Adaptive Reactive Power Injection by Solar PV Inverter to Minimize Tap Changes and Line Losses

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***Abstract*—Deployment of direct grid feeding solar Photovoltaic (PV) inverters are increasing. With the increase in PV penetration, fluctuation in Point of Common Coupling (PCC) voltage occurs more frequently. This happens due to weather dependent active power generation characteristics of PV inverters. Voltage variation might also violate ANSI C84.1 standard. On Load Tap Changing (OLTC) transformers are installed at Medium Voltage level to maintain the PCC voltage to its nominal value. OLTC experiences increased number of tap changing operations due to voltage fluctuations causing reduced life span of the transformer and OLTC components. To address this issue, a scheme is proposed to optimally inject reactive power through PV inverter which ensures minimal number of tap changing operations along with minimum losses in line. To validate this scheme, simulation is carried out with grid connected PV inverters at the distribution level with different levels of reactive power compensation. It is shown that optimal level of reactive power compensation can be chosen to achieve good compromise between the number of tap changes and losses in the line.**

***Index Terms*—On Load Tap Changer (OLTC), Point of Common Coupling(PCC), Photovoltaic (PV).**

NOMENCLATURE

P_{inv}	Real power handled by Inverter
P_{pv}	Maximum available power from PV
S_{inv}	Apparent power of Inverter
V_g	Voltage at PCC
V_{rms}	RMS value of V_g
k_p	Maximum allowable rate of change of P_{pv}
k_s	Slope of S_{inv}

I. INTRODUCTION

Grid connected PV inverters are gaining popularity at Low Voltgae (LV) distribution level for providing clean and affordable energy. Typically, solar PV inverters generate active power depending upon solar irradiation and inject it at unity power factor (UPF) into the grid. With increasing penetration level of solar PV inverters, sudden change in active power generation due to partial shading results in poor voltage regulation in LV system. In addition to this, problems like voltage flickering and frequency deviation from their nominal values also occur in LV system. It is stated that the fluctuation might be severe when PV penetration exceeds 20% [1]. This fluctuation in voltage and frequency results in poor power quality. So corrective measures are needed in order to mitigate these problems.

To maintain the voltage profile at point of common coupling (PCC), On Load Tap Changing (OLTC) transformers are used. Typically, OLTCs are installed in distribution substation with tap changing mechanism at the high voltage side of the transformer as shown in Fig 1.

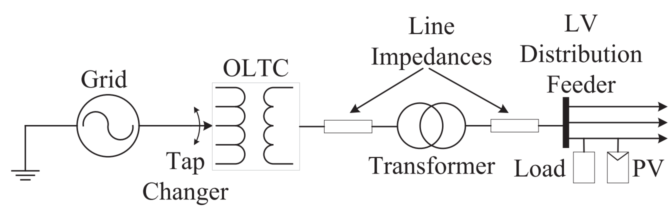

Fig. 1. Single line diagram of a LV system with OLTC installed at MV side.

In case the load end voltage goes out of the allowed band, OLTC operates by changing tap to maintain the load end voltage. The lifespan of OLTC is limited by total number of tap changing operations. Typically, for an oil-filled OLTC the life-span is 7 years or 50,000-100,000 operations [2]. With increase in penetration level of solar PV inverters fluctuation in PCC voltage occurs more frequently. This happens due to uncertainty in active power generation of solar PV inverters. This results in large number of tap changing operations of OLTC, leading to reduction in its lifespan. According to earlier grid code IEEE 1547 distributed resources units cannot participate in voltage regulation of PCC [3]. So, with this restriction to address voltage fluctuation issue several techniques are discussed in [1]. One of the suggested scheme is to use of Zinc-Bromine battery as energy source in solar PV inverters. With the use of battery during low PV power generation, active power is supplied to the grid. This leads to less fluctuation in voltage but involves additional cost of battery. Another solution discussed in [1], is to use larger size feeder conductor in which voltage drop will be minimal. This is not a viable solution, as all the feeders need to be reconstructed using this conductor which would involve significant cost. Coordination between OLTC action and reactive power support by DSTATCOM is discussed in [4]. This solution is also not economically viable as this incurs additional cost of DSTATCOM in the distribution system. Price of STATCOM is around 50-55US$/kVAR [5]. Aforementioned techniques use additional energy storage or reactive power supply elements, which increases cost of the

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system. Considering large number of distribution systems, these approaches may not be viable.

