Reactive power optimization and voltage control in Distribution System using particle swarm optimization

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Abstract: The renewable policies in various countries are driving significant growth of grid connected renewable generation sources such as Solar Photovoltaic (PV), wind, biomass, Fuel Cell (FC), or microturbines. Among all the proportion of photovoltaic (PV) generation into existing power system generation mix has significantly increased in recent times. Most of the PV plants are getting connected to low/medium voltage distribution level as distributed generation (DG). The uptake of an intermittent power from the PVs is challenging the power system operation and control. The network voltage control is one of the major challenges during the operation of the distribution connected PVs. The active power injection from a PV plant causes variable voltage rise. This forces the existing voltage control devices such as on-load tap-changer (OLTC) and voltage regulator (VR) to operate continuously. The consequence is the reduction of the operating life of the voltage control mechanism. Also, the conventional non-coordinated reactive power control results in the operation of the VR at its control limit (VR runaway condition). But the existing methods are does not consider detailed impact of DG such as PV on autonomous local control setting of voltage regulator. This paper proposes a new technique for voltage regulation of a radial medium (MV) distribution system in presence of distribution generation (DG) units. The proposed technique consists of the coordinated actions of on-load tap changer (OLTC) of transformer and reactive power coordination in the distribution network by the impact of PV generation. Simulation results reveal that the proposed control method is capable of maintaining the system voltage within the permitted range.

Keywords: Distribution system, Photovoltaics, on-load tap changer, volatage regulator, reactive power coordination.

I. INTRODUCTION

Solar photovoltaic distributed generation (PV-DG) systems are one of the fastest-growing types of renewable energy sources being integrated worldwide onto distribution systems.The cumulative global capacity of PV generation is expected to grow up to 200GWp by the year 2017. The cumulative global installed capacity is approximately 137GW, till the end of 2013. PV plants are integrated both at the transmission level and the distribution level from the power system integration point of view.Most of the PV plants are getting connected to low/medium voltage distribution level as distributed generation (DG). However, PV-DG impacts on distribution systems can be either steady-state or dynamic in nature, and they include:

➢ Changes in feeder voltage profiles, including voltage rise and unbalance.
➢ Changes in feeder loading, including potential equip-ment and component overload.
➢ Frequent operation of voltage-control and regulation devices, such as load tap changers (LTCs), line voltage regulators (VRs), and capacitor banks
➢ Reactive-power flow fluctuations due to operation of switched capacitor banks
➢ Overvoltage issues can allow the DGs to absorb reactive power
➢ Power quality, PV-DG intermittency may lead to voltage fluctuation issues.

The severity of these impacts varies with the penetration level, the location of the PV-DG, and the electrical characteristics of the distribution systems. For instance, a high PV-DG penetration level could cause a feeder to become an active circuit and inject power back to the transmission system. This high penetration condition may affect voltage profiles, over current protection, and capacitor-bank operation. Such a situation may occur on feeders selected for integrating multiple utility-scale PV-DG plants. Because both PV-DG output and feeder load vary throughout the day, it is necessary to investigate impacts for different degrees of penetration of PV-DG and also to assess the effects under various conditions of feeder loading. The injection of PV generator active power impacts the operation of OLTCS and VRs. Present day voltage control practices do not consider detailed impacts of PVs on these voltage control mechanisms.

This paper presents the detailed analysis of the impact PV on OLTCs and VRs and reactive power coordination. Various voltage regulation strategies to tackle the possible adverse impact of PVs are also developed.

II. PV GRID INTEGRATION STANDARDS AND GENERATION MODELING

The capacity of a PV plant determines the voltage level at which it should be integrated. The PV generation is getting integrated mostly at the low voltage and the medium voltage distribution level. The grid integration standards are evolving in various countries in order to achieve a seamless integration. The PV plants need to comply with the various technical requirements prescribed in a grid integration standard. The set of technical requirements depend upon the voltage level at which the PV plant is getting integrated. The power system operators in different countries have developed the country specific guidelines in the integration standards. The major low voltage and medium voltage standards reviewed here are as follows.

➢ IEC61727-Photovoltaic systems characteristics of the utility interface
➢ IEEE1547-Standard for interconnecting distributed resources with electricpower systems
➢ VDEARN4105-Technical requirements for the connection to and parallel operation with LV distribution networks (Germany)
➢ BDEW-Technical Guideline for generating plants connected to the MV network (Germany)
➢ G83-Recommendations for the connection of type tested small-scale embedded generators (up to 16A per phase) in parallel with LV distribution systems (UK)

The aim of reviewing the guidelines is to study the network operator's expectations from the PV inverters. The existing standards try to address some of the grid integration challenges. The technical requirements in the standards can be categorized into three broad areas, the protection set points, the power quality limits and the grid support functions. This is discussed in upcoming sections in detail.

A.Protection Settings

There are two kinds of PV generation protection settings. There are the PV plant settings, which protect a PV generator itself from abnormal operating conditions. The other kind of protection settings mitigate the impact of a PV plant on a utility network during abnormal power system conditions. The grid integration standards mostly specify the requirements which mitigate the impact on a utility network.
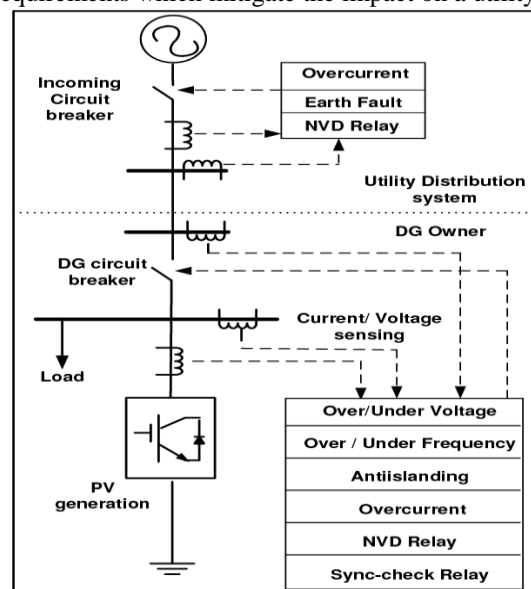

