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Energy and Economic Yield of Photovoltaic Systems: Reactive-Power Impact

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Abstract. The reactive-power service will be or is already obligatory for new grid-connected photovoltaic systems. The paper investigates the impact of the reactive-power service on the energy yield of a photovoltaic system and its effect on the inverter sizing and economic yield. Based on simulations and analysis of an operating photovoltaic system we show that energy losses due to the reactive-power service are low but become notable at high irradiance levels. Also, the optimal inverter sizing is affected by the reactive-power service more at low irradiance levels than at the high ones. Nonetheless, economically there is no reason to oversize the inverter due to reactive power needs. A photovoltaic system with a balanced or slightly larger inverter can provide the reactive-power service and achieve a little lower but still optimal internal rate of return.

Keywords: reactive power, PV system, energy yield, economic analysis

Energijski in ekonomski donos fotonapetostnega sistema: vpliv jalove energije

Zagotavljanje pretoka jalove energije bo oziroma je že obveza obveznost v vseh novih fotonapetostnih sistemih. Članek obravnava vpliv pretoka jalove energije na energijski donos fotonapetostnega sistema, na dimenzioniranje razsmernika in ekonomsko upravičenost. Simulacije in analiza obstoječega fotonapetostnega sistema je so pokazalapokazale , da ima jalova energija majhen vpliv na energijski donos sončne elektrarne, ki pa postane bolj izrazit pri visokih vrednostih sončnega obsevanja. Optimizacija razsmernika ima večji vpliv pri nižjih obsevanjih kot pri visokih. Iz ekonomskega vidika ni potrebe po predimenzioniranju razsmernika zaradi zagotavljanja pretoka jalove energije. Fotonapetostni sistem z uravnoteženim ali le nekoliko predimenzioniranim razsmernikom lahko omogoča pretok jalove energije z minimalno manjšo interno stopnjo donosa.

1 INTRODUCTION

In an alternating current (AC) system of a linear source and purely resistive load both the current and voltage are sinusoidal and in phase. In reality, the loads have resistive, inductive and/or capacitive load profiles which lead to a shift of the phase between the current and voltage. When the voltage and current are not in phase, two power components (real and imaginary) are present: active power (measured in Watts) and reactive power (measured in VArs). The reactive power does not transfer the energy but is required to maintain the voltage to deliver the active power over the transmission lines. The grid-connected photovoltaic (PV) systems behave more or less as a linear source and do not produce the reactive power. With the increasing share of the PV energy in the electric power grid, the demand of producing the reactive power becomes more and more justified. Nowadays, most PV inverters cannot produce the reactive power, but following the new regulations adopted in the EU countries they will need to be able to supply the reactive power in the very near future.

In Slovenia since May 2011 [1] and in Germany since August 2011 [2], all the newly installed PV systems must be able to supply the grid with the reactive power. In Slovenia, each newly installed PV system must be capable to provide the reactive power with a power factor of 0.8 or dynamically change the reactive power service. Due to this new regulation, many installers as well as distributors oversize the inverters to ensure that all the produced active power is delivered to the grid. While the industrial consumers in Slovenia have to pay for the reactive power, the producers are not eligible to ask for reimbursement for the reactive power service. The question is whether the PV systems are able to supply the reactive power without affecting the system energy yield? If they are, does this have an impact on the profitability of the investment?

In the paper we are present results of investigating the reactive-power impact on the energy and economic yield of the PV systems. We analyse the actual energy production of a PV system in Slovenia and simulate the impact of the phase shift with regard to the Slovenian regulations on the system energy yield. We make to support investors in their decision making while complying with the enforced regulations.

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2 THEORY OF THE REACTIVE POWER

When the voltage and current are not in phase, we get two power components: active (P) and reactive power (Q). The total power is referred to as an apparent power (S). The relation between the power components shown in Fig. 1 can be described as:

$$S^2 = P^2 + Q^2 \tag{1}$$

Usually, the share of the active power is given by the cosine of the phase shift between the current and voltage and is referred to as the power factor (PF):

$$PF = \cos(\varphi) = \frac{P}{S} = \frac{P}{\sqrt{P^2+Q^2}} \tag{2}$$

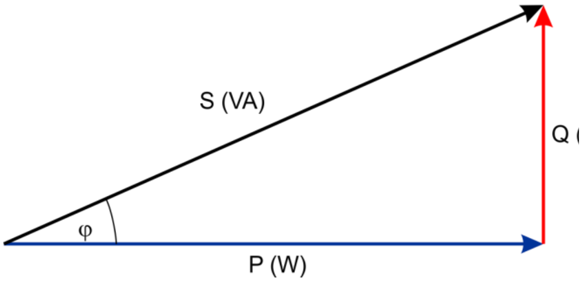

Figure 1. Active (P), reactive (Q) and apparent (S) power.

