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Voltage Control and Unbalance Compensation Operation Modes of DGs

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Abstract: Considering the important role of Distributed Generation (DG) in the future distribution networks there is a need for effective algorithms and models to integrate DGs in distribution system power flow analysis. The forward/backward method is a relatively simple and efficient method that has been widely used for distribution system load flow. This study integrates a more detailed model of DGs in forward/backward power flow formulation. DGs, operating as remote voltage controller or partial unbalance compensator are modeled in this power flow formulation. Also, the conventional operation mode of DGs as constant voltage source and constant power factor system is modeled. The proposed unbalanced power flow algorithm is capable of switching between DG's different operation modes. The developed software is verified by comparing the results of the distribution system which does not have any DG with the result of IEEE 37 bus test system. Then, the power flow is carried out in various cases to demonstrate the different features incorporated in the developed algorithm and study the impact of different operation modes of DGs on the voltage profile.

Key words: Distributed generation, distribution system power flow, forward/backward method, remote voltage control, partial unbalance compensation, radial system analysis

INTRODUCTION

The load flow programs are one of the essential tools for the simulation of the power system. An effective load flow method should have the ability to accurately model different characteristics of the power system and its components. Two basic approaches have been used to deal with the power flow problem (Garcia *et al*., 2001):

- Newton-Raphson and Newton like methods
- Load flow for radial networks

The distribution system has some specific features such as radial or semi-radial topology, higher resistance to reactance ratio (R/X), asymmetric structures, grounded or ungrounded operation modes, asymmetric distributed loads along branches, great number of buss and branches and distributed generation units (Mok *et al*., 1999; Teng, 2000).

Because of the above mentioned features, the Fast Decoupled Newton-Raphson (FDNR) Method is not suitable for the distribution system analysis. There are some approaches that have tried to modify the conventional FDNR method in order to use it for distribution power flow studies. A FDNR power flow method has been presented by Zimmerman and Chiang (1995) which takes into account the unbalanced and radial topology of distribution systems (Lin *et al*., 1999) has modified the FDNR Method to develop a power flow with less data preparation. The Jacobean matrix in this method can be decoupled both in phases and real and imaginary parts.

Although, the Newton like methods have been adapted to converge in radial feeders but still radial networks specific methods are widely used for analyzing distribution networks, since they utilize the radial structure to minimize the required memory and calculations. Xu *et al*. (1998) have used the concept of component level modeling for a generalized formulation of power flow which has been implemented in EMTP. A direct approach for unbalanced networks has been used by Teng (2003) that tries to use the special topological characteristics of distribution networks by introducing two matrices, the bus-injection to branch-current and the branch-current to bus-voltage matrices. The unbalanced power flow has been carried out by Ulinuha *et al*. (2007) by using the forward/backward propagation method (Teng, 2000; Cheng and Shirmohammadi, 1995; Khushalani and Schulz, 2006; Khushalani *et al*., 2007) have improved the forward/backward method which is very suitable for the radial networks.

New components such as FACTS elements and DGs, should be modeled in these programs. Cheng and Shirmohammadi (1995) have presented a new method for the distribution system load flow that considers the effect of the PV buses, voltage regulators and shunt capacitors. Khushalani *et al*. (2007) have used the presented method by Cheng and Shirmohammadi (1995) with more details for distributed generation (Khushalani and Schulz, 2006). A detailed power for three phase unbalanced terrestrial distribution system has been developed in Khushalani *et al*. (2007). In this research, the distributed generator buss have been modeled as PQ and PV buses. This solution can handle multiple DGs and allows the switching of DG modes from constant voltage to constant power.

DGs are also capable of controlling the voltage of a nearby bus by considering a P bus that controls the voltage of PQV bus remotely, known as voltage remote control. This is especially useful in cases where the local reactive current compensation is not available. In (Garcia *et al*., 2001), a model for remote bus voltage control has been presented which is suitable to be used with the Three-phase Current Injection Method (TCIM) for power flow calculations but this model cannot be applied to the forward/backward method which has a complete different type of formulation.

In this study, a detailed model of DG units which can be used in forward/backward method is presented. The new model takes into account the DG operation mode as remote voltage controller as well as the conventional modes as PQ and PV buses. Also, modeling of new DG units which control the current of each phase separately in current control mode and therefore are able to compensate the voltage unbalance is included in this model.

MATERIALS AND METHODS

Distribution generation modeling: Depending on the control strategy, the DG output power may be set at either constant power factor or constant voltage. The DG may also control its bus voltage or the voltage of adjacent buses. Thus, four types of DG models are developed in this study.

Type 1: PQ buses which have constant P and Q (for small DGs) and modeled as a negative load with constant current injection into the buses.

Type 2: PV buses (for large DGs) which can be used for local control.

Type 3: P-buses (for large DGs) which can be used for remote control.

Type 4: PV-buses which can inject currents to three phases separately to compensate unbalanced voltages. In forward/backward power flow method, all types of DGs can be modeled by using an iterative method in which the injecting current of the DG (I_q) is updated by using the Eq. 1, until the voltage mismatches (ΔV) of the specified buses (from defined values) is less than the minimum acceptable value (Cheng and Shirmohammadi, 1995):

$$\Delta I_q = Z_s^{-1} * \Delta V_1 \quad (1)$$

In Eq. 1 Z_s is an $n_i \times n_i$ matrix known as the sensitivity impedance matrix. However, forming the sensitivity matrix is different for above mentioned types of DGs.

Sensitivity matrix

Type 1 (PQ bus): DGs, operating at a constant power factor, inject constant amount of reactive current. Therefore, the ΔI_q will be zero for these DGs and they are not included in the sensitivity matrix and simply modeled as negative loads.

Type 2 (PV bus): Suppose that after an iteration, the power flow has converged and the voltage magnitudes at PV buses are not equal to the scheduled values. In order to obtain the scheduled voltage magnitude at a PV-bus, the correct amount of reactive power or reactive current injection generated by the unit should be determined. Therefore, the problem of compensating PV-bus voltage magnitude is expressed as follows:

Find the reactive current injection for each PV bus so that the voltage magnitude of the specified buses is equal to the scheduled values.

