Impact of High PV Penetration on Radial Unbalanced Distribution Network

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Abstract: The power distribution system is a core part of the electric grid which links transmission systems and end users or the consumers. Penetrating renewable distributed generators (DGs) such as solar panels, wind turbines into low voltage distribution network is being a popular tradition nowadays. Increased interconnection of renewable DGs such as solar PVs arise several crucial issues that actually impose limitations on the amount of solar PV penetration. In this paper, high PV penetration impact is studied on IEEE 13 bus system. To overcome challenges due to high PV penetration, intelligent and robust voltage control strategy has been designed and implemented to regulate the feeder voltage within allowable limit.
Keywords- Distribution system; solar photovoltaic; high voltage; distribution generator; renewable energy sources**.**

I. INTRODUCTION

The development of renewable energy resource technologies allows researchers to perceive renewable energy resources as a supplement to existing power resources. In the near future it is also expected that the use of renewable energy resources will increase to meet growing power demands [1]. Generators connected to distribution systems are known as distributed generators (DG). Although it is known that distribution systems are planned, designed and constructed to provide electric power to the end users or consumers, the integration of DGs introduces changes to existing networks.

The most significant issues that arises due to large scale PV interconnection with low voltage power distribution system is voltage regulation issue. Due to high power generation during midday by solar PVs, the excess power, after satisfying the load demand, reverses back to distribution grid, which causes voltage rise through the feeder. On the other hand, during evening, there is increased load demand and there is no PV generation. As a result, evening peak load consumes high power from distribution grid, which causes voltage sag. These phenomena cause the feeder voltage to exceed the allowable voltage zone and trip the power supply. To interconnect solar PVs into distribution grid spontaneously, intelligent and robust voltage control strategies should be designed and implemented to regulate the feeder voltage within allowable limit.

The integration of solar photovoltaic (SPV) into electric power system is increasing drastically. This provides more power from renewable energy sources but cause adverse effects as well in the distribution grid like voltage limit violation at point of common coupling, frequency disturbances, grid stability issues etc. Grid codes and regulations has been modified by the authorities to accommodate the grid connected PV systems. IEEE 1547, IEC 61727 and VDE-AR-N4105 are major standards for SPV integration as a distribution generator (DG) in low voltage distribution systems [2]. These standards define and used to maintain the stability and power quality specified by grid codes for SPV interconnections.

Authors in [3] presented current and historic status of integration of renewable energy sources (RES) into utility grids, control and network planning. Codes and standards are also described by researchers with the technologies of grid integration. Voltage fluctuations are major concern for grid connected SPV systems which may lead to voltage limit violations. Overvoltage or voltage rise occurs when the PV penetration increases and cause reverse power flow which may cause unstable operation of grid. A typical low voltage (LV) system is usually design in such a manner that the power will flow from a high voltage (HV) substation to the low voltage consumer loads. Introducing SPV at distribution system level with high penetration distorts the voltage limits and with high voltage at consumer end reverse power flow starts. This undermine the security of the distribution network and stability of the grid.

With the massive utilization of solar photovoltaic energy generation as a distribution generation, it becomes mandatory to deploy efficient and coordinated control measures for the integration and measurement related issues. These control approaches are helpful in accommodating and facilitating the integration of SPV systems into distribution grid with benefits. Numerous approaches have been proposed by researchers to mitigate the voltage rise issues. The distribution voltage regulation techniques for high PV penetration can be broadly classified into three categories.

1. Electrical energy storage (ESS) based strategies
2. Strategies based on active power curtailment of SPV systems
3. Reactive power control based techniques

Many review studies on voltage regulation in distribution system during high SPV penetration are available in literature. A comprehensive review on the problems associated with intermittent nature of SPV system power output when it is integrated with the distribution grid and mitigation methods is presented in [4]. The researchers provided a discussion on the methods for mitigating PV output power fluctuations for individual PV installation using energy storage, diesel generators, fuel cell, maximum power point tracking (MPPT), power curtailment and dump loads. A review study on the voltage regulation challenges raised from increased renewable distribution generation interconnection with LV distribution networks is presented [5-8]. Challenges of high PV penetration with voltage control strategies to mitigate the adverse effects on voltage profile is also presented. In addition, various topologies available in literature also discussed with favorable features of each method. However, review on detail description of mitigating methods especially on active power curtailment and reactive power control by PV inverter is rarely available in literature.

