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Reactive power control of three-phase low voltage system based on voltage to increase PV penetration levels

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A B S T R A C T

High penetration levels of distributed (PV) generation on electrical distribution system show many opportunities and challenges for Egyptian Distribution Utilities. The sovereign purposiveness of this threshing was to augment the penetration level of the PV power production in three-phase LV grids, by using solar inverters with reactive power control inconvertibility, imposed by certain grid codes. This method, which is based on the grid voltage profile for location – dependent PF set premium could be cushioned to whole solar inverter. The main target was to mitigate unnecessary Q absorption. This method combines two droop function power factor active power and Q-(V) strategies. The performance of each inverter is to compare the output voltage measured and control the quantity of Q. Therefore, improvement of the voltage profile at a certain bus can reduce the total losses, saving consumed power by customer and increase the system capacity by 4.5%.

1. Introduction

The world continues to demand electric energy, and on the other hand the traditional energy, introduces pollution as carbon taxes. The green energy provides promotion [1].

It is expectant that future LV networks will help for high penetration levels of small-scale PV. The high penetration of PV Power may cause several problems, such as voltage fluctuations, encumbering of grid appliances, harmonics current radiations grid thinking, flicker, direct current injection..., etc. [2,3].

This study focuses on the grid voltage to keep it inadmissible limitations, especially in the case of reduction in the power demands with high active power injections by PV inverters.

In Egypt, the traditional electricity demand is growing rapidly, especially the residential loads (42.7%) and the industrial loads (27%) of the total energy [4]. So, the Egyptian government forwards its efforts direct to integrate dispersed generators, especially for residential power demand of small-scale PV up to 10 kW. In addition, Egypt has the best locations with high intensity of direct solar radiation, the range was between 2000 and 3200 kW h/m^2/year from north to south, and the sun shines duration was between 9 and 11 h/day [5]. So the Egyptian government, has approved the fed-in tariff and subsidized the customers and investors to promote the PV penetration levels.

The main purpose of this paper was to increase the penetration attribution of PV power producing in three-phase LV network-connected in Egyptian networks, by controlling of reactive power capability, which is generated from the solar inverter and P.F- P. in this paper the control of PV inverter is implemented using proportional plus integral (PI) controller to maintain the voltage at the PV bus.

2. Reactive power supply capability of basic concepts in analysis of distributed generators

To increase the higher penetration levels to the power distribution systems, it may require a lot of efforts, to integrate dispersed generators. The optimum benefits from solar inverters installed on grid were to promote penetration levels more. The semiconductor switches are control of the Q quantity of inverter. When the active power injection is less than the inverter rated apparent power, the remaining capacity can be used for supplying reactive power. New generation of solar inverters power factor (PF) is set at 0.9 PF, which keeps them at rated active power injection for network ancillary services. Reactive power can control the grid – connected

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inverters on LV distribution networks [6]. As a toss network cryptogram, the minimums P.F value is set at 0.9 by the control of the loll encyclopedia in the sequence that could be acclimated in the Egyptian grid code. In addition to this, if the solar irradiation decreases from 100% to 10%, the inverter can use the remaining capacity to provide the reactive power supply to compensate the voltage drop [7].

Further, the grid voltage levels must be defined clearly as the power injections from the distributed generators, cause rise in the total voltage on the LV and MV grids which should be finite at ±10% and ±5% of the nominative grid voltage, consecutively. Thus, at apiece bond speck, it is required to measure these voltage changes that are triggered by the generators, where maximally permissible power injecting is specifiable. Thus, the following conditions can be realized:

1. Unlimited number of inverters can be connected to the same transformer, with considering the full loading that is 100%. Fig. 1 shows the structure of network and installed inverters location, depending on adaptive Q and V method [8]. To control higher voltage drop at the end of the feeder, this method is based on the voltage sensitivity analysis measurements.
2. The inverters should have coordination among each other and with the equal distance (100 m), to work in the acceptable network voltage without a communication medium.
3. All the PV_S installation capacity is 10 kW at the same time.

