Evaluation of Photovoltaic Systems for Reactive Power Compensation in Low Voltage Power Systems

Mesut Uğur, Erencan Duymaz, Murat Göl, Ozan Keysan
Department of Electrical and Electronics Engineering
Middle East Technical University
Ankara, Turkey

***Abstract*— The four-quadrant operation ability of photovoltaic (PV) inverters makes them promising candidates for reactive power compensation in low voltage systems. In this paper, utilization of PV inverters instead of conventional reactive power compensation units is evaluated. The use of PV inverters for reactive power compensation as well as active power supplying is investigated considering a real life system. The considered system suffers from low capacitive power factor due to the connected online UPS system. The paper firstly analyzes utilization of low voltage PV systems for reactive power compensation purpose technically, and then presents a detailed economic study in terms of short and long-term costs. The costs are evaluated considering reactive demand charge to the customer.**

***Index Terms*-- Solar power generation, reactive power compensation, PV inverters, reactive demand charge**

I. INTRODUCTION

Apart from the environmental concerns, low prices due to technological advances and government incentives are factors that affect the choice of investment in power plants. As a result, the share of renewable sources in total installed capacity reached significant levels in recent years. Aside from its benefits, renewable energy sources bring challenges to system operators in voltage regulation and frequency stability.

Photovoltaic (PV) systems are renewable sources that are commercially available even for small sizes. Regulations that allow installation of PV systems at residential buildings caused also increased the demand for those systems. However, the radial structure of the low voltage network creates several power quality problems especially when the generation exceeds consumption. Reverse power flow phenomenon creates voltage rises on the load side, which may result in unintentional load or generator tripping. Hence, PV inverters are expected to cooperate with system operators.

PV inverters are capable of supporting additional services to the grid thanks to their four-quadrant operation ability. In [1], PV inverters are used as Active Power Filter (APF) to suppress the current harmonics and reactive currents. Study in [2] focuses on smart utilization of the PV inverters such as reactive power compensation, voltage regulation and harmonic distortion elimination. In [3], reactive power injection strategies in single-phase inverters by considering grid requirements are investigated in order to support grid voltage and to comply with the LVRT dynamics. Moreover, in the study [4], two techniques for reactive power compensation are given for the low voltage grid with high PV penetration. The methods are mainly investigated in terms of communication infrastructure and power quality factors. Studies [5], [6] emphasize the operation of PV inverters as Static Synchronous Compensator (STATCOM) during night operation. In [7], the potential of distributed renewable sources is emphasized due to the fact that conventional reactive power sources are in transmission level and system operators ask for reactive power generation to maintain a stable grid operation. The paper mainly focuses on the incentives that system operators pay to the costumers.

In this paper, utilization of PV inverters instead of conventional capacitor banks or namely reactive power compensation units (RPCUs) will be investigated from an economic point of view. The study will be conducted using real system of the Ayaslı Research Center located at Middle East Technical University, Ankara, Turkey. In Section II, the problem will be defined in detail. Section III will explain the static solution and in Section IV, the static solution is analyzed and evaluated in terms of short-term and long-term costs. In Section V, use of RPCUs and PV inverters as reactive power compensators is discussed.

II. PROBLEM DEFINITION

In the power system network, active power is the main component of the apparent power that does useful work. However, reactive power, especially inductive reactive power is also required for the successful operation of some electrical loads such as industrial motors. However, demanding reactive power from the grid causes voltage drops as well as additional losses in the transmission and distribution systems. Hence, system operators restrict such demands on the point of common coupling (PCC), such that customers are responsible for complying defined power factors at the PCC. Considering the fact that load is assumed to be inductive most of the time, common practice is utilizing RPCUs to compensate the

978-1-5386-4505-5/18/$31.00 ©2018 IEEE

inductive reactive power at the PCC by using capacitor banks. Nevertheless, there has been a paradigm shift in the sense of power system network over the last decade with the increasing trend towards renewable energy. Due to the fact that rooftop PV systems spread everywhere in the low voltage network, the system experiences bidirectional power flow, voltage rise at the PCC and disturbance in the power factor.