This paper is organized as follows: Section II presents the various models of distribution system in detail. Then in results, impact of high PV Penetration and technique to overcome the overvoltage in network have been analyzed in unbalanced distribution system in section III. Finally, conclusion of paper is given in brief in section IV.

II. MODELLING OF DISTRIBUTION SYSTEM

Modelling of distribution system components and their proper placement in the network is key factor of electricity used by consumers. Poor modelling affects power and voltage quality (waveforms) which in turn increases energy losses in the system. So, it would be necessary to properly model the components like line, load, shunt capacitor, and transformer in distribution system.

2.1 Line Modelling

Lines are one of the important components in distribution system modelling. It can be overhead or underground line. It becomes necessary to determine series and shunt impedance of the line before doing modelling of any distributed system. J. Carson developed several equations for computing self and mutual impedances of unbalance distributed line in his paper. Physical layout of Carson's concept has been shown in Fig. 1.

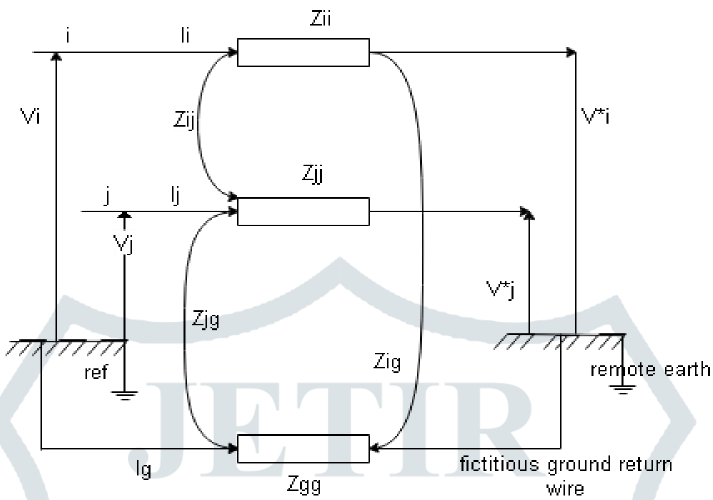

Fig. 1 Physical Layout of Carson's Theory

He represented line with one end of conductor connected to source and other end grounded with earth. Grounded conductor becomes path for returning unbalance currents. It is assumed that earth has uniform surface with constant resistivity therefore any effect from neutral grounding is neglected [9].

If frequency=60 Hz and earth resistivity=100 Ohm per meter. Approximated Carson's self (z_{ii}) and mutual (z_{ij}) impedances are:

$$z_{ii} = r_i + 0.09530 + j0.12134\left(ln\frac{1}{GMR_I} + 7.93402\right) \text{ Ohm/mile} \quad (1)$$

$$z_{ij} = 0.09530 + j0.12134\left(ln\frac{1}{D_{ij}} + 7.93402\right) \text{ Ohm/mile} \quad (2)$$

Where,

GMR_I = Geometrical mean radius of conductor

D_{ij} = Geometrical mean distance of conductor

After calculating impedances, impedance matrix $[Z_{abc}]$ is designed and with help of this matrix, voltage and current matrices of line are given below.

Voltage matrix at node 'n',

$$[VLG_{ABC}]_n = [a].\,[VLG_{abc}]_m + [b_t].[\,I_{abc}]_m\text{L} \quad (3)$$

Where,

$$[a] = [U] + \frac{1}{2}[Z_{abc}].[Y_{abc}], \quad (4)$$

$$[b] = [Z_{abc}] \quad (5)$$

Current matrix -

$$[I_{abc}]_n = [c].\,[VLG_{abc}]_m + [d].[I_{abc}]_m \quad (6)$$

Where,

$$[c] = [Y_{abc}] + \frac{1}{4}\,[Y_{abc}].[Z_{abc}].[Y_{abc}], \quad (7)$$

$$[d] = [U] + \frac{1}{2}[Z_{abc}].[Y_{abc}] \quad (8)$$

Voltage required at node m is the function of voltage at node n and current at node m.

Voltage matrix at node 'm',

$$[VLN_{abc}]_m = [A_t].[VLN_{ABC}]_n - [B_t].[I_{abc}]_m \quad (9)$$

Where,

$$[A_t] = [a_t]^{-1}, \quad (10)$$

$$[B_t] = [a_t]^{-1}.[b_t] \quad (11)$$

Shunt calculation requires conductance and susceptance. Conductance is neglected when it is compared with susceptance. Susceptance calculation is done in similar way that of inductance in series impedance section.

