UTILIZATION OF PHOTOVOLTAIC SYSTEMS FOR REACTIVE POWER COMPENSATION IN LOW VOLTAGE POWER SYSTEMS

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Abstract

The ability of four quadrant operation of photovoltaic inverters can be employed for additional services for grid power quality. In this paper, employment of PV inverters to replace conventional reactive power compensation units is proposed. The capability of grid connected PV systems to absorb/inject reactive power from/to the grid in a continuous manner makes them promising candidate for reactive power compensation in low voltage systems. The employment of PV inverters is investigated on a test case where capacitive reactive power problem exists due to online UPS systems. This problem even gets worse due to the existence of PV system which decreases the active power demand and makes power factor poor. The proposed solution has been investigated in terms of short term installation costs due to inverter size increase as well as long term costs due to additional losses on the system. The results are evaluated and compared considering the reactive demand charge to the customer.

1 Introduction

Environmental concerns related to global warming and CO_2 emissions have increased the popularity of renewable power sources. Moreover, low prices due to technological advances and government incentives are also other factors that affect the choice of investment in the power plants. As a result, the share of renewable sources in total installed capacity reached significant levels. Aside from its benefits, it also brings challenges to system operators such as voltage regulation and frequency stability. Now, most of the system operators ask for low voltage ride-through (LVRT) capabilities from renewable sources as ancillary service. Some countries require inertial frequency support to increase frequency stability in the power system network. These are all achievable services for renewable sources which are connected to grid with power electronics due to the freedom of controlling active and reactive power independently.

Photovoltaic (PV) systems are the most common type of renewable sources since they are commercially available even for small sizes. Regulations that allows for residential buildings increased the utilization of PV sources in low voltage network. However, the old fashion design of the low voltage network (radial design) creates many problems especially when the load generates more than it consumes. This reverse power flow phenomenon creates voltage rises on the load side, unintentional load or generator tripping. Hence, PV inverters are expected to cooperate with system operators.

PV inverters are capable of supporting many additional services during it generates active power to grid thanks to their four quadrant operation ability. In [1], PV inverters are used as Active Power Filter (APF) to supress the current harmonics and reactive currents. Study in [2] focuses on the PV inverter to provide smart functions 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 work [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] and [6] emphasize the operation of PV inverters as Static Synchronous Compensator (STATCOM) during night operation. The idea to use PV inverters as reactive power compensators has been studied in the literature for many years. 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 pays to costumers.

In this paper, utilization of PV inverters to replace conventional capacitor banks or namely reactive power compensation units (RPCUs) will be investigated as a solution to a real world problem experienced in Ayaslı Research Center located in Middle East Technical University, Ankara, Turkey. In Section II, the problem will be defined in detail. Section III will propose the solution and in Section IV, the method is analysed and evaluated in terms of short-term and long-term costs. In Section V, comparison of using RPCUs and PV inverters as reactive power compensators is discussed.

2 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 powers from system operators causes voltage drops as well as additional losses in the transmission and distribution level. Hence, system operators restrict such demands on the point of common coupling (PCC) with the term called “power factor”. Therefore, customers are responsible for complying defined power factors in the PCC. Considering the fact that load is assumed to be inductive most of the time, common practice is utilizing RPCUs to compensate the inductive reactive power in 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. Especially the low voltage network is designed with the assumption that power flows radially, i.e., tree-like topology starting from the low voltage side of distribution transformers. However, roof-top PV systems are spread everywhere with connection to low voltage network that creates reverse power flows, voltage rises in the PCC and disturbance in the power factor.

In this work, a case study for Ayaslı Research Center located in Electrical and Electronics Engineering Department in METU, Turkey will be considered. The building is equipped with a PV system with 50 kWp installed power, two distinct loads with 20 kVA and 120 kVA, respectively, each having its own uninterruptible power supply (UPS), and an RPCU with 50 kVAr rating. The single line diagram of the system is shown in Figure 1.

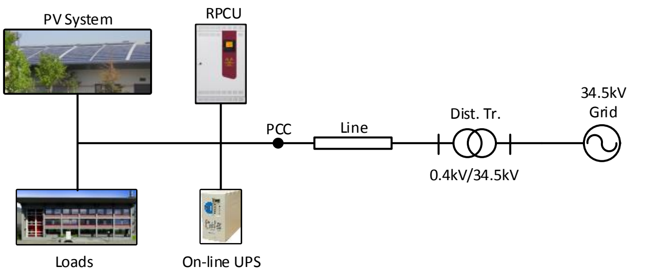

Figure 1: Ayaslı Research Center single line diagram

The loads in the system have electronics components such as computers, air conditioners that are equipped with power electronics and do not absorb too much reactive power and the power factor of the load is assumed to 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. Firstly, 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.

Second major problem in such buildings is the power factor limitation. In Turkey, for industrial buildings with power rating more than 9 kW, it is obligatory to use electricity meter with the capability to measure reactive power and impose sanctions to limit the power factor [ref]. In the normal operation, power factor might be within these acceptable limits. However, if the PV power generation is above the active power demand, then very low or even zero active power might be observed on 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 on the PCC. In such a case, the customer will be penalized by distribution system operator since the power factor is out of permissible limits. Hence, the reactive power should be compensated to maintain the power factor within the acceptable limits.

