

Article

Reactive Power Compensation with PV Inverters for System Loss Reduction

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Abstract: Photovoltaic (PV) system inverters usually operate at unitary power factor, injecting only active power into the system. Recently, many studies have been done analyzing potential benefits of reactive power provisioning, such as voltage regulation, congestion mitigation and loss reduction. This article analyzes possibilities for loss reduction in a typical medium voltage distribution system. Losses in the system are compared to the losses in the PV inverters. Different load conditions and PV penetration levels are considered and for each scenario various active power generation by PV inverters are taken into account, together with allowable levels of reactive power provisioning. As far as loss reduction is considered, there is very small number of PV inverters operating conditions for which positive energy balance exists. For low and medium load levels, there is no practical possibility for loss reduction. For high loading levels and higher PV penetration specific reactive savings, due to reactive power provisioning, increase and become bigger than additional losses in PV inverters, but for a very limited range of power factors.

Keywords: PV inverters; reactive power generation; reactive power compensation; loss reduction

1. Introduction

When reactive power compensation in distribution systems is considered, almost exclusively, the case of inductive loading and compensation with capacitor banks is meant [1]. However, in the case of low loading conditions and/or networks with substantial cable sections, opposite conditions (capacitive loading) arise. Networks with high load variation, such as touristic areas with considerable difference between high-season and low-season consumption represent another example of mentioned conditions.

In medium voltage (MV) distribution systems, most of the reactive power compensation is done with classic (passive) technologies. New technologies, such as static var compensator (SVC), static synchronous compensator (STATCOM), etc. are predominately used in high voltage (HV) transmission systems. However, in recent years, there have been several contributions [2–10] where usage of grid-connected photovoltaic (PV) system inverters for reactive power generation (i.e., compensation) in distribution systems was proposed.

Several national standards and grid codes [11,12] predict operation of PV systems with power factor below unity. Most of the contributions consider usage of PV systems' inverters as ancillary service providers [2–4,11–15] but some of them analyzed the influence of reactive power compensation on power system losses. In general, compensation of inductive reactive power with high share proliferation of PV systems is considered.

In Reference [3] both economic and technical analysis of reactive power supply from distributed energy resources (DER) in microgrids is presented. Total operating costs of a grid-connected microgrid containing PV and battery storage systems is considered. PV inverter losses are considered in the

same way as in Reference [4]: the cost of reactive power is calculated as additional inverter power loss multiplied by the cost of the electricity. Multi-objective optimization incorporating technical and economic objectives is performed using a genetic algorithm. In the base case, a distribution system with high share of PV integration (80%) and batteries (40%) is considered.

In Reference [5], a cost-benefit analysis of reactive power generation by PV inverters is given. The PV losses are considered in detail and cost of the produced kVArh is estimated. Savings due to reactive power compensation are compared with average network losses (arbitrarily chosen in the range of 2–8%) and for load power factor range of 0.85–0.95. Detailed analysis of network losses is not given, neither is explicitly analyzed the case of low loading conditions.

Reference [6] deals with the problem of line losses and operation costs minimization in distribution networks with a high level of DER connection. Although presented research does not give an explicit model for inverter losses, the optimization problem considers reactive power costs as a quadratic function. Both variable and opportunity costs of DERs are taken into consideration when formulating relations for calculating reactive power costs. The cost of relatively small amounts of generated reactive power is low with nearly exponential rise.

In Reference [7] a reactive power and voltage control strategy is proposed in order to reduce overall losses in the wind farm. Reactive power/voltage sensitivity matrix is used to optimize power flows. Contribution of additional losses in wind turbines due to reactive power generation is not considered.

Low voltage distribution networks are known to have a high R/X ratio, therefore competitiveness for reactive power generation by PV inverters also increases. Total network losses minimization of a low voltage distribution network, by optimal allocation of decentralized reactive power compensation is presented in Reference [8]. The proposed decentralized reactive power compensation by PV inverters and passive devices was able to maintain voltage deviations within allowable limits and network losses were efficiently reduced. Presented research also disregards inverter losses.

New control strategies for PV inverters installed in low voltage distribution systems are presented in Reference [9]. It was shown that proposed strategies can compensate load imbalance, reduce overvoltages and minimize reactive power flows. Again, opportunity costs increase when generating reactive power was not considered.