Since, the relation between I_q and $|V|$ is not linear, I_q is determined iteratively. In most cases, the average of the voltage magnitude of all three phases is the voltage magnitude that is regulated. Then, the use of the positive sequence representation for voltage regulation makes it possible to properly represent the Automatic Voltage Regulation (AVR) of a generating unit. The incremental relation between the magnitude of the positive sequence voltage ΔV_1^i and the magnitude of the positive sequence reactive current injection ΔI_q^j is expressed by using the sensitivity matrix, Z_{ij} as follows:

$$\Delta V_1^i = Z_{ij} . \Delta I_q^j \quad (2)$$

The ith column of the sensitivity matrix which determines the effect of the reactive current injection in ith PV-bus on voltages of other PV-buses is calculated by varying from zero to unity when all loads and sources have been removed and the voltage differences in all PV buses have been determined (Cheng and Shirmohammadi, 1995). The dimension of the sensitivity matrix is $n_{PV}\times n_{PV}$, where n_{PV} is the number of PV buses. The sensitivity matrix is as follows:

$$\begin{bmatrix}\Delta V_1\\ \vdots\\ \Delta V_j\\ \Delta V_i\\ \Delta V_n\end{bmatrix}=\begin{bmatrix}Z_{11} & \cdots & Z_{1j} & Z_{1i} & Z_{1n}\\ \vdots & . & \vdots & \vdots & \vdots\\ Z_{j1} & \cdots & Z_{jj} & Z_{ji} & Z_{jn}\\ Z_{i1} & \cdots & Z_{ij} & Z_{ii} & Z_{in}\\ Z_{n1} & \cdots & Z_{nj} & Z_{nk} & Z_{nn}\end{bmatrix}\begin{bmatrix}\Delta I_1\\ \vdots\\ \Delta I_j\\ \Delta I_i\\ \Delta I_n\end{bmatrix} \quad (3)$$

The diagonal element, Z_{ii} is equal to the sum of the positive sequence impedance of all line sections between PV-bus I and the root bus (substation bus). If two PV-buses, i and j have completely different path to the root bus then the off-diagonal element, Z_{ij} is equal to zero. If i and j share a piece of a common path to the root bus then Z_{ij} is equal to the sum of the positive sequence impedance of all line sections on this common path. Thus, the sensitivity matrix $[Z_{ij}]$ can be formed by identifying the paths between PV buses and the root bus.

Type 3 (remote voltage controller): The remote voltage controller adjusts the voltage magnitude of a distribution bus by a DG unit which is not connected to the same bus. The modeling of the remote voltage control requires the consideration of a so called PQV bus which will be controlled by a new P type bus. For a general system having a P bus i, controlling the voltage at a PQV bus k, a similar procedure can be used for calculating the sensitivity matrix. The sensitivity matrix in this case is as follows:

$$\begin{bmatrix}\Delta V_1\\ \vdots\\ \Delta V_j\\ \Delta V_k\\ \Delta V_n\end{bmatrix}=\begin{bmatrix}Z_{11} & \cdots & Z_{1j} & Z_{1i} & Z_{1n}\\ \vdots & . & \vdots & \vdots & \vdots\\ Z_{j1} & \cdots & Z_{jj} & Z_{ji} & Z_{jn}\\ Z_{k1} & \cdots & Z_{kj} & Z_{ki} & Z_{kn}\\ Z_{n1} & \cdots & Z_{nj} & Z_{nk} & Z_{nn}\end{bmatrix}\begin{bmatrix}\Delta I_1\\ \vdots\\ \Delta I_j\\ \Delta I_i\\ \Delta I_n\end{bmatrix} \quad (4)$$

In Eq. 4 ΔV_i and Z_{ij} are replaced by ΔV_k and Z_{kj}, respectively. The voltage variation of the bus k is related to the reactive current variation of the bus i. Z_{kj} is equal to the sum of the positive sequence impedance of all line sections on the common path between buses k and i to the root bus.

Type 4 (unbalance compensator): Conventional AVR systems which use positive sequence voltage as a reference for voltage regulation, inject the same amount of reactive power to each phase. Therefore, although they compensate for the voltage drop of the bus but the voltage unbalance can still remain. Current source converters and other new DG technologies which are capable of injecting different currents to the three phases can partially compensate for the voltage unbalance. To model these devices in the radial forward/backward power flow, the sensitivity matrix has to be modified. The calculation of each is similar to the PV model but since in this case the voltage mismatch value for each DG, ΔV_i will be a vector as well as ΔVI_q it means that to calculate, Z_{ij} the 3×3 impedance matrixes will be summed up in the common path of two DGs to the root bus. Thereby, the Z_{ij} is a 3×3 matrix. For example, the sensitivity matrix of two DGs will be in the following form:

$$\begin{bmatrix}\begin{bmatrix}\Delta V_{a1}\\ \Delta V_{b1}\\ \Delta V_{c1}\end{bmatrix}\\ \begin{bmatrix}\Delta V_{a2}\\ \Delta V_{b2}\\ \Delta V_{c2}\end{bmatrix}\end{bmatrix}=\begin{bmatrix}\begin{bmatrix}z_{aa} & z_{ab} & z_{ac}\\ z_{ba} & z_{bb} & z_{bc}\\ z_{ca} & z_{cb} & z_{cc}\end{bmatrix}_{11} & \begin{bmatrix}z_{aa} & z_{ab} & z_{ac}\\ z_{ba} & z_{bb} & z_{bc}\\ z_{ca} & z_{cb} & z_{cc}\end{bmatrix}_{12}\\ \begin{bmatrix}z_{aa} & z_{ab} & z_{ac}\\ z_{ba} & z_{bb} & z_{bc}\\ z_{ca} & z_{cb} & z_{cc}\end{bmatrix}_{21} & \begin{bmatrix}z_{aa} & z_{ab} & z_{ac}\\ z_{ba} & z_{bb} & z_{bc}\\ z_{ca} & z_{cb} & z_{cc}\end{bmatrix}_{22}\end{bmatrix}\begin{bmatrix}\begin{bmatrix}\Delta I_{a1}\\ \Delta I_{b1}\\ \Delta I_{c1}\end{bmatrix}\\ \begin{bmatrix}\Delta I_{a2}\\ \Delta I_{b2}\\ \Delta I_{c2}\end{bmatrix}\end{bmatrix} \quad (5)$$

Distribution system power flow

Bus renumbering: Buses in the radial network are renumbered by layers away from the root bus (substation or slack bus) (Shirmohammadi *et al*., 1988). Branch numbering is not necessary as branch orders are equal to their end bus number. Figure 1 shown the renumbering scheme for a radial distribution system.

Sensitivity matrix: The sensitivity matrix calculation method has been presented in this study.