This paper discusses a case study based on a real life case experienced at Ayaslı Research Center located in METU, Turkey. The building is equipped with a 50 kWp PV system, two distinct loads with 20 kVA and 120 kVA, each of which has its own uninterruptible power supply (UPS), and an RPCU with 50 kVAR rating. The single line diagram of the system is shown in Fig. 1.

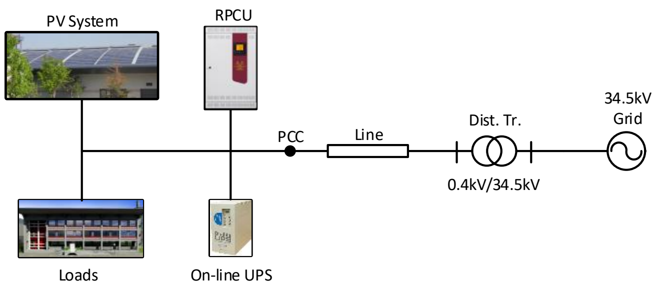

Figure 1. Ayaslı Research Center single line diagram

The loads in the system have electronic components such as computers and air conditioners, with assumed power factor of 0.98 inductive. On the other hand, on-line UPS systems equipped in the building are adjusted to generate capacitive reactive power when there is no interruption in the system. First, it is aimed to extend the lifetime of the batteries by continuous charge-discharge operation. Second, the loads are assumed to operate in inductive mode so that UPS systems are adjusted to operate in capacitive mode by default. Therefore, buildings equipped with such loads and UPSs may encounter capacitive operations although loads are assumed to be inductive normally. In Ayaslı Research Center, it has been noticed that the RPCU has not worked for five years due to the capacitive nature of the load. This results in impair investment which brings unnecessary installation cost.

Moreover, the power factor limitation constitutes another problem associated with this approach. In Turkey, for buildings with power rating more than 9 kW, it is obligatory to use electricity meter with the capability to reactive power measurement, and impose sanctions to limit the power factor. In the normal operation, power factor might be within these acceptable limits. However, if the PV power generation is around the active power demand, then very low or even zero active power might be observed at the PCC. Therefore, even if the reactive power drawn or injected to grid is negligible in the normal operation, poor power factor will be observed at the PCC. In such a case, the customer will be penalized by the distribution system operator. Hence, the reactive power should be compensated to maintain the power factor within the acceptable limits. Another problem in systems employing PV panels is voltage regulation issues due to the reverse power flow when loads are interrupted. Depending on the design, PV inverters may trip resulting in loss of power generation and loss of profit. This is not experienced in the studied case; hence it is kept out of the scope of this paper.

III. Static Solution

The PV systems can be utilized for reactive power compensation instead of the RPCUs. In the studied case, the RPCUs actually do not operate at all due to the load being capacitive because of the UPS. This situation results in an extra installation cost to the customer despite it cannot solve the power factor problem. The first advantage of the proposed static solution is the four-quadrant operation of the PV inverters. In this way, reactive power compensation can be achieved not only when the load in inductive, which is the general case, but also when the load is capacitive as in this case. Moreover, PV inverters can operate as reactive power compensators even if the active power input from the panels is zero, e.g. at night. In such a case, they operate just like a STATCOM, and can be used whenever compensation is needed. Finally, the amount of reactive power flow can be adjusted in a continuous manner with PV inverters, although RPCUs can only achieve this with discrete steps.

Reactive power compensation with a PV system can be achieved in two ways. Either the size of the PV system is increased according to the maximum amount of reactive power, or the amount of active power injected to the grid is reduced whenever the apparent power rating is exceeded. In this research, both cases will be considered and evaluated in terms of their long-term cost to the system. In the first case, the static solution will have impact on the installation cost as well as long-term cost due to the increased losses. The latter case will decrease the efficiency of the system since the system is required to operate outside of the maximum power point (MPP), and the profitability because of the reduced active power injection. The static solution may also have impact on the DC link capacitor size in terms of capacitance requirement and RMS ripple current requirement, which is highly dependent on each specific design and type of the DC link capacitor used. In both of the cases, additional power factor measurement will be required and control complexity will increase.