In this article, the authors explore in more detail whether is it possible to use PV inverters to compensate reactive power in systems with different loading conditions and PV integration share index. This is done by comparing PV inverter losses with losses in MV distribution system alone. In fact, PV inverter losses increase when reactive power is being generated. These additional losses yield opportunity costs since active power generation must be reduced in order to generate reactive power. These additional opportunity costs for PV inverters operating at power factors less than unity is often neglected by researchers (e.g., in References [7–9]). This in turn could present a major obstacle for reactive power compensation by PV inverters for network losses reduction. When explicitly considered, PV inverter losses are occasionally calculated and compared with the help of approximations (e.g., in References [5,6]). It is the goal of this paper to find a suitable technique for comparing system losses and PV inverter losses.

Results and conclusions drawn in this paper could be of interest for both distribution system operators (DSO) and PV DER owners. Presented results could be the basis for price assessment of reactive power delivery. On the other hand, DSO-s could consider presented results to determine the effectiveness of reactive power compensation in relation to system loading level and PV integration share index. Of particular interest for DSO-s is the transition period from traditional grids to smart grids, with small or medium PV integration, where only simple strategies for reactive power generation are possible due to lack of distributed and synchronized measurements and communication possibilities among network elements.

Additionally, system losses due to reactive power flows constitute only a small part of total system losses and both total losses and losses due to reactive power flows have a quadratic relationship upon loading level. This could limit even more the application of PV inverters in low loading conditions

or systems with low PV integration share index. Therefore, networks with high share of PV sources are the most prominent and interesting cases for overall network losses reduction by reactive power compensation with PV inverters. Nevertheless, reactive power generation by sparse PV sources could also be proposed in some situations, even in low loading conditions. Both less favorable scenarios, will be further examined.

In this paper, for a specific distribution MV system, the applicability of reactive power compensation by PV inverters, considering both loading level increase and PV share increase will be investigated. The rest of the paper is organized as follows: Sections 2 and 3 give theoretical summary of PV inverter's capability for reactive power compensation and overview of distribution systems losses. Section 4 deals with cost analyses. In Section 5 simulation results are given for a typical distribution system with different loading conditions and different PV integration levels. Finally, the most important results and findings are given in Section 6.

2. Analysis of Reactive Power Compensation by PV Inverters

All distributed generators connected to the distribution system through power inverters are, in general, able to provide reactive power [4]. This possibility has been accounted for in several latest revisions of national Grid Codes [2,11,12], and thus most of the commercially available PV inverters are able to provide reactive power.

The ability of PV inverters for reactive power (Q) supply is limited by:

$$|Q| \leq \sqrt{S_r^2 - P^2} \equiv Q^{max}, \quad (1)$$

where S_r is inverter's rated power, P is inverter's generated power (output power), and Q^{max} is the reactive power limit of the inverter when supplying active power P .

Different methods exist when determining inverter's S_r and Q^{max} . Here, it is assumed that the inverter is not intentionally oversized in order to increase the capacity for reactive power supply, and therefore it is assumed that there are no additional investment costs to attribute to reactive power generating capabilities. Additionally, it is assumed that no curtailment of active power generation is done in order to increase Q^{max} . This would create additional opportunity costs of several orders of magnitude higher than the considered ones.

In cases when the PV system generates active power (i.e., sufficient irradiance for active power generation-daytime mode), the inverter losses are compensated by PV panels' generated DC power (P_{DC}).

Possibly, reactive power supply even in periods of low or no irradiance, i.e., no active power generation (nighttime mode or var at night mode) could be of benefit to the distribution power system. Several examples of such inverter topologies and control schemes can be found (e.g., [16–22]). To cover power losses during reactive power supply, the inverter has to absorb active power from the grid or from an internal energy storage. Most commercially available inverters lack the ability to operate in this mode.

Several potential advantages of generating reactive power by PV inverters with respect to passive solutions can be emphasized:

- inverters can generate both inductive and capacitive power,
- generated power can be adjusted precisely and fast when needed,
- there is no need for additional investment costs if existing inverters are used.

In the next sections, potential drawbacks of the proposed usage of PV inverters for reactive power compensation will be analyzed in more detail.