3. Inverter controller

Fig. 2 shows that, at the network-side inverter, a back-to-back remitted, the phase angle of the current to the primate grid is defined. In the DC - DC converter is used for maximum power point tracking. Moreover, the grid side inverter is used to control both of the DC link voltage and the voltage at the point of common coupling (PCC). The three-phase voltage at the PCC is sensed and follows a phase locked loop (PLL) circuit to generate the transformation angle. The actual three- phase currents at the PCC are converted from the abc to dq0 frames. The proportional plus integral (PI) controllers are used for this control action and produce the firing angles to the power electronic switches of the inverter.

The output voltage of inverter can also be adapted by applying a controller itself in the inverter. Most commonly used method for the inverter is the sinusoidal pulse width modulation (PWM) technique. By implementing this method, a constant DC input voltage is disposed into the inverter. Also an unflappable AC output voltage is accessed by regulating the on/off duration of the inverter units, PWM techniques [9].

The phase shift of the current vector can be arbitrarily controlled as long as the absolute value of the current. Appendix A shows that the relation between phase shift and voltage (θ ° limits 17.44–30.34 with active and reactive power can be considered). The power commute P_{act} (within its boundary P_{min} and P_{max}) during the inverter is in general dealt by the executive control of the

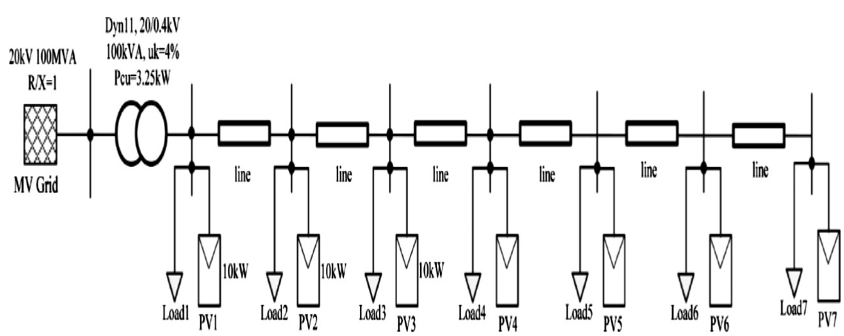

Fig. 1. Network feeder for the voltage gradient.

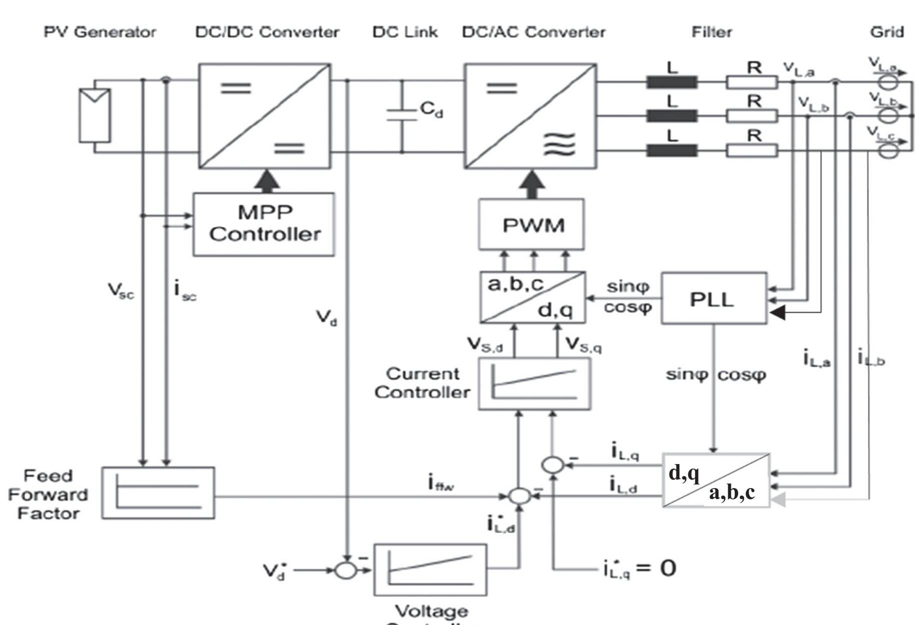

Fig. 2. Block diagram of the control structure.