2.2 Line Modelling

There are various types of load combination which can be modelled in terms of constant ZIP (impedance, current and power) or different combination of constant ZIP. Current is controlling parameter because it can be controlled in effective and efficient way as compared to any other parameter. Modelling equations in current parameter terms for constant impedance, constant current, and constant power load models are given as-

2.2.1 Constant Impedance:

$$Z_{a,b,c} = \frac{|V_{a,b,c}|^2}{S_{a,b,c}^*} = \frac{|V_{a,b,c}|^2}{|S_{a,b,c}|}\angle\theta_{a,b,c} \quad (12)$$

$$= |Z_{a,b,c}|\angle\theta_{a,b,c} \quad (13)$$

$$IL_{a,b,c} = \frac{V_{a,b,c}}{Z_{a,b,c}} = \frac{|V_{a,b,c}|}{|Z_{a,b,c}|}\angle(\delta_{a,b,c} - \theta_{a,b,c}) \quad (14)$$

$$= |IL_{a,b,c}|\angle\alpha_{a,b,c} \quad (15)$$

2.2.2 Constant Current:

$$IL_{a,b,c} = |IL_{a,b,c}|\angle(\delta_{a,b,c} - \theta_{a,b,c}) \quad (16)$$

$$= |IL_{a,b,c}|\angle\alpha_{a,b,c} \quad (17)$$

2.2.3 Constant Power:

$$|S_{a,b,c}|\angle\,\theta = P_{a,b,c} + jQ_{a,b,c} \quad (18)$$

$$IL_{a,b,c} = \left(\frac{S^{a,b,c}}{V^{a,b,c}}\right)^* = \frac{|S_{a,b,c}|}{|V_{a,b,c}|}\angle(\delta_{a,b,c} - \alpha_{a,b,c}) \quad (19)$$

$$= |IL_{a,b,c}|\angle(\alpha_{a,b,c}) \quad (20)$$

And

$$V_{a,b,c} = |V_{a,b,c}|\angle\delta_{a,b,c} \quad (21)$$

Where,

$V_{a,b,c}$ is voltage of three phase load, $IL_{a,b,c}$ is line current of three phase load, $S_{a,b,c}$ is complex power of load, $P_{a,b,c}$ is active power, $Q_{a,b,c}$ is reactive power, $\delta_{a,b,c}$ is line-to-neutral voltage angles, $\alpha_{a,b,c}$ is diff. angle between line to neutral and power factor angle, $\theta_{a,b,c}$ is power factor, and $Z_{a,b,c}$ is impedances of load.

All of these load models are included in load file for calculation purpose.

2.3 Shunt Capacitor Modelling

Shunt capacitor provides reactive power in distribution system to improve voltage levels and to minimise requirement of reactive power demand. Modelling of Wye- Connected Capacitor bank is done by using following equations.

2.3.1 Wye- Connected Capacitor:

Susceptance (B_C) for each unit is

$$B_C = \frac{Kvar}{kV_{LN}^2 \cdot 1000}\text{S} \quad (22)$$

And,

$$IC_a = jB_a \cdot V_{an} \quad (23)$$

$$IC_b = jB_b \cdot V_{bn} \quad (24)$$

$$IC_c = jB_c \cdot V_{cn} \quad (25)$$

Where, IC_a, V_{an} are phase current and phase voltage respectively. In our system, Wye connected capacitor bank is considered for load flow solution.

2.4 Transformer Modelling

Transformers are required to transfer voltage from transmission level to distribution feeder level. These are classified as stepping up, stepping down and phase shifting type transformers. There are different transformers combinations which can be used in radial distribution system as below-

1. D–Grounded Y
2. Open Y–Open D
3. Grounded Y–Grounded Y
4. Ungrounded Y–D
5. D–D

Where,
Y= star, and D= delta.

In our proposed system, type 1 and 3 are used for load flow solution purpose.

Transformer equations of voltage and current matrices are -

$$[VLG_{abc}]_m = [A_t].[VLN_{ABC}]_n - [B_t].[I_{abc}]_m \quad (26)$$

$$[I_{ABC}]_n = [C_t].\,[VLG_{abc}]_m + [D_t].[\,I_{abc}]_m \quad (27)$$

Where, A_t, B_t, C_t, D_t are coefficients and their value depends on type of transformer connections used for calculation purpose [6].