To address these issues, various grid codes are modified to enable reactive power support using solar PV inverter. Modified grid code IEEE 1547a-2014 allows distributed resources to actively participate in voltage support whenever it is necessary by providing reactive power compensation [6]. German grid code for PV penetration prescribes to include distributed resources in dynamic voltage support [7]. After these modification, many reactive power injection schemes through solar PV inverters to mitigate voltage regulation problem are discussed in [8]–[11]. To ensure smooth voltage profile reactive power injection is discussed by increasing the rating of inverters in [8]. Increment by 10% in kVA rating provides 45% reactive power support. Enhancement in rating is realized by use of higher rating switches which makes the solution costlier. Droop control based reactive power injection is discussed in [9]. In this, reactive power is fed based on the voltage profile of the feeder. But, this technique is altered by tap changes of OLTC at MV level. So, the technique is suitable for High voltage or extra high voltage level. Active Power Curtailment (APC) to increase Reactive Power Injection (RPI) is discussed in [10]. But APC is not desirable in grid feeding solar PV inverters due to Feed-In-Tariffs (FITs). A technique to provide reactive power support and selective harmonics mitigation by repetitive controller through PV inverter during low irradiation is discussed in [11]. In this paper, line losses due to reactive power injection is not minimized.

In the aforementioned techniques, role of OLTC to regulate voltage is not investigated. Since the voltage regulation in a distribution system depends on both OLTC and solar PV power, the effect of OLTC can not be neglected in these studies. The primary objective of this paper is to suggest a suitable control scheme to reduce number of tap change operations in OLTC, thereby increasing its lifespan. Reactive power compensation is provided only when active power generation by solar PV inverter decreases abruptly. This helps in maintaining a smoother PCC voltage profile. This would subsequently result in reduced number of tap change. Trade off between number of tap change operations in OLTC and minimization of line losses is also discussed in this paper.

This paper is organized as follows. In section II, the proposed scheme has been discussed. Selection of slope of S_{inv} is discussed in section III. In section IV, simulation results and discussions have been provided for different reactive power compensation level. Section V includes conclusion of the paper.

II. Proposed Scheme

The technique proposed in this paper is based on coordination between reactive power injection into the grid and active power generation by solar PV inverter. Whenever power generation by PV reduces suddenly due to cloudy weather condition, real current flows from the grid to load side in distribution system. This results in sudden dip in PCC voltage. To maintain the PCC voltage within specified range, OLTC operates. Fig. 2 shows the operating mechanism of OLTC transformer. Here, voltage at PCC (in pu) is measured and is compared with reference voltage. If the difference in voltages is greater or lesser than 0.04 pu, OLTC operates after T_d seconds to maintain reference voltage at PCC. In order to reduce number of tap changes in OLTC, PCC voltage profile should be kept within specified band. Maintaining PCC voltage profile within a specified band demands smooth active power generation characteristics of solar PV inverter. However, active power generation only depends on solar radiation, and therefore can not be controlled. In the proposed scheme, reactive power injection by solar PV inverter is used to ensure smooth change in the apparent power from the solar PV inverter. In case of a sudden dip in real power, reactive power is injected to reduce the voltage drop in the distribution line. This leads to regulation of the load end voltage and thereby avoiding tap changing action. However, in case of continuous supply of reactive power from inverter, losses due to reactive current in the distribution line and transformers would increase. This is addressed by fixing a fixed value of slope of S_{inv} to k_s, when the change in PV power per unit time exceeds the maximum allowable value k_p.