3. Distribution System Losses

3.1. Specific Reactive Losses

The following considerations emphasize losses generated by reactive power flow. To compare losses generated within different system components, specific reactive losses are introduced. The equation for specific reactive losses is as follows:

$$p_{loss,Q} = \frac{P_{loss,Q}}{Q}, \quad (2)$$

where $P_{loss,Q}$ is the power loss due to reactive power flow, and Q is the reactive power causing the loss. $p_{loss,Q}$ can be expressed in W/kvar or in percent value.

3.2. Cables and Overhead Lines

At no load conditions, power cables absorb capacitive reactive power as given:

$$Q_{c,kap} = -U^2 \omega C_1 l, \quad (3)$$

where U is the line voltage, ω is the angular frequency, C_1 is the unit cable capacitance, and l is the cable length.

With loading increase, inductive reactive power also rises and consequently the overall cable reactive power is:

$$Q_c = \left(\frac{S}{U}\right)^2 \omega L_1 l - U^2 \omega C_1 l = U^2 \omega C_1 l \left[\left(\frac{S_{load}}{P_0}\right)^2 - 1 \right]. \quad (4)$$

In Equation (4), P_0 is cable's natural power: $P_0 = U^2 / \sqrt{L_1 / C_1} = U^2 / Z_0$, where L_1 is cable's unit inductance and Z_0 is the cable's surge impedance. For low-load conditions, the ratio $(S_{load} / P_0)^2$ can be neglected and cable's reactive power reduces to Equation (3). Of course, when calculating overall losses, the power flow due to loads must also be considered.

Cable inductance and capacitance are uniformly distributed along the cable and therefore produce losses equivalent to a distributed load [23]. Total losses in cables and lines are therefore:

$$P_{loss} = \frac{1}{3} I^2 R_1 l, \quad (5)$$

where R_1 is cable's unit resistance and I is the total current:

$$I^2 = I_{load}^2 + I_{Qc}^2. \quad (6)$$

I_{load} is the load current (due to load's apparent power S_{load}) and I_{Qc} is the cable's reactive current (due to Q_c).

Losses due to I_{Qc} are:

$$P_{loss,Qc} = \frac{1}{3} U^2 \omega^2 C_1^2 R_1 l^3 \left[\left(\frac{S_{load}}{P_0}\right)^2 - 1 \right]. \quad (7)$$

From Equation (7), losses due to cable reactive current flow increase with the third power of cable length and decrease with cable loading for $S_{load} < P_0$. For $S_{load} > P_0$, net cable reactive power becomes inductive and losses $P_{loss,Qc}$ start to increase again. No load operation is the worst-case scenario in this context, when losses are determined by Equation (3).

To compare losses due to reactive power flow at different points in the system, specific reactive losses were introduced in the previous section. In case of reactive power flow generated only due to inherent cable capacitance, given by Equation (3), specific reactive losses are given by:

$$p_{loss,Q_c} = \frac{1}{3} \omega C_1 R_1 l^2. \quad (8)$$

When considering reactive power flow attributed to loads with power factor below unity, for loads uniformly distributed along the line, losses and specific reactive losses are given by the next equations, respectively:

$$P_{loss,Qload} = \frac{1}{3} \left(\frac{S_{load}}{U} \right)^2 R_1 l, \quad (9)$$

and:

$$p_{loss,Qload} = \frac{1}{3} q_{load} \frac{R_1}{Z_0} l. \quad (10)$$

q_{load} is the load's relative reactive power ($q_{load} = Q_{load}/P_0$). $p_{loss,Qload}$ depends on cable type, cable length and relative reactive power of the load.

Table 1 gives the calculated unity values of reactive power generated in cables at no load conditions ($Q_{c,cap}$), the length at which specific cable losses due to reactive power flow reach 0.1% ($l_{0.1\%}$) at no load, and the R_1/Z_0 values for some standard 20 kV cable types. It can be observed that the $l_{0.1\%}$ values are in accordance with typical lengths of actual medium voltage distribution lines (feeders). In the case that q_{load} equals 10%, $p_{loss,Qload}$ is in the range 0.15–0.3%, for considered cable types.

