INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
N. Padole and R. M. Moharil, Vol.13, No.2, June, 2023

Effect of PV Penetration on Voltage Profile of Three-Phase Unbalanced Radial Distribution Network

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Received: 23.02.2023 Accepted:01.05.2023

Abstract- Solar Photovoltaic (SPV) power penetration in the distribution grid is considered as a viable alternative for fossil fuel power plants in the current deregulated power system. SPV power penetration helps to reduce the distribution losses, improves voltage profile of the system, reduces load on the substation etc. However, increased SPV penetration has concerns about protection, reverse power flow, voltage rise etc. In this paper voltage profile assessment and the voltage unbalance calculation of eight bus three phase unbalanced system is done with and without SPV with forward/backward sweep approach for radial distribution network. The distribution system considered in this paper has the voltage level of 11 kV. Voltage profile at all the buses has been discussed for PV penetration at one particular bus. Various percentage PV penetration levels (30 – 80 percent) are considered for the comparative analysis. Best preferred location for the installation of SPV system have been investigated on the basis of voltage profile improvement and percentage voltage unbalance.

Keywords: Solar Photovoltaic (SPV), PV Penetration, Voltage profile improvement, Voltage unbalance, Forward Backward Sweep (FBS) load flow algorithm.

1. Introduction

Peak energy demands can be met, energy losses in distribution feeders can be reduced, and voltage support can be provided by integrating Renewable Energy Systems (RES) into the Low Voltage (LV) distribution network. The exponential development of RES installations, on the other hand, may have adverse implications for the existing distribution network, posing various power quality, stability, and protection difficulties. Considering the adverse implications of RES installations, understanding the technical effects of high SPV system penetration levels on the running performance of these networks is crucial [1]. IEEE test feeder systems are taken into consideration while analysing the possible power quality effects on LV distribution networks with high PV penetration levels [2].

The spectacular expansion in integrated SPV capacity has resulted into recent developments in distribution networks, where the SPV power from most distributed SPVs is first expended by local loads, with the spare power supplied to the grid [3], [4]. This integration of SPV leads to massive changes in distribution networks, such as changes in power flow characteristics, increases in load forecast uncertainty, effects on supply of voltage and power loss [5]-[8] and even changes in network structure and control mechanism.

As a result, power flow analysis is essential for voltage profile assessment of LV distribution networks with significant PV penetration [9]. The load flow method for the transmission system has been developed by many researchers, however, the load flow analysis for distribution systems is still under development. This is as a result of the distribution system's highly unfavourable features, high R/X ratio, and increased penetration of erratic distributed energy resources (DER). The distribution network (DN) was not a good fit for the standard Newton-Raphson (NR) load flow approach or the fast decoupled load flow method. The performance characteristics of the Forward/Backwards Sweep (FBS) method and the NR method with a changeable load pattern are discussed in [10],[11].

The analysis of the load flow in distribution systems is different from that of transmission systems due to the distinctive characteristics of distribution networks. The NR and conventional Fast Decoupled Load Flow methods may not converge because of the high R/X ratios and unbalanced operation in distribution systems and may give erroneous findings. Therefore, it is impossible to directly apply traditional load flow techniques to the distribution networks. The Radial Distribution Networks (RDN) are frequently unbalanced due to single phase, two phase, and three phase loads. To handle such unbalanced cases, load flow analysis must be examined on a three phase basis rather than a single-phase basis which is used for the transmission network [12].

In light of this, there are several practices in the literature that are specifically created to address the power flow problem in RDN. For the solution of RDN, the majority of the developed approaches rely on FBS algorithm and the application of FBS method is used to examine the effect of PV penetration on the power system parameters [13]-[20].

SPV expansion on the LV grid has alarmed distribution network operators, who are concerned about the negative impact of high PV penetration levels. The behaviour of the standard LV grid is being influenced by issues such as abrupt voltage rise and reverse power flow [21]-[24].

Previous researchers discussed the application of FBS algorithm for balanced and unbalanced RDN without considering PV systems and obtained the results based on voltage profile and power losses. Few researchers considered the DER and calculated active and reactive power flow in the RDN for the balanced load.

This paper presents the impact analysis of SPV penetration on voltage profile and the voltage unbalance of the 8 bus Three-Phase unbalanced RDN by applying FBS load flow algorithm. The voltage profile and the voltage unbalance has been analysed by considering the system with (30 % to 80 %) PV and without PV penetration. The system performance has been investigated in terms of voltage variation. While presenting these results the effect of PV penetration on remaining buses is also investigated. A comparative analysis has been done to identify the best bus for PV installation to obtain the best voltage profile and minimum voltage unbalance for the 8 bus three phase unbalanced RDN.

The rest of the paper is categorised into 5 sections. Section 2 provides a detail of 8 bus three-phase unbalanced RDN along with the FBS algorithm. Section 3 summarises the steps for FBS approach via flowchart. Section 4 presents the result and discussions, where the analysis of voltage profile and voltage unbalance with and without integration of PV system is carried out. Section V provides the concluding remarks of the paper.

2. Load flow Analysis of 8 Bus Three Phase Unbalanced Radial Distribution Network

One of the most significant tools for analysing power system performance at both the design and operation stages is the load flow analysis. Although many academicians have developed load flow algorithms for transmission systems, such as the Newton Raphson technique, the rapid decoupling approach, and the Gauss Seidel method etc., while analysing the load flow in distribution systems, different approaches or algorithms have been preferred. This is due to the distribution system's having a high R/X ratio, fluctuating reactive power requirement, and having a higher penetration of unpredictably DER.

A load flow analysis is required for various planning and operational issues. Before tackling issues like network reconfiguration, loss reduction, load balancing, or service restoration, load flow studies are required. The load flow studies play a significant part in achieving correct voltage management in a distribution system. This is basically necessary as distribution companies commit to provide the power with a narrow voltage margin of ± 6-10 % or less in the competitive market. To maintain this voltage range customer as well as Distribution Company takes efforts by managing volt var optimization. Programs created especially for distribution systems are more effective and straightforward than those created for high voltage systems. Load flow studies in distribution networks are required for studying balanced as well as unbalanced systems. The algorithm suggested for the three-phase unbalanced radial distribution system have been presented in the following subsection.

Fig. 1 represents the 8 bus three phase unbalanced radial distribution system. This unbalanced system is consisting of total 8 buses and 7 branches. It has one three phase line segment, one two phase line segment and five single phase line segments.