PV system with first imperative so that its boundary is the maximum possible reactive power preparation $|Q|_{max}$ in Eq. (1).

$$|Q|_{max}(t) = \sqrt{s_{max}^2 - p_{act}^2(t)} \quad (1)$$

The current faces accessorial boundary Q_{min} and Q_{max} essentiality due to causes of stability and availability. The executive purview (uploaded receptivity) of an inverter is shown in Fig. 3. Within these limitations, the reactive power of the inverter can be controlled with response to these limits as shown in Appendix B (P_{min} = 2.5 and P_{max} = 10 KW), (Q_{min} = 0 and Q_{max} = 10 KVAR).

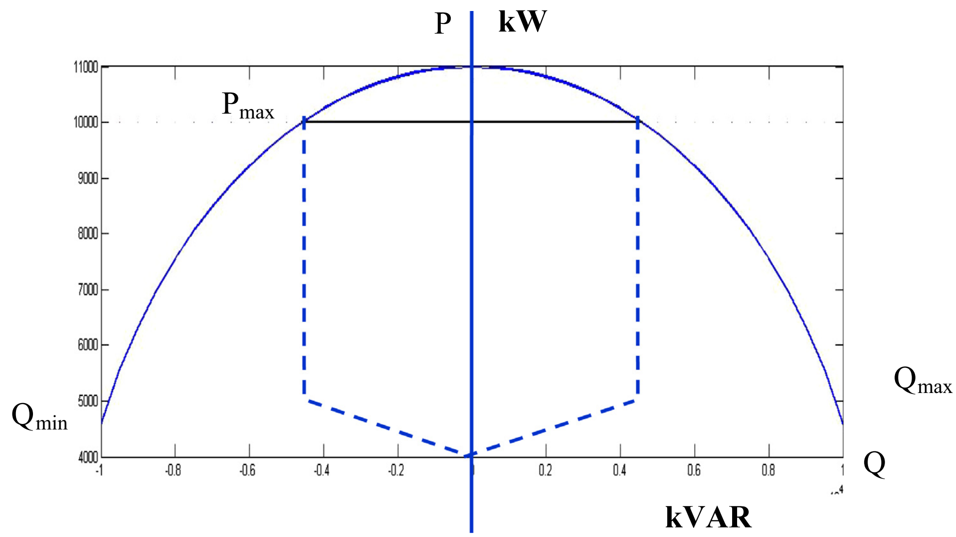

Fig. 3. Loading inconvertibility graph of an Inverter with its P_{min}, P_{max}, Q_{min} and Q_{max} limits.