Initialization: In this step, it is supposed that all the voltage control devices initially operate in PV bus mode. In the next iterations, some of them may change into PQ buses if they violate the maximum nominal reactive power constraint. For the PV-buses the real power and positive sequence voltage are specified. The reactive power of all PV buses are initialized to zero (Cheng and Shirmohammadi, 1995).

Forward/backward unbalanced load flow: The iterative algorithm for solving the radial system uses the forward/backward method. The forward/backward method or ladder iterative method involves two sweeps of calculations (Kersting, 2002). The forward sweep starts

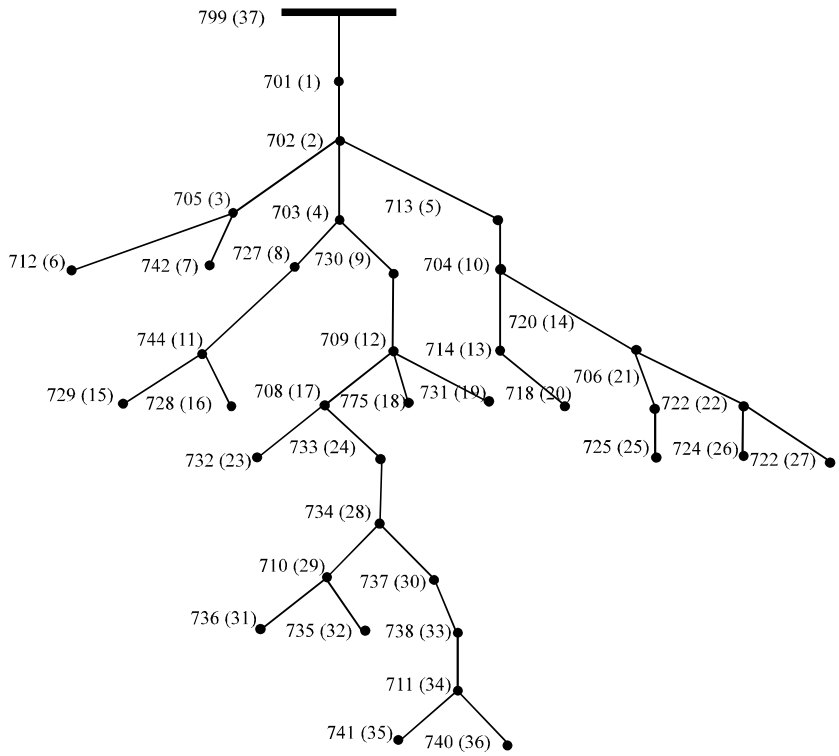

Fig. 1: Branch numbering scheme for radial distribution network

from the last layer. In each layer, the bus voltages and branch currents are calculated. These currents and voltages are used to yield currents and voltages of upper layer branches. In the backward sweep, the voltages of downstream buss are obtained by using the calculated branch currents as moving toward the end buss.

If the root bus is considered to be the slack bus (with known voltage magnitude and angle) and the initial voltage for all other buss be equal to the root bus voltage; then the iterative algorithm for solving the radial system can be summarized In three steps for each iteration as follows (Cheng and Shirmohammadi, 1995).

Step 0: Initialization the end branch voltages are initialized at 1 pu (usually) for the first iteration.

Step 1: Forward sweep to sum up line section current. The voltages and currents of upstream branches are calculated starting at the buses at the load end (last layer) of the radial branch and solving up to the source bus (the first layer) by using the current summation method (Kersting, 2000). The voltage of each breakpoint in the forward sweep is assigned from the maximum calculated voltage of the bus.

Step 2 (convergence check): Convergence occurs when the calculated source voltage in the forward sweep corresponds to specified source voltage.

Step 3 (backward sweep to update nodal voltage): The backward sweep starts at the source bus (the first layer) with the specified value of the source bus (typically 1 pu) and calculates voltages by using the current calculated from the forward sweep, until the load end (the last layer) of the radial branches. The voltages from the backward sweep are used for the next iteration in the forward sweep calculations. The above mentioned algorithm provides the solution for a three-phase radial network.

Calculation of the voltage mismatches: After convergence, the positive sequence voltage magnitude mismatch at the PV-bus should bechecked as follows:

$$\Delta V_1^i = \left|V_{1sp}^i\right| - \left|V_{1cal}^i\right| \le \varepsilon \tag{6}$$

where, ΔV_1^i is the voltage of the positive sequence at the bus I. Thus, ΔV_1 can bewritten as follows:

$$\Delta V_1 = \left[V_1^i\right]^T \quad i = 1, ..., N_{PV} \tag{7}$$

In the case of remote control of bus k by the bus i, the mismatch of the voltage of bus k respect to the specified value is calculated and replaced in the row i of ΔV_1. In the case of unbalance compensation, ΔV_1^i would be a vector and is calculated as follows:

$$\Delta V_i = \begin{bmatrix} 1 \\ 1\angle -120 \\ 1\angle 120 \end{bmatrix} \cdot V_{set} \cdot e^{j(\angle V_{positive})} - \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (8)$$

If the voltage mismatch is within the specified tolerance, the PV or Remote PV (RPV) bus voltage has converged to the specified value. If a voltage mismatch at the bus is more than the specified tolerance, then the procedure will go to the next step.

In the remote voltage control in order to achieve 1 pu. Voltage at the specified bus, the voltage of the DG bus may become greater than 1 pu. There is voltage limitation (V_j^{limit}) for set of DGs which control the voltages of other buses (S_2) too:

$$\Delta V_j = V_j^{limit} - V_j^{cal} \quad j \in S_2(\text{Pnodes}) \quad (9)$$

If ΔV_j becomes negative then the voltage is fixed at the limiting value (V_j^{limit}) and this bus is now changed to a PV bus. In the next iteration if the voltage is in the acceptable range, then the bus returns to RPV bus.

Calculation of the current injections: The reactive current injected to the bus is calculated in order to maintain the voltage at the specified value as follows:

$$\Delta I_1 = Z_s^{-1} * \Delta V_1 \quad (10)$$

where, Z_s is the $n_i \times n_i$ sensitivity impedance matrix. The sensitivity impedance matrix is calculated considering the algorithm explained in section 2.