Table 1. Unity values of reactive power generated in cables at no load conditions ($Q_{c,cap}$), the length at which specific cable losses due to reactive power flow reach 0.1% ($l_{0.1\%}$) at no load, and the R_1/Z_0 values for some standard 20 kV cable types (cable parameters are given in Appendix A).

Cable (mm ²)	$Q_{c,cap}$ (kVAr/km)	$l_{0.1\%}$ (km)	$\frac{R_1}{Z_0}$	Cable (mm ²)	$Q_{c,cap}$ (kVAr/km)
150 (Cu)	31.5	17.5	0.0031	150 (Cu)	31.5
150 (Al)	31.5	13.6	0.0052	150 (Al)	31.5
185 (Al)	34.2	14.6	0.0043	185 (Al)	34.2
240 (Al)	38.0	15.9	0.0036	240 (Al)	38.0

Results presented in the previous table will be used to estimate the range of system loadings for which compensation of reactive power (both capacitive and inductive) could be done with reduction of overall losses.

3.3. Transformers, Capacitors and Inductors

A similar approach can be used to estimate $p_{loss,Q}$ for HV/MV transformers. In this case, transformer resistance is a concentrated parameter and therefore there is no 1/3 reduction as is the case for lines with uniformly distributed parameters.

The transformer resistance can be calculated from transformer's rated power S_r , line voltage U , and the resistive part of transformer's short circuit voltage u_R :

$$R_T = \frac{u_R \cdot U^2}{S_r}. \quad (11)$$

Combining the transformer reactive power loss formula ($I_Q^2 R_T$) with Equation (11), the following expression is obtained:

$$P_{g,Q} = \frac{u_R}{S_r} Q^2 = u_R q Q \rightarrow p_{g,Q} = u_R q. \quad (12)$$

Equation (12) gives, in a manner similar to Equations (8) and (10), a fast way of transformer reactive losses estimation. For example, for a 20 MVA transformer with u_R of 1% and q of 10%, $p_{g,Q}$ results in 0.1%.

For capacitors, a loss of 15 W/kvar, or 0.15% is assumed, according to Reference [5]. For inductors, a loss (u_R) of 0.5% is assumed (similar to transformers), but losses as low as 0.2% can also be found.

3.4. PV Inverters

PV Inverter efficiency is defined as [4]:

$$\eta = \frac{P}{P_{DC}} = \frac{P}{P + P_{loss}}, \quad (13)$$

where P is inverter's generated power (output power), P_{DC} is the input DC power from PV modules, and P_{loss} are inverter's losses.

P_{loss} can be approximated with a second order polynomial function of P [4]:

$$P_{loss}(P) = c_0 + c_{loss,V}P + c_{loss,R}P^2. \quad (14)$$

In the previous equation c_0 is a constant that depends on losses at no load conditions, $c_{loss,V}P$ are the power electronic losses related to voltage, and $c_{loss,R}P^2$ are the losses related to the square of current. Inverter losses and efficiency are usually given as a function of the generated active power, since inverters normally work with unity power factor.

Measurements performed while inverters provided reactive power beside active power, and thus working with reduced power factor, demonstrated that Equation (14) can be generalized substituting P with inverter's apparent power S [4]:

$$P_{loss}(S) = c_0 + c_{loss,V}S + c_{loss,R}S^2. \quad (15)$$

Equation (13) can be modified in the same way, when the inverter is providing reactive power. Inverting (13), P_{loss} for inverter generating apparent power S , and with known efficiency curve, can be obtained according to:

$$P_{loss}(S) = \frac{1 - \eta(S)}{\eta(S)} S. \quad (16)$$

In the following discussion, efficiency curve of a 208 kWp inverter, with peak efficiency of 96.4% and $\eta_{EU} = 95.6\%$, given in Reference [4], is considered.

Furthermore, it is useful to distinguish two different working conditions [5]:

- (a) Night mode—in this case, only reactive power is generated and the total P_{loss} is attributed to reactive power generation, i.e., $P_{loss,Q} = P_{loss}$;
- (b) Daytime mode—both active and reactive power are generated and only additional losses due to inherent increase of S when reactive power is generated, are attributed to reactive power, i.e., $P_{loss,Q} = P_{loss}(S) - P_{loss}(P)$.

Since apparent power does not increase linearly with reactive power, the $p_{loss,Q}$ during daytime are generally much lower than $p_{loss,Q}$ during nighttime.