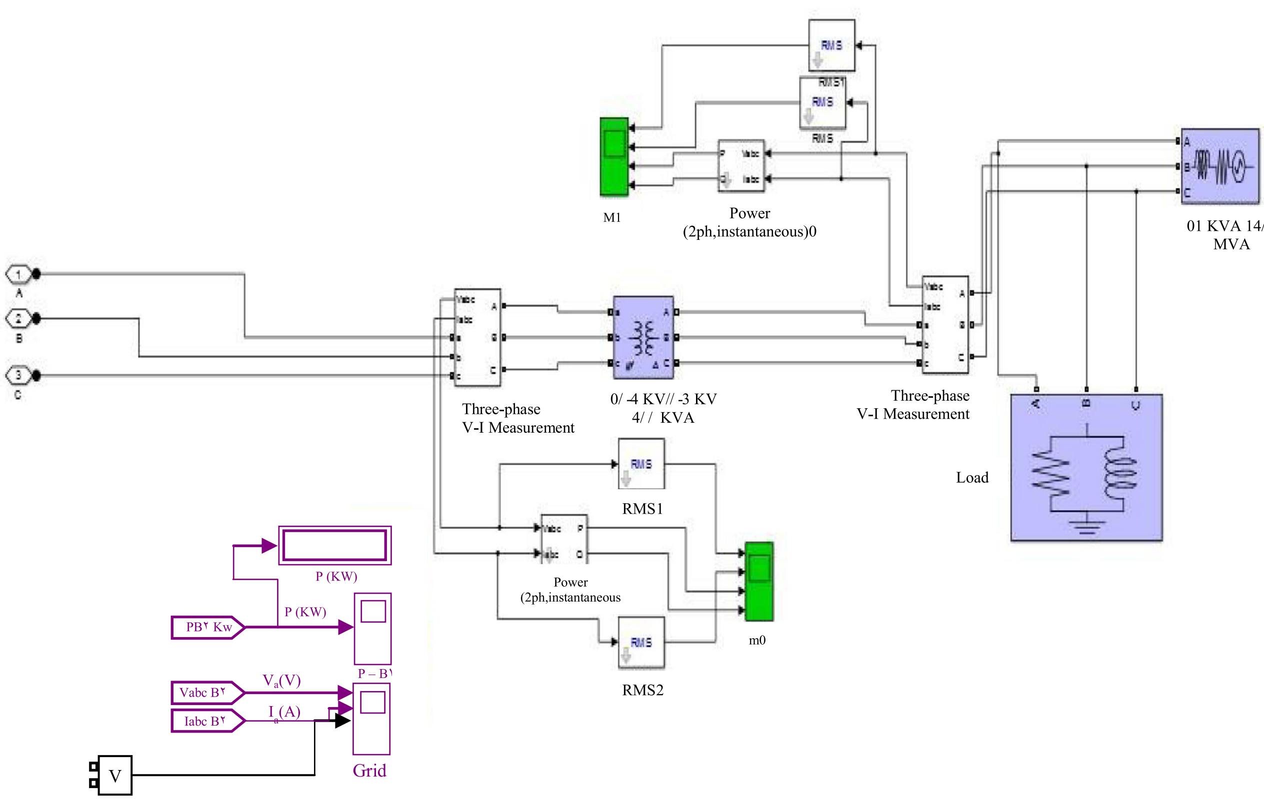

Fig. 4. The configuration of Simulated PV system.

4. Simulation results

The inverter is simulated by MATLAB Simulink [10]. Results are shown. It is developed by voltage VL-L of 380 V rms.

The Simulation of power control of the PV system under environmental condition changes is shown Fig. 4.

The PCC Voltage (0.38/11 kV) is load (10 kW, 4.5 Kvar), and the PV system is compound of solar arrays.

The PV system configuration with 8 parallel connections and 5 series connections accomplishes the aspired DC power and DC voltage input for an inverter system, the PV type is monocryt line and 17.2% efficiency, and the data of the PV module are indicated in [11]. Table 5 illustrates the PV module parameters.

The maximum power of the PV arrays is around 10 kW. Simulation is done with Matlab/Simulink program.

The parameters of solar module at 25 °C which used in the simulations are listed in Table 1.

The results of simulation for the proposed PV unit based on I-V and P-V clc's are shown in Figs. 5a and 5b.

The results of PV module based on P-V and I-V clc's at different values of cell temperatures and irradiations are shown in Figs. 6a and 6b.

Voltage analyzed can rim the supernumerary influential locations and require quantities, to serve reactive power for the grid voltage support from the distributed solar inverters. Assume that the 8- bus radial pretest feeder has three – phase balancing power stream as shown in Fig. 1.

The 8- bus radially test feeder is utilized measurements of the different values of the parameters for load flow calculations. It shows the values of voltage regulation for the grid voltage (V_g) and the load voltage (V_L) for each PV location of the grid. These data depend on the connection points of the inverters, that are closest and faraway of the transformer, while neglects the power demand from the consumers.

Fig. 7, shows the voltage values before PVs installation.

Table 2 shows the values of voltage regulation (ε) for V_g and V_L at each PV location of the grid. Eq. (2) estimates the voltage regulation (ε) values for each location.

$$\varepsilon = \frac{V_{g-V_L}}{V_g} \tag{2}$$

Fig. 8 shows the voltage values after installation of PVs, and the variation of ε values was based on measurements of voltages before PVs installation.

Table 3 shows the enhancement of measurements for the voltage values after the installation of PVs without control of reactive power with the distance between the inverter and transformer

Table 1
The solar module's, parameters at 25 °C.