Fig.1. Typical PV generator protection

The abnormal utility situations such as faults etc. result in frequency and/or voltage excursions at the point of common coupling (PCC). The PV grid integration standards define the permissible PCC voltage variation range and the permissible grid frequency variation range under which, the PV generation should continue to operate. The normal operation zone defined by the standard IEC61727 is shown in Fig.2. The standard recommends that a PV generation should continue to operate normally if a PCC voltage variation is between -15% to +10% from the nominal value. Similarly, a PV plant should not be disconnected from a grid if a grid frequency variation is ±2% from the nominal value. There should be a PV plant disconnection if either of these bands of the PCC voltage or the frequency is violated. The standard further also prescribes the time

interval within which disconnection of the PV plant should occur if the grid frequency or the PCC voltage violation is detected.
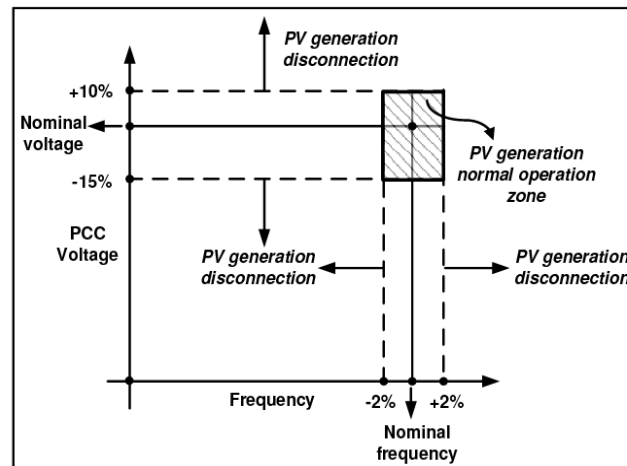

Fig.2.Permissible PCC voltage and frequency variation

B.Power Quality Limits

The impact on the power quality due to an introduction of PV generation is mitigated by prescribing limits in the grid codes. The standards prescribe the limits on the harmonic distortion, the unbalance and the voltage flicker to mitigate the possible adverse impact due to PV generation.

C. Grid Support Features

The network operators are expecting increased participation from the PV generations into the grid support operations. This is due to the vast growth of the PV generation units. The grid support features expected from a PV generation are described in some of the standards. These can be subdivided into two major categories, namely the dynamic grid support features and the steady state grid support features.

1) Dynamic grid support

This category of features includes the services provided by a PV generation duringsystem disturbance events. The major services expected in various grid codes are the low voltage ride through, the fault reactive current injection and the frequency support.

2) Steady state voltage support

The most pressing steady state operational challenge faced by the IEEE1547 distributionnetwork operator is an intermittent overvoltage due to a PV plant. expects a PV plant to operate at a unity power factor. The operation of a PV generation at an unity power factor means no contribution from a PV inverter towards the reactive power or the voltage support functionality. The network operators are increasingly demanding a contribution from PV generators towards a steady state voltage control functionality. The voltage support functionality by PV plant can be offered by an active power curtailment and a reactive power support.

The contribution of a reactive power at the highest active power capacity of a PV plant necessitates an interface inverter overrating. This is indicated in terms of a PV generation capacity curve in Fig.3. The grid codes usually recommend a power factor range as shown in the capacity curve at which PV plant should be able to operate even at its maximum active power capacity. This determines an apparent power rating of a PV inverter must be able to operate at 0.95 lead/lag power factor(Pf).
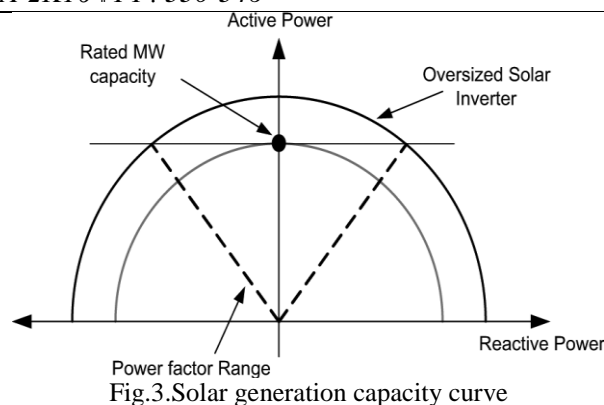
Fig.3.Solar generation capacity curve

The various LV and MV network standards both expect PV generation to offer a reactive power support as requested by a network operator. Most of the standards expect a reactive power support through the following different ways.

1. Constant power factor (Pf)
2. Constant reactive power (Q)
3. Variable power factor as active power varies (Pf(P) characteristic)
4. Variable reactive power as voltage varies (Q(U) characteristic

The constant Pf mode and constant Q mode expect a PV plant to operate at a constant preset Pf or a constant reactive power value when active power varies. However the other two modes of operational characteristics Pf (P) and Q (U) adopt variable reactive power injections when active power or PV plant point of common coupling voltage varies.

Pf (P) characteristic

The overvoltage condition in a power system typically occurs near the highest active power injection. In this scenario a PV inverter can offer an inductive reactive power support. The default Pf(P) curve defined in VDEARN4105 is depicted in Fig.4. There is no reactive power support till a PV plant active power output reaches 50%. Then an inductive reactive power support is offered by a PV inverter by operating at a lagging Pf. The PV plant is operated at a lagging Pf limit of 0.95 at the rated active power output. A similar strategy with a PCC voltage check is implemented in Italian grid code. That is, a PV plant operates in a lagging Pf if a PCC voltage is above a preset value.

Q(U) characteristic

This method monitors a PV PCC voltage. An appropriate value of a inductive or a capacitive reactive power support is offered to improve the PCC voltage profile. This method of a voltage support through *Q(U)* characteristic is prescribed in BDEW standard. Typical characteristic as prescribed in BDEW is shown in Fig.5. There is a voltage deadband zone in the *Q(U)* characteristic where no reactive power support is offered.Both the *Pf(P)* and the *Q(U)* characteristics consider a gradient to avoid sudden changes in a PCC voltage value.
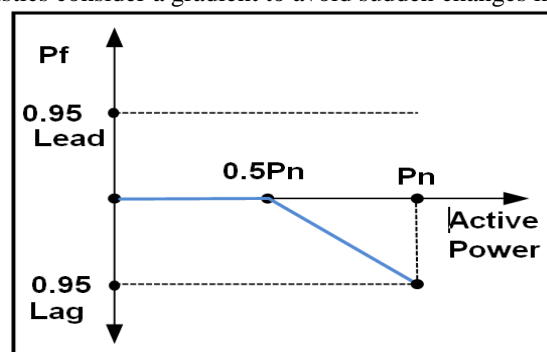

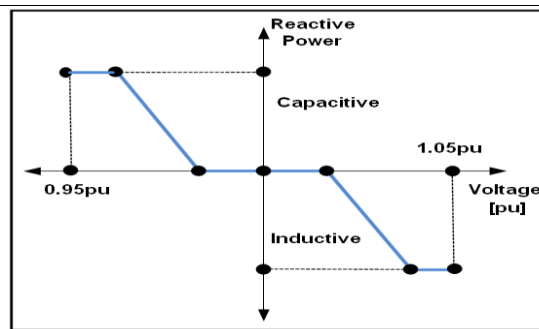Fig.4. Pf(P) characteristic as per voltage support

Fig.5. Q(U) characteristic for voltage support

The BDEW guideline recommends that every individual network operator should decide either characteristic or target reactive power setpoints. Further, a remote control of the PV inverters to convey reactive power setpoints is recommended.