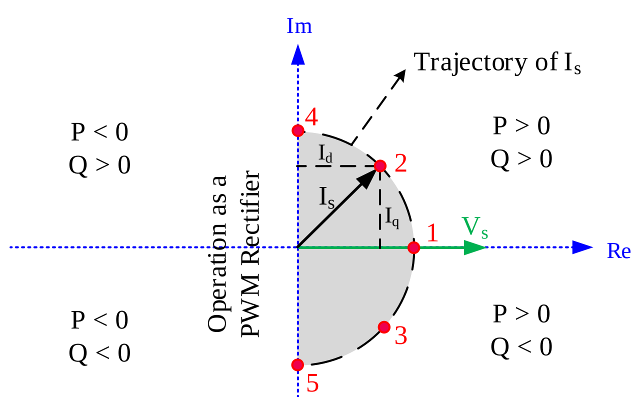

Figure 2. Phasor diagram of a PV inverter

A grid-connected inverter can operate at four quadrants of the V-I plane as mentioned before. PV inverters use only two quadrants where active power is always positive according to the sign convention. Low power PV systems connected to low voltage grid are aimed to operate at unity power factor as marked in the phasor diagram in Fig. 2 as Point 1. By keeping the magnitude of the current (and hence the apparent power) constant, a PV system can be operated as inductive or capacitive as in Point 2 and Point 3, respectively. They can also be operated as STATCOMs with purely inductive and purely capacitive as in Point 4 and Point 5, respectively.

This wide range of operation can be achieved by using the reactive component of the reference current as an additional control variable to the control system for reactive power compensation. The modification on the control system is shown in Fig. 3 on a conventional control block diagram of a PV inverter in which active and reactive components (d and q components) of the injected current are controlled separately. These components are also marked in Fig. 2 (Point 2) for an inductive case.

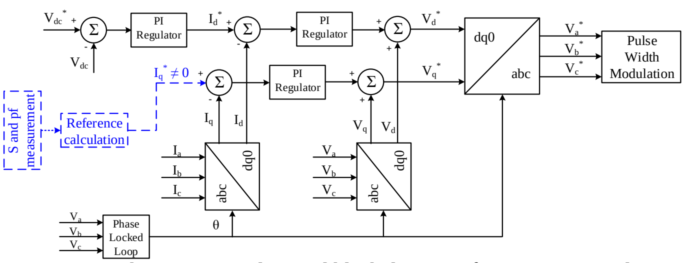

Figure 3. The conventional control block diagram of a PV inverter and modification for RPC

Conventionally, the reference to the reactive component (Iq*) is set to zero to operate the PV system at unity power factor (Point 1 on Fig. 2). With the proposed modification, this reference can be used to adjust the reactive power by either an external reference signal or additional measurements.

IV. Cost Analysis and Evaluation

In this section, the static solution will be evaluated in terms of short-term and long-term cost and will be compared to the conventional system specific to the case study, which is under investigation.

A. DC Link Capacitor Size

In grid connected PV inverters, DC Link capacitors have the duties of supplying the inverter current at switching frequency, smoothing the DC Link voltage waveform, supplying the transient power deviations and hold-up energy when power failure occurs in the system. The ability of a PV inverter to transfer reactive power is also achieved by DC Link capacitor; i.e., it handles the power fluctuation on the DC side due to reactive power. There are two major parameters of a DC Link capacitor, which will be affected directly by reactive power compensation capability of a PV inverter: capacitance and RMS current rating.

Aluminum electrolytic capacitors are the most commonly used types in DC Link applications due to their low cost and high capacitance per volume. However, their RMS current ratings per volume are very low and lifetime is short. On the contrary, metal film capacitors have higher cost, lower capacitance, higher current rating and better lifetime [8]. In this study, both types will be considered for evaluation.