I_{mp} (current at MPP)	7.7098 A
V_{mp} (voltage at MPP)	35 V
Pmax (maximum electrical power)	270 w
V_{OC} (open circuit voltage)	44.4999 v
Is.c (short circuit current)	8.1998 A

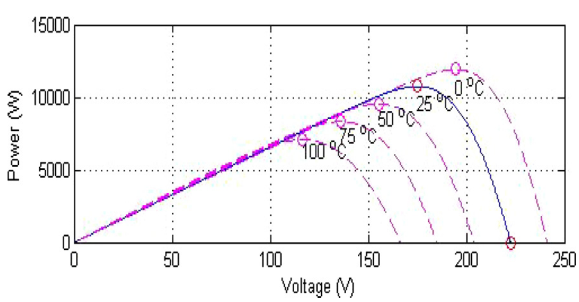

Fig. 5a. I-V Characteristics of PV Module at different irradiations.

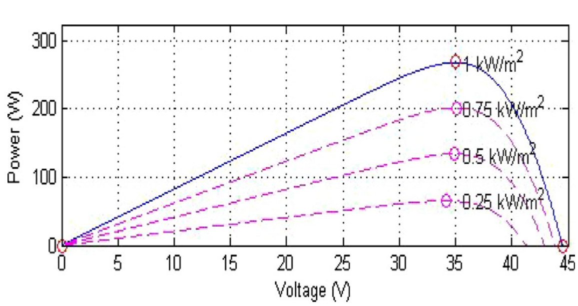

Fig. 5b. P-V Characteristics of PV Module at different temperatures.

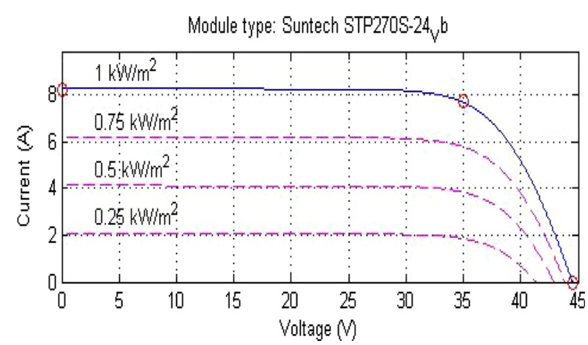

Fig. 6a. P-V Characteristics of PV Module at different temperatures.

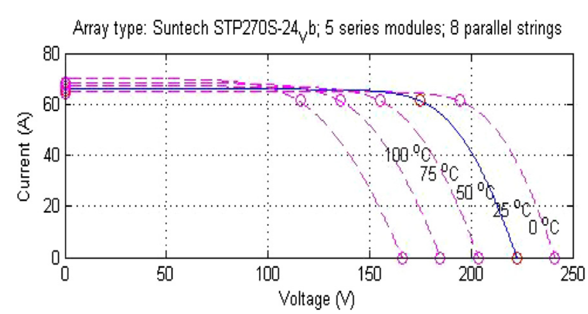

Fig. 6b. I-V Characteristics of PV Module.

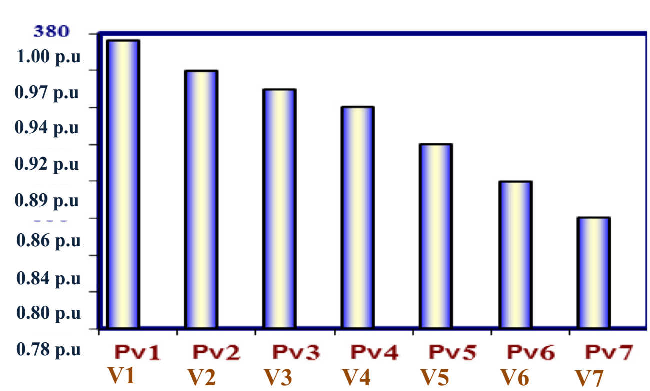

Fig. 7. Voltage values before PVs installation.

Table 2
Voltage values before installation of PV for v_1–v_7.