D. PV Topology

A typical topology of a grid integrated PV and a control structure of its power inverter is shown in Fig.6. The topology comprises three main subsystems : a PV panel, a grid interface power converter and a converter control system. A PV panel converts solar energy into dc electrical energy. The dc electrical energy generated from a PV panel is injected into a power system at the nominal grid voltage and the nominal grid frequency by utilizing a power electronic converter. The control structure of a power converter ensures an efficient operation and also incorporates the grid support features.
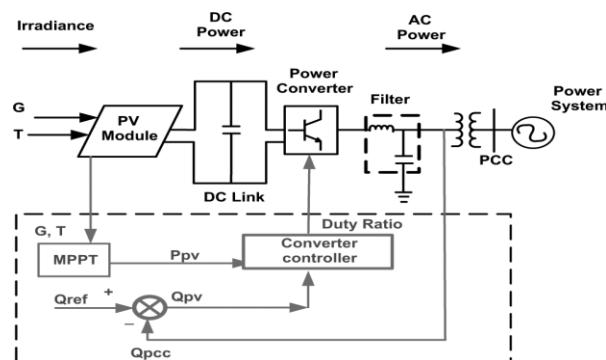

Fig.6. Generic grid integrated PV topology

III. DETRMINISTIC VOLATGE CONTROL

This section deals in detail with deterministic steady state voltage control in the presence of PV generation. The detailed impact of PV on Voltage Regulators (VRs) and On-load tap changers (OLTCs) is also considered. A coordination strategy is proposed to mitigate the overvoltage and to alleviate the negative impact on OLTC and VR using reactive power option from a PV plant.

Distribution Network Operators (DNOs) maintain appropriate voltage profile across the network with the help of on load tap changers (OLTCs), voltage regulators(VRs) and capacitors. In most of the distribution feeders these devices are controlled based on the local signals, for example, bus voltage for OLTC and VR and time control or local bus voltage control for capacitors. In this conventional voltage control method all devices operate autonomously in a non coordinated manner. This non coordinated approach and unity power factor PV generation impacts the operation of OLTCs and VRs. The presence of PV on distribution feeders will lead to increased number of OLTC and VR operations and wear and tear of the devices. The result is an increase in the OLTC and VR maintenance/overhaul cost incurred by the DNOs. Under the scenario of significant power injection by PV, power flows can reverse on a distribution feeder. Some OLTC construction is such that permissible reverse power flow is less than the apparent power rating of the transformer. Under specific operational scenario VR fails to control voltage at the regulated bus and reaches the lowest or highest tap limits. This phenomenon is widely referred to as reverse power tap changer runaway condition. This highlights the fact that in the presence of PV on the feeder, an appropriate consideration of OLTC, VR and their control settings are necessary for an effective voltage control strategy.

Most of the recent approaches replace local autonomous control of the voltage control devices with communication based supervisory control. voltage control devices are remotely dispatched on an hourly basis through a communication channel to achieve flat voltage profile in the system without DG with Unity power factor PV in distribution systems is considered. Further, two way communication based real time smart grid Volt-Var control is proposed. Though the above mentioned schemes will certainly be able to alleviate the challenges, they require communication with all voltage control devices.
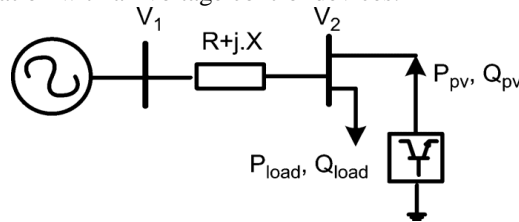

Fig.7. PCC voltage control by PV plant

However the operation of VRs is still autonomous based on local signals, without communication links on many distribution feeders. The switched capacitors also lack communication links on some feeders and timer control is still operational in Europe. Considering this fact, a combined local and remote voltage control strategy is discussed. It proposed that by opting for complete remote control of voltage control devices, they could lose their ability to react to load changes. A local communication-less Volt-Var control in the presence of synchronous machine based DG is considered.

Most of the available literatures does not consider detailed impact of DG such as PV on autonomous local control setting of VR. It is also important to have an insight into what possible interaction a PV and its reactive power settings will have with the autonomous operation of a VR. This chapter investigates these challenges and proposes an optimal coordination strategy.

A. Radial Feeder Voltage Variation

Fig.7. is a simple equivalent circuit of a radial feeder. The feeder has a connected load and a PV generator. The active/reactive power consumption by a load and the active power injection by a PV both will cause a voltage drop on a feeder. This voltage drop can be mathematically derived as follows. In Fig.7. V_1 is a constant substation voltage. The vector diagram of the operation of feeder is shown in Fig.8.
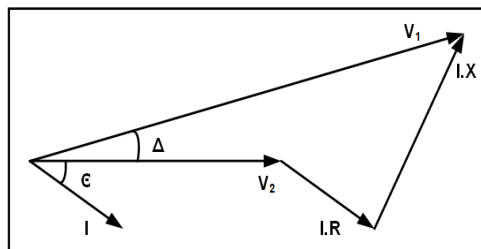

Fig.8. Vector diagram of radial feeder

Current I flowing on the feeder can be calculated as:

$$I = \frac{(P_{load} - P_{pv}) - j.(Q_{load} \pm Q_{pv})}{V_2} \qquad \cdots\cdots\cdots (1)$$

PV generation MPPT active power is denoted by P_{pv} and reactive power output is Q_{pv}. Load power is denoted by P_{load} and Q_{load}. R + jX represent impedance of the line. Let us denote ΔV as the voltage drop across the feeder impedance R+j.X,

$$\Delta V = V_1 - V_2 = (R + j.X) \qquad \cdots\cdots\cdots (2)$$

Substituting the eq.(4.1) in (4.2) :

$$\Delta V = \frac{R(P_{load} - P_{pv}) - X.(Q_{load} \pm Q_{pv})}{V_2} + j. \frac{X(P_{load} - P_{pv}) - R.(Q_{load} \pm Q_{pv})}{V_2}$$

$$\cdots\cdots\cdots (3)$$

The imaginary term in eq.(3) on the distribution feeders is typically very small and can be neglected. Thus voltage drop ΔV on the feeder can be calculated as :

$$\Delta V \cong \frac{R(P_{load} - P_{pv}) + X.(Q_{load} \pm Q_{pv})}{V_2} \qquad \cdots\cdots\cdots (4)$$

The voltage drop equation in (4) signifies that there is ΔV voltage drop due to P_{load}, Q_{load} and P_{pv}. Further this ΔV voltage drop (and voltage V_2) will vary as the load power P_{load}, Q_{load} and the injected PV power P_{pv} will vary. The load power P_{load}, Q_{load} is not controllable to mitigate the voltage V_2 variation. Thus in order to control the voltage drop either P_{pv} needs to be curtailed or Q_{pv} needs to be controlled. Q_{pv} control can mitigate the voltage drop by injecting either inductive or capacitive reactive power. PV connected to a strong substation bus is controlled more effectively in these reactive power or power factor control modes. It is also important to note that depending on the capacity of PV plant and fault level at PCC, PV can be operated in voltage control mode.