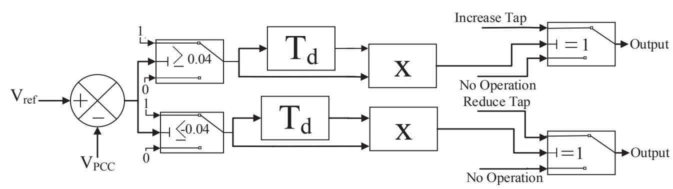

Fig. 2. Control diagram of Tap Changing Mechanism

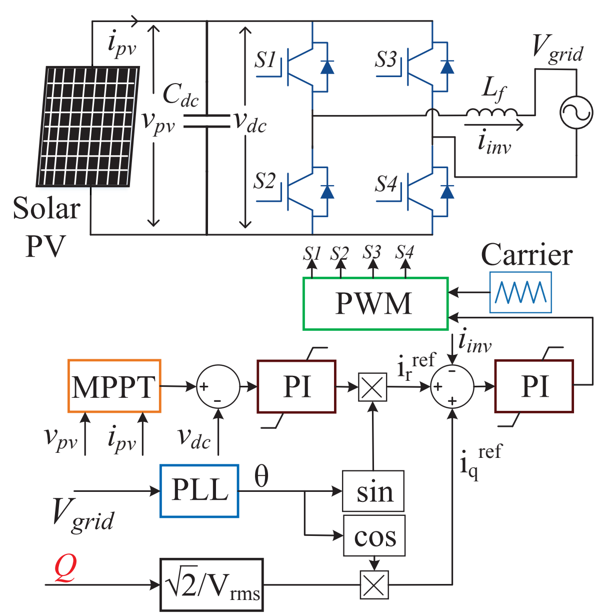

Fig. 3. Diagram of grid tied solar PV inverter with inner current and outer voltage control loop.

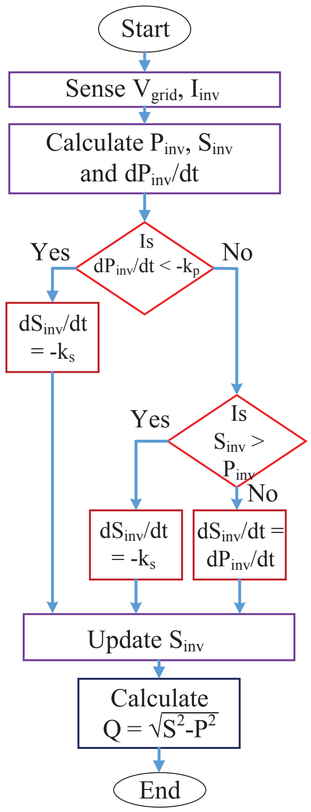

Fig. 4. Flow chart of the proposed scheme.

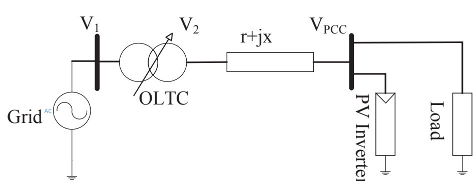

Fig. 5. SLD of a power system with grid connected PV inverter.