The reactive power is required to maintain the voltage to deliver the active power over the grid. When there is not enough reactive power, the voltage drops and the active power cannot be transferred over the grid. Despite impacting on the voltage grid it, does no useful work but is mandatory for motors needing the reactive power to produce the magnetic field for their operation [3].

In the PV systems, the situation is different. The PV generator (PV modules) produces the DC power which is transformed in the inverter to a pure active power. Presently, most grid-connected inverters do not have the ability to supply the grid also with the reactive power. If the inverters can control the reactive power (like SMA, Kaco…) [4, 5], they usually can supply the power at a constant power factor by themselves. The variable power factor according to the output power or the grid voltage can be controlled only over an external controller [6, 7]. With the increasing share of the PV energy fed to the grid, the demand of controlling the reactive power also in the PV systems [8] will become a reality and the inverters need to be able to dynamically control the reactive power [9-11]. In several countries like Germany and Slovenia, new PV systems must be able to provide the reactive-power service. The question of how much this will affect the energy yield of the system or the profitability of the investment calls to be thoroughly analysed.

The active-power output of the inverter is the real part of the product of the current and voltage. If the current and voltage are out of phase the active power is lower by the power factor (PF). The same active-power output, as the one when the current and voltage are in phase, can be achieved only if the apparent power S is increased by the inverse value of PF ($1/PF$). Example: A 10 kVA inverter feeds the grid with 10 kW of the active power at a power factor of 1. If a power factor of 0.8 is required and 10 kW of the active power are to be produced, the inverter should be replaced with a 12.5 kVA nominal power inverter (see Eq. 1 and Fig. 1).

Following the theory, most grid operators as well as some inverter manufacturers [12] recommend installing a stronger inverter (with its apparent power (P_{AC}) larger than the rated DC power (P_{DC}) of the PV generator) to prevent decreasing the active power due to the reactive-power service. But since the inverters in a fixed-positioned (non-tracked) PV system in the Central Europe operate below their power limit most of the time (due to the climatic conditions), using a larger inverter seems to be unnecessary. Braun [13] shows that a PV system is not able to guarantee a 100% availability of the reactive power in Germany without oversizing the inverter or reducing the active power. However, at a rated PV generator power (P_{DC}) vs. the nominal inverter power (P_{AC}) ratio of 1 and at a power factor of 0.8, it is able to guarantee more than 99.9 % of the required reactive power without reducing the active power. To estimate the impact of the reactive-power service on the PV system and to find an optimal PV system (optimal P_{DC}/P_{AC}) in view of the energy or economic yield, comprehensive energy and economic yield analyses have to be carried out with the respect to the local climatic conditions, feed-in tariff and investment costs.

3 ENERGY LOSSES DUE TO REACTIVE POWER SERVICE

3.1 Simulation

To investigate the impact of the reactive-power supply on the PV system energy yield (Y_{pv}), one can either simulate the solar irradiance in a given plane of array or take the measured solar irradiance data. The simulated solar irradiance data are based on averaged 10-year observations and normally given on an hourly basis, which leads to underestimations of the reactive-power service impact [14]. We therefore decided to use the 5-minute measured solar-irradiance data. The irradiance was measured from January 1st, 2011 to December 31th, 2012 in Ljubljana, Slovenia. To extend the simulation results also to the areas outside the Central Europe we simply multiplied the irradiation intensity by a corresponding factor and presented the results with the yield factor of a PV system.