The PV can regulate the voltage of a weak bus having lower fault level. In the context of Fig.7. the PCC voltage V_2 can be controlled or kept constant by the PV plant. Besides this voltage variation introduced by PV active power injection, a PV plant active power injection has an impact on the operation of OLTC and VR. It is important to study operational details of these classical equipments to examine the impact from a PV plant. This is discussed in the next section.

B. Classical Voltage Control Devices
1) On-Load Tap Changer
The On-load tap changer (OLTC) is primarily responsible for feeder voltage control. OLTCs are typically installed in the substation from where a feeder emanates. The typical voltage control mechanism in an OLTC is represented in Fig.9. An operator will specify the particular voltage setpoint to control the voltage of a regulated bus. The turns ratio of a transformer can be adjusted in steps from the transformer windings. The OLTC controls the voltage of the regulated bus within the defined dead band settings. The regulated bus voltage is compared with user defined setpoint by the comparator. The tap is not varied if the measured voltage is within the deadband. The taps are moved after an operator defined time delay if the measured voltage is outside the deadband.

2) Voltage regulator (VR)
A VR is typically an autotransformer with ±10% voltage regulation capability. The VR maintains the load terminal voltage at the set value by adjusting the tap position as the load current varies. The deadband and the delay time concept is similar to the OLTC. The typical VR schematic diagram is shown in Fig.10.
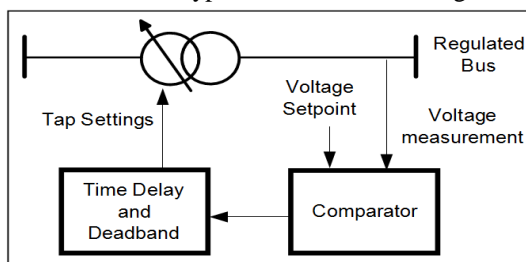

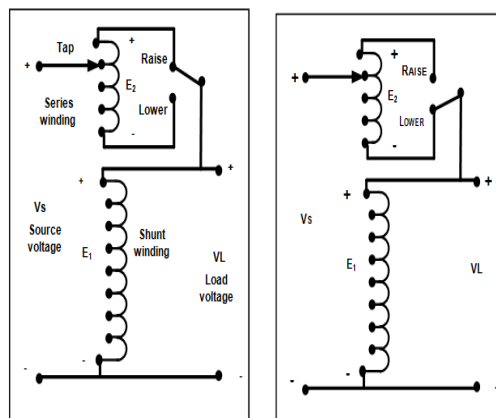Fig.9. OLTC Voltage Control mechanism

Fig.10. Voltage regulator

C. Feeder Operational Challenges
A typical MV radial distribution feeder as shown in Fig.11 is under consideration here. This feeder has PV along with its reactive power control capability. The other voltage control devices available are OLTC and VR. The VR operates in an autonomous mode. It consists of normally open switch which connects to an

alternate power feeding point. A grid integrated PV model is Fig.6. The converter control achieves the best possible active power capture through MPPT. Fig.12 shows the equivalent circuit of the MV distribution feeder of Fig.11. There is a possibility of power flows in the reverse direction towards the source substation OLTC, particularly when PV penetration is high. This causes a rise in the load voltage as can be seen from the vector diagram in Fig.13. The voltage control challenge will be more complex where a PV plant has a reactive power control option. There will be interaction between VR and PV voltage control. The nature of the control interaction between VR and PV and its overall effectiveness depends on various factors such as the driving point impedance, PV capacity, PV reactive power setting, VR setting, and system topology. Table1 summarizes generic interactions between VR autonomous mode and PV reactive power setting. It is not difficult to appreciate that for low driving point impedance i.e. strong voltage source there is a real risk of the VR hitting its limit or operating in runaway condition thus compromising its control effectiveness. There are primarily two autonomous operational modes of VR where they can potentially interact with a PV voltage control action. The details of the operational challenges during these VR operational modes are discussed next with reference to the model feeder topology of Fig. 4.11 and Fig. 4.12.
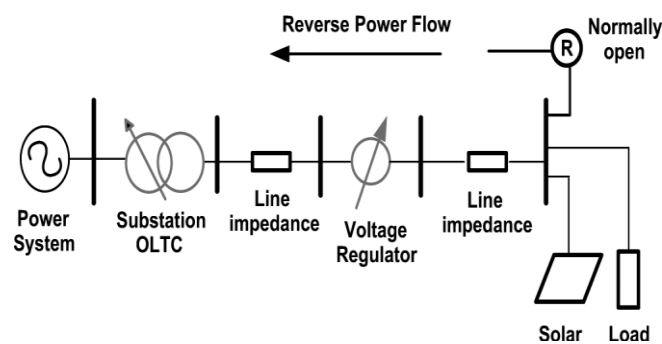

Fig.11. Radial system topology

Table 1: Interaction between PV reactive power support mode and VR autonomous setting

	PV plant setting		
	Unity Pf	**Constant Q or pf, Pf(P) or Q(U)**	**Constant voltage**
Voltage regulator setting: Bidirectional	**Caution:** Runaway during reverse power flow if low substation driving point impedance.	**Caution:** runaway during reverse power flow if low substation driving point impedance and no optimum Q from PV.	**Caution:** runaway during reverse power flow if low substation driving point impedance and no optimum voltage set point from PV.
Voltage regulator setting: Reactive bidirectional	Mostly for loop distribution systems. **Caution:** No impact on reactive current setting of VR due to PV.	Mostly in loop distribution systems. **Caution:** reactive current set point of VR can be impacted by PV.	Mostly in loop distribution systems. **Caution:** reactive current set point of VR can be impacted by PV.

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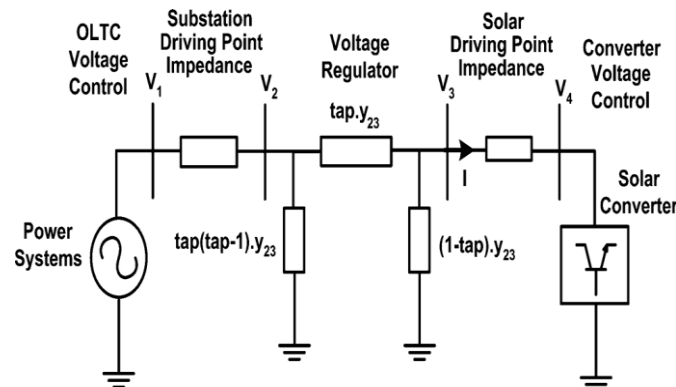| Voltage regulator setting: Co-generation	**Caution:** interference with the line drop compensator setting.	**Caution:** interference with the line drop compensator setting.	**Caution:** runaway for forward/reverse active power flow if PV driving point impedance is low for high capacity PV.