The DG can operate in lagging as well as leading power factor modes. Thus, the injection of current will depend on the sign of voltage mismatch ΔV_1^i. If ΔV_1^i is positive, then the reactive power is supplied by DG with a leading reactive current and when ΔV_1^i is negative then the reactive power is absorbed by DG with a lagging reactive current. The reactive current injection for PV and P buses are calculated as follows:

$$\begin{aligned} \Delta I_{qa}^i &= j \cdot \text{sgn}(\Delta V_1^i) \cdot \Delta I_1^i \cdot e^{j(\angle V_a^i)} \\ \Delta I_{qb}^i &= j \cdot \text{sgn}(\Delta V_1^i) \cdot \Delta I_1^i \cdot e^{j(\angle V_b^i)} \\ \Delta I_{qc}^i &= j \cdot \text{sgn}(\Delta V_1^i) \cdot \Delta I_1^i \cdot e^{j(\angle V_c^i)} \end{aligned} \quad (11)$$

where, $\angle V_a^i, \angle V_b^i$ and $\angle V_c^i$ are the angles of the ith bus voltage in the network without DG. To calculate the current injection of Dgs that control another bus (remote PV bus) ΔV_1^i is replaced by ΔV_1^k. The reactive current injections for unbalance compensation are calculated as follows:

$$\begin{aligned} \Delta I_{qa}^i &= j \cdot \text{sgn}(\Delta V_a^i) \cdot \Delta I_a^i \cdot e^{j(\angle V_a^i)} \\ \Delta I_{qb}^i &= j \cdot \text{sgn}(\Delta V_b^i) \cdot \Delta I_b^i \cdot e^{j(\angle V_b^i)} \\ \Delta I_{qc}^i &= j \cdot \text{sgn}(\Delta V_c^i) \cdot \Delta I_c^i \cdot e^{j(\angle V_c^i)} \end{aligned} \quad (12)$$

The DG reactive currents are updated in each iteration by using the following equation:

$$[I_q(k)] = [I_q(k\text{-}1)] + [\Delta I_q] \quad (13)$$

Since, the reactive power capability of DG is limited, then these limits m4 ustbe checked first to determine whether the required current injections are available, i.e.:

$$Q_{DG,\min}^i \le Q_{DG}^i \le Q_{DG,\max}^i \quad (14)$$

If the reactive power of any of DGs exceeds the limits, during the computation, then it is fixed at the limiting value and this bus will be treated as a PQ-bus. The limiting value is calculated as the three-phase reactive power limit. Thus, the total per-phase reactive current that the DG can inject before exceeding its limit is given by the following equation:

$$I_{q,\,limit}^i = \frac{\dfrac{Q_{G,\,limit}^i}{3}}{\text{mag}(V_1^i)} \quad (15)$$

If the calculated current injection of the Eq. 5 for the ith DG is beyond the acceptable limit, $I_{q,\,limit}^i$, then the currents are set to the limit value and the ith DG is considered as a PQ bus in the next iteration (i.e., limithit (j) = 1). The sensitivity matrix should be modified to omit the related elements of ith DG in the sensitivity matrix.

In the next iteration of the load flow if the reactive power of the PV-bus which had been converted to PQ-bus is in the limiting values, the bus is changed again to PV-bus.

Calculation of reactive power injection: The injected reactive power of PV mode DGs are calculated by using the currents calculated which should be used in the next iteration of the load flow.

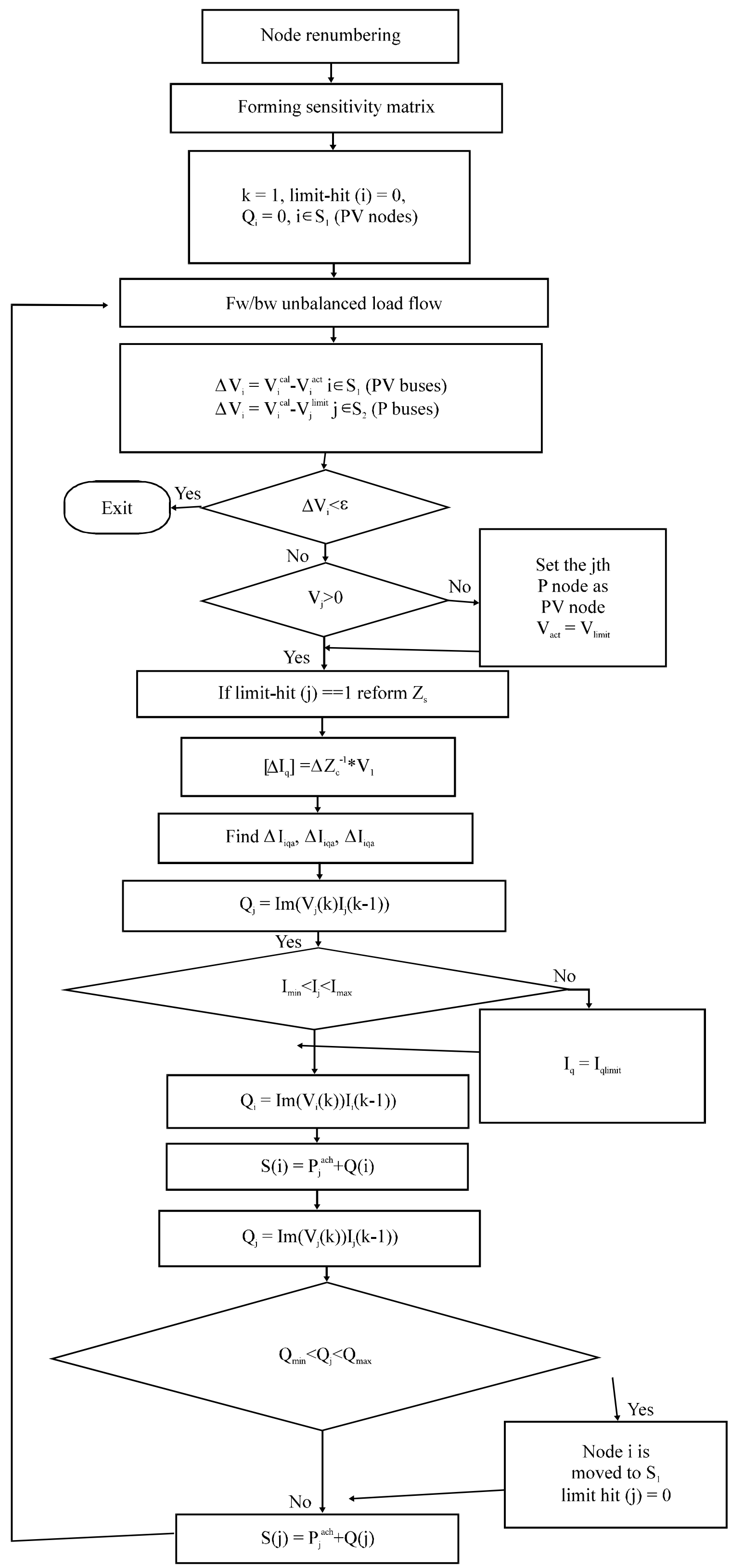

Fig. 2: Flow chart of load flow algorithm

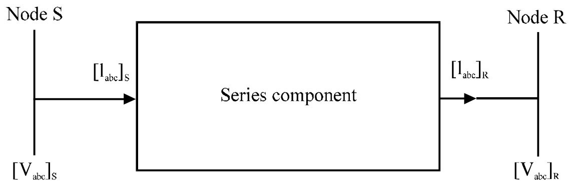

Fig. 3: General form of series component and matrices representing source side and end side