Fig. 3 shows a single phase grid tied solar PV inverter along with its controller. Sampled values of PV voltage (v_{pv}) and current (i_{pv}) is given to Maximum Power Point Tracker (MPPT) block. The output of this block becomes the voltage reference which is realized by voltage and current control loops. Phase locked loop (PLL) is used to provide phase and angle information of the grid to feed current at desired power factor. The difference in DC link voltage (v_{dc}) and v_{pv} is passed to Proportional Integrator (PI). The output obtained is multiplied with the sine of θ obtained from PLL and it becomes the real current reference i_r^{ref}. Reactive power Q is used to obtain reference value for reactive current i_q^{ref}. Addition of i_r^{ref} and i_q^{ref} is the current reference to be tracked by current controller. The error of the inverter current i_{inv} and current reference is processed through PI and its output is compared with carrier signal to obtain switching signals for inverter. The flowchart for obtaining Q as per the proposed scheme is shown in Fig. 4. The steps involved are as follows:

- Sampled values of V_g, and inverter current (I_{inv}) are used to calculate the active power being fed into the grid.
- Based on this, calculation of rate of change of P_{inv} of solar PV inverter is done. S_{inv} is also calculated.
- dP_{inv}/dt value is evaluated and is compared with $-k_p$. This step determines the level of reactive power compensation to be done by solar PV inverter.
- Based on the decision taken from previous step.
  - If condition $dP_{inv}/dt < -k_p$ is true, then dS_{inv}/dt is fixed to $-k_s$.
  - If $dP_{inv}/dt < -k_p$ is false, then $S_{inv} > P_{inv}$ condition is checked. If this is true, then value of dS_{inv}/dt is kept equal to $-k_s$. Otherwise, $dS_{inv}/dt = dP_{inv}/dt$ is maintained to ensure no reactive power injection during both positive and constant slope of active power from PV.
- The value of dS_{inv}/dt is used to update S_{inv}. With the updated value of S_{inv} and calculated value of P_{inv}, Q is determined.

The value of Q so obtained is used to derive the reactive current reference for the solar PV inverter. This algorithm is repeated every time to update the value of Q which effectively controls the level of reactive power compensation.

III. Selection of Slope of S_{inv}

Fig. 5 represents single line diagram of representative feeder with integrated PV inverter. Power transfer through the feeder is,

$$S = \overline{V}_{PCC} \cdot \frac{\overline{V}_2^* - \overline{V}_{PCC}^*}{r - jx} \tag{1}$$

where, r and x are resistance and reactance of line. V_2 and V_{PCC} are secondary voltage of OLTC and load end voltage, respectively. Real power flow from the feeder is simplified to,

$$P_L - P_{inv} = V_{PCC}.V_2 \frac{r}{r^2 + x^2} cos\delta + V_{PCC}.V_2 \frac{x}{r^2 + x^2} sin\delta - V_{PCC}^2 \cdot \frac{r}{r^2 + x^2} \tag{2}$$

where, P_L is the real component of load power, δ is phase angle difference between grid side and load side and P_{inv} is the active power supplied by PV inverter. Similarly for reactive power,

$$Q_L - Q_{inv} = V_{PCC}.V_2 \frac{x}{r^2 + x^2} cos\delta - V_{PCC}.V_2 \frac{r}{r^2 + x^2} sin\delta - V_{PCC}^2 \cdot \frac{x}{r^2 + x^2} \tag{3}$$

where, Q_L is load reactive power and Q_{inv} is reactive power supplied by solar PV inverter. When magnitude of V_{PCC} is within allowed band, Q_{inv} is zero. From (2), expression for V_{PCC} is determined,

$$V_{PCC} = \frac{V_2(rcos\delta + xsin\delta)}{2r} + \frac{\sqrt{V_2^2(rcos\delta + xsin\delta)^2 - 4(P_L - P_{inv})(r^2 + x^2)r}}{2r} \tag{4}$$

replacing V_{PCC} in (3), expression for Q_{inv} is given by,

$$Q_{inv} = Q_L + [V_2 \frac{rcos\delta + xsin\delta}{2r(r^2+x^2)} + \frac{1}{2r(r^2+x^2)} \sqrt{V_2^2(rcos\delta+xsin\delta)^2 - 4(P_L - P_{inv})(r^2+x^2)r}] [V_2 rsin\delta - V_2 xcos\delta + \frac{xV_2}{2r}(rcos\delta + xsin\delta) + \frac{x}{2r}\sqrt{V_2^2(rcos\delta + xsin\delta)^2 - 4(P_L - P_{inv})(r^2+x^2)r}] \tag{5}$$