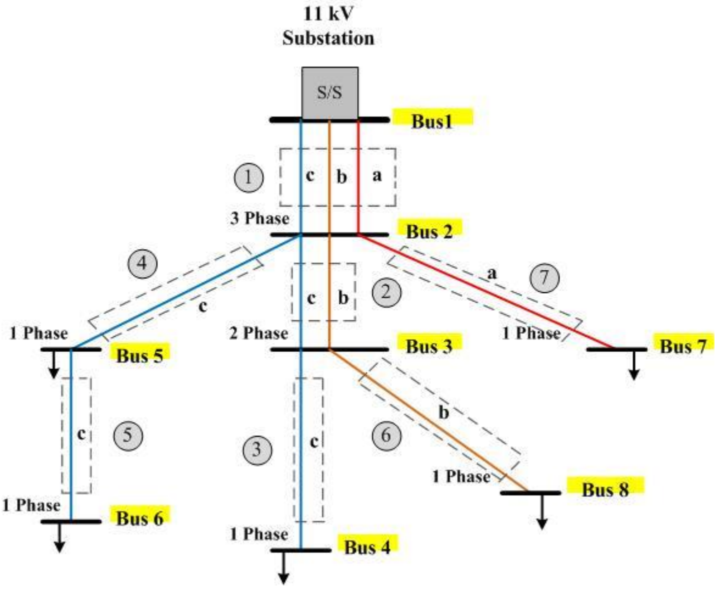


Fig. 1. Eight Bus Three Phase Unbalanced Radial Distribution Network with total number of branches

An 8-bus, three-phase, unbalanced radial distribution system is selected for the analysis in order to verify the efficacy of the FBS algorithm. The base kV and base kVA are selected as 11 kV and 1000 kVA, respectively, for the load flow of an eight-bus system. Tables are provided with the load and line data (Table 1 – 4). At 0.0001, the convergence tolerance is set. Program convergence occurs when the error voltage falls below the tolerance threshold.

Table 1. Phase wise decomposition of three phase unbalanced 8 Bus RDN

Sr. No.	Bus Number	Phases	Phase type
1	Bus 1	3 phases	a-b-c
2	Bus 2	3 phases	a-b-c
3	Bus 3	2 phases	b-c
4	Bus 4	1 phase	c
5	Bus 5	1 phase	c
6	Bus 6	1 phase	c
7	Bus 7	1 phase	a
8	Bus 8	1 phase	b

Table 2. Line Data (Self Impedance in pu)

Sr. No	Branch	Input Bus	Output Bus	Phase a $(*10^{-4})$	Phase b $(*10^{-4})$	Phase c $(*10^{-4})$
1	1	1	2	7.74 + j3.33	7.74 + j3.33	7.74 + j3.33
2	2	2	3	0	12.9 + j5.55	12.9 + j5.55
3	3	2	5	0	0	3.87 + j1.665
4	4	2	7	3.87 + j1.665	0	0
5	5	3	4	0	0	2.58 + j1.11
6	6	3	8	0	5.16 + j2.22	0
7	7	5	6	0	0	6.45 + j2.77

Table 3. Line Data (Mutual Impedance in pu)

Sr. No.	Branch	Phase a $(*10^{-4})$	Phase b $(*10^{-4})$	Phase c $(*10^{-4})$
1	1	2.58 + j1.11	2.58 + j1.11	2.58 + j1.11
2	2	4.3 + j1.85	0	0
3	3	0	0	0
4	4	0	0	0
5	5	0	0	0
6	6	0	0	0
7	7	0	0	0

A three phase four wire line section model between bus 1 and bus 2 is shown in Fig. 2. Using Carson's equations, the impedance matrix consisting of both self and mutual impedances is presented in Eq. (1).

Table 4. Load Data (P + jQ)

Sr. No.	Bus No.	Phase a (pu)	Phase b (pu)	Phase c (pu)
1	2	0.519 + j0.250	0.259 + j0.126	0.515 + j0.250
2	3	0	0.259 + j0.126	0.486 + j0.235
3	4	0	0	0.324 + j0.157
4	5	0	0	0.226 + j0.109
5	6	0	0	0.145 + j0.070
6	7	0.486 + j0.235	0	0
7	8	0	0.267 + j0.129	0

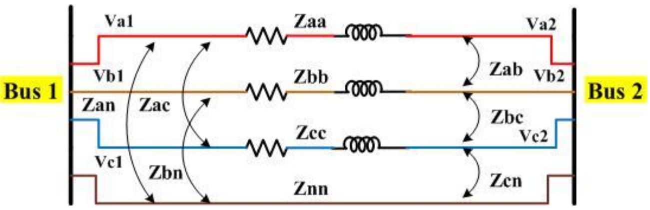


Fig.2.Three phase four wire line section model between bus 1 and bus 2.

An expression for a 4x4 matrix that accounts for the self- and mutual coupling effects of the unbalanced three phase line section is as follows:

$$Z_{12}^{abcn} = \begin{bmatrix} Z_{12}^{aa} & Z_{12}^{ab} & Z_{12}^{ac} & Z_{12}^{an} \\ Z_{12}^{ba} & Z_{12}^{bb} & Z_{12}^{bc} & Z_{12}^{bn} \\ Z_{12}^{ca} & Z_{12}^{cb} & Z_{12}^{cc} & Z_{12}^{cn} \\ Z_{12}^{na} & Z_{12}^{nb} & Z_{12}^{nc} & Z_{12}^{nn} \end{bmatrix} \tag{1}$$

By using Kron's reduction and keeping in mind the effects of the neutral and ground wires, this equation may be reduced to a 3x3 matrix as illustrated in Eq. (2).

$$Z_{12}^{abc} = \begin{bmatrix} Z_{12}^{aa} & Z_{12}^{ab} & Z_{12}^{ac} \\ Z_{12}^{ba} & Z_{12}^{bb} & Z_{12}^{bc} \\ Z_{12}^{ca} & Z_{12}^{cb} & Z_{12}^{cc} \end{bmatrix} \tag{2}$$

The feeder in Fig. 3 can now have the receiving end voltages connected to the sending end voltages as indicated in Eq. (3);

$$\begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} = \begin{bmatrix} V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix} + \begin{bmatrix} Z_{12}^{aa} & Z_{12}^{ab} & Z_{12}^{ac} \\ Z_{12}^{ba} & Z_{12}^{bb} & Z_{12}^{bc} \\ Z_{12}^{ca} & Z_{12}^{cb} & Z_{12}^{cc} \end{bmatrix} * \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{3}$$

For both single phase and two phase systems, the same strategy will be applied. In a two phase system, the disconnected phase will have zero in the associated impedance matrix row and column.