Another problem in such 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 case study, hence it is kept out of the scope of this paper.

3 Proposed Solution

The photovoltaic (PV) systems can be utilized for reactive power compensation in such systems replacing the RPCUs. In the case explained in this study, the RPCUs actually do not operate at all due to the load being capacitive because of the UPSs. This brings extra cost to the system while even not solving the power factor problem.

The advantages of the proposed solution are as follows:

- PV inverters can operate in four-quadrants, in other words they can both inject/absorb reactive power from/to the system. This way, reactive power compensation can be achieved not only when the load in inductive, which is most of the case, but also when the load is capacitive as in our case.
- PV inverters can operate as reactive power compensators even when the active power input from the panels is zero, for example at night. In such a case, they operate just like a STATCOM and they can be used whenever compensation is needed.
- 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. For an RPCU, the controllability can be increased by adding more steps, however the cost will increase in that case.

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 reducing the amount of active power injected to the grid when 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 proposed method 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 efficiency is decreased because of the reduced active power injection. The proposed method 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.

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 in the block diagram shown in Figure 2. Low power PV systems connected to low voltage grid are aimed to operate at unity power factor as marked in the phasor diagram in Figure 3 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.

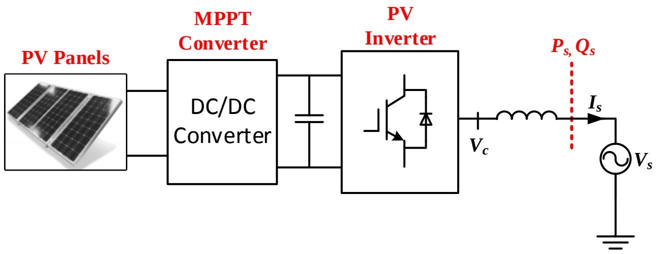

Figure 2: Block diagram of a PV system

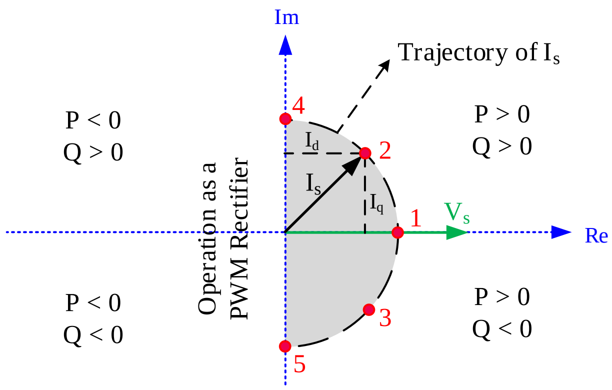

Figure 3: Phasor diagram of a PV inverter

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 Figure 4 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 Figure 3 (Point 2) for an inductive case.

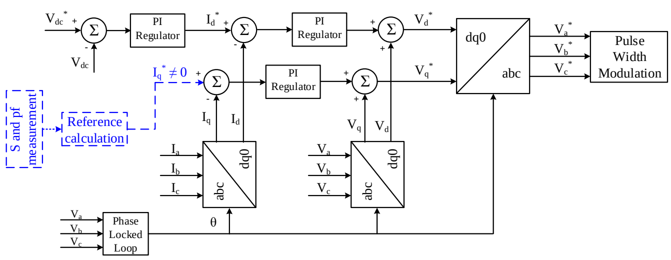

Figure 4: The conventional control block diagram of a PV inverter and modification for RPC

Conventionally, the reference to the reactive component (I_q^*) is set to zero to operate the PV system at unity power factor (Point 1 on Figure 3). With the proposed modification, this reference can be used to adjust the reactive power by either an external reference signal or additional measurements.

4 Cost Analysis and Evaluation

In this section, the proposed method 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.

4.1 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.

Aluminium 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 is determined by voltage ripple constraint as well as hold-up energy requirement. In Equations (1) and (2), general expressions for ripple requirement and hold-up energy are provided, respectively.

$$C_{dc} > \frac{M \times (\widehat{I_s} - I_{avg})}{\sqrt{2} \times V_{dc,r} \times f_{sw}} \quad (1)$$

$$C_{dc} > \frac{I_{avg} \times \Delta t}{\Delta V} \quad (2)$$

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 580 μF, 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 M is the modulation depth and pf is the power factor.

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

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.

4.2 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 are shown in Equations (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.

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.

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.

	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

Table 1: Cases considered for loss calculation

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

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

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

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

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.

	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

Table 2: Power semiconductor loss results

4.3 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 Figure 5. 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 Figure 5. The apparent power of the PV inverter and daily reactive power demand from the PV inverter is shown in Figure 6, supposing that reactive power compensation is performed by the PV inverters to make the PCC power factor unity.