For solar PV inverter

$$S_{inv}^2 = P_{inv}^2 + Q_{inv}^2 \tag{6}$$

Differentiating (6), with time,

$$S_{inv} k_s = P_{inv} k_p + Q_{inv} \frac{dQ_{inv}}{dt} \tag{7}$$

Rearranging (7),

$$Q_{inv} = \int \frac{S_{inv}k_s - P_{inv}k_p}{\sqrt{S_{inv}^2 - P_{inv}^2}} dt \tag{8}$$

Replacing expression of Q_{inv} in (5),

$$\int \frac{S_{inv}k_s - P_{inv}k_p}{\sqrt{S_{inv}^2 - P_{inv}^2}} dt = Q_L + [V_2 \frac{rcos\delta + xsin\delta}{2r(r^2+x^2)} + \frac{1}{2r(r^2+x^2)} \sqrt{V_2^2(rcos\delta+xsin\delta)^2 - 4(P_L - P_{inv})(r^2+x^2)r}] (V_2 rsin\delta - V_2 xcos\delta + \frac{xV_2}{2r}(rcos\delta + xsin\delta) + \frac{x}{2r}\sqrt{V_2^2(rcos\delta + xsin\delta)^2 - 4(P_L - P_{inv})(r^2+x^2)r}] \tag{9}$$

Secondary side voltage of OLTC is given by,

$$V_2 = V_1 \frac{N_2}{N_1} \tag{10}$$

where, V_1 is grid voltage, N_2 and N_1 is nominal turns ratio of OLTC. In OLTC, N_1 is changed to maintain reference voltage at load end. Replacing V_2 in (9),

$$\int \frac{S_{inv}k_s - P_{inv}k_p}{\sqrt{S_{inv}^2 - P_{inv}^2}} dt = Q_L + [V_1 \frac{N_2}{N_1} \frac{rcos\delta + xsin\delta}{2r(r^2+x^2)} + \frac{1}{2r(r^2+x^2)} \sqrt{(V_1 \frac{N_2}{N_1})^2(rcos\delta+xsin\delta)^2 - 4(P_L - P_{inv})(r^2+x^2)r}] (V_1 \frac{N_2}{N_1} rsin\delta - V_1 \frac{N_2}{N_1} xcos\delta + \frac{xV_1 \frac{N_2}{N_1}}{2r}(rcos\delta + xsin\delta) + \frac{x}{2r}\sqrt{(V_1 \frac{N_2}{N_1})^2(rcos\delta + xsin\delta)^2 - 4(P_L - P_{inv})(r^2+x^2)r}] \tag{11}$$

It is observed from (11), that number of tap changing operation decreases with increase in ks. From (8), it is observed that total reactive power flow increases with increase in ks. Thus, trade-off exists between no. of tap changing operations and reactive power flow in line. To limit reactive power flow to a specific value , k_s is calculated using (8). Corresponds to that k_s value, no. of tap changing operations of OLTC is determined using (11).

IV. Simulation Result And Discussion

Fig. 6 is a single line diagram of the representative 440 V radially distributed feeder with high PV penetration. Load is assumed to be balanced for the considered system. Simulation is carried out for the system using MATLAB/SIMULINK. The parameters of the system and OLTC transformer are given in Table. I and Table II respectively.