A) *Forward and Backward Sweep (FBS) Load Flow Algorithm*

According to the review of the literature on load flow methods for distribution systems by Mishra and Das (2008), the FBS approach to the network tree representation has served as the foundation for the majority of the radial distribution load flow methods. The following is true for the apparent reason that this method is easy to use, quick, and reliable. Two fundamental steps of the general algorithm are forward sweep and the backward sweep. Calculating the voltage drop through a feeder or lateral from the root node to the far end is the primary goal of the forward sweep. A current, power, or admittance summation based on voltage updates from the feeder's far end to the sending end is the main function of the backward sweep.

1.1. Calculation of Bus currents

Bus current calculation: On the basis of initial voltages, the first step is to determine how much current will be injected at each bus in the feeder as a result of loads. The Bus currents are computed using the revised voltages in the subsequent iterations.

By considering the eight bus three phase radial distribution system shown in Fig. 1, according to Eq. (4), the total line current delivered through phases of the connecting buses 1 and 2 is represented.

$$\begin{bmatrix} I_{aj}^{(k)} \\ I_{bj}^{(k)} \\ I_{cj}^{(k)} \end{bmatrix} = \begin{bmatrix} \left(\dfrac{P_{aj} + jQ_{aj}}{V_{aj}^{(k-1)}} \right)^{*} \\ \left(\dfrac{P_{bj} + jQ_{bj}}{V_{bj}^{(k-1)}} \right)^{*} \\ \left(\dfrac{P_{cj} + jQ_{cj}}{V_{cj}^{(k-1)}} \right)^{*} \end{bmatrix} \tag{4}$$

For j = 2, 3, 4…………..,8.

1.2. Calculation of Branch/ Line currents: Backward Sweep

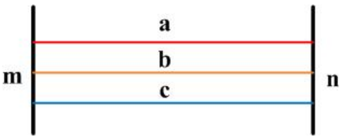


Fig.3. Three phase line section model between bus m and bus n.

Backward sweep: At iteration k, all branch currents are determined by using current summation, moving from the branches at the lowest layer towards the branches connected to the root node. The branch current is determined as follows for a branch mn:

$$\begin{bmatrix} I_{a_{mn}}^{(k)} \\ I_{b_{mn}}^{(k)} \\ I_{c_{mn}}^{(k)} \end{bmatrix} = \begin{bmatrix} I_{a_n}^{(k)} \\ I_{b_n}^{(k)} \\ I_{c_n}^{(k)} \end{bmatrix} + \begin{bmatrix} \Sigma\, all\ the\ currents\ of\ branches\ emanated \\ from\ bus\ n\ and\ phase\ a \\ \Sigma\, all\ the\ currents\ of\ branches\ emanated \\ from\ bus\ n\ and\ phase\ b \\ \Sigma\, all\ the\ currents\ of\ branches\ emanated \\ from\ bus\ n\ and\ phase\ c \end{bmatrix} \tag{5}$$

1.3. Calculation of Bus Voltages: Forward Sweep

Forward sweep: In a forward sweep, nodal voltages are updated from the first-layer branches to the last-layer branches. Using the root node as the starting point, updated voltage is corrected as follows:

$$\begin{bmatrix} V_{a_n}^{(k)} \\ V_{b_n}^{(k)} \\ V_{c_n}^{(k)} \end{bmatrix} = \begin{bmatrix} V_{a_m}^{(k)} \\ V_{b_m}^{(k)} \\ V_{c_m}^{(k)} \end{bmatrix} - \begin{bmatrix} Z_{mn}^{aa} & Z_{mn}^{ab} & Z_{mn}^{ac} \\ Z_{mn}^{ba} & Z_{mn}^{bb} & Z_{mn}^{bc} \\ Z_{mn}^{ca} & Z_{mn}^{cb} & Z_{mn}^{cc} \end{bmatrix} * \begin{bmatrix} I_{a_{mn}}^{(k)} \\ I_{b_{mn}}^{(k)} \\ I_{c_{mn}}^{(k)} \end{bmatrix} \tag{6}$$

For all n = 2, 3, 4…….., 8.

Where m is the node at which the voltage is updated, n is the node at which the voltage is updated from the previous layer, and Z is the branch series impedance.

3. Flow Chart

Fig. 4 depicts the Backward and Forward sweep algorithm applied to an unbalanced eight bus system. Only one connection in Fig. 3 connects the bus n to the substation bus m, which feeds the bus n. Using Eq. (5), one can calculate the total line current that was supplied through this line to bus n.

The technique employs Eq. (6) to calculate the voltage at receiving end bus n with the knowledge of the current flowing between buses m and n or at the nth bus.

With this approach, the algorithm calculates the voltages at each system bus, starting at the substation and moving downstream to each bus. If the variation in the estimated bus voltage magnitudes across successive iterations is within the tolerance limit, the algorithm terminates.

4. Result and Discussion

Impact of PV penetration on the voltage profile of the three phase 8 Bus unbalanced distribution network has been analyzed by applying FBS load flow algorithm. Further, a comparative analysis has been carried out between the voltage profile of the system without PV penetration and voltage profile after the installation of different PV capacities at various buses.

Since, usually the rooftop PV system is used in the distribution network of 11 kV with the limited number of connections, Hence, to analyze the effect, 8 bus system is taken into consideration. Results are presented in a tabular form to get clarity over the per phase voltage magnitudes.

Table 5. Load Flow results of 8 Bus RDN Without PV

	Phase a		Phase b		Phase c	
Bus No	Voltage (pu)	Angle (rad)	Voltage (pu)	Angle (rad)	Voltage (pu)	Angle (rad)
1	1	0	1	-2.0944	1	2.0944
2	0.9995	-0.0003	0.9997	-2.0942	0.9987	2.0942
3	0	0	0.9992	-2.0937	0.9976	2.0938
4	0	0	0	0	0.9975	2.0937
5	0	0	0	0	0.9985	2.0942
6	0	0	0	0	0.9984	2.0942
7	0.9993	-0.0004	0	0	0	0
8	0	0	0.9991	-2.0935	0	0

Table 5 shows the voltage profile of 8 bus three phase unbalanced RDN without PV penetration. It has been found that voltage magnitudes of the end buses from the root node are decreasing gradually due to the voltage drop across this RDN. The lowest voltage magnitude can be observed at bus 4 phase c (0.9975 pu).

Therefore, to improve the voltage profile at the load end and to keep the voltage at its rated value, different % PV penetrations have been considered to investigate the system performance at various buses. The variation in phase angle with the base case is not much significant and hence, angles are not represented in the further comparative analysis.