Capacitance selection of a DC Link capacitor (C_{dc}) is determined by voltage ripple constraint as well as hold-up energy requirement. In (1) and (2), general expressions for ripple requirement and hold-up energy are provided where M is the modulation index, f_{sw} is the switching frequency, $V_{dc,r}$ is the DC-link voltage.

$$C_{dc} > \frac{M \times (\hat{I}_S - I_{avg})}{\sqrt{2} \times V_{dc,r} \times f_{sw}} \tag{1}$$

$$C_{dc} > \frac{I_{avg} \times \Delta t}{\Delta V} \tag{2}$$

Considering a generic design for a 50 kWp central PV inverter with a switching frequency of 5 kHz (f_{sw}), DC Link average voltage of 750 V (V_{dc}), peak to peak ripple constraint of 1%, and hold-up requirement of 500 V for a full fundamental cycle of the grid, the capacitance requirements come out to be 5.3 mF and 0.58 mF, respectively. As a result, capacitance requirement is determined by hold-up energy, which is dependent on the kVA rating of the inverter. For a PV inverter, which can operate down to 0.8 pf at the same active power, the capacitance is increased by 25%, which should be taken into account in capacitor size evaluation. When the total power rating is kept constant, there will be no change.

RMS ripple current requirement of the DC Link capacitor has also been derived as in Equation (3) [8], where pf is the power factor.

$$I_{c,rms} = I_{s,rms} \sqrt{\left[2M \left(\frac{\sqrt{3}}{4\pi} + pf^2 \left(\frac{\sqrt{3}}{\pi} - \frac{9}{16} M \right) \right) \right]} \tag{3}$$

In our case, the ripple current of the DC Link capacitor increased by 18% if the size of the inverter is increased for 0.8 pf operation and by 5% if the total kVA rating is kept constant.

B. Power Semiconductor Losses

Making a PV inverter to operate at non-unity power factor will affect the long-term cost of the system due to additional semiconductor losses even if the total kVA rating is kept constant. In this study, power semiconductor losses will be evaluated with selected commercial IGBTs, including transistor conduction (P_{tc}) and switching loss (P_{ts}) and anti-parallel diode conduction (P_{dc}) and reverse recovery loss (P_{dr}). General formulation of semiconductor losses is shown in (4) – (7). In this formulation, E_{on} and E_{off} are turn-on and turn-off switching energies, I_{cp} and I_{ep} are the peak current, $V_{ce,sat}$ is the saturation voltage drop, V_{ec} is the forward voltage drop of the diode, I_{rr} and t_{rr} are recovery current and time, and $V_{ce,p}$ is the peak reverse recovery voltage.

$$P_{tc} = I_{cp} \, V_{ce,sat} \left(\frac{1}{8} + \frac{M \, pf}{3 \, \pi} \right) \tag{4}$$

$$P_{ts} = \left(E_{on} + E_{off}\right) \frac{f_{sw}}{\pi} \quad (5)$$

$$P_{dc} = I_{ep}\, V_{ec} \left(\frac{1}{8} - \frac{M\, pf}{3\,\pi}\right) \quad (6)$$

$$P_{dr} = I_{rr}\, t_{rr} V_{ce,p}\, \frac{f_{sw}}{8} \quad (7)$$

For loss calculation, a 150A, 1200V IGBT is selected for 50kVA case and a 200A, 1200V IGBT is selected for 70kVA case from the same HV-IGBT family of Powerex. There are three cases under investigation for comparison where solar panel power is considered as 50 kW for all cases, as shown in Table 1. Case-1 is the conventional system with no reactive power injection; Case-2 is the same system operating at 0.8 pf and Case-3 is the system where inverter size is increased for reactive power compensation.

TABLE 1: CASES CONSIDERED FOR LOSS CALCULATION

	P_{out}	Q_{out}	pf	Inverter size
Case - 1	50 kW	0	1.0	Same
Case - 2	40 kW	30 kVAr	0.8	Same
Case - 3	50 kW	50 kVAr	0.7	Increased

For these cases, all the losses are found and listed as in Table 2. First, each loss component is found and total loss of the inverter (P_{loss}) and active power injected to the grid (P_{grid}) are determined. In addition, total effective loss (P_{loss_eff}) is found considering the capacity of the solar panels, since the actual effect of reactive power compensation to the customer is the effective power loss.