TABLE I
System Parameters

System Frequency	50 Hz
R/X ratio of MV line	3.91
R/X ratio of LV line	7.58
Base Voltage	440 V
Base Power	10 MVA
Rating of Load	40kVA
Rating of solar PV inverter	24 kW
Feeder Distance	30 km
Power rating of distribution transformer	1 MVA
Voltage rating of distribution transformer	11 kV/440 V(Y-Y)
Rating of Capacitor bank	15 kVAR

TABLE II
OLTC Parameters

Power rating of OLTC transformer	1 MVA
Voltage rating of OLTC transformer	33 kV/11 kV (Y-Y)
Number of taps	10
Deadband(pu)	1±0.02
Change in voltage(pu/tap)	0.015
Tap selection time	3 s (vary between 3-10 s)

Solar data for August 8, 2015 is taken from Solar Energy Research Enclave-IIT Kanpur. The performance of the proposed scheme is validated by comparing the performance of (A) solar PV inverter connected to grid and operating at UPF and (B) solar PV inverter connected to grid and controlled reactive power is supported through PV inverter.

A. Conventional Scheme : Inverter Operates At Unity Power Factor

The solar PV inverter is connected to grid and operating at unity power factor. The simulation result for this condition is shown in Fig. 7. V_g varies from 0.97 pu to 1.03 pu as shown in Fig. 7(a). The variation of P_{inv} and S_{inv} are shown in Fig. 7(b) and (c). It is observed from Fig. 7 (d) that total number of tap changes are 26 throughout the day. No reactive power is being fed into the grid is supported by the fact that waveform of S_{inv} is same as P_{inv}.

B. Proposed scheme : Controlled Reactive power Injection Through PV Inverter

As per the proposed scheme, reactive power is injected to the grid through the PV inverter when the slope criteria of dP_{inv}/dt is satisfied. When the value of dP_{inv}/dt falls below $-k_p$, then reactive power compensation is provided. The level of reactive power compensation level varies with k_s. The following subsections are simulated with different values of k_s.

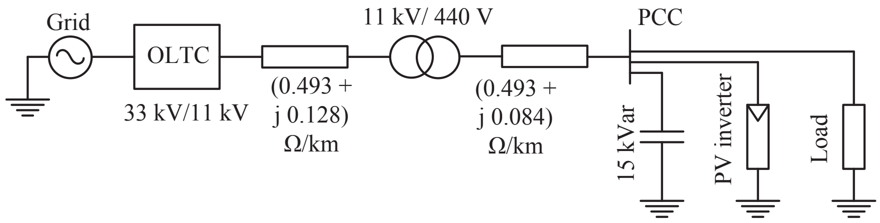

Fig. 6. Single line diagram of the simulated system.

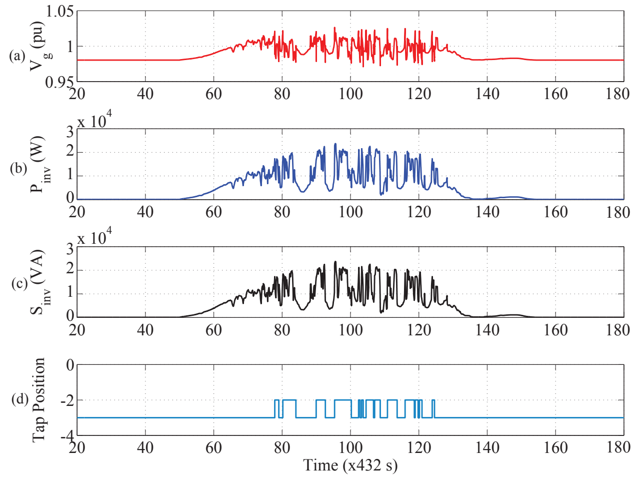

Fig. 7. (a) PCC voltage (pu), (b) Active power generation of PV inverter (W), (c) Apparent power delivered by PV inverter (VA) and (d) Tap position