To calculate the PV power, we used a typical model of a wafer-based multicrystalline silicon PV module. For the simulation model to be as accurate as possible, we used the measured module temperature for the same period of time. The PV system output power at different irradiation levels was calculated as:

$$P_{system} = P_{module@STC} * N * \frac{H_{poa}}{1000\,W/m^2} * \left(1 - \gamma * (T_{module} - 25°C)\right) * \eta_{DC} * \eta_{inv} * \eta_{AC} \quad (3)$$

where N is the number of modules, H_{poa} is irradiance in the plane of array, γ is the PV module power temperature coefficient and η_{DC}, η_{inv}, η_{DC} are the efficiency on the DC side (mismatch losses, DC cabling losses, etc.), inverter efficiency and efficiency on the AC side (AC cabling losses), respectively. The impact of the inverter was modelled with the SMA STP-17000TL inverter efficiency curve. The maximum output power (P_{max}) was limited by the inverter nominal output power (S_{nom}).

The simulated system was based on an actual PV system sited on the roof of the Faculty of Electrical Engineering of the University of Ljubljana (46.07° N, 14.52° E). The PV system consists of 75 modules with a rated power of 233 W each, resulting to the total rated DC power of 17475 W. The system uses a single three-phase inverter SMA STP-17000TL with the nominal DC input power of 17600 W and the nominal AC apparent power of 17000 VA.

In our simulations we didn't use the actual power of the module but artificially changed the DC to the AC power ratio (P_{DC}/P_{AC}) of the PV system in discrete steps from 0.7 to 1.6. Following the SunnyDesign calculations, the technical P_{DC}/P_{AC} limit of the STP-17000TL inverter with 233 W PV modules is 1.58.

To calculate the energy losses due to the reactive-power service and due to the output capped inverter P_{AC} power, we first calculated the PV system reference yield, where the reactive power service (PF = 1) and the inverter apparent power limit were neglected. The yield losses were then calculated with regard to this reference yield.

The yield losses of the power-balanced system (P_{DC}/P_{AC} = 1) due to the reactive power service and apparent power limit of the inverter at PF of 1.0, 0.9 and 0.8 are presented in Figure 2.

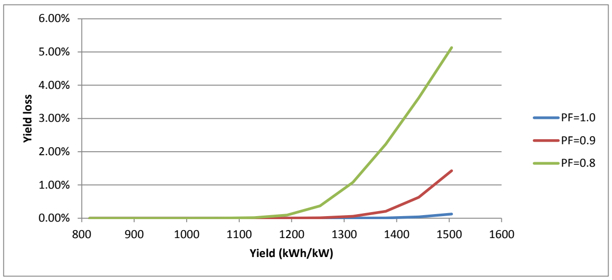

Figure 2. Yield losses of a balanced PV system vs. a PV system yield (P_{DC}/P_{AC} = 1.0).

The inverter apparent-power limit losses are shown with the blue curve in Fig. 2 (PF = 1.0) and are evident only at higher yields. The total yield losses (reactive-power losses and apparent-power limit losses) of a PV system with a P_{DC}/P_{AC} = 1 in the Central and Northern Europe (Y_{pv} < 1300 kWh/kW) are below 0.1 % and 1 % at PF of 0.9 and 0.8, respectively. In the Southern Europe as well as for tracked PV systems in the Central Europe when the PV system yields can reach the values above 1300 kWh/kW the losses of over 1 % or 5 % can be expected at PF of 0.8 or 0.9, respectively.

If the inverter is undersized (P_{DC}/P_{AC} > 1) the energy losses due to reactive power service as well as due to the power capping to S_{nom}, become very prominent. The losses at P_{DC}/P_{AC} = 1.5, close to the inverter limit, are shown in Fig. 3.

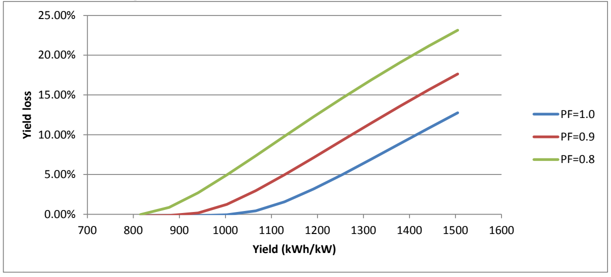

Figure 3. Yield losses of a balanced PV system vs. a PV system yield (PDC/PAC = 1.5).

At a yield of 1100 kWh/kW and P_{DC}/P_{AC} of 1.5, the energy losses due to the inverter apparent-power limit are around 1 %. When the reactive-power service at PF of 0.9 is required, an additional 2.5% energy loss must be taken into account. At PF of 0.8, the total energy loss is over 8 %.