Table 6 depicts the system voltage magnitudes of the various buses when the 30%, 50% and 80% PV is penetrated at bus 4 phase c. To get more clarity over the effects of PV penetration on the various buses, the results are represented graphically in Fig. 5. In Fig. 5, the minimum to maximum range of voltage magnitude considered for the graphical representation in per unit is 0.9974 pu to 1 pu, respectively. The effect of PV penetration can be experienced on phase b and phase c of all the buses also, when the 30% PV is penetrated at bus 4 phase c. The voltage magnitudes of phase a and phase b are somewhat improved than the without PV installation case as shown in Table 6. After increasing the % PV penetration to 50% and 80% respectively, the effect of this PV penetration on the voltage magnitudes of phase a and phase b also gradually increases than 30% PV penetration at bus 4 phase c.

From the Fig. 5 (b) and (c), by comparing phase c voltage magnitudes of all the buses when PV is connected at bus 3 (phase c) and bus 4 (phase c) respectively, it can be inferred that the greatest voltage improvement can be noted at all the buses (phase a and phase b) when PV is connected at bus 3 as compared to bus 4. As the voltage profile of phase c of all the buses is boosted when 80% PV is penetrated at bus 3 (phase c) as shown in Fig. 5 (b).

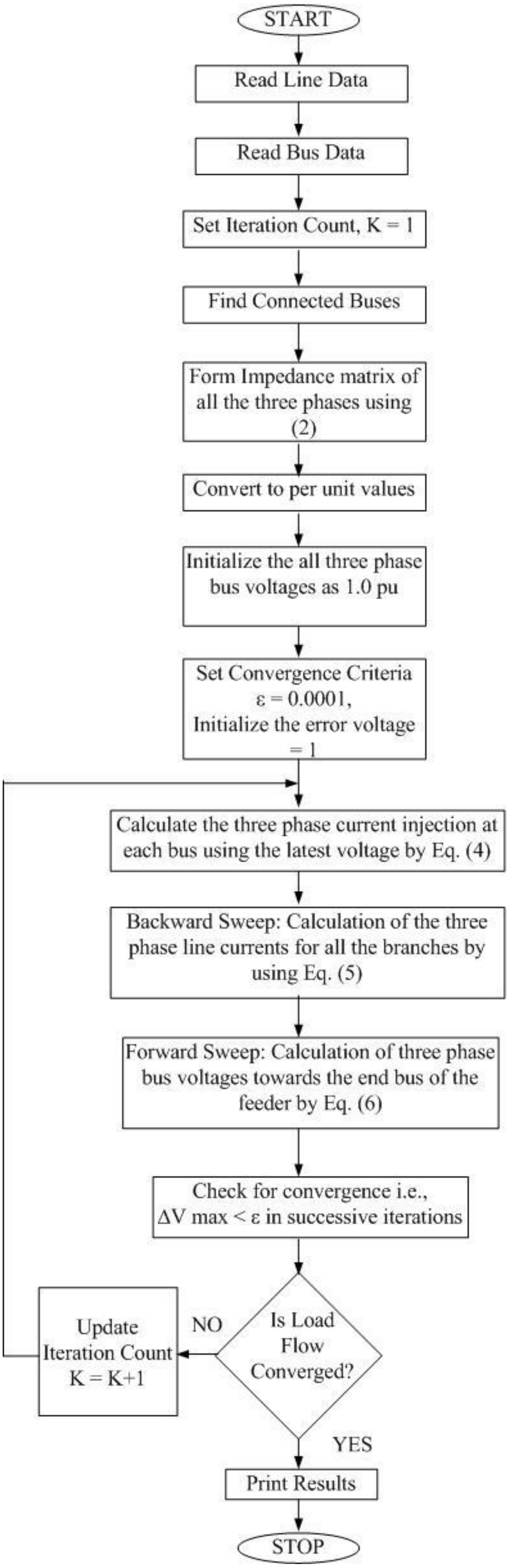


Fig.4. Flow chart of Backward Forward Sweep Algorithm

Table 6. Effect of different % PV penetrations at Bus 4 phase c on various phases of the buses

Without PV Penetration				30 % penetration at Bus 4 c			50 % penetration at Bus 4 c			80 % penetration at Bus 4 c		
Bus No.	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
1	1	1	1	1	1	1	1	1	1	1	1	1
2	0.9995	0.9997	0.9987	0.9994	0.9997	0.9988	0.9994	0.9998	0.9988	0.9994	0.9998	0.9989
3	0	0.9992	0.9976	0	0.9992	0.9978	0	0.9993	0.9979	0	0.9994	0.9981
4	0	0	0.9975	0	0	0.9977	0	0	0.9979	0	0	0.9981
5	0	0	0.9985	0	0	0.9986	0	0	0.9986	0	0	0.9987
6	0	0	0.9984	0	0	0.9985	0	0	0.9985	0	0	0.9986
7	0.9993	0	0	0.9993	0	0	0.9993	0	0	0.9993	0	0
8	0	0.9991	0	0	0.9992	0	0	0.9992	0	0	0.9993	0

While comparing phase a voltage magnitude of all the buses when PV is installed at bus 2 and bus 7 from Fig. 5 (a) and (d) respectively, it is seen that voltage profile of phase a of bus 2 and bus 7 is increased than without PV installation case. The effect of PV penetration on phase a of bus 2 and bus 7 can also be observed on phase b and phase c of all the buses as presented in Fig. 5.

Fig. 6 depicts the phase wise comparison of voltage magnitudes when 30%, 50% and 80% PV is penetrated at each bus. When 30%, 50% and 80% PV is penetrated at phase a of bus 2 and bus 7, it is found that voltage profile of phase a is enhanced as compared to voltage magnitudes without PV systems.

While considering bus 8 phase b, insignificant changes observed in phase b after penetration of PV power at different buses. Also, single phase load on phase b of 2, 3 and 8 bus are remaining same and therefore its effect on voltage is not much significant.

As per the Fig. 6, after connecting PV with different penetration levels at phase c of the respective buses, it can be concluded that the PV connected at phase c of bus 3 provides the best voltage profile of phase c of all the buses.

A. Voltage Unbalance

When the phase voltage magnitudes or phase angles in a three-phase system deviate from the balanced circumstances, or when both deviates, voltage unbalance occurs. In LV distribution networks, voltage unbalance is viewed as a power quality issue that requires serious concern.

The voltages at the utilization level may not be balanced, despite the fact that they are reasonably evenly distributed at the generator and transmission levels, due to the uneven system impedances and the uneven distribution of single-phase loads.

Voltage imbalance in LV distribution networks is caused by a number of variables, including uneven solar generation, uneven system impedances, and the intermittent nature of PV. Voltage unbalance is also influenced by distributed PV's location and capacity. Voltage imbalance is low and maintained below the standard limit at the beginning of a distribution feeder, regardless of the number, placement, and capacity of rooftop PVs that have been installed, but it may increase to levels that are higher than the standard limit at the feeder's end. Unbalanced voltage increases as a result of uneven loading, with a high load and no PV being the worst-case situation.