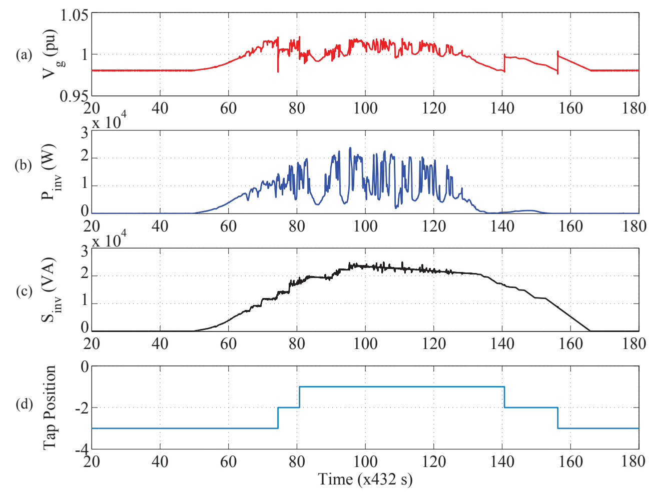

Fig. 8. (a) PCC voltage (pu), (b) Active power generation of PV inverter (W), (c) Apparent power variation of PV inverter (VA) and (d) Tap position.

1) With $k_s = -14W/min$:
The falling slope (k_s) of S_{inv} is set to $-14W/min$ when $k_p < -600W/min$. Fig. 8 (a) shows PCC voltage profile (pu). It is observed that voltage variation is from 0.98 pu to 1.02 pu. Fig. 8 (b) and 8 (c) depicts the variation of P_{inv} and S_{inv} respectively. The variation in S_{inv} is smooth as compared to variation in P_{inv} due to reactive power injection. The number of tap changes in OLTC reduced drastically to 4 as observed in Fig. 8 (d). With this level of reactive power injection, reactive energy ($\int Qdt$) flown through the lines is 1.32 MVar-s.

2) With $k_s = -70W/min$:
The falling slope (k_s) of apparent power S (k_s) is set to $-70W/min$ when $k_p < -600W/min$. Fig. 9 (a) shows PCC voltage profile(pu). It is observed from this graph that voltage variation is still within 0.98 pu and 1.02 pu. Fig. 9 (b) and 9 (c) depicts the variation of P_{inv} and S_{inv} respectively. The number of tap changes in OLTC increased to 6 compared to earlier case as observed in Fig. 9 (d). With this level of reactive power injection, reactive energy flown through the lines is 0.6 MVar-s. The reduction in reactive energy is expected because reactive power injection level is reduced and hence line losses.

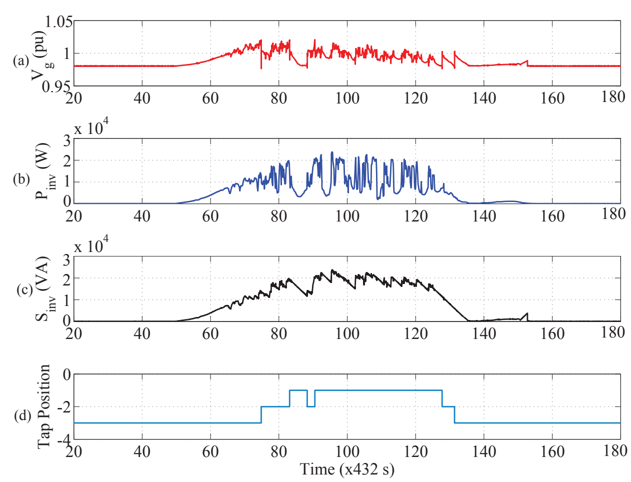

Fig. 9. (a) PCC voltage (pu), (b) Active power generation of PV inverter (W), (c) Apparent power delivered by PV inverter (VA) and (d) Tap position

3) With $k_s = -140W/min$:
In this case when k_p goes less than$-600W/min$, k_s is set to be equal to $-140W/min$. So among the three cases total number of tap change operation will be highest in this case but also reactive energy supplied by PV converter will also be least. Fig. 10 (a) shows PCC voltage (pu). The number of tap changes in an OLTC has increased to 12 but still less than that

of without reactive power compensation as observed in Fig. 10 (d). The variation of P_{inv} and S_{inv} are shown in Fig. 10 (b) and Fig. 10 (c) respectively. The reactive energy is least among the three cases considered and is equal to 0.46 MVar-s.