TABLE 2: POWER SEMICONDUCTOR LOSS RESULTS

	Case - 1	Case - 2	Case - 3
P_{tc} (W)	44.39	25.51	59.07
P_{ts} (W)	26.6	26.66	40.78
P_{dc} (W)	6.81	26.15	18.9
P_{dr} (W)	15.92	15.92	20.29
P_{loss} (W)	562.68	565.44	834.24
P_{grid} (kW)	49.43	39.43	49.166
P_{loss_eff} (W)	562.68	10565.44	834.24

It has been shown that, both of the methods have their own benefits and drawbacks. Increasing the size of the PV inverter (Case-3) yields size increase on power semiconductors, capacitor and possibly other elements which will result in installation cost increase, while the increase on the effective loss is 50% (nearly 270W) for rated conditions. On the other hand, using the same inverter for reactive power compensation (Case-2) does not require much size increase for components while the effective loss is too much (18 times the original case) which will result in operational cost to the customer.

C. Long Term Cost Evaluation

The interpretation of the loss results to cost is required for the comparison of the two proposed methods. For this purpose, the actual case study in Ayaslı Research Center is investigated for long term. The daily power generation of the PV panels in winter and summer are shown in Fig. 4. The load active and reactive power demand and the UPS reactive power injection, which are assumed to be constant throughout the year are also shown in Fig. 4.

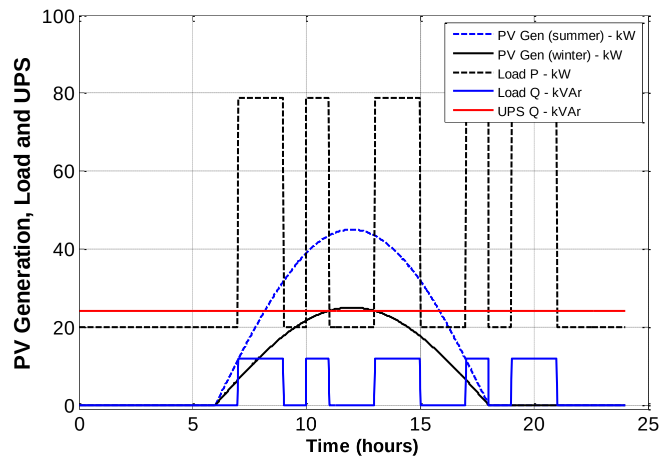

Figure 4. Daily profiles of PV generation, load and UPS

The apparent power of the PV inverter and daily reactive power demand from the PV inverter is shown in Fig. 5, supposing that reactive power compensation is performed by the PV inverters to make the PCC power factor unity.

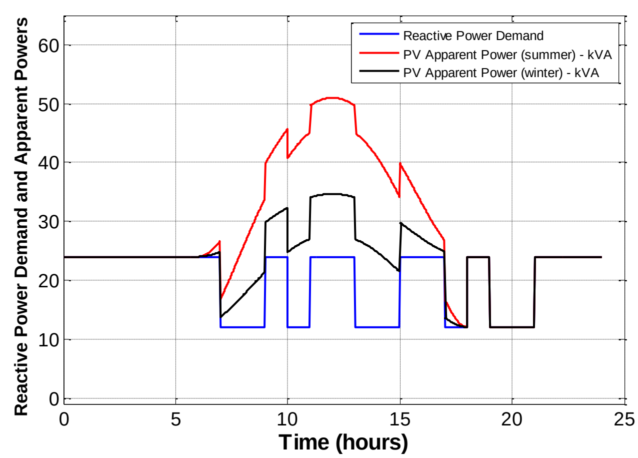

Figure 5. PV inverter apparent power and daily reactive power demand in case it is used for reactive power compensation

Moreover, the active power, reactive power and the power factor at the PCC are also obtained and shown in Fig. 6 and Fig. 7, for the cost and penalty calculation due to reactive power. The electricity prices are 6.5 ¢/kWh and 3.1 ¢/kVArh, however, the reactive power charge is only evaluated when Q > 0.2P which has been taken into account in the cost evaluation.