3.2 Energy losses of a real PV system

The PV system capability of handling the reactive power was also analysed on a real 17.5 kW PV system operating in Ljubljana, Slovenia. The PV system installed on the roof of the Faculty of Electrical Engineering is oriented 25° east (from south) with an inclination angle of 30°. The rated power on the DC side is by 2.8 % greater than the nominal apparent output power of the inverter (P_{DC}/P_{AC} = 1.028). The output power of the inverter is monitored at 5 minute intervals. The system produces a pure active power (PF = 1) and is connected to the internal grid of the Faculty. The PV system has been in operation since December 2010. The energy yield of the system in 2011 was 1277 kWh/kW.

Compliably with the new reactive-power regulations in Slovenia [1], any new electricity generating system must be capable of delivering a reactive power of a power factor of 0.8. To simulate the impact of the reactive-power demand on the PV system performance, we used the 5-minute output-power data from the inverter and capped them with the limited maximum active-power output of 13.6 kW, which is the maximum active-power output of the 17 kVA inverter of a power factor of 0.8. Comparing the actual energy production of our system to the capped data, the annual energy loss in 2011 is 0.98 %. This figure is in a good agreement with the simulation results at the same yield and P_{DC}/P_{AC} ratio.

Besides the fixed power factor, we simulated also the impact of the reactive-power service when the inverter is capable to dynamically change the power factor compliably with the grid voltage [1]. At a dynamic power factor specified in Ref. [1], the losses of the fixed PV system due to the reactive-power service are only 0.004 %.

The output power (*P*) results of the fixed *PF* of 0.8 and dynamic *PF* are shown in Fig. 4 and Fig. 5 for the first year of operation and for one day, respectively.

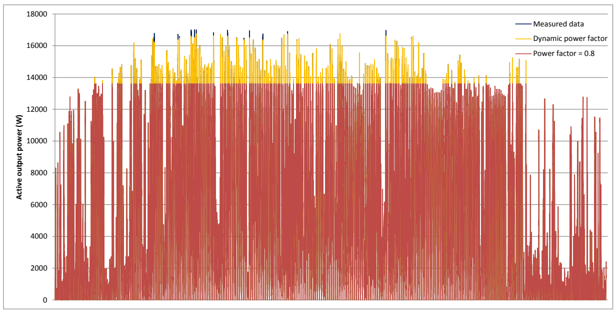

Figure 4. Measured and with the power factor limited active-power output of the inverter.

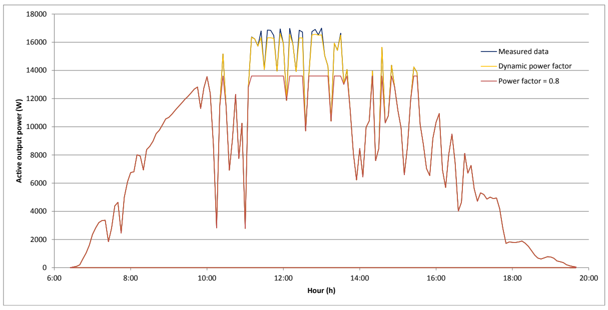

Figure 5. Measured and with reactive-factor limited active-power output of the inverter on a spring day (13th April 2011)

The estimated energy losses of the observed PV system are presented together with the simulation results at a system yield of 1277 kWh/kW. At the bottom of Table 1 we added results from the SunnyDesign software [15]. The PV inverter designing tool of the SMA manufacturer estimates the energy loss to be 0.348 % at a fixed power factor of 0.8 for the same system (P_{DC}/P_{AC} = 1.028). Despite these results, the manufacturer suggests using a 125 % stronger inverter (P_{DC}/P_{AC} = 0.8) when the reactive power of a power factor of 0.8 is needed [12].

Since the losses due to the reactive-power service of the observed PV system were estimated on the basis of the data measured in 2011, we can assume that the losses will decrease over years due to a rather slow but non-negligible PV module degradation. This again confirms that there is no stronger inverter needed due to the reactive-power service. Our results demonstrate that the losses of the reactive-power service could be largely reduced if the inverter were able to dynamically change the power factor compliably with the grid voltage.

Table 1. Relative annual energy loss due to the reactive-power service.