2.5 ZIP Load Modelling

The polynomial expression known as the ZIP coefficients model represents the variation (with voltage) of a load as a composition of the three types of constant loads Z, I, and P. Z, I, and P stand for constant impedance, constant current, and constant power loads, respectively. The expressions for active and reactive powers of the ZIP coefficients model are:

$$P = P_0\left[Z_p\left(\frac{V_i}{V_o} + I_p\frac{V_i}{V_o} + P_p\right)\right] \tag{28}$$

$$Q = Q_0\left[Z_q\left(\frac{V_i}{V_o} + I_q\frac{V_i}{V_o} + P_q\right)\right] \tag{29}$$

Where, P and Q are the active and reactive powers at operating voltage (V_i); P_0 ,and Q_0 are the active and reactive powers at rated voltage (V_0); Z_p, I_p, and P_p are the ZIP coefficients for active power and Z_q, I_q, and P_q are the ZIP coefficients for reactive power.

2.6 PV (Photovoltaic) Modelling

The output power of solar depends on intensity of solar irradiance. Since solar irradiance changes throughout the day time hence output power also changes and its expression is given in the following equation.

$$Po_{pv} = \eta_{pv} \times A_{pv} \times \emptyset \tag{30}$$

Here, Po_{pv} is the total output power of PV unit in MW or kW

η_{pv} is the efficiency of PV unit in (%),

A_{pv} is the surface area of PV array in m^2,

$\emptyset$ is the solar irradiance in W/m^2.

III. Analysis Of Case Studies And Results

Three phase load flow analysis is done by interfacing MATLAB with Open DSS on IEEE 13 bus radial distribution network. Different case studies have been demonstrated for various PV impact on the system and to overcome the overvoltage in the system, voltage regulator control technique is implemented.

3.1 Case 1: With 50% PV Penetration

Firstly, three phase load flow results are obtained for IEEE 13 bus distribution system. Then for further analysis purpose, 3^{rd} phase voltage profile is taken as impact of PV penetration is more visible on 3^{rd} phase as compared to 1^{st} and 2^{nd} phases for IEEE 13 bus network.

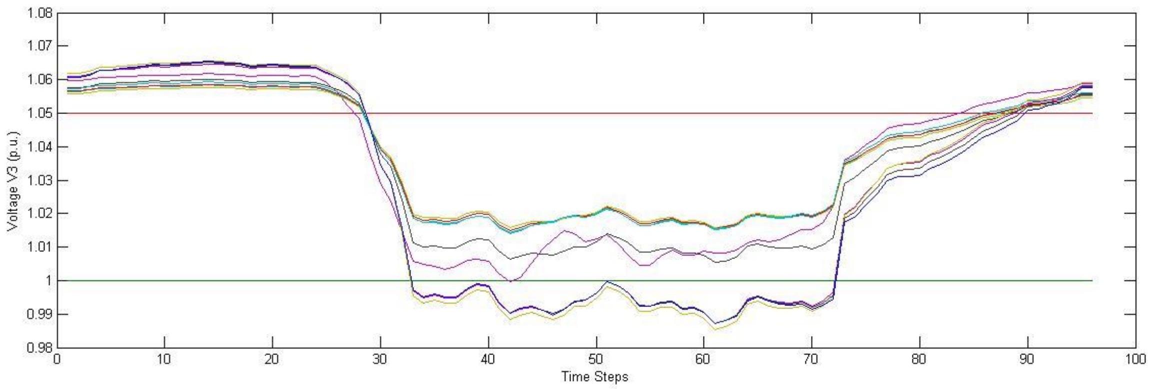

Fig. 2 Voltage Profile with 50% PV Penetration

In Fig. 2, we can see that voltage of the system is going beyond voltage limits i.e. (0.95-1.05 p.u.). Here, voltage is rising upto 1.06 p.u. which is due to 50% PV penetration impact. Therefore, reverse power starts flowing into the system because power generation in the system is more than the power demand.

3.2 Case 2: With 50% PV Penetration and Voltage Regulator Control

In order to overcome PV penetration impact, voltage regulator control technique is implemented on the system. By using voltage regulator control, voltage of the system remains in its specified limits i.e. (0.95-1.05 p.u.) as shown in Fig. 3.