Voltage unbalance can be calculated using following steps;

Step 1: The line voltages between the phases should be measured.

Step 2: The three phase voltage measurements' average should be determined.

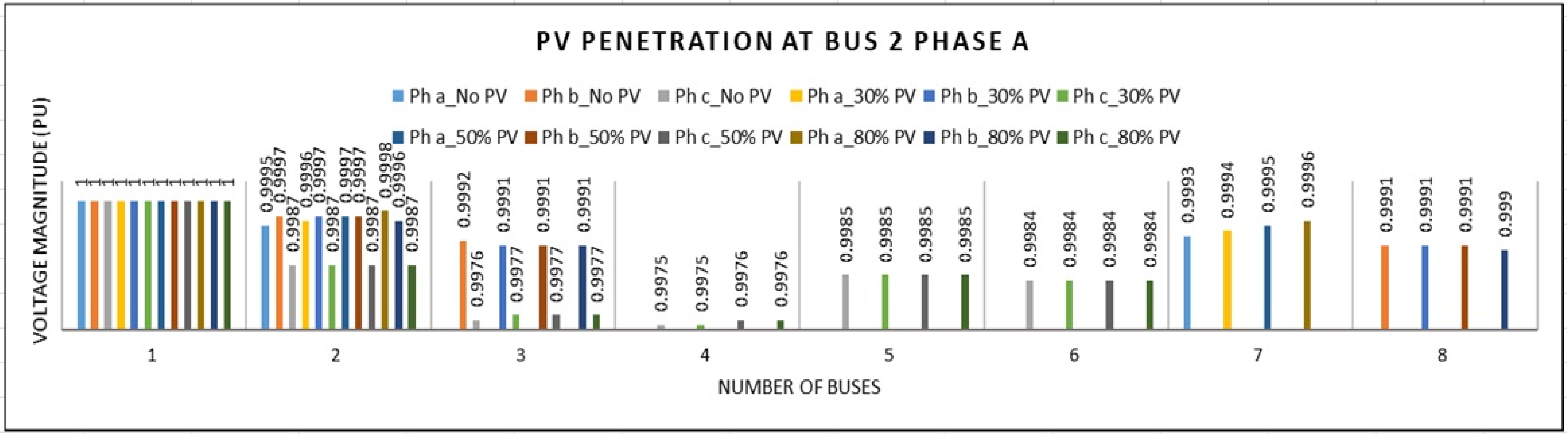
Step 3: By calculating the disparity between each phase voltage (step 1) and the average voltage (step 2), find the unbalance for each phase. Verify that a positive number results from the subtraction.

Step 4: Take the largest unbalance from step 3 and divide it by the average volts found in step 2. Multiply by 100 to put it into a % form. The formula for the same is represented in Eq. (7).

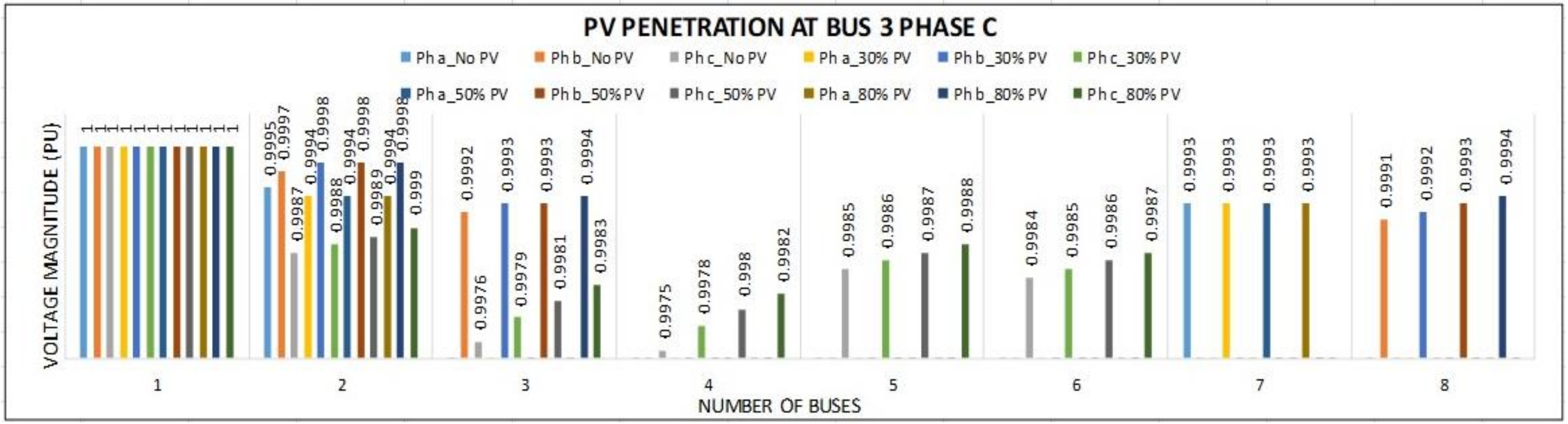
A voltage unbalance exceedingly more than 2% in a three-phase system can cause excessive current unbalance among the windings.

$$\%\,Voltage\,Unbalance = \frac{Maximum\,voltage\,deviation}{Average\,voltage} \times 100 \tag{7}$$