	Yearly energy losses
the actual PV system at fixed *PF* = 0.8	**0.980%**
simulations of the actual PV system at system yield of 1277 kWh/kW and fixed *PF* = 0.8	**1.002%**
SunnyDesign simulator of the actual PV system at fixed *PF* = 0.8	**0.348%**

The results also indicate that an optimal P_{DC}/P_{AC} and the inverter sizing are slightly different when other PV technologies are used, this being mostly due to different temperature coefficients of the PV modules [16].

4 ECONOMIC ASPECTS

In the previous section we analysed the energy yield of theoretical and real PV system and came to the conclusion that the losses due to the reactive-power services are rather low but not negligible. Only a larger inverter or system with DC to AC power ratios below 1 ($P_{DC}/P_{AC} < 1$) could be able to support the grid with the reactive power and would not affect the active power fed to the grid. But, since the PV system is always optimized by the investment analysis, we have to study also the economic aspects. From the previous studies [17-19] and from field experiences [20] we know that in the optimal crystalline silicon PV system the DC power (P_{DC}) can be by 20 % greater than the nominal inverter power since the PV generator in Germany and also in Slovenia rarely reaches the rated power.

Our investment analysis is based on a 17 kW PV system and Slovenian financial data for 2011. To simulate the impact of the P_{DC}/P_{AC} ratio on the investment, we changed the ratio in discrete steps (as in Section 3.1) and accordingly also the amount of the investment. By changing the DC power, we changed the module investment cost as well as the cost of construction and manpower. All other costs that are not directly linked to the modules are kept unchanged (inverter, project, measurements, etc.). The parameters used in the investment analysis are collected in Table 2. We assumed that the inverter caps the active output power to its nominal value.

To get a clear picture on the investment and profitability of the project, we have to make a comprehensive analysis that is normally used for new company project evaluations. A widely used economic parameter for comparing different investment scenarios is the internal rate of return (IRR). IRR is used to measure the investment profitability.

The change in the P_{DC}/P_{AC} ratio (adding or removing modules and keeping the same inverter) results in the change in the investment cost as well as in the energy production and income. Higher P_{DC}/P_{AC} ratio results in a lower specific investment cost given in €/W. As long as the inverter output-power limit does not affect the energy output significantly, we can expect also higher IRRs.

Table 2: Cost calculation parameters

Module power degradation	0.80	%/year
Feed-in tariff	0.29082	€/kWh
Feed-in tariff period	15	years
Operational cost	25.00	€/kW/year
Cost increase	2.0	%/year
Investment	2.83	€/W
Depreciation	5	years
Profit tax	20	%
Discount rate	6.0	%

IRRs of the PV systems as a function of the P_{DC}/P_{AC} ratio and energy yield for the case without the reactive-power service and with it (PF = 0.8 and 0.9) are presented in Fig. 6. The analysis is based on the adopted Slovenian feed-in tariff [21] and weather conditions in Ljubljana, and incorporates a comprehensive cost calculation with all expenses, module degradation, reactive-power losses, taxes, etc. (Table 2). The calculations are made on a 10-year IRR which is an average expected lifetime of an inverter. A long term calculation just changes the IRR values while the observed trends remain the same.

The results show that IRR strongly depends on the irradiance level and on the P_{DC}/P_{AC} ratio. The optimal P_{DC}/P_{AC} ratio, in case of a 10-year IRR, depends on the irradiation level and is higher at lower yields. When no reactive-power service is required, the highest IRR can be achieved at P_{DC}/P_{AC} of 1.1 at the PV system yield of 1500 kWh/kW. At lower irradiations, the optimal ratio moves to higher values until it is limited (at some 1050 kWh/kW) by the inverter technical limits.

The reactive-power service lowers the optimal P_{DC}/P_{AC}. The impact is more evident at lower irradiation levels (see the left-hand side of the graphs in Fig. 6).

From the economic analysis we can conclude that in most cases a better IRR can be achieved at $P_{DC}/P_{AC} > 1$ even if the reactive-power service is provided by the PV system. But, since the results strongly depend on the irradiation level, each PV system has to be analysed separately with regard to the required power factor and expected yield value. In the Central and Northern Europe, where PV system yield is up to some 1200 kWh/kW, the inverters have not been oversized ($P_{DC}/P_{AC} < 1$) to provide the reactive-power service without lowering the profit (Fig. 7 – top). Only in the southern parts of Europe, where the PV system yields are above 1400 kWh/kW, a slightly oversized inverter is suggested to be used when the reactive-power service at a constant power factor of 0.8 is requested (Fig. 7 – bottom).