V_1	V_2	V_3	V_4	V_5	V_6	V_7
0.0%	2.7%	4.1%	5.6%	8.6%	10.89%	15.7%

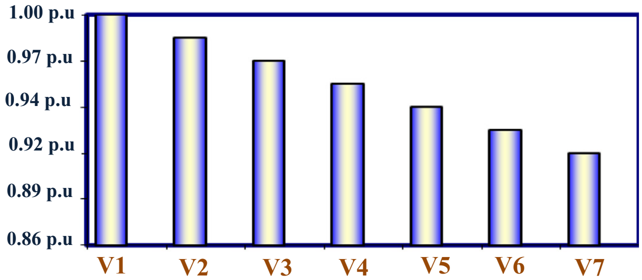

Fig. 8. Rise of voltage values after installation of PVs.

Fig. 9, shows the voltage values after control by reactive power to compensate VD.

Table 4 shows the voltage rise due to the converted part of the real power (m_i), produced from V_1 to V_7 to reactive power, to compensate the voltage drop that increases with the distance from the transformer. With the set valuable of PF, this finitely reactive power spotting can still profoundly furnish supplemental voltage drops on the transformer and the outlines. From the voltage analysis the lower PF values could be appropriated to the inverters, which are connected to the transformer, to obtain the optimum voltage values in admissible rate imposed by certain grid codes as shown in Table 5. The required PF can be determined for each inverter as shown in Eqs. (3) and (4).

$$\Delta U = S_{UP}.\Delta P + S_{UQ}.\Delta Q = 0 \tag{3}$$

$$\mathrm{PF_i} = \frac{1}{\sqrt{1+m_i^2}}, \quad \mathrm{m_i} = \frac{S_{UP}(j,i)}{S_{UQ}(j,i)} \tag{4}$$

where S_{UP}, S_{UQ}, PF_i and mi respectively, are the voltage sensitivity to active power, the voltage sensitivity reactive power, PF and mi required at i th bus. In addition to this i_{th} corresponds to the bus code at the PVs coupling point in this case, as shown in Fig. 6 10 kW of constant active power injection (P = 10 kW) appropriated to all inverters instataets time, and the required PFs to keep the voltage level until bus 7 inadmissible limitation [12].

Fig. 10 illustrates the simulation results of the system in the case of without V1, with V7, and with PV and Q control.

Fig. 11, shows the voltage drop of the system for three cases :-

1. without P.V
2. with P.V and without Q controlled
3. with P.V and Q controlled

4.1. Reduced line losses

Fig. 12 shows the load and line connecting at PF is 0.9, the active power by load is 10.5 kW, and the reactive power is 4.5 KVAR.

When the load side injects a θ_c equal 0.156 KVAR, the load P.F is 0.948 and active power is 10.5 kW, and reactive power is 458 KVR. The reactive power is increased due to voltage rise and the current is reduced. The line loss is estimated by Eq. (5).

$$\mathrm{P_{loss}} = 3\ \mathrm{I^2R} = 3\frac{p^2+Q^2}{V^2}\mathrm{R} \tag{5}$$

The total system losses is 3%, when the saving in losses equals 3% × 10.39% = 0.3%, as shown in Appendix C.

The total saving is equal 8.99 kW h/year, and the overall total system is equal to 90 kW h/year.

4.2. Increase system capacity

The reduction line of the values of current flow before and after is indicated in equations[6,7].

$$I_1 = \frac{\sqrt{P_1^2+Q_1^2}}{V_1} \tag{6}$$

$$I_2 = \frac{\sqrt{P_2^2+Q_2^2}}{V_2} \tag{7}$$

The reduction in the system current is given in Eq. (8).

$$\frac{I_1 - I_2}{I_1} \tag{8}$$

where P_1, Q_1 and I_1 are the values before control.

P2, Q_2 and I_2 are the values after control.

The capacity of the system, is increased by 4.5%.