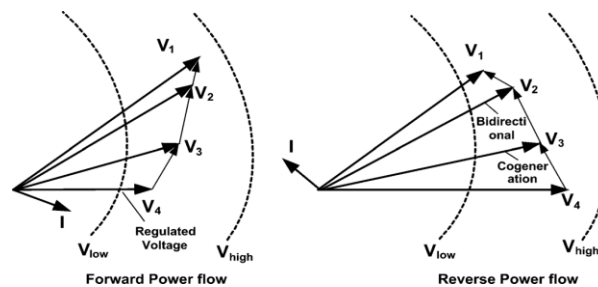Fig..12: Equivalent circuit of a radial system with VR

Figure 4.13: Vector diagram of a radial system

The operational requirements with respect to OLTC and VR in the presence of PV are summarized as follows :

➤ The VR should not run away under any system scenario described in Table.1.
➤ The voltage control in distribution system has to be achieved with minimum tap counts of OLTC and VR. This requires optimal control coordination.

IV. CASE STUDY

The UK Generic distribution system (UKGDS) is considered that all of the 95 buses in the system are at 11-kV voltage level. The proposed model associated with PV-DG is applied to Matlab simulation program. The topology of the UKGDS IEEE 95-bus system is shown in Fig.14. There are two PV plants considered in this system each of 1 MW capacity. The PV plants can operate at 0.95 lead/lag power factor during peak active power injection. The system considers a typical bus which serves a mixture of four types of consumers: domestic unrestricted, domestic economy, industrial and commercial. The load profiles on 100kW base is shown in Fig.15. The solar active power output profile on 100kW base is shown in Fig.16. The same irradiance profile is considered for both the plants. The system voltage values during peak loading condition at different buses without PV are shown in Fig.17.
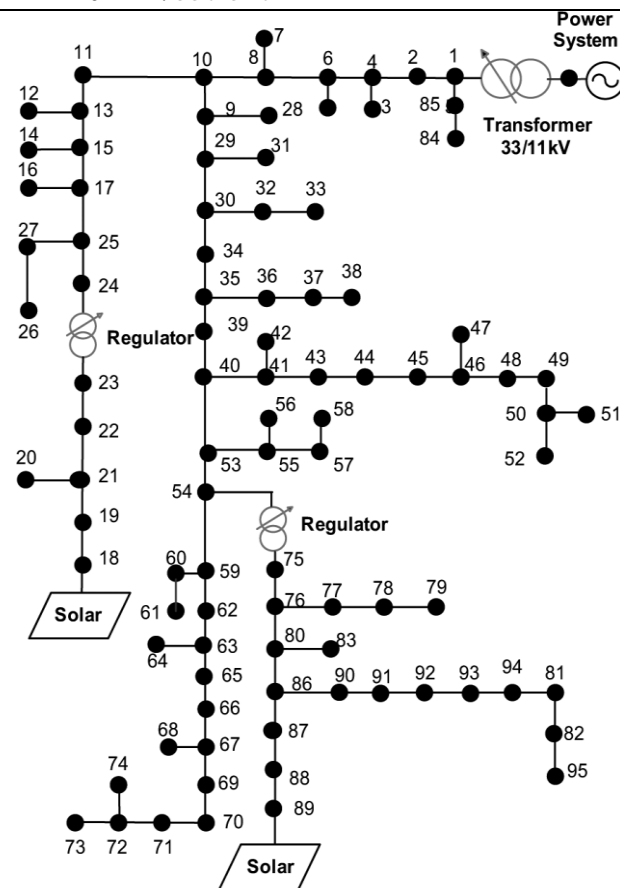
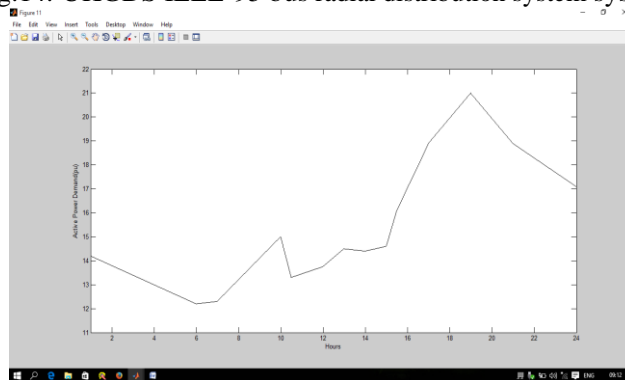Fig.14: UKGDS IEEE-95 bus radial distribution system system
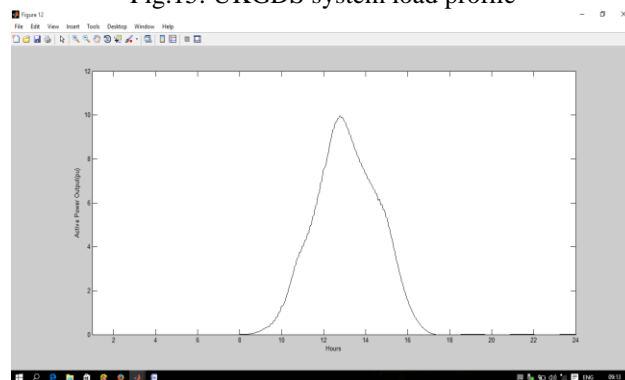

Fig.15: UKGDS system load profile
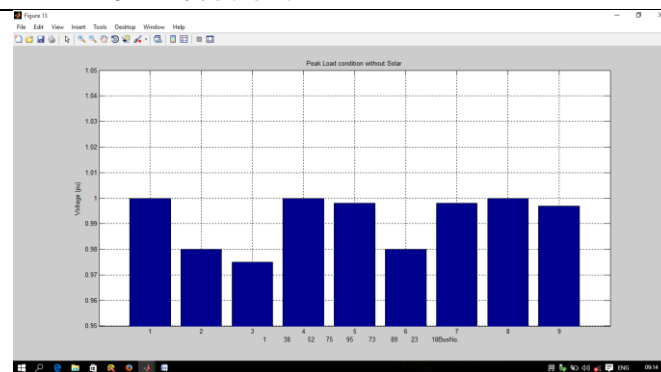

Fig.16: Solar active power profile

Fig.17. UKGDS system voltages during peak load condition without PV (nominal voltage at bus 1)

SIMULATION RESULTS

The UKGDS system considers two DGs at bus 18 and 89. The PV generation plants are considered at the same locations. The VR is considered in an autonomous mode. Both OLTC and PV generation plants are coordinated to achieve the voltage control. The objective function guarantees reduced tap counts and reduced operation of VR in non preferred zone in a preferential manner formulated using weighted combinations. The scalar weights W_c and W_r are varied such that $W_c + W_r = 1$. Table 2 demonstrates simulation results for different values of weights. In Table 2, VR1 represents VR connected between bus 54 and 75, and VR 2 represents VR connected between bus 24 and 23. Parameters for the penalty function are chosen such that, the penalty function value should not be too small or too large as compared to base case tap count objective function when equal weights are assigned for both objective functions. At the end of the control range for the voltage regulator (at tap position ±16), the penalty value is significantly higher than the tap count objective function (when the weight W_r corresponding to the voltage regulator runaway is non zero). This ensures that even for the smaller value of Wr the voltage regulator operation at absolute limit is avoided. In order to maintain the control margin for the voltage regulator and avoid runaway, a higher tap non-preferred zone is defined. The preferred zone for both VR is considered to be between tap positions +10 to -10.