$$Q_i = \text{Im}\,(V_i(k)I_i^*(k)) \quad S(i) = P_i^{sch} + Q(i) \tag{16}$$

The determined reactive power of buses which have been changed from PV bus to PQ-bus (in the previous iteration) is also calculated by using the following equation:

$$Q_l = \text{Im}(V_l(k)I_l^*(k\text{-}1)) \quad S(l) = P_l^{sch} + Q(l) \tag{17}$$

If the reactive power does not violate the reactive power constraint (i.e., $Q_{min}<Q_l<Q_{max}$), the bus should be changed into PV-bus. The flow chart of the distributed generation power flow algorithm is shown in Fig. 2.

Distribution system modeling: The components of distribution system are divided into series and shunt elements. Shunt components includes Distributed and lump loads, Generators (DGs) and compensators. Series elements are line sections, transformers, switches and regulators. The capacitor banks are modeled as constant susceptances connected in either Wye or delta connection. Loads on a distribution feeder can also be modeled as a Wye or delta connection. The loads can be three-phase, two-phase or single-phase with different degrees of unbalance and can be modeled as follows:

- Constant real and reactive power (constant PQ)
- Constant current
- Constant impedance

All series components can be modeled by using the generalized matrices. In the forward sweep and according to Fig. 3, the matrix equations for computing the voltages and currents (i.e., $[VLG_{abc}]_S$ and $[I_{abc}]_S$) at bus-S (source side) as a function of the voltages and currents (i.e., $[VLG_{abc}]_R$ and $[I_{abc}]_R$) at bus-R (end side) can be expressed by the following equation:

$$\begin{bmatrix} [VLG_{abc}]_S \\ [I_{abc}]_S \end{bmatrix} = \begin{bmatrix} [a] & [b] \\ [c] & [d] \end{bmatrix} \cdot \begin{bmatrix} [VLG_{abc}]_R \\ [I_{abc}]_R \end{bmatrix} \tag{18}$$

where, [a], [b] [c] and [d] are the generalized matrices of the modeled component. In the backward sweep it is necessary to compute the voltages at bus-R as a function of the voltages at bus-S and the currents entering to bus-R:

$$[VLG_{abc}]_R = [A]\cdot[VLG_{abc}]_S - [B]\cdot[I_{abc}]_R \tag{19}$$

where, [A] and [B] are the generalized matrices of the modeled component. Transformers are modeled in four different types of connections: Delta-Delta, Grounded Wye-Grounded Wye, Delta-Grounded Wye and Wye-Delta. Also, three types of step-voltage regulator connections, i.e., Wye-connected, closed Delta-connected and open Delta-connected are modeled. The step-voltage regulator consists of a series autotransformer and a voltage drop compensator. The autotransformer tap is set to its nominal value in the first iteration of power flow and the required taps are obtained by using the line-drop compensator. In the second iteration of power flow, the obtained taps are applied to the autotransformer.

For line segments, in three-wire and four-wire systems, the impedance matrices are modeled by a phase frame matrix consisting of self and mutual equivalent impedances of three phases. In a four-wire system, the primitive impedance matrix need to be reduced to a phase frame matrix. The equations for various components of the distribution system are presented by Xu *et al*. (1998).

RESULTS AND DISCUSSION

The IEEE 37-bus feeder has been used for case study. Load types in this system consist of spot loads, single-phase and three-phase balanced and unbalanced loads, delta connected, constant kW, constant KVAR, constant Z and constant I type.

The overhead and underground line are three-phase lines with different spacing of phases. The substation and inline transformers are connected in delta-delta. The unbalanced load flow software has been developed in MATLAB. Validation of obtained result from the proposed power flow program with the result presented in IEEE 37 bus test system with no DG and a step voltage regulator has been presented in Table 1. It can be seen that the obtained results have good agreement with the result. The developed power flow has also been carried out for different modes of DG's operation to demonstrate