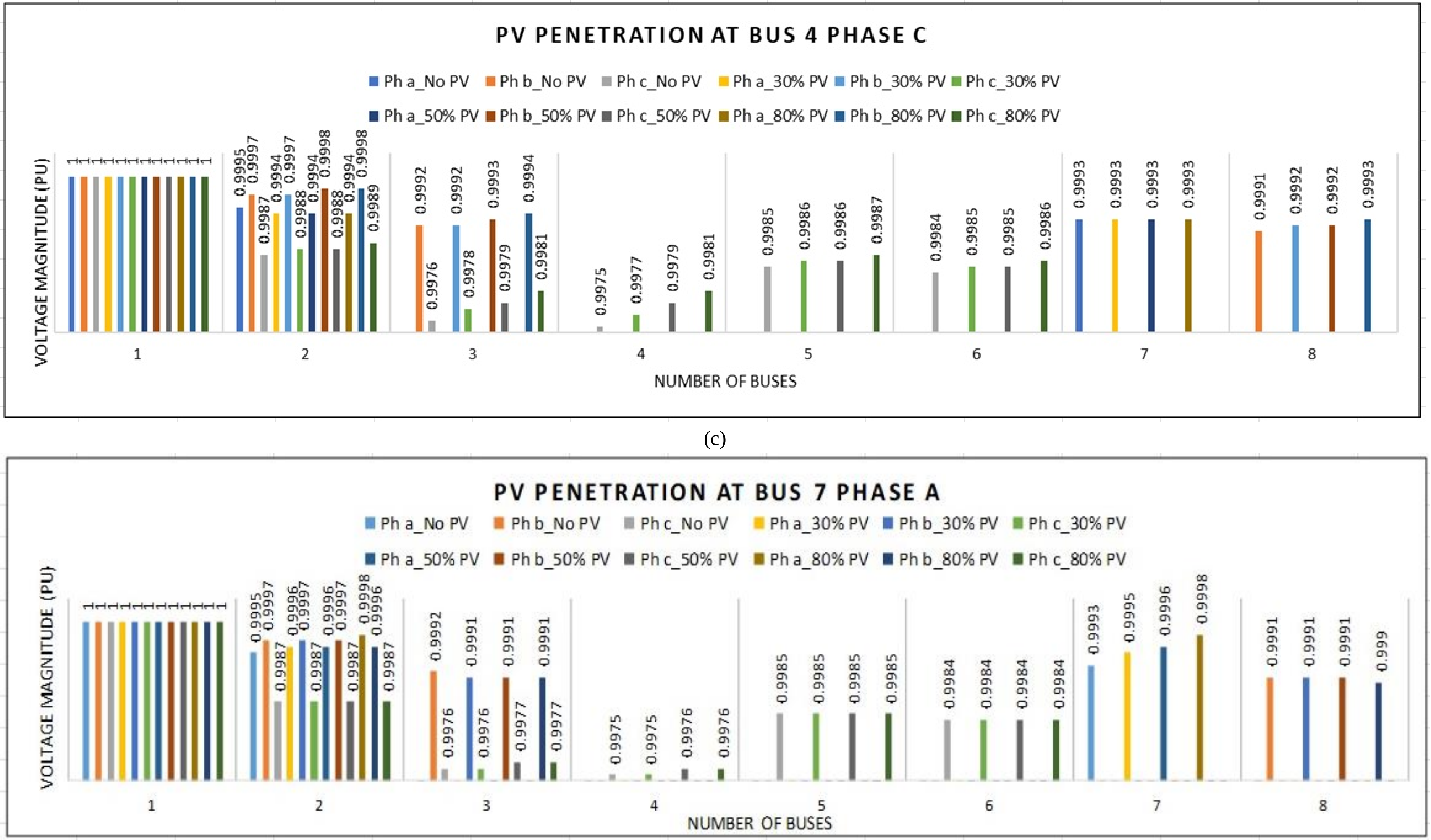
Table 7 shows the % Voltage Unbalance at Bus 2 With 30 %, 50 % and 80 % PV Penetration at the Various Buses. It can be assessed that the lowest % Voltage Unbalance is 0.0372 % when 30 % and 50 % PV is penetrated at the bus 7 a. The reason behind this is that 7 a is connected to bus 2 ‘a’ and the local load demand at bus 7 a is 0.486 pu which is compensated by 30 % and 50 % PV penetration at bus 7 a. It further reduces the voltage unbalance among three phases of the bus 2. However, when 80 % PV is penetrated at bus 7 a, the excess PV power flows back towards grid making the three phase lines of bus 2 more unbalanced (0.0664 % voltage unbalance).


PV PENETRATION AT BUS 2 PHASE A
Ph a_No PV
Ph b_No PV
Ph c_No PV
Ph a_30% PV
Ph b_30% PV
Ph c_30% PV
Ph a_50% PV
Ph b_50% PV
Ph c_50% PV
Ph a_80% PV
Ph b_80% PV
Ph c_80% PV
VOLTAGE MAGNITUDE (PU)
NUMBER OF BUSES
1
2
3
4
5
6
7
8
1 1 1 1 1 1 1 1 1 1 1 1
0.9995 0.9997 0.9987 0.9996 0.9997 0.9987 0.9997 0.9997 0.9987 0.9998 0.9996 0.9987
0.9992 0.9976 0.9991 0.9977 0.9991 0.9977 0.9991 0.9977
0.9975 0.9975 0.9976 0.9976
0.9985 0.9985 0.9985 0.9985
0.9984 0.9984 0.9984 0.9984
0.9993 0.9994 0.9995 0.9996
0.9991 0.9991 0.9991 0.999

(a)


PV PENETRATION AT BUS 3 PHASE C
Ph a_No PV
Ph b_No PV
Ph c_No PV
Ph a_30% PV
Ph b_30% PV
Ph c_30% PV
Ph a_50% PV
Ph b_50% PV
Ph c_50% PV
Ph a_80% PV
Ph b_80% PV
Ph c_80% PV
VOLTAGE MAGNITUDE (PU)
NUMBER OF BUSES
1
2
3
4
5
6
7
8
1 1 1 1 1 1 1 1 1 1 1 1
0.9995 0.9997 0.9987 0.9994 0.9998 0.9988 0.9994 0.9998 0.9989 0.9994 0.9998 0.999
0.9992 0.9976 0.9993 0.9979 0.9993 0.9981 0.9994 0.9983
0.9975 0.9978 0.998 0.9982
0.9985 0.9986 0.9987 0.9988
0.9984 0.9985 0.9986 0.9987
0.9993 0.9993 0.9993 0.9993
0.9991 0.9992 0.9993 0.9994

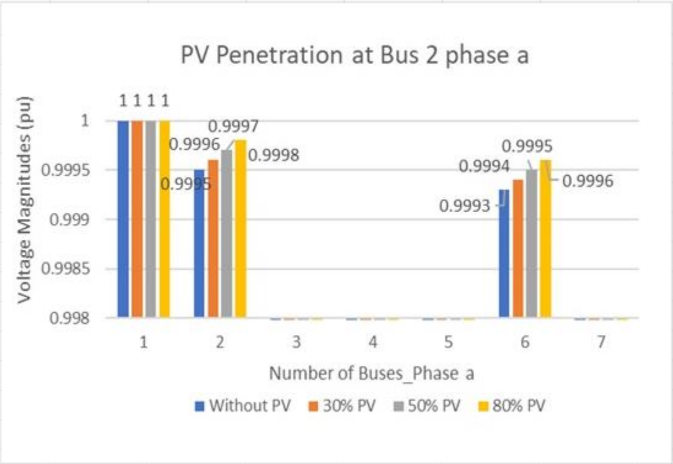
(b)