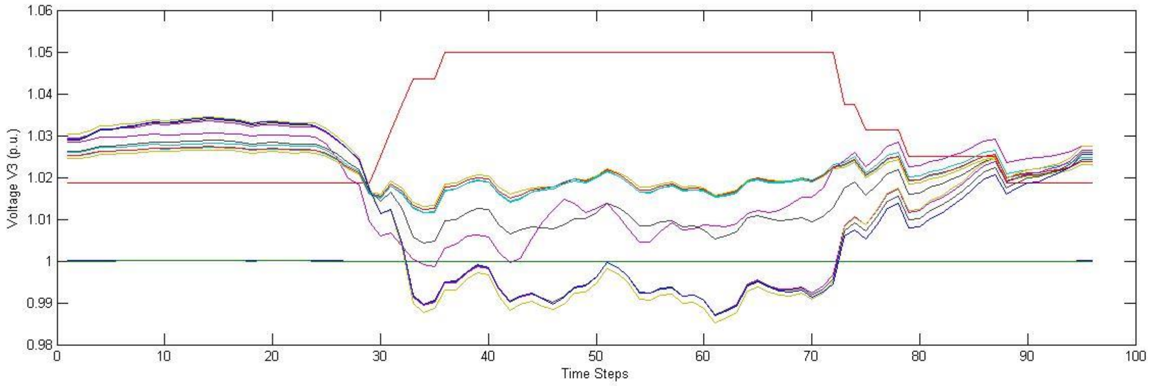

Fig. 3 Voltage Profile with 50% PV Penetration with Voltage Regulator Control

3.3 Case 3: With 70% PV Penetration

Similarly, In Fig. 4, we can see that voltage of the system is going beyond voltage limits i.e. (0.95-1.05 p.u.). Here, voltage is rising upto 1.07 p.u. which is due to 70% PV penetration impact. Therefore, reverse power starts flowing into the system because power generation in the system is more than the power demand.

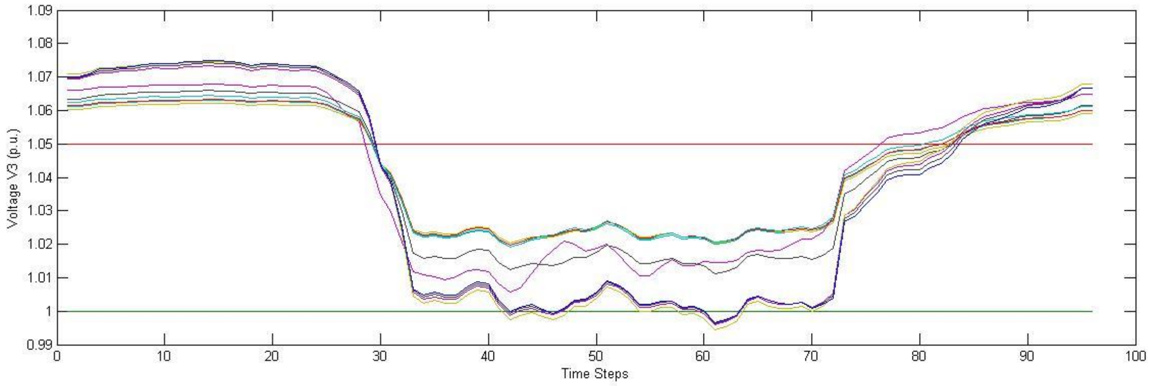

Fig. 4 Voltage Profile with 70% PV Penetration

3.4 Case 4: With 70% PV Penetration and Voltage Regulator Control

Similarly, In order to overcome PV penetration impact, voltage regulator control technique is implemented on the system. By using voltage regulator control, voltage of the system remains in its specified limits i.e. (0.95-1.05 p.u.) as shown in Fig. 5.

