phase 'B' Voltage Angle (Deg)	−120	−120.38	−122.85	−125.83
Phase 'C' Voltage Angle (Deg)	120	119.25	115.87	105.81
Zero Sequence	1.67×10^{-16}	0.0051727	0.012913	0.072333
Neg. Sequence	1.11×10^{-16}	0.00019602	0.013082	0.039696
NEMA Unbala. Factor	0	0.0032301	0	0.050001
IEEE Unbala. Factor	1.11×10^{-16}	0.0019643	0.013084	0.044418

5.4. Comparison Between Three-phase Power Flow in Different Cases

Table 5 shows minimum and maximum voltage amplitude, total active and reactive power losses and NEMA and IEEE unbalance factor in different conditions with and without DG. These results showed that in the presence of DGs, losses and voltage unbalance are reduced.

Tab. 5: Comparing results of four buses network.

Different Cases of three-phase power flow	Whitout DG	Whit DG PQ model	Whit DG PV model
Total active power losses (pu)	0.32157	0.24673	0.22577
Total reactive power losses (pu)	0.88963	0.60588	0.55086
Maximum voltage amplitude (pu)	1	1.0006	1
Minimum voltage amplitude (pu)	0.76415	0.82803	0.8678
NEMA Unbalance Factor	0.10124	0.079875	0.050001
IEEE Unbalance Factor	0.064413	0.052495	0.044418

6. Conclusion

A useful list of DG models with their method of connection to the network (direct or indirect) for power flow studies is considered in this paper. DG's model for power flow studies selected based on initial energy of DG unit that is injected to the network through an electrical machine(which is directly connected to the network). Also, DGs are connected to the network through a power electronic interface, or through combination of the electric machine beside power electronic interface.

With the suggested newton-Raphson three-phase power flow algorithm it is possible to study DGs in PV and PQ models and good divergence of this algorithm makes it to be the most successful method accepted in the industry. DGs reduce network losses and improve voltage profile.

References

[1] JOUANNE, A. and B. BANERJEE. Assessment of Voltage Unbalance. *IEEE Trans. on power delivery.* 2001, vol. 16, no. 4, pp. 782–790. ISSN 0885-8977. DOI: 10.1109/61.956770.

[2] PILLAY, P. and M. MANYAGE. Definitions of voltage unbalance. *IEEE Power Engineering Review.* 2001, vol. 21, no. 5, pp. 49–51. ISSN 0272-1724. DOI: 10.1109/MPER.2001.4311362.

[3] SANTOS VALOIS, P. V., C. M. VIEIRA TAHAN, N. KAGAN and H. ARANGO. Voltage unbalance

in low voltage distribution networks. In: *International Conference and Exhibition on Electricity Distribution*. Amsterdam: IET, 2001, pp. 1–5. ISBN 0-85296-735-7. DOI: 10.1049/cp:20010770.

[4] CHEN, T. H., M. S. CHEN, T. INOUE, P. KOTAS, and E. A. CHEBLI. Three-phase co-generator and transformer models for distribution system analysis. *IEEE Transactions On Power Delivery*. 1991, vol. 6, no. 4, pp. 1671–1681. ISSN 0885-8977. DOI: 10.1109/61.97706.

[5] CHOQUE, J. L., D. RODAS and A. PADILHA-FELTRIN. Distribution Transformer Modeling for Application in Three-phase Power Flow Algorithm. *IEEE Latin America Transaction*. 2009, vol. 7, no. 24, pp. 196–202. ISSN 1548-0992. DOI: 10.1109/TLA.2009.5256829.

[6] CORCOLES, F., L. SAINZ, J. PEDRA, J. SANCHEZ-NAVARRO and M. SALICHS. Three-phase Transformer Modelling for Unbalanced Conditions. *IET Electric Power Applications*. 2008, vol. 2, no. 2, pp. 99–112. ISSN 1751-8660. DOI: 10.1049/iet-epa:20070290.

[7] PALMA-BEHNKE, R., J. L. A. CERDA, L. S. VARGAS and A. JOFRE. A distribution company energy acquisition market model with integration of distributed generation and load curtailment options. *IEEE Trans. on Power Systems*. 2005, vol. 20, no. 4, pp. 1718–1727. ISSN 0885-8950. DOI: 10.1109/TPWRS.2005.857284.

[8] LI, H., Y. LI and Z. LI. A multi-period energy acquisition model for a distribution company with distributed generation and interruptible load. *IEEE Trans. on Power Systems*. 2007, vol. 22, no. 2, pp. 588–596. ISSN 0885-8950. DOI: 10.1109/TPWRS.2007.894862.

[9] IEEE PES. *Distribution Test Feeders* [online]. 2013. Available in http://ewh.ieee.org/soc/pes/dsacom/testfeeders/index.html.

[10] CHEN, M.-S. and T.-H. CHEN. Application of Three-phase Load Flow to Power System Distribution Automation. In: *International Conference on Advances in Power System Control, Operation and Management*. Hong Kong: IEEE, 1991, pp. 472–478. ISBN 0-86341-246-7.