Table 1: Comparison of results of developed program with results

Bus No.	Results of developed program $\lvert V_{ab}\rvert$	$\angle V_{ab}$	Results $\lvert V_{ab}\rvert$	$\angle V_{ab}$	Calculated $\lvert V_{bc}\rvert$	$\angle V_{bc}$	IEEE 37 $\lvert V_{bc}\rvert$	$\angle V_{bc}$	Calculated $\lvert V_{ca}\rvert$	$\angle V_{ca}$	IEEE 37 $\lvert V_{ca}\rvert$	$\angle V_{ca}$
701	1.032	-0.1062	1.032	-0.08	1.016	-120.3916	1.014	-120.39	1.019	120.5766	1.018	120.61
702	1.025	-0.1663	1.025	-0.14	1.010	-120.5834	1.009	-120.58	1.010	120.3921	1.010	120.43
703	1.018	-0.2021	1.018	-0.17	1.006	-120.7045	1.005	-120.70	1.004	120.1640	1.003	120.20
727	1.017	-0.1844	1.017	-0.16	1.005	-120.6923	1.004	-120.69	1.003	120.1560	1.003	120.19
744	1.017	-0.1852	1.016	-0.16	1.005	-120.6844	1.004	-120.68	1.002	120.1410	1.002	120.17
728	1.016	-0.1812	1.016	-0.15	1.005	-120.6815	1.004	-120.68	1.002	120.1440	1.002	120.18
729	1.016	-0.1819	1.016	-0.15	1.005	-120.6752	1.004	-120.67	1.002	120.1330	1.002	120.17
730	1.013	-0.1472	1.013	-0.12	1.003	-120.7342	1.002	-120.73	0.998	120.0700	0.998	120.10
709	1.012	-0.1312	1.011	-0.11	1.002	-120.7361	1.001	-120.73	0.997	120.0310	0.997	120.07
708	1.009	-0.1050	1.009	-0.08	1.001	-120.7377	1.000	-120.73	0.995	120.0160	0.995	120.02
732	1.009	-0.0940	1.009	-0.07	1.001	-120.7474	1.000	-120.74	0.994	119.9800	0.994	120.02
733	1.007	-0.0710	1.006	-0.05	1.000	-120.7328	0.999	-120.73	0.993	119.9200	0.993	119.96
734	1.004	-0.0340	1.003	-0.01	1.000	-120.7427	0.998	-120.74	0.990	119.8700	0.989	119.88
710	1.003	-0.0140	1.002	0.01	0.998	-120.7690	0.997	-120.77	0.988	119.8770	0.988	119.91
735	1.003	0.0100	1.002	0.03	0.998	-120.7814	0.997	-120.78	0.988	119.8800	0.987	119.91
736	1.003	-0.0330	1.002	-0.02	0.997	-120.7536	0.995	-120.75	0.988	119.9200	0.988	119.95
737	1.000	0.0100	1.000	0.02	0.999	-120.7141	0.997	-120.71	0.987	119.7590	0.987	119.79
738	0.999	0.0320	0.999	0.04	0.999	-120.7185	0.997	-120.71	0.986	119.7298	0.986	119.76
711	0.999	0.0460	0.998	0.06	0.998	-120.7429	0.996	-120.74	0.985	119.7240	0.985	119.76
740	0.999	0.0580	0.998	0.07	0.998	-120.7530	0.996	-120.75	0.985	119.7271	0.985	119.76
741	0.999	0.0550	0.998	0.07	0.998	-120.7509	0.996	-120.75	0.985	119.7223	0.985	119.76
731	1.012	-0.1500	1.011	-0.13	1.001	-120.7390	1.000	-120.74	0.997	120.0620	0.996	120.10
775	1.012	-0.1300	1.011	-0.11	1.002	-120.7361	1.001	-120.73	0.997	120.0410	0.997	120.07
705	1.025	-0.1540	1.024	-0.13	1.010	-120.5967	1.008	-120.59	1.009	120.4200	1.009	120.46
712	1.025	-0.1340	1.024	-0.11	1.009	-120.6113	1.007	-120.61	1.008	120.4260	1.008	120.46
742	1.024	-0.1750	1.024	-0.15	1.009	-120.5880	1.007	-120.59	1.009	120.4460	1.009	120.48
713	1.024	-0.1740	1.023	-0.15	1.009	-120.0604	1.007	-120.60	1.009	120.4100	1.008	120.44
704	1.022	-0.1930	1.022	-0.17	1.006	-120.6130	1.004	-120.61	1.007	120.4300	1.007	120.46
714	1.022	-0.1920	1.021	-0.17	1.006	-120.6060	1.004	-120.60	1.007	120.4300	1.006	120.46
718	1.021	-0.1820	1.020	-0.16	1.006	-120.5716	1.004	-120.57	1.006	120.3980	1.006	120.42
720	1.021	-0.2320	1.021	-0.21	1.003	-120.6590	1.001	-120.66	1.004	120.5020	1.004	120.53
706	1.021	-0.2440	1.020	-0.22	1.003	-120.6610	1.001	-120.66	1.004	120.5160	1.004	120.54
725	1.021	-0.2510	1.020	-0.23	1.002	-120.6570	1.000	-120.65	1.004	120.5220	1.004	120.55
707	1.019	-0.3250	1.019	-0.30	0.998	-120.6250	0.996	-120.62	1.003	120.6440	1.003	120.67
722	1.019	-0.3241	1.019	-0.30	0.997	-120.6220	0.995	-120.62	1.003	120.6560	1.002	120.68
724	1.019	-0.3420	1.018	-0.32	0.997	-120.6160	0.995	-120.61	1.003	120.6670	1.002	120.69

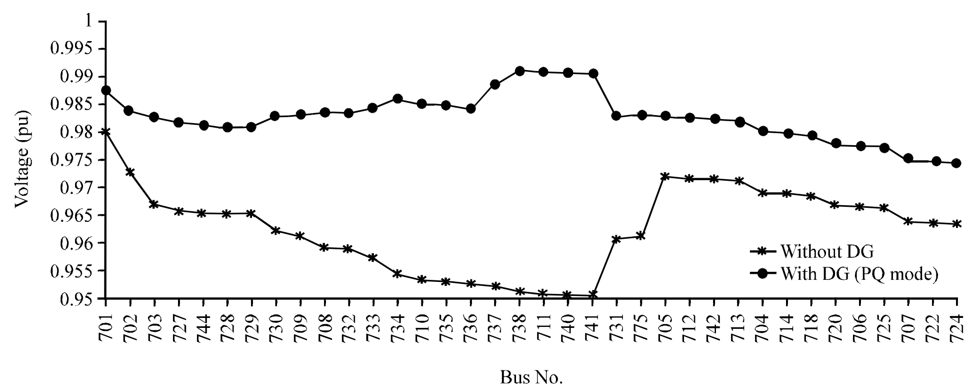

Fig. 4: Voltage profile of 37 bus network without DG and with a 900 kW DG installed at bus 738 (operating as PQ bus)

various features which is modeled in the software. Sum of Deviations of the Voltages (SDV) have been calculated in each case using the following equation:

$$SDV = \sum_{i=0}^{n} \left|V_i - 1\right| \quad (20)$$

Case 1 (900 kW DG unit connected at bus 738 operating as PQ bus): Figure 4 shows the voltage profile with a 900 kW DG unit connected at bus 738 and compares it with the case without DG. The DG is operating in PQ mode with its nominal power factor that is 0.9. Deviation of the voltages decrease from 1.35-0.90s7 after DG connection.

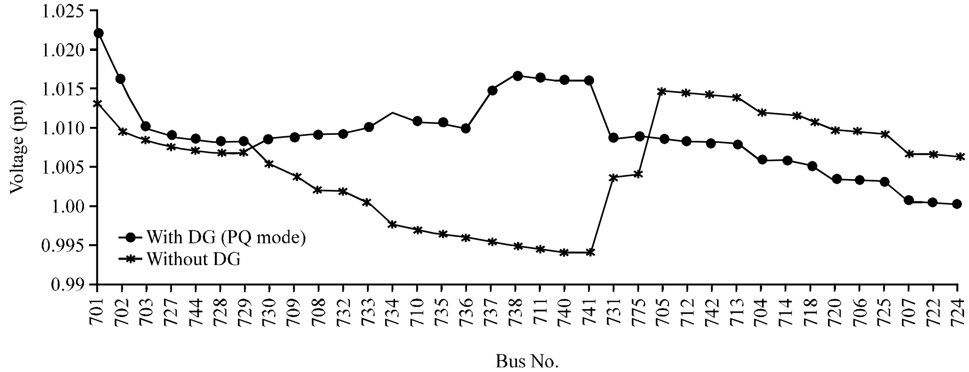

Fig. 5: Voltage profile of 37 bus network in presence of a step regulator without DG and with a 900 kW DG installed at bus 738 (operating as PQ bus)