4.3. Advantages and disadvantages of PV system

Although the benefits of PV system were mentioned previously, the nature of solar power depend on the sun, when reduction or no

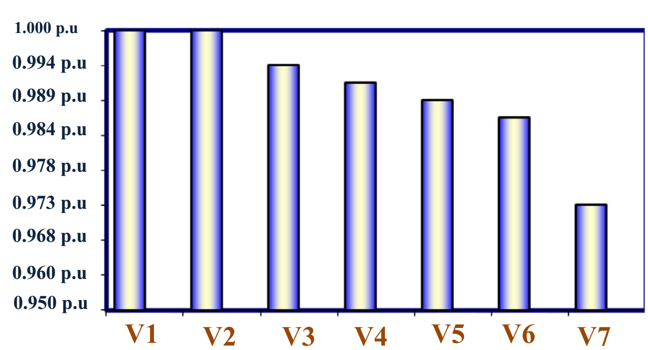

Fig. 9. Voltage values after control by reactive power to compensate VD.

Table 3
Voltage regulation values after installation of PV for V_1–V_7 Before control of Q (u).

V_1	V_2	V_3	V_4	V_5	V_6	V_7
0%	1.3%	2.7%	4.1%	5.6%	7%	8.6%

Table 4
The reactive power and the PF values set for each inverter.

m_i	0.1	0.2	0.25	0.3	0.35	0.4	0.46
PF_{PVI}	0.99	0.98	0.97	0.95	0.94	0.92	0.9
Q_{KVAR}	1	2	2.5	3	3.5	4	4.6

Table 5
Voltage regulation values after control of Q (u) & cos φ (P) to PV_1 – PV_7.

V_1	V_2	V_3	V_4	εV_5	V_6	V_7
0.0%	0.0%	0.53%	0.8%	1.1%	1.3%	2.7%

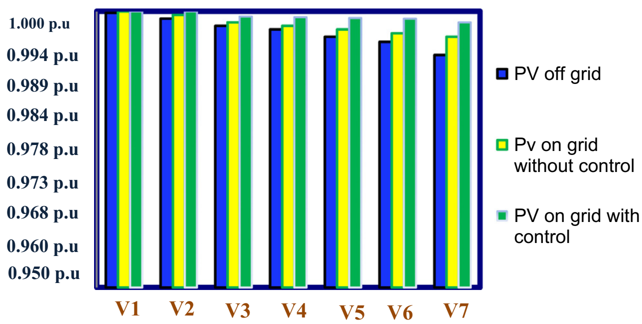

Fig. 10. Values of voltage for case study (PV off grid - Pv on grid without control and -PV on grid with control).

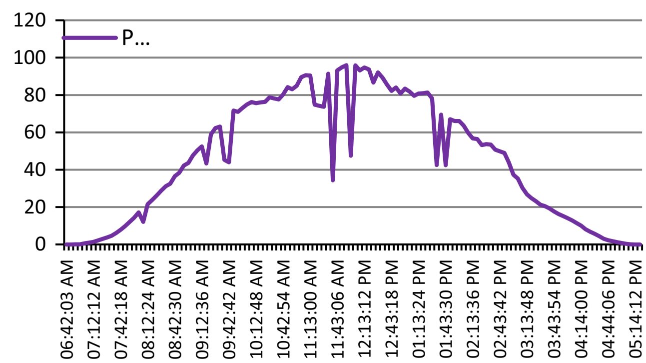

Fig. 13. Fluctuation in Output Power of PV System For one day.

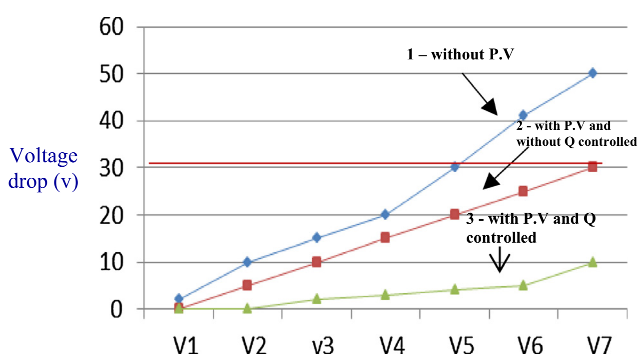

Fig. 11. Voltage drop line LV studied with distance from the transformer before and after installation of PVs, and PVs installation with control.