Case 1 is considered at unity power factor non-coordinated operation. It can be observed that in Case 1 the total number of tap count is 76 and number of operations of VR1 in the non preferred zone is 11 and that for VR2 is 8. The next case demonstrates the minimization of tap operation in the non preferred zone. The weight W_r is set to 1 and no weight is attached to tap counts. It can be observed that all the operation of the VR1 occurs in preferred zone. But the total tap count remains 61 which is high. In the third case weight W_c is set to 1 and no weight is attached to the penalty function. Tap counts are reduced to 33 but tap operation instances in the non preferred zone are 9 for VR1 and 12 for VR2. This casedemonstrates the benefits of penalty function. Conventional objective functions do not consider the proposed penalty. It can be observed that though tap counts are reduced, tap operation happens close to its limit. Case 4 gives the most satisfactory value of the objective function. The following step by step procedure is considered while tuning weights.

Step 1: There are two objectives : tap counts minimization and avoiding operation in the non preferred zone. Tap count minimization is considered to be the preferred objective in this study. The weight tuning is done in preferential manner, so intuitively weight assigned for tap count minimization W_c has to be higher.

Step 2: W_c is set to 1 and W_r to 0 and the best possible objective value of the tap count is calculated. Table 2 shows the values achieved.

Step 3: W_r is set to 1 and W_c to 0 and the best possible objective value of the tap in the preferred zone is calculated. Table 2 shows the values achieved.

Step 4: The target reduction in tap counts from the base case is decided. In this simulation study it is considered 50.

Step 5: The values of W_c are varied in steps of 0.1 from 0 to 1. The values of both objective functions are noted. Fig.18 shows the variation in both objective function values. Case 1 tap count is 76, considering target tap count reduction to 50, the weight range selected is W_c from 0.6 to 1.

Step 6: While selecting the final value of W_c (from 0.6 to 1) along with the frequency of operation of voltage regulators in non preferred zone, the voltage regulator control margin is also considered. The control margin of a voltage regulator is defined as the difference between the voltage regulator limit and the nearest operation of the voltage regulator to its limit.

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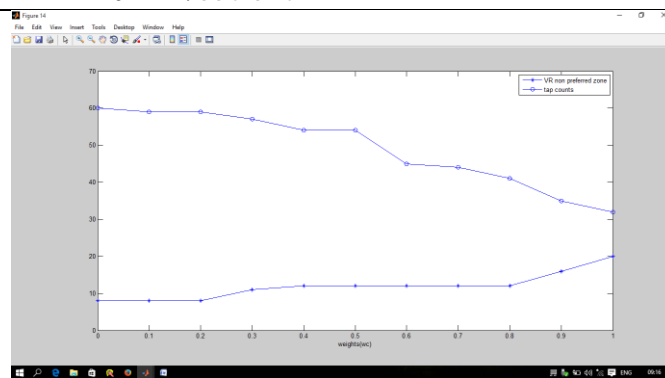*www.ijlemr.com || REETA-2K16 || PP. 330-346*

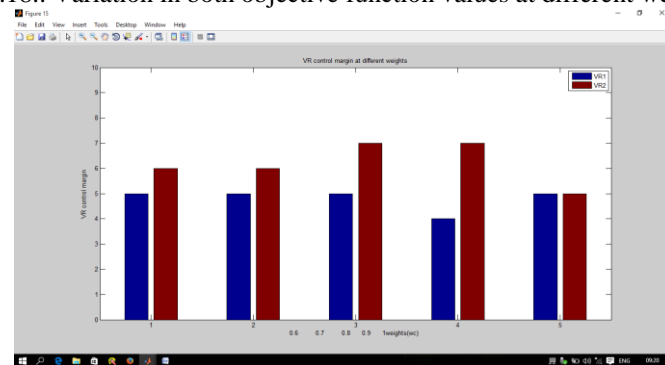Fig.18.. Variation in both objective function values at different weights

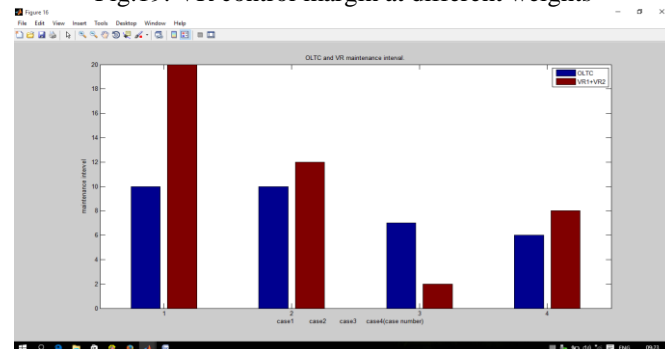Fig.19. VR control margin at different weights

Fig.20. OLTC and VR maintenance interval

Step 7: The voltage regulator preferred zone of operation is considered between tap values +10 to -10. Hence a value above 6 is a good control margin. For every value of weight W_c from 0.6 to 1, the control margin for both voltage regulators is plotted. Fig.19 demonstrate the control margin for both VR in the system.

Step 8: It can be observed from Fig.18 and Fig.19 that W_c equal to 0.8 offers the same number of tap operations in non preferred zone as W_c equal to 0.7 and the same control margin as can be achieved by W_c equal to 0.9, hence the final selection of weights is W_c is equal to 0.8 and W_r is equal to 0.2. Thus the final optimal weight tuning is achieved for Case 4 of Table 2.