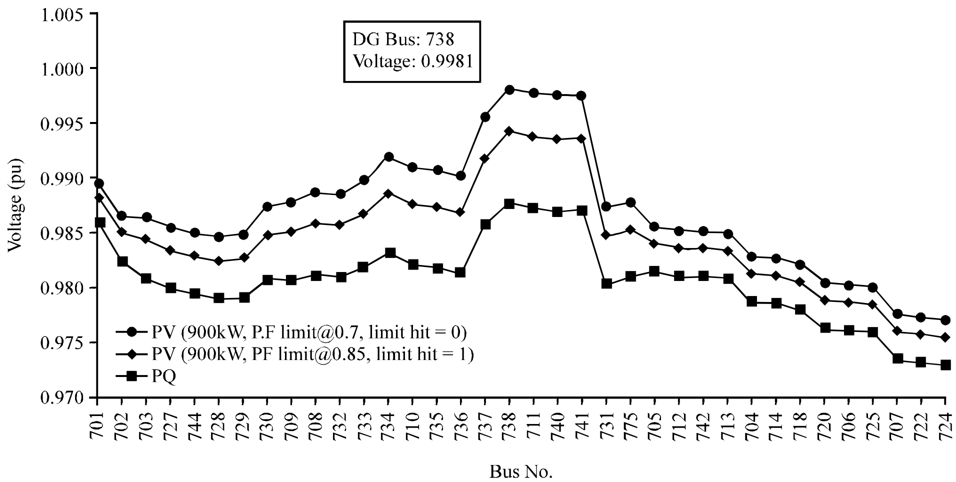

Fig. 6: Voltage profile of 37 bus network with a 900 kW DG installed at bus 738 (for 3 cases: operating as PQ bus, a PV bus with maximum power factor limit of 0.85 and a PV bus with maximum power factor limit of 0.7)

Case 2 (900 kW DG unit connected at bus 738 operating as PQ bus in presence of a step regulator: The voltage profile with the same DG and a step voltage regulator is shown in Fig. 5. It can be observed that, also SDV has remained constant on 0.252 after installation of DG, the voltage profile is smoother with the DG and the maximum and minimum voltages are closer to 1 pu.

Case 3 (900 kW DG unit connected at bus 738 operating as PV-bus): The voltage profile for the same DG operating an PV mode isoperation. It is notable that when the DG operates as PV mode it tries to set its bus voltage to 1 pu. However, if the DG has a limited capability in providing the reactive power injection (for example, here when the minimum power factor of DG is limited to 0.85) the DG's maximum reactive power limit is reached and the DG operates as a constant power factor generator with its maximum available reactive power. SDV before reaching the limit is 0.5616 and after operating in constant power is 06912. It is obvious when the DG is operated in PV mode the voltage profile is better. When the DG's power factor limit is 0.7, the DG can produce enough reactive power to set the bus voltage at 1 pu and remain as PV bus. The voltage profile in this case with SDV of 0.489 has improved in comparison with PQ operation and PV with power factor limit of 0.85 (Fig. 6).

Case 4 (900 kW DG unit connected at bus 738 operating as RPV bus): Figure 7 shows the voltage profile, when the DG is operating as a remote voltage controller. The bus to be controlled is bus 734 which is located above the DG's bus in the network. In order to shift the controlled bus voltage to 1 pu. The DG must inject more reactive power and its own bus voltage would be <1 pu. Here, with the

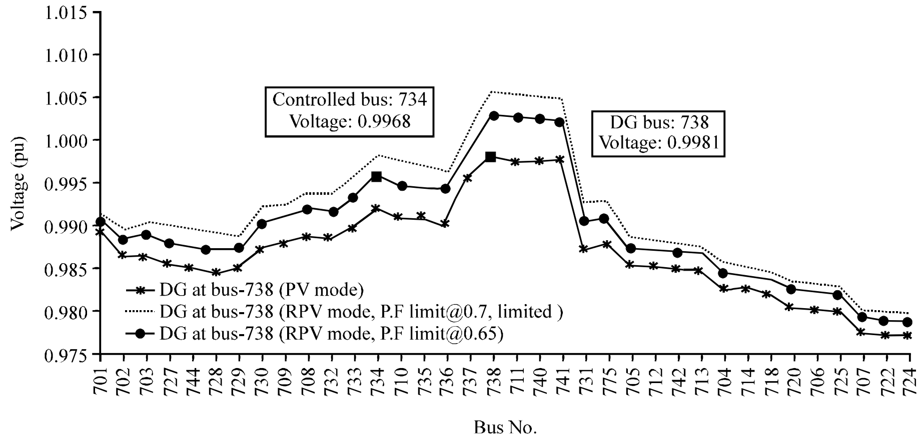

Fig. 7: Voltage profile of 37 bus network with a 900 kW DG installed at bus 738 (for 3 cases: operating as PV bus, a RPV bus with maximum power factor limit of 0.7 and an imaginary case of RPV bus with maximum power factor limit of 0.65)

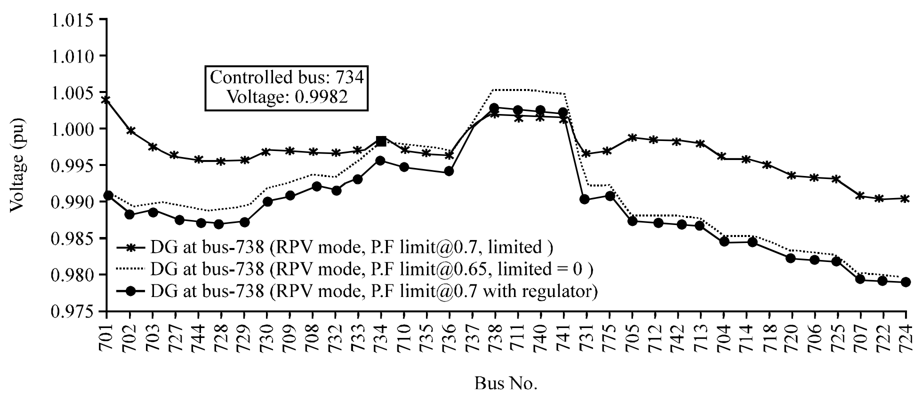

Fig. 8: Voltage profile of 37 bus network with a 900 kW DG installed at bus 738 (for 3 cases: operating as a RPV bus with maximum power factor limit of 0.7, an imaginary case of RPV bus with maximum power factor limit of 0.65 and a RPV bus with maximum power factor limit of 0.7 in presence of a step regulator)

power factor limited at 0.7, the generator fails to completely compensate its target bus voltage (compare the voltage profile with the dashed line when compensation is complete), even though the target bus voltage is very close to unity. Therefore, the DG operates as PQ-bus. Figure 8 shows the voltage profile with the same DG when the step regulator is installed. In this case, the step regulator contributes in compensating the target bus voltage and thereby the DG's reactive power limit is not hit.