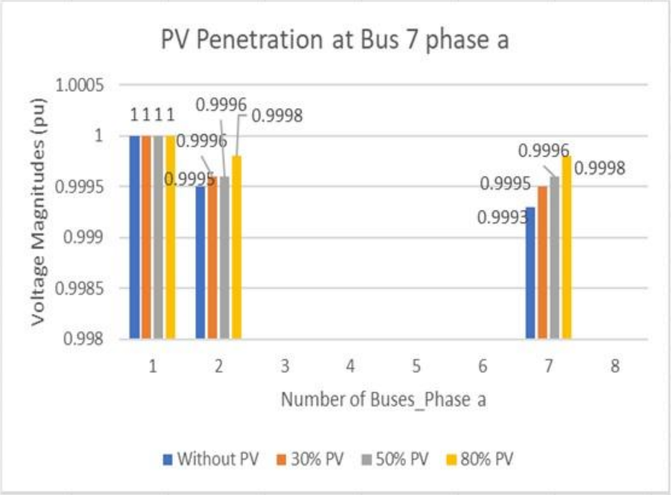
(c)

(d)

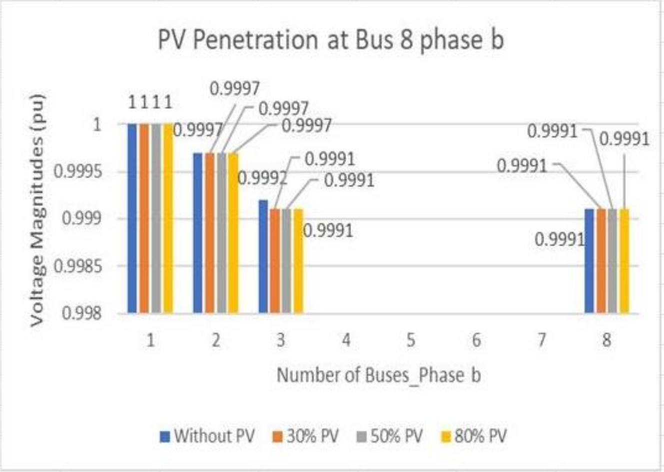
Fig.5. Effect of different % PV penetrations at various phases of the buses


PV Penetration at Bus 2 phase a
Voltage Magnitudes (pu)
1
0.9995
0.999
0.9985
0.998
1 1 1 1
0.9996
0.9997
0.9998
0.9995
0.9994
0.9995
0.9993
0.9996
1
2
3
4
5
6
7
Number of Buses_Phase a
Without PV
30% PV
50% PV
80% PV

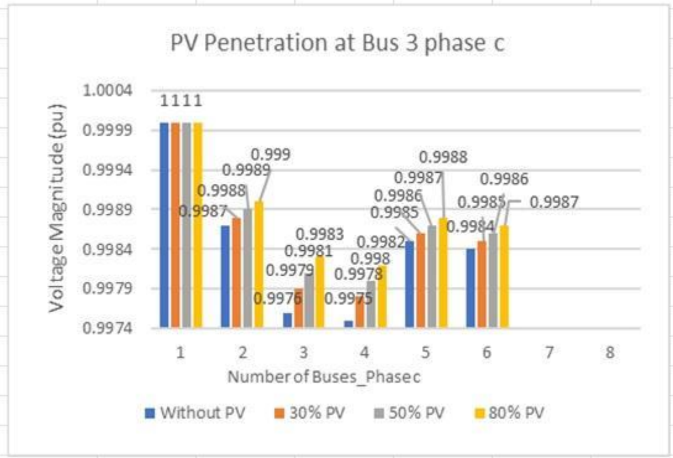
(a)


PV Penetration at Bus 7 phase a
Voltage Magnitudes (pu)
1.0005
1
0.9995
0.999
0.9985
0.998
1 1 1 1
0.9996
0.9998
0.9996
0.9995
0.9996
0.9995
0.9998
0.9993
1
2
3
4
5
6
7
8
Number of Buses_Phase a
Without PV
30% PV
50% PV
80% PV

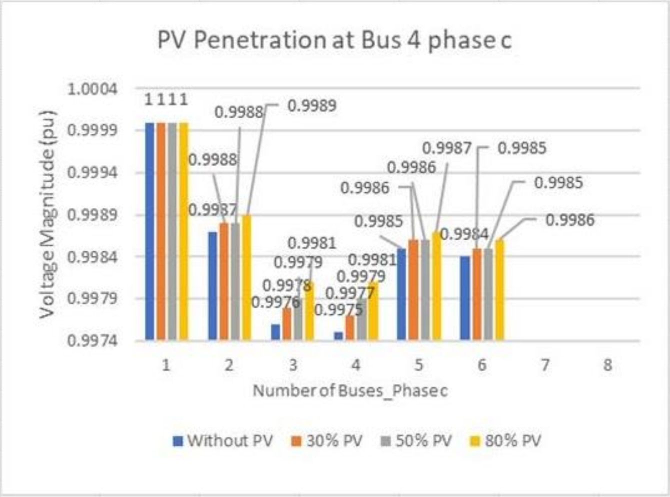
(b)


PV Penetration at Bus 8 phase b
Voltage Magnitudes (pu)
1
0.9995
0.999
0.9985
0.998
1 1 1 1
0.9997
0.9997
0.9997
0.9997
0.9991
0.9992
0.9991
0.9991
0.9991
0.9991
0.9991
0.9991
1
2
3
4
5
6
7
8
Number of Buses_Phase b
Without PV
30% PV
50% PV
80% PV

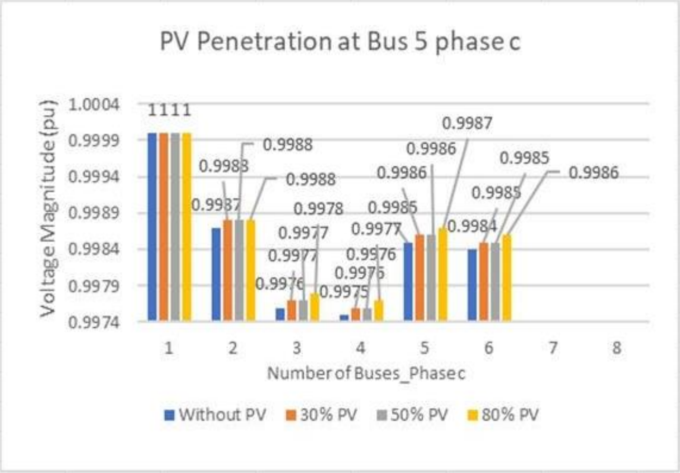
(c)


PV Penetration at Bus 3 phase c
Voltage Magnitude (pu)
1.0004
0.9999
0.9994
0.9989
0.9984
0.9979
0.9974
1 1 1 1
0.999
0.9989
0.9988
0.9987
0.9983
0.9981
0.9979
0.9976
0.9982
0.998
0.9978
0.9975
0.9988
0.9987
0.9986
0.9985
0.9986
0.9985
0.9987
0.9984
1
2
3
4
5
6
7
8
Number of Buses_Phase c
Without PV
30% PV
50% PV
80% PV