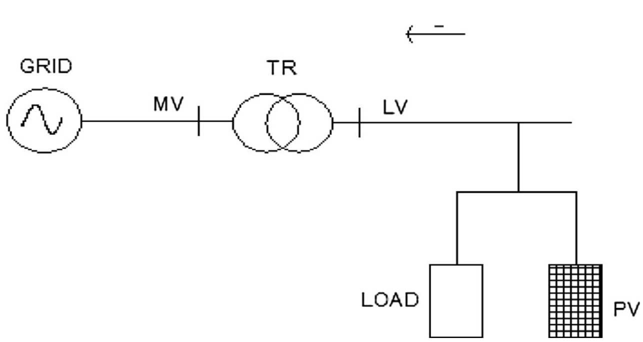

Fig. 12. The load and PV system in structure.

power at some of the time, is caused by power fluctuation [13]. Power production from PV power plants shows systematic patterns determined by apparent movement of the sun in the sky. This profile is disturbed by short-term variability driven by clouds. Fig. 13 shows an example of the PV power fluctuations due to the variations in irradiance. The fluctuation is apparent. Fig. 13 shows the fluctuation output power of PV system for one day, illustrating the frequency of these variations of power output depending on the quantity of irradiance. For some utilities, these fluctuations have a negative impact [14].

The power is generated from a PV system designed to inject some or all output power into the grid. If any violation occurs, the utilities forward the owners to treat their PV systems. There are many of the technologies used for storage or delivery generated power to enhance PV systems [15].

5. Conclusion

With the ever-increasing PV penetration at the distribution systems, several problems can arise. One of the main problems is voltage fluctuation at the distribution network buses so this study has presented a new approach of location – P.F- P and Q-V droop characteristics method. It can be considered as standby solution, to control Q-V droop method imposed by certain grid codes. High penetration of grid installed PVs, and voltage support from the inverters close to the transformer is required. This method enhances the voltage profile of the grid and compensates line voltage drop in admissible limit especially at the end feeder without requiring any new infrastructure. Therefore, improvement of the voltage profile of the system buses can reduce the total losses of the network and saving consumed power by customers and increases the system capacity by 4.5%. In the future work, we will study the improvement of PV systems by smoothing its output power.

Appendix A

The relationship between phase shift and related voltage at PCC certain bus.

θ °	P.F	P	Q	V
17.44	0.954	10.494	3.297	325.264
18.44	0.948	10.428	3.5	335.128
19.44	0.943	10.373	3.66	342.702
20.44	0.937	10.307	3.842	351.120
21.44	0.930	10.23	4.043	360.187
22.44	0.924	10.16	4.215	367.769
23.44	0.917	10.087	4.387	375.198
24.44	0.910	10.01	4.5609	382.526
24.36	0.91	10.01	4.560	382.5
25.36	0.903	9.933	4.726	389.425
26.36	0.89	9.79	5.0155	401.175
27.36	0.888	9.68	5.224	409.429
28.36	0.8799	9.678	5.228	409.586
29.36	0.871	9.581	5.404	416.423
30.34	0.86	9.46	5.613	424.399

Appendix B

The related results between active power and controlled phase shift.

P	Q	P.F	θ °
0.5	10	0.045	87.42
1	10.95	0.0909	84.78
1.5	10.89	0.136	82.18
2	10.81	0.1818	79.52
2.5	10.71	0.227	76.87
3	10.58	0.272	74.21
3.5	10.42	0.318	71.45
4	10.24	0.363	68.71
4.5	10.03	0.409	65.85
5	9.797	0.4545	62.96
5.5	9.526	0.5	60
6	9.216	0.545	56.97
6.5	8.87	0.59	53.84
7	8.485	0.636	50.50
7.5	8.046	0.681	47.07
8	7.549	0.727	43.36
8.5	6.982	0.772	39.466
9	6.324	0.818	35.11
9.5	0.545	0863	30.34
10	4.582	0.9090	24.36
10.5	3.278	0.954	17.44
11	0	1	0

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