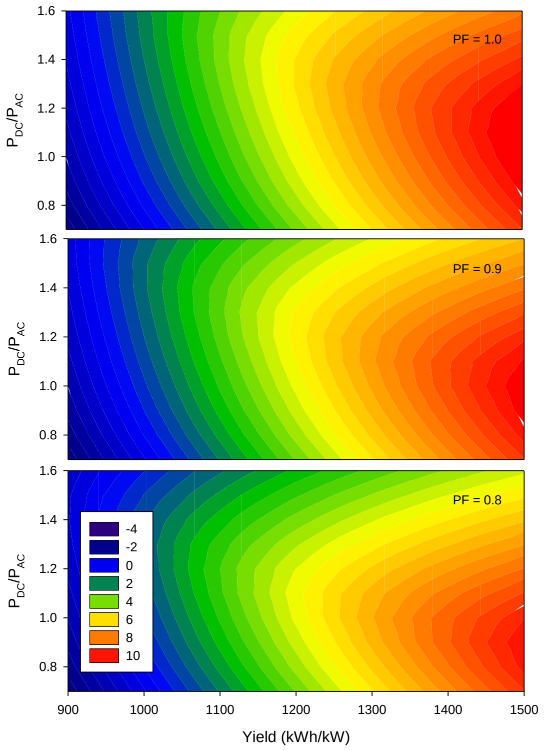

Figure 6. IRR vs. the PV system yield and the P_{DC}/P_{AC} ratio.

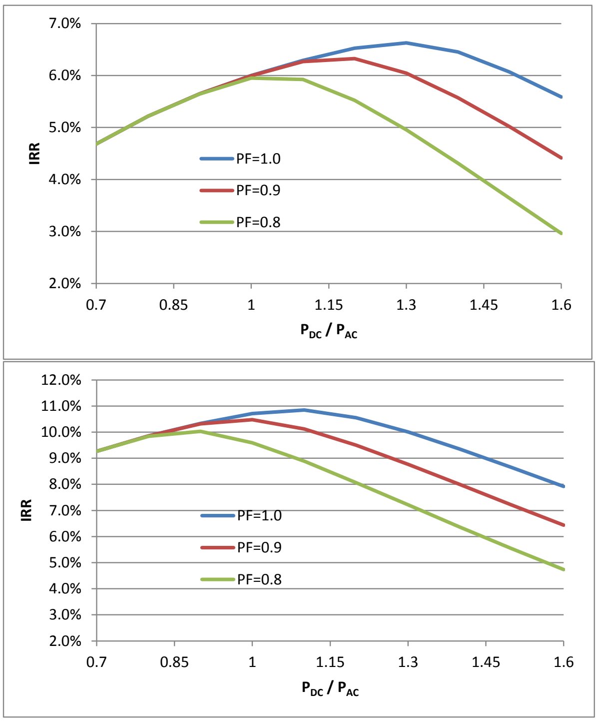

Figure 7. Internal rate of return vs. P_{DC}/P_{AC} ratio at 1200 kWh/kW (top) and 1500 kWh/kW (bottom).

5 CONCLUSION

We presente the impact of the reactive-power service through energy-loss simulations and investment analysis of the PV systems using the feed-in tariff in Slovenia. Our simulations based on the actual irradiance data show that the annual energy loss due to the reactive-power service is rather low if the P_{DC}/P_{AC} is around 1 or lower. When the reactive-power service at PF of 0.8 is required, the energy loss of a PV system with P_{DC}/P_{AC} = 1 is close to 1 % but rises by over 5 % if the DC side is largely oversized (P_{DC}/P_{AC} = 1.5). The actual energy loss strongly depends on the actual irradiance levels and local climatic conditions over the year.

A detailed economic analysis of the PV system with different P_{DC}/P_{AC} ratios shows that the optimal inverter size in Slovenia (Central Europe) is around P_{DC}/P_{AC} = 1.3 at a *PF* of 1 if all economic aspects are taken into account. When the reactive-power service at PF of 0.8 is requested, the optimal ratio drops to 1.1 by loosing 0.5 % of the IRR, absolutely. There is also no need to oversize the inverter for the inverse value of the power factor to be able to support the grid with the reactive power. A PV system with P_{DC} balanced to the P_{AC} power or with a slightly larger inverter is able to provide the reactive-power service and achieve a little lower but still optimal internal rate of return.