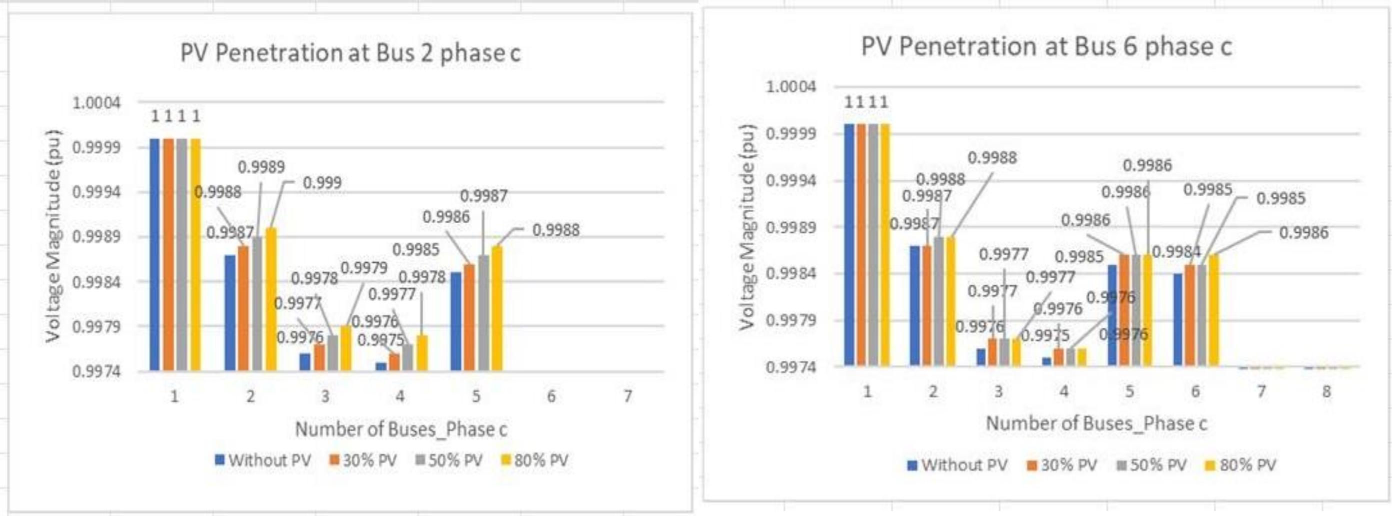
(e)


PV Penetration at Bus 4 phase c
Voltage Magnitude (pu)
1.0004
0.9999
0.9994
0.9989
0.9984
0.9979
0.9974
1 1 1 1
0.9988
0.9989
0.9988
0.9987
0.9981
0.9979
0.9978
0.9976
0.9981
0.9979
0.9977
0.9975
0.9987
0.9985
0.9986
0.9986
0.9985
0.9985
0.9984
0.9986
1
2
3
4
5
6
7
8
Number of Buses_Phase c
Without PV
30% PV
50% PV
80% PV

(f)


PV Penetration at Bus 5 phase c
Voltage Magnitude (pu)
1.0004
0.9999
0.9994
0.9989
0.9984
0.9979
0.9974
1 1 1 1
0.9988
0.9988
0.9988
0.9987
0.9978
0.9977
0.9977
0.9976
0.9985
0.9977
0.9976
0.9976
0.9975
0.9987
0.9986
0.9986
0.9985
0.9985
0.9986
0.9984
1
2
3
4
5
6
7
8
Number of Buses_Phase c
Without PV
30% PV
50% PV
80% PV

(g)



(d)

(h)

Fig. 6. Comparative analysis of voltage magnitudes of the different phases of the buses with and without PV penetration

Table 7. Percentage Voltage Unbalance at Bus 2 with 30 %, 50 % and 80 % PV Penetration at the Various Buses

Sr. No.	% Voltage unbalance at bus 2 without PV	PV penetration at the various buses	% Voltage unbalance at bus 2 with		
			30% PV penetration at corresponding bus	**50%** PV penetration at corresponding bus	**80%** PV penetration at corresponding bus
1	0.0600 %	3 b	0.0564	0.0564	0.0564
2		3 c	0.0527	0.0463	0.0400
3		4 c	0.0600	0.0463	0.0526
4		5 c	0.0500	0.0527	0.0527
5		6 c	0.0564	0.0500	0.0527
6		7 a	0.0372	0.0372	0.0664
7		8 b	0.0564	0.0564	0.0564

Previously, from voltage profile assessment (Fig. 5 and Fig. 6), the best suitable location for the PV system installation for 8 bus RDN is found to be bus 3 which comes in middle of this network and therefore providing the boosted voltage profile throughout all the phases (a, b and c) of the system that is from source node to the end node when 30%, 50% and 80% is penetrated at bus 3 (phase c).

Hence, from the above observations, it can be noted that the best suitable location for the PV system installation for 8 bus RDN in case of voltage profile improvement will be bus 3. However, in case of % voltage unbalance, the preferred location of PV penetration will be bus 7 a.

Voltage unbalance is based on distribution of load in different phases of the line and voltage drop depends upon the magnitude of the current and impedance of the line. Hence, the best location of PV installation for the voltage drops and voltage unbalance are different.

5. Conclusion

The paper mainly focuses upon voltage profile improvement and voltage unbalance assessment of the three phase unbalanced distribution network. Three phase unbalanced 8 bus system has been considered for the analysis. Voltage profile of the selected system with PV +penetration has been compared with the system without PV penetration. Three different % PV penetration levels such as 30%, 50% and 80% are taken into account for investigating the system performance. Effect of PV penetration of one particular bus on the remaining phases of the buses have been studied and observed that if the PV is penetrated at bus 3 (phase c) then there is a voltage improvement at the phase a, phase b and phase c of all the buses. Similarly, phase wise comparison has been carried out and it can be concluded that the PV connected at phase c of bus 3 provides the best voltage profile of phase c, phase a as well as phase b of all the buses.

While commenting on voltage unbalance, % voltage unbalance has been calculated for bus 2 (a-b-c phases) with 30%, 50% and 80% PV penetration at various buses. However, in case of % voltage unbalance, bus 7 a will be the preferable place for the PV penetration due to the lowest percentage voltage unbalance observed at bus 2. Hence, the recommended location for the PV installation will be bus 3 phase c in case of voltage profile improvement and bus 7 phase a in case of % voltage unbalance.

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