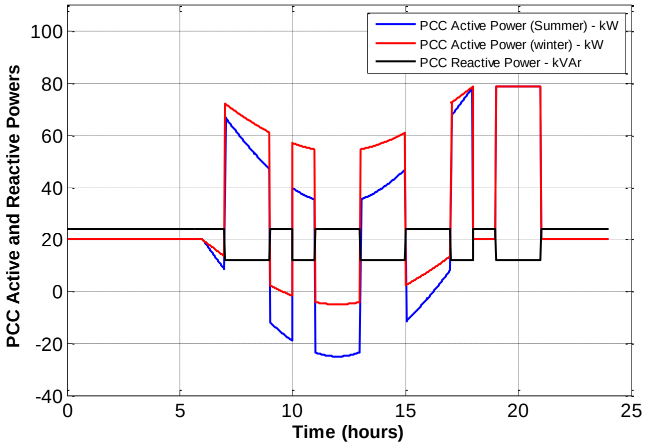

Figure 6. PCC reactive power and active power

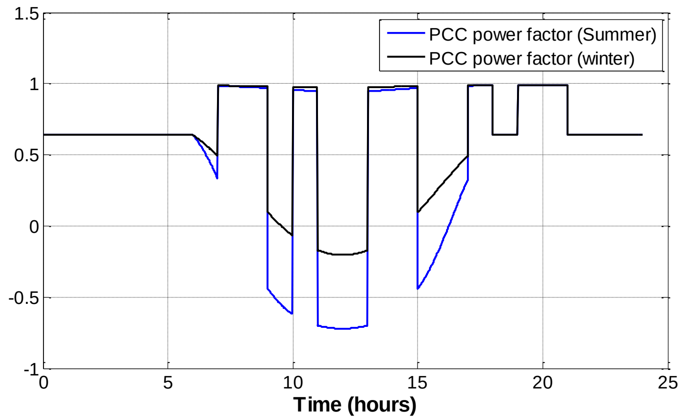

Figure 7. PCC power factor

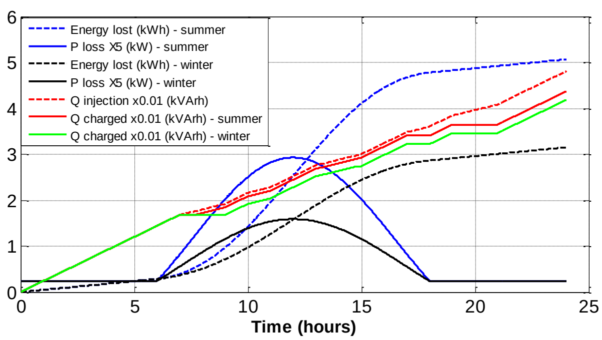

Figure 8. Daily power loss and reactive power charge for the conventional system (Case-1)

In Fig. 8, daily power loss, cumulative energy lost and reactive power injection and charge are shown for case-1. Fig. 9 and 10 show the daily power loss and cumulative energy lost when reactive power is compensated with PV inverters for case-2 and case-3, respectively.

Long term cost evaluation results are shown in Table 3 in per year base, where reactive power charged to the customer by the distribution system operator (Q), total cost of reactive power penalty (CostQ), total lost energy (E) and total cost of active power loss (CostP) are shown for the three cases.

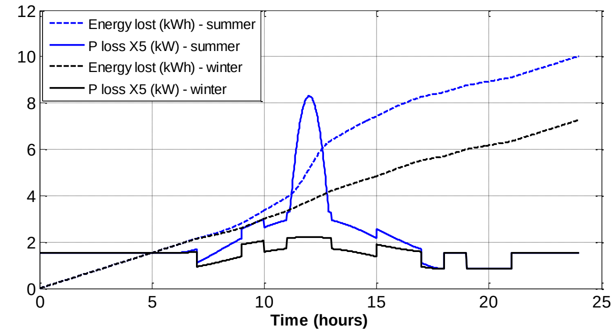

Figure 9. Daily power loss (Case-2)

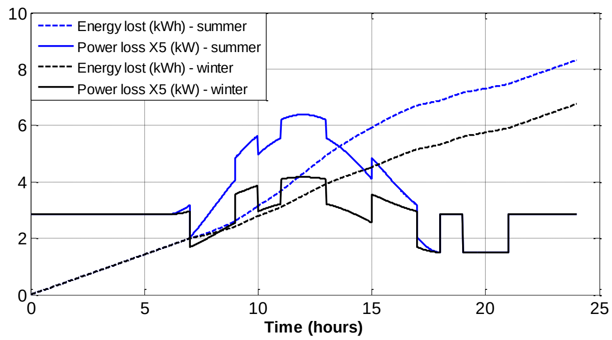

Figure 10. Daily power loss (Case-3)