Case 5 (multiple DG installation, a 900 kW DG installed at bus 738 operating as a RPV bus and a 300 kW DG installed at bus 725 operating as a RPV): The voltage profile with two DGs is shown in Fig. 9. The first DG with the capacity of 900 kW has been installed at bus 738 and the second one with the capacity of 300 kW is installed at bus 725. Both DGs are operating as remote voltage controllers. It is obvious that multiple DG installation can better improve the voltage profile.

Case 6 (900 kW DG installed at bus738 operating as a current source compensator): Finally, the positive and negative voltage sequences for the IEEE 37 bus system when the DG is operating as a current source compensator is shown in Fig. 10. The results have been compared with the conventional PV and PQ mode of operations. As it is expected, the negative sequence voltage in current source compensator mode is less than the conventional PV mode which indicates that the voltage balance is better in this mode. It is also notable that the negative voltage sequence in both PQ and PV modes are almost the same. But, in PV mode the three phase voltages are lifted the same amount and the voltage unbalanced is not compensated.

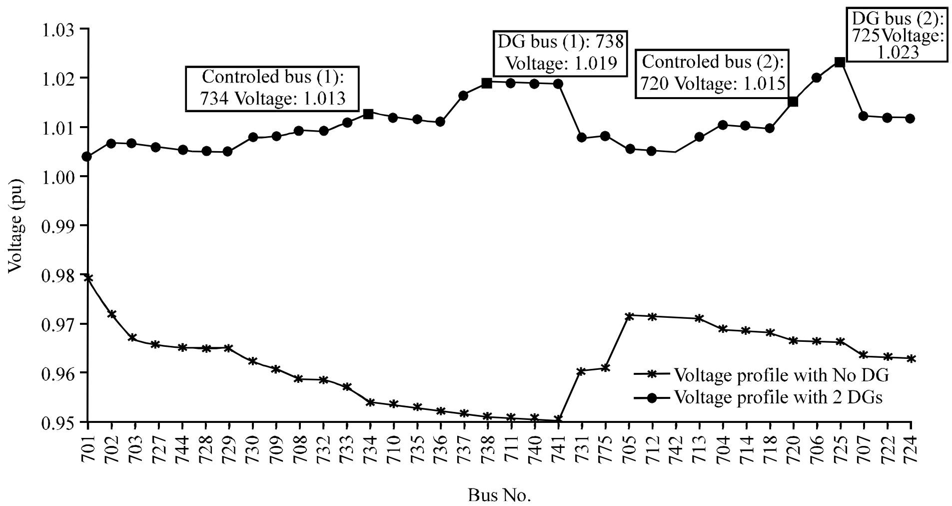

Fig. 9: Voltage profile of 37 bus network with multiple DG installation, a 900 kW DG installed at bus 738 operating as a RPV bus and a 300 kW DG installed at bus 725 operating as a RPV

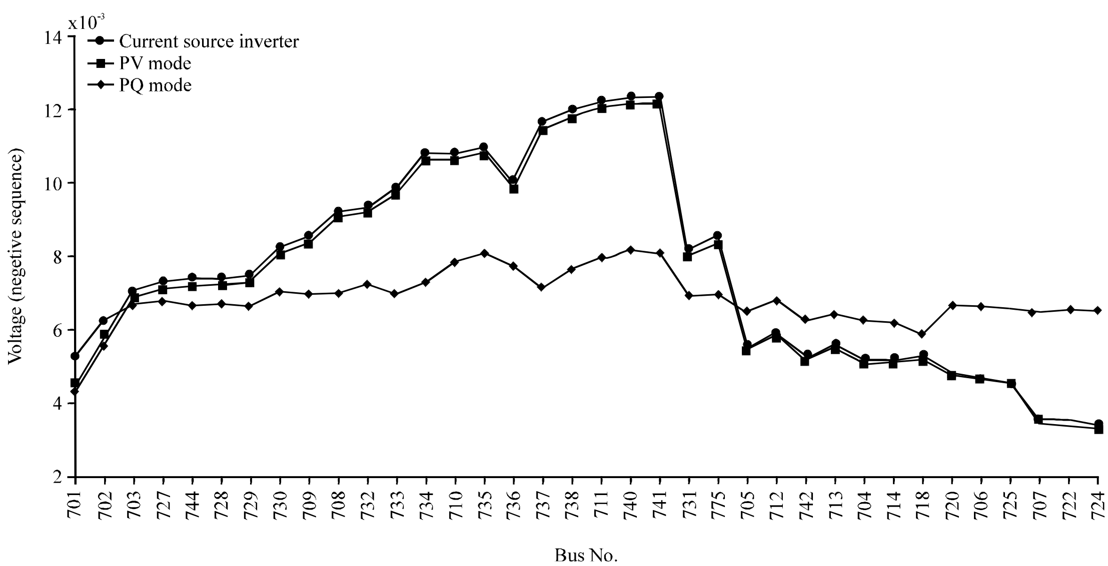

Fig. 10: Negative sequence voltage profile of 37 bus network with a 900 kW DG installed at bus 738 (for 3 cases: operating as a PV bus as PQ bus and as a partial unbalance compensator)

CONCLUSION

In this study, a three-phase unbalanced power flow algorithm has been presented which can model DGs as remote PV buses, current controlled PV buses or PV or PQ buses. The algorithm has been tested on an IEEE 37-bus test system. Comparing the results of the unbalanced power flow without DG with IEEE 37-bus test system demonstrates the accuracy of the proposed program. Studies on the IEEE 37-bus test system with DG and step regulator demonstrate the impact of DG model type, size, number and step regulator on the results. It also shows that the operation of DG as PV bus does not improve the voltage unbalance, since in the regular PV mode but using the current injection the unbalance voltage can be compensated.

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