Table 2: UKGDS 95 bus system performance

Case	Weights		Tap Count				Operation in non preferred zone		
	Wc	Wr	OLTC	VR1	VR2	Total	VR1	VR2	Total
1	-	-	40	19	17	76	11	8	19
2	0.0	1.0	40	4	17	61	0	8	8
3	1.0	0.0	29	2	2	33	9	12	21
4	0.8	0.2	25	14	2	41	12	0	12

Table 3: Percentage reduction in OLTC and VR tap count

Case	2	3	4
OLTC	0%	27.5%	37.7%
VR1+VR2	41.66%	88.9%	55.56%

Table 4: OLTC and VR Set Points

	Set points	**Dead band**
OLTC	1.01	0.02
VR1,VR2	1.02	0.02

Table 5: Tap count with no reactive power support from solar at zero irradiance

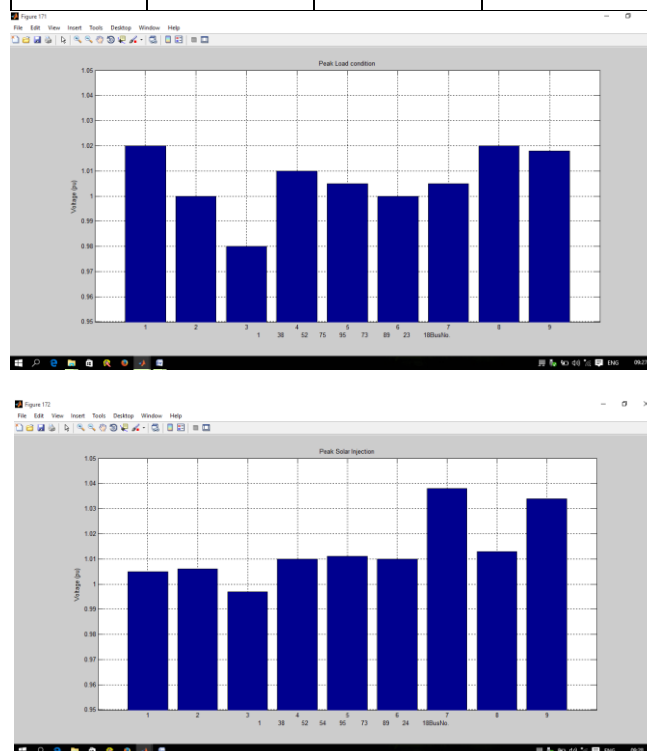| OLTC	VR1	VR2	TOTAL
29	10	11	50

Fig21. Voltages during peak load condition and peak solar injection at different buses (Optimal case W_c =0.8 and W_r=0.2)
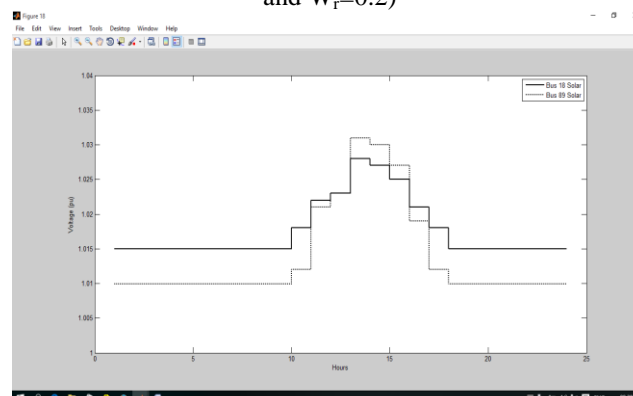

Fig.22. Hourly PV plant voltage setpoints

The results of Table 2 are confirmed with 30 sec time step load flow. Table 3 shows the percentage reduction in the OLTC and VR tap counts. Typical life of transformer and VR is 30 years. The typical maintenance interval of OLTC and VR is after 3 years. So in the base case, a total of 10 maintenance schedules are considered for each VR and OLTC. Fig.20. shows a reduction in maintenance intervals for this test system if the daily percentage reduction as in Table 3 is achieved. Fig.21 shows voltage values at different buses for Case 4 during the peak solar injection and the peak load. It can be observed that in both operating conditions, the voltage profile across the feeder is maintained within ±5%. Table 4 shows OLTC and VR set points. The hourly voltage set points for both PV plants are shown in Fig.22.

Table 5 demonstrates Case 3 for which W_c is 1 and W_r is 0. The comparison with case 3 in Table 2 shows that, there is significant increase in tap counts when no reactive power support is considered from PV at zero irradiance.

Case	Weights		Tap Count				Operations in non preferred zone		
	Wc	Wr	OLTC	VR 1	VR 2	Total	VR 1	VR 2	Total
Base Case	-	-	31	21	17	69	5	8	13
Optimal Case	0.5	0.5	27	16	2	45	6	0	6

The operation of both PV plants for a particular day under consideration is represented in Fig. 22. The active power and apparent power consumption of both the PV plants is represented in Fig. 22. The solid line represents the inverter capacity. Fig.22. demonstrates sufficient reactive power margin available at all the operating values. Also PV plant operates at MPPT at all instants. As can be observed from Fig. 21, there are in total 24 optimal voltage set points calculated. It can be observed from Fig.17. that the voltage at bus 52 is acceptable but lower during peak load condition. Distribution feeders are equipped with switched capacitor at bus 52.
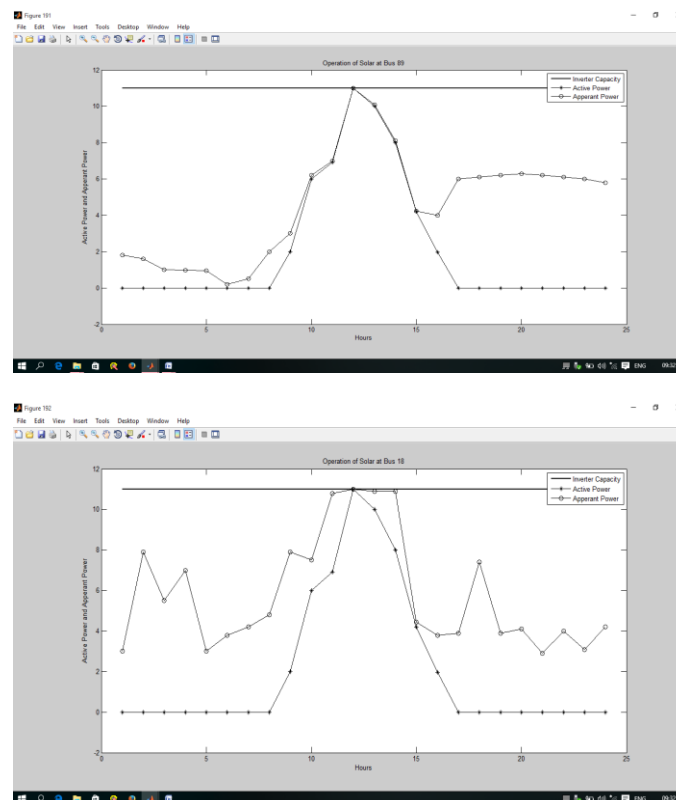