Figure 1 gives $p_{loss,Q}$ for the analyzed inverter, as function of the power factor and for different inverter's active power output. It is clear that inverter's apparent power is limited by $S_r(1)$, and therefore the power factor can only decrease to a value of output power (in p.u. of S_r). The convenience of the presented representation lies in the possibility of easy comparison of inverter's specific reactive power losses and system losses or savings. By knowing the overall system losses $p_{loss,Q}$, one can easily find the range of inverter's output power factor, and as a consequence the range of reactive power that can

be supplied, when inverter losses $p_{loss,Q}$ are lower than distribution system losses $p_{loss,Q}$. It is clear that this would additionally limit reactive power capabilities of the inverter.

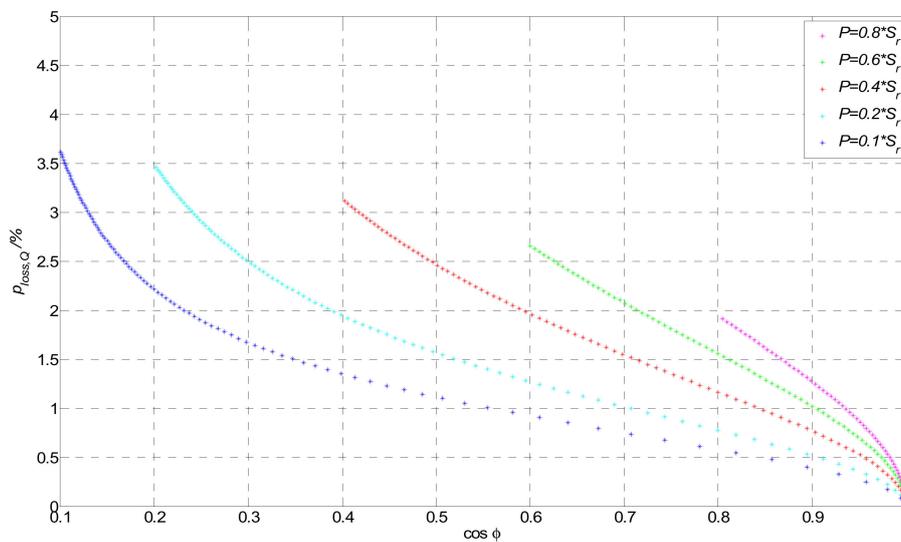


Figure 1. $p_{loss,Q}$ for analyzed inverter, as a function of power factor and for different active power output of the inverter.

4. Cost Analysis

While performing cost analysis for capacitor banks and inductors both operational and investment costs are considered. On the other hand, for PV inverters only opportunity costs are assumed, since no oversizing of inverters is presumed. Considered opportunity costs are due to losses in the compensating device and dependable upon the cost of kWh. Furthermore, no additional operational costs due to maintenance costs or due to inverter’s lifetime decrease caused by increased output current, are considered, although increase of inverter’s apparent power influences its lifetime [24,25].

The investment cost of a capacitor (inductor) can be integrated in the cost of generated kVArh by considering the annuity term [3]:

$$A = \frac{(1+p)^n p}{(1+p)^n - 1}, \tag{17}$$

where p is the interest rate, and n is investment lifetime.

Annual cost of investment is given by:

$$C_{A,invest} = c_Q Q A, \tag{18}$$

where c_Q is investment cost per kVAh, and Q is the capacity of the compensating device.

Losses cost can be calculated from the following equation:

$$C_{loss,Q} = c_{kWh} p_{loss,Q} Q, \tag{19}$$

where c_{kWh} is the cost of kWh.

Cost of the generated kVArh with the compensating device can be obtained by summing annual investment cost reduced to an hourly base and losses cost:

$$c_{kvarh} = \frac{\left(\frac{C_{A,invest}}{n_h} + C_{loss,Q}\right)}{Q} = \frac{c_Q \cdot A}{n_h} + c_{kWh} p_{loss,Q}, \tag{20}$$

where n_h is the number of hours per year during which the compensating device is in operation. If constant operation throughout the year is presumed, n_h is equal to 8760, and the C_{kvarh} is minimal. With the yearly operating hours decrease, a significant increase in c_{kvarh} is observed. For intermittent operation of the compensation device, the c_{QA}/n_h term becomes large and the compensation cost increases.