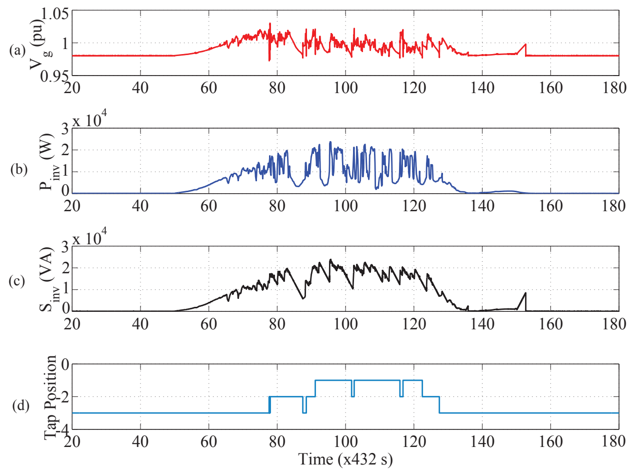

Fig. 10. (a) PCC voltage (pu), (b) Active power generation of PV inverter (W), (c) Apparent power delivered by PV inverter (VA) and (d) Tap position

The consolidated results for the above simulations have been shown in Table III.

TABLE III
EFFECT OF k_s ON NUMBER OF TAP CHANGE OPERATION AND REACTIVE ENERGY

Simulation Conditions	Value of $k_s(W/min)$	number of Tap Changes	Reactive Energy (MVar-s)
Without Reactive Power Injection	-	26	0
With Proposed Scheme	-14	4	1.324
	-70	6	0.6
	-139	12	0.46

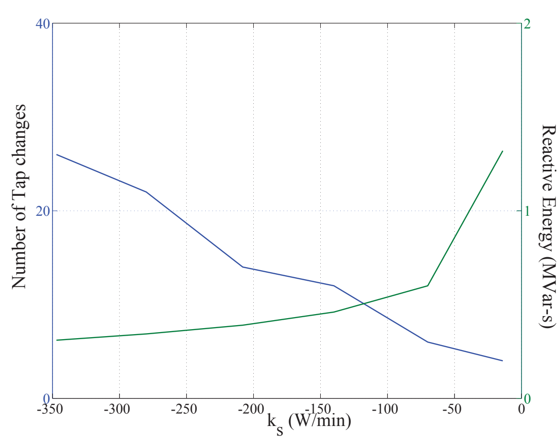

Fig. 11. Number of tap change (left) and Reactive Energy (right) with variation in slope of S.

Fig. 11 shows the trend of number of tap changes and reactive energy flowing in the system with different level of reactive power compensation. The injection of reactive power helps in reducing number of tap changing operations and thereby reducing stress on OLTC. To keep dS_{inv}/dt low, more reactive power is to be injected into the line. But with injection of reactive power, losses in the line would increase. Therefore, a trade-off between number of tap changing operations and losses in the line exist.

V. CONCLUSION

In this paper, effect of solar PV inverters on OLTC operation and scheme to minimize the tap changing actions is discussed. In the literatures, the reactive power minimization techniques are reported but scope of OLTC tap change minimization is not investigated. In this paper, a scheme of injecting controlled reactive power through solar PV inverter is proposed. Maintaining the slope of dS_{inv}/dt during steep change of P_{pv} is done by deriving required Q and injecting into the grid. Detailed simulation studies are carried out using the mission profile of solar PV power. With the scheme implemented, number of tap changes reduced to 4 from 26 throughout the day. Hence, increased lifespan of OLTC. With various values of k_s simulated, it is concluded that there exist a compromise between minimization of number of tap changes and line losses.

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