[11] LUO, G. X. and A. SEMLYEN. Efficient load flow for large weakly meshed networks. *IEEE Trans. on Power Systems*. 1990, vol. 5, no. 4, pp. 1309–1316. ISSN 0885-8950. DOI: 10.1109/59.99382.

[12] CHENG, C. S. and D. SHIRMOHAMMADI. A three-phase power flow method for real-time distribution system analysis. *IEEE Trans. on Power Systems*. 1995, vol. 10, no. 2, pp. 671–679. ISSN 0885-8950. DOI: 10.1109/59.387902.

[13] KHUSHALANI, S. and N. SCHULZ. Unbalanced distribution power flow with distributed generation. In: *Transmission and Distribution Conference and Exhibition*. Dallas: IEEE, 2006, pp. 301–306. ISBN 0-7803-9194-2. DOI: 10.1109/TDC.2006.1668508.

[14] KHUSHALANI, S., J. M. SOLANKI and N. N. SCHULZ. Development of three-phase unbalanced power flow using PV and PQ models for distributed generation and study of the impact of DG models. *IEEE Trans. on Power Systems*. 2007, vol. 22, no. 3, pp. 1019–1025. ISSN 0885-8950. DOI: 10.1109/TPWRS.2007.901476.

[15] AGALGAONKAR, A. P., S. V. KULKARNI and S. A. KHAPARDE. Impact of wind generation on loss and voltage profile in a distribution system. In: *Conference on Convergent Technologies for Asia-Pacific Region*. Bangalore: IEEE, 2003, pp. 775--779. ISBN 0-7803-7651-X.

[16] TENG, J.-H. Modelling for Distributed Generation in Three-Phase Distribution Load Flow. *IET Generation, Transmission & Distribution*. 2008, vol. 2, no. 3, pp. 330–340. ISSN 1751-8687. DOI: 10.1049/iet-gtd:20070165.

[17] SHIQIONG, T. and K. N. MIU. A Network-Based Distributed Slack Bus Model for DGs in Unbalanced Power Flow Studies. *IEEE Trans. on Power Systems*. 2005, vol. 20, no. 2, pp. 835–842. ISSN 0885-8950. DOI: 10.1109/TPWRS.2005.846056.

[18] MOGHADDAS-TAFRESHI, S. M. and E. MASHHOUR. Distributed Generation Modeling for Power Flow Studies and a Three-Phase Unbalanced Power Flow Solution for Radial Distribution Systems Considering Distributed Generation. *Electric Power Systems Research*. 2009, vol. 79, no. 4, pp. 680–686. ISSN 0378-7796. DOI: 10.1016/j.epsr.2008.10.003.

[19] CHEN, H., J. CHEN, D. SHI and X. DUAN. Power flow study and voltage stability analysis for distribution systems with distributed generation. In: *Power Engineering Society General Meeting*. Montreal: IEEE, 2006, pp. 1–8. ISBN 1-4244-0493-2. DOI: 10.1109/PES.2006.1709198.

[20] NIKNAM, T., H. ZEINODDINI-MEYMAND, H. DOAGOU-MOJARRAD and J. AGHAEI. Multi-objective Daily Operation Management of distribution network considering Fuel Cell Power Plants. *IET Renewable Power Generation*. 2011, vol. 5, no. 5, pp. 356–367. ISSN 1752-1416. DOI: 10.1049/iet-rpg.2010.0190.

[21] NIKNAM, T., A. KAVOUSIFARD and J. AGHAEI. Optimal operation management of fuel cell/wind/photovoltaic power sources connected to distribution networks. *Journal of Power Sources*. 2001, vol. 196, no. 20, pp. 8881–8896. ISSN 0378-7753. DOI: 10.1016/j.jpowsour.2011.05.081.

[22] NIKNAM, T., A. KAVOUSIFARD and J. AGHAEI. Scenario-Based Multi-objective Distribution Feeder Reconfiguration considering Wind Power Using Adaptive Modified PSO. *IET Renewable Power Generation*. 2012, vol. 6, no. 4, pp. 236-247. ISSN 1752-1416. DOI: 10.1049/iet-rpg.2011.0256.

About Authors

Hassan BARATI was born in Dezful, Iran, in 1969. He received his B.Sc degree in electronic engineering from the Isfahan University of Technology, Isfahan, Iran in 1992. He received his M.Sc degree in electrical engineering from the Tabriz University in 1996. He obtained the Ph.D. degree in Electrical Engineering from the Islamic Azad University, Science and Research Branch, Tehran, Iran, in 2007. His research interests are power system analysis, restructured power system, FACTS devices, DGs and renewable energies.

Abdol Rasool FATHI was born in Larestan, Iran. He received his B.Sc degree in electronic engineering from the Islamic Azad University, Kazeroun Branch, Kazeroun, Iran in 1999. He received his M.Sc degree in electrical engineering from the Islamic Azad University, Dezful Branch in 2011. His research interests are power system analysis and FACTS devices.