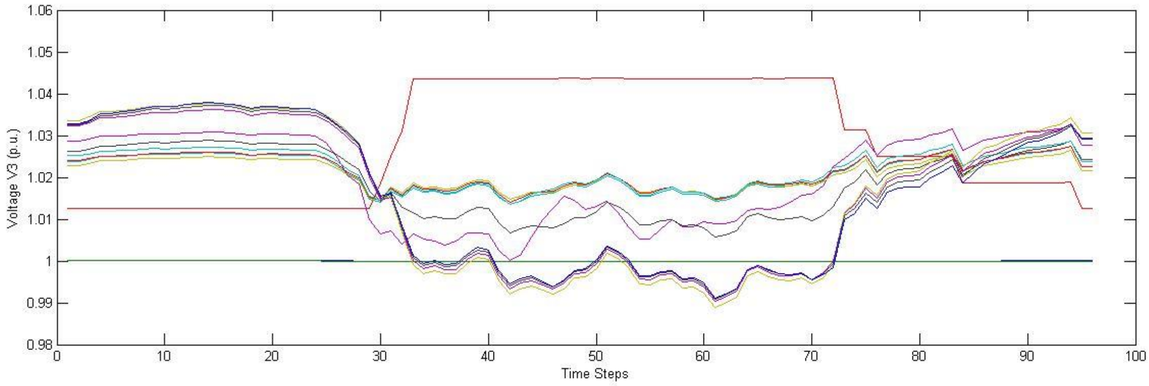

Fig. 5 Voltage Profile with 70% PV Penetration with Voltage Regulator Control

3.5 Case 5: With 90% PV Penetration

Similarly, In Fig. 6, we can see that voltage of the system is going beyond voltage limits i.e. (0.95-1.05 p.u.). Here, voltage is rising upto 1.08 p.u. which is due to 90% PV penetration impact. Therefore, reverse power starts flowing into the system because power generation in the system is more than the power demand.

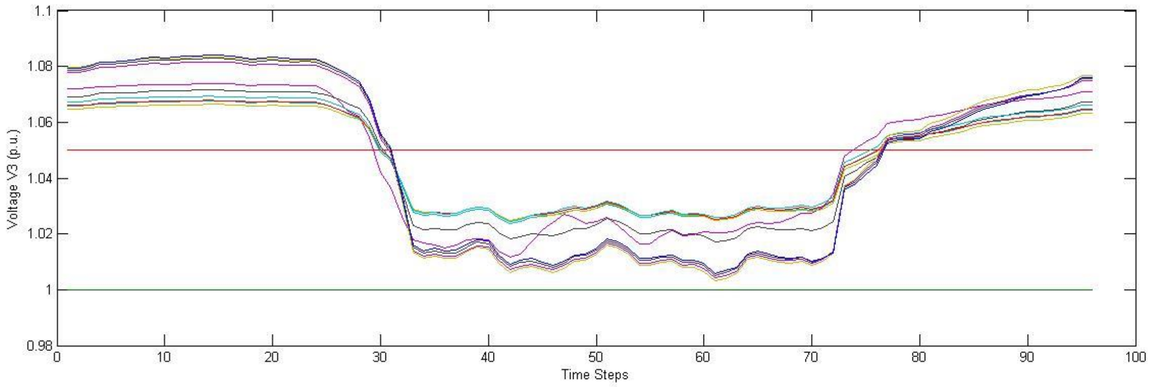

Fig. 6 Voltage Profile with 90% PV Penetration

3.6 Case 6: With 90% PV Penetration and Voltage Regulator Control

Similarly, In order to overcome PV penetration impact, voltage regulator control technique is implemented on the system. By using voltage regulator control, voltage of the system remains in its specified limits i.e. (0.95-1.05 p.u.) as shown in Fig. 7.

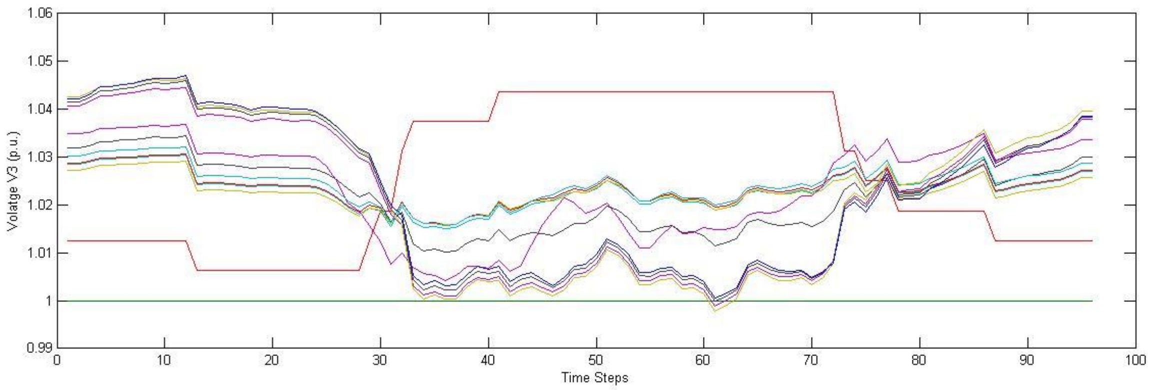

Fig. 7 Voltage Profile with 90% PV Penetration with Voltage Regulator Control

IV. Conclusion

In this paper, PV penetration impact with varying penetration levels and technique to overcome the overvoltage have been examined on the proposed system. Solar photovoltaic technology is becoming very attractive day by day for the power generation because of its various advantages. The power generated from SPV technology is fluctuating in nature, therefore it creates the grid stability and reliability issues.

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