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REFERENCES

[1] Electricity distribution system operator - SODO, “Sistemska obratovalna navodila za distribucijsko omrežje električne energije” http://www.sodo.si/druzba_sodo/zakonodaja/sondo (accessed on 5. Apr 2013)

[2] German Association for Electrical, Electronic and Information Technologies – VDE, Technical standard for the connection and parallel operation of generators at low voltage levels, VDE-AR-N 4104, Frankfurt, August 2011

[3] Importance of Reactive Power for System http://electricalnotes.wordpress.com/2011/03 /21/importance-of-reactive-power-for-system/ (accessed on 5. Apr 2013)

[4] SMA GmbH, Solar Inverters, http://www.sma.de/en/products/solar-inverters.html (accessed on 5. Apr 2013)

[5] Kaco new energy, Solar Inverters, http://www.kaco-newenergy.com/products/solar-inverters (accessed on 5. Apr 2013)

[6] SMA GmbH, Power reducer box, http://www.sma.de/en/products/monitoring-systems/power-reducer-box.html (accessed on 5. Apr 2013)

[7] A. Cagnano, F. Torelli, F. Alfonzetti, E. De Tuglie , Can PV plants provide a reactive power ancillary service? A treat offered by an on-line controller, Renew. Energy 36 (2011), pp. 1047-1052.

[8] H. Yu, J. Pan, A. Xiang, A multi-function grid-connected PV system with reactive power compensation for the grid, Solar Energy 79 (2005), pp. 101-106.

[9] G. Tsengenes, G. Adamidis, Investigation of the behavior of a three phase grid-connected photovoltaic system to control active and reactive power, Electr. Power Syst. Res. 81 (2011), pp. 177-184

[10] F.L. Albuquerque, A.J. Moraes, G.C. Guimarães, S.M.R. Sanhueza, A.R. Vaz, Photovoltaic solar system connected to the electric power grid operating as active power generator and reactive power compensator, Sol. Energy 84 (2010), pp. 1310-1317.

[11] L. Hassainea, E. Oliasa, J. Quinteroa, M. Haddadib, Digital power factor control and reactive power regulation for grid-connected photovoltaic inverter, Renew. Energy 34 (2009), pp. 315–321.

[12] Reactive Power and Grid Integration with SUNNY MINI CENTRAL and SUNNY TRIPOWER http://files.sma.de/dl/7418/ReactivePower-UEN101310.pdf (accessed on 5. Apr 2013)

[13] M. Braun, Reactive Power Supplied by PV Inverters - Cost-Benefit-Analysis, 22nd EuPVSEC (2007).

[14] K. Brecl, M. Topič, The influence of the reactive power service on the PV system energy and economic yield: Case study of feed-in tariff and investment, 27th PVSEC (2012), pp. 4047-4049.

[15] SMA GmbH, Sunny Design, http://www.sma.de/en/products/software/sunny-design.html (accessed on 5. Apr 2013)

[16] A.A. Bayod-Rújula, A. Ortego-Bielsa, A. Martínez-Gracia, Photovoltaics on flat roofs: Energy considerations, Energy 36 (2011), pp. 1996-2010.

[17] B. Burger, R. Rüther, Inverter sizing of grid-connected photovoltaic systems in the light of local solar resource distribution characteristics and temperature, Sol. Energy 80 (2006), pp. 32-45.

[18] L. Keller, P. Affolter, Optimizing the panel area of a photovoltaic system in relation to the static inverter – practical results, Sol. Energy 55 (1995), pp. 1-7.

[19] J. Uhu, R. Bründlinger, T. Mühlberger, T. R. Betts, R. Gottschalg, Optimised inverter sizing for photovoltaic systems in high-latitude maritime climates, IET Renew. Power Generation 5 (2010), pp. 58-66.

[20] T. Stetz, J. von Appen, M. Braun, G. Wirth, Cost-Optimal Inverter Sizing for Ancillary Services -Field Experience In Germany And Future Considerations, 26th EuPVSEC (2011), pp. 3069-3074.

[21] Official Gazette of the Republic of Slovenia http://www.uradni-list.si/1?year=2010&
edition=201094 (accessed on 5. Apr 2013)

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