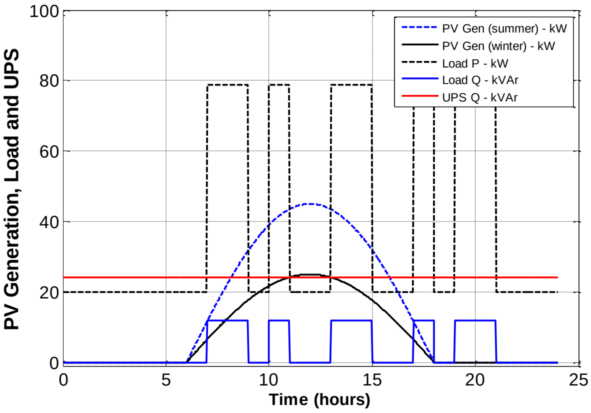

Figure 5: Daily profiles of PV panel generation, load and UPS

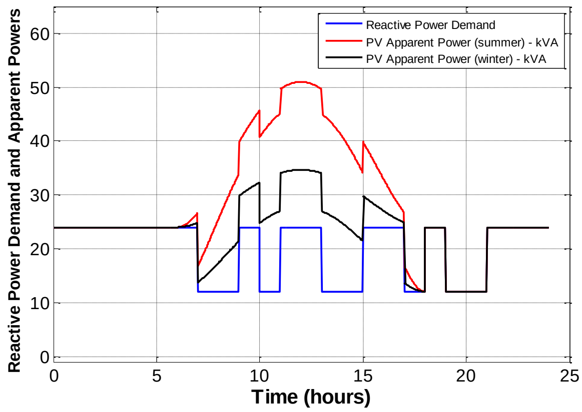

Figure 6: PV inverter apparent power and daily reactive power demand in case it is used for reactive power compensation

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

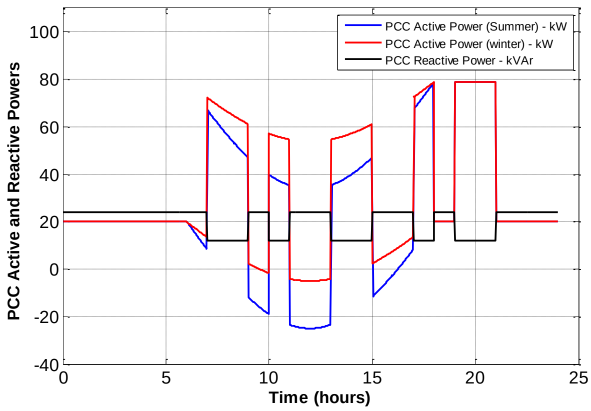

Figure 7: PCC reactive power and active power

In Figure 8, daily power loss, cumulative energy lost and reactive power injection and charge are shown for case-1. Figure 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.

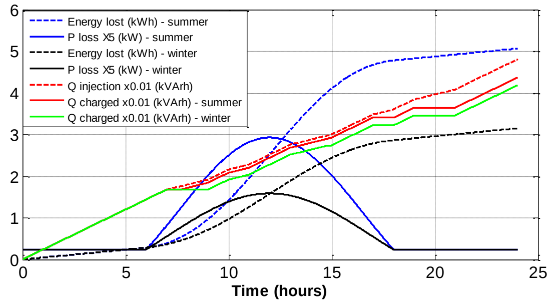

Figure 8: Daily power loss and reactive power charge for the conventional system (Case-1)

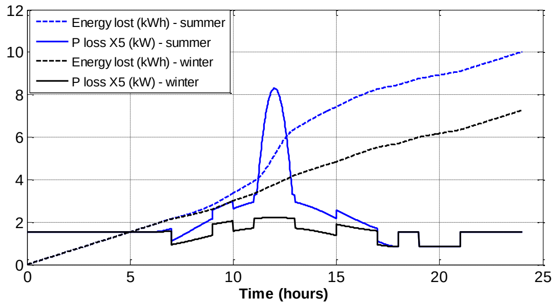

Figure 9: Daily power loss with reactive power compensation (Case-2)

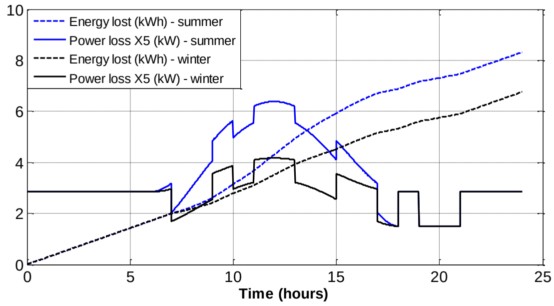

Figure 10: Daily power loss with reactive power compensation (Case-3)

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.

	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

Table 3: Long term cost evaluation

5 Discussions

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 to be 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. Size increase yields a little less long term cost due to power losses than using original inverters. However, size increase of the IGBTs, DC Link capacitors and other major equipment on the PV system will bring higher installation cost.

Projeye atıf: One of the major reasons that such case exists in the low voltage network is the lack of monitoring mechanisms. To avoid this 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.

6 Conclusion

Acknowledgements

Bizim projeye teşekkür etcez.

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