Fig. 23. PV plant operation

The simulation model of the UKGDS IEEE 95-bus system with two switched bank capacitors is shown in Fig.24.The capacitor bank C1 and C2 each has rating of 200 kVAr at rated voltage (1pu). This will ensure that voltage at bus 52 is 1pu. Both VR and capacitor are in autonomous mode. So, based on the daily load and irradiance profile, OLTC and PV reactive power set points are coordinated. Again similar to the base case, scalar weights W_c and W_r are varied such that $W_c + W_r = 1$. Table 6 demonstrates simulation results for base case

and optimal case. Fig.25. shows the PV plant voltage set points for the optimal it can also be seen from fig.26 and fig.27 that voltages at all buses remain within the prescribed limits.
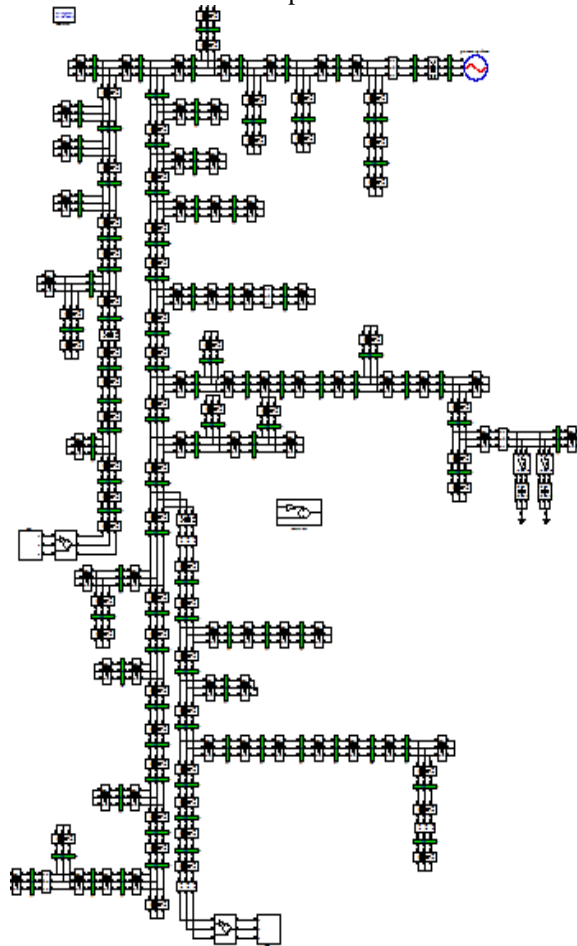

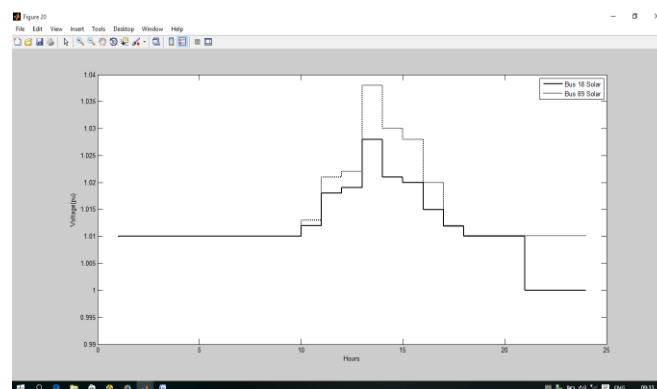Fig.24. UKGDS IEEE-95 bus system simulation model with two switched capacitor bank at bus 52

Fig.25: PV plant voltage setpoints with capacitors at bus 52

The following advantages are observed with the inclusion of capacitor:
➤ The number of tap counts is to achieve voltage control is lower when capacitors are placed at Bus 52.
➤ The number of operations of the voltage regulator in the non preferred zone is reduced with the presence of capacitor.
➤ Reactive power utilization from PV inverter is less when capacitor is considered.
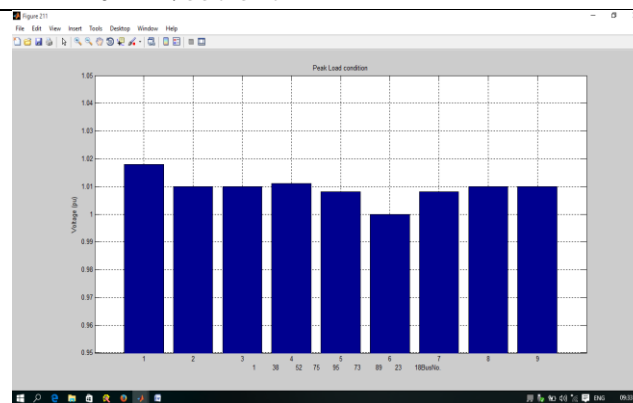
Fig.26: Voltages during peak load condition
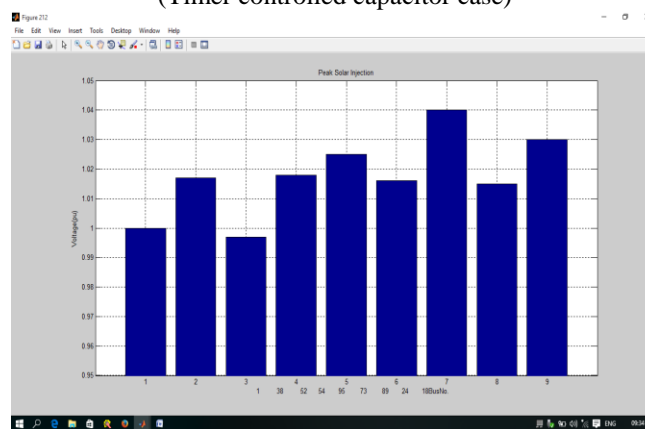(Timer controlled capacitor case)

Fig.27. Voltages during peak solar injection
(Timer controlled capacitor case)

The case studies demonstrate reduction in tap counts and operation of VR without runaway using the proposed optimization procedure. The reduction in OLTC and VR maintenance cost comes at the cost of solar inverter over capacity. There can be a scenario in which a feeder is supplied by only one OLTC substation transformer. The OLTC maintenance in this area will require a feeder disconnection and the revenue will be lost. However, to have reactive power support from solar its inverter needs to be oversized. The cost benefit analysis needs to be carried out while planning inverter over capacity. Implementation of additional fast control devices such as STATCOM had a positive impact on the tap changer operation. However, STATCOM is costly equipment. Hence it is recommended that costly equipment such as STATCOM should be implemented only after detailed cost benefit analysis during planning study. The conventional STATCOM or switched capacitors if present on the feeder can be considered in the proposed optimization procedure.

V. CONCLUSION

The active power injection at unity power factor by PV impacts the operation of OLTCs and VRs mechanisms and non-coordinated reactive power control in distribution system. This paper has proposed strategy strategy ensures minimum number of tap counts of the OLTCs and VRs and mitigates the runaway. The strategy defines the non preferred zone of operation around the VR extreme tap values to avoid runaway. The strategy coordinates various voltage control devices and the PV generation reactive power support mode. The proposed reactive power coordination strategy is effective in minimizing tap counts, avoiding the runaway and maintaining the feeder voltage within the specified limits. Further system also considers a night time reactive power support from PV inverters. It is found that tap operations can be minimized by utilising reactive power support capabilities of PV inverters when PV active poweroutput is zero

This paper concluded that voltage regulation strategies in the presence of PV generation will be useful to distribution network operators. The strategies can be utilised in designing various voltage control devices setpoints and deciding control settings of OLTCs, VRs and PV generators etc during daily operation of a distribution feeder.

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