TABLE 3: LONG TERM COST EVALUATION

	Q (MVArh)	CostQ ($)	E (MWh)	CostP ($)
Case - 1	156	4848	1.500	97
Case - 2	0	0	3.154	205
Case - 3	0	0	2.751	179

V. CONCLUSION

It has been shown that the customer is faced with a high reactive power injection charge when no additional reactive power compensation is applied, even though RPCU is installed in the building. The reason is the capacitive nature of the UPS systems and the active power injection by the PV system. When the same inverters are used for reactive power compensation, the cost due to active power losses increased over 100%, which is still very small compared to no reactive power compensation case.

In the case-3, increased inverter size yields a little less long term cost than using original inverters thanks to the utilization of solar panels at full power. However, size increase of the IGBTs, DC Link capacitors and other major equipment on the PV system will bring higher installation cost. On the inverter power stage, the cost increase of these fundamental components has been estimated as 25%, however, exact installation cost increase cannot be told. The reason is that these inverters are subject to mass production and cost of each item will not be the same as commercial off-the-shelf products. In addition, there are R&D investments and service expenditures. Even so, it is very clear that the installation cost will be much larger for case-3.

One of the major reasons that such case exists in the low voltage network is the lack of monitoring mechanisms. To avoid such problems, low voltage should be monitored extensively. In this way, more secure low voltage can be achieved as well as such problematic consumers can be detected. Finally, it should also be noted that the penalization by power factor should be replaced by the amount of reactive power demand in the regulations to avoid these problems with the increasing number of photovoltaic systems in low voltage network.

ACKNOWLEDGMENT

This work is partially supported by Scientific and Technological Research Council of Turkey (TUBITAK) under the TUBITAK project number 115E146.

REFERENCES

[1] S. Biricik, H. Komurcugil, and M. Basu, “Photovoltaic Supplied Grid-Tie Three-Phase Inverter with Active Power Injection and Reactive Harmonic Current Compensation Capability,” pp. 3–8, 2016.

[2] F. Barrero-Gonzalez, V. Minambres-Marcos, M. Guerrero-Martinez, E. Romero-Cadaval, M. Milanes-Montero, and E. Gonzalez-Romera, “Photovoltaic inverter with smart grid functions,” *EEEIC 2016 - Int. Conf. Environ. Electr. Eng.*, no. Dcdc, 2016.

[3] Y. Yang, H. Wang, and F. Blaabjerg, “Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements,” *IEEE Trans. Ind. Appl.*, vol. 50, no. 6, pp. 4065–4076, 2014.

[4] M. Castilla, M. Velasco, J. Miret, P. Martí, and A. Momeneh, “Comparative study of reactive power control methods for photovoltaic inverters in low-voltage grids,” *IET Renew. Power Gener.*, vol. 10, no. 3, pp. 310–318, 2016.

[5] M. S. E. Rao and K. Obulreddy, “Utilization Of Pv Solar Farm As Statcom During Night Hours In A Distribution Network,” *Int. J. Sci. Technol. Res.*, vol. 3, no. 8, pp. 33–39, 2014.

[6] N. Solanki and J. Patel, “Utilization of PV solar farm for Grid Voltage regulation during night; analysis & control,” in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, 2016, pp. 1–5.

[7] a. J. Von Appen, B. C. Marnay, C. M. Stadler, D. I. Momber, E. D. Klapp, and F. A. Von Scheven, “Assessment of the economic potential of microgrids for reactive power supply,” *8th Int. Conf. Power Electron. - ECCE Asia*, no. June, pp. 809–816, 2011.

[8] J. W. Kolar and S. D. Round, “Analytical calculation of the RMS current stress on the DC-link capacitor of voltage-PWM converter systems,” *IEE Proc. - Electr. Power Appl.*, vol. 153, no. 4, p. 535, 2006.