Presented calculations show the amount of costs that the DER owners should be compensated for in order to generate reactive power in a profitable manner. Different approaches are adopted by distribution network operators for charging consumers for reactive energy consumption. For example, in Germany, distribution network operators charge (i.e., penalize) the consumers if their power factor is lower than 0.9 on average [5]. Similar solution is adopted in Croatia, where the consumers are charged if their power factor is lower than 0.95 on average. On the other hand, in Spain, if a DER unit provides reactive power it receives an incentive, given in percent of the price of active energy (kWh). In both cases (Germany and Croatia) of consumer penalization for low power factor or incentive for power factor improving, the price of reactive power is not directly linked to the cost of generation, but it is obvious that the cost of generation of reactive power by PV inverters should be lower than compensation by the operator.

5. Simulations

For simulation purposes, a radial distribution MV network (based on a part of a characteristic Croatian MV distribution system) connected to a 110/20 kV substation, has been modeled in NEPLAN (Figure 2.). Two 110/20 kV power transformers of 40 MVA rated power, supply the distribution network which consists of 170 km underground cable lines and 34 km overhead lines. Power lines with 150 mm² cross section are predominant in the modeled network.

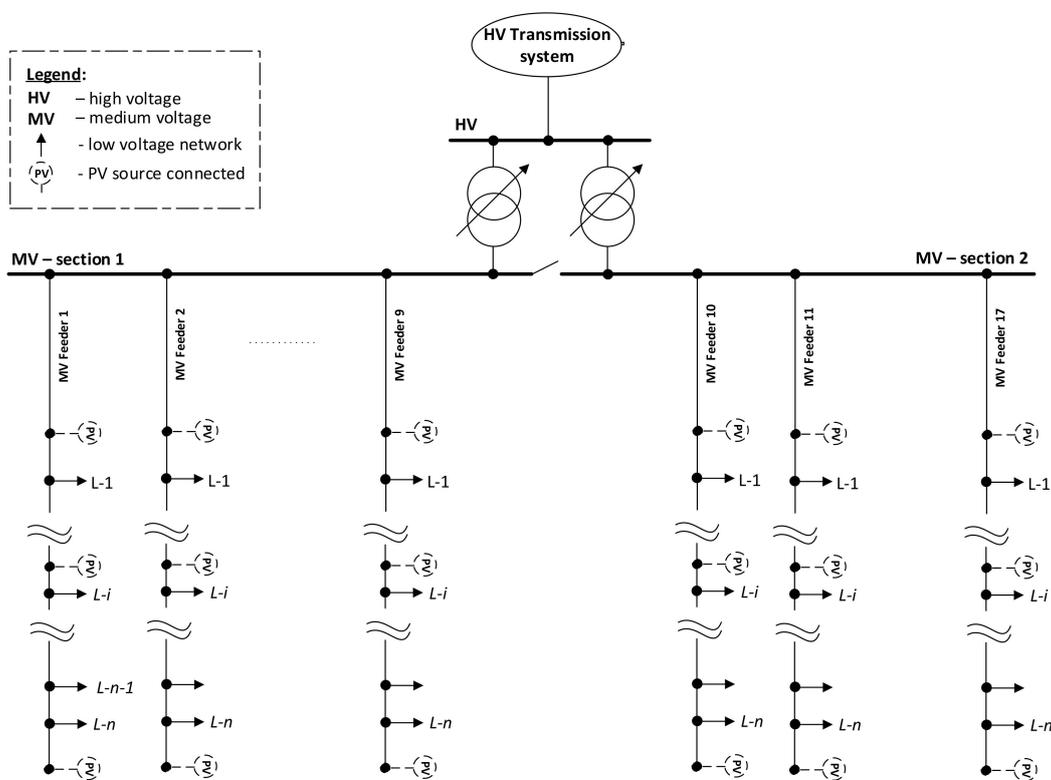


Figure 2. Schematic diagram of the simulated distribution network.

17 predominantly underground cable type feeders of different length supply a composite load with residential ($\cos\phi = 0.98$) and industrial ($\cos\phi = 0.8$) type loads.

For simulation purposes, PV plants with inverters of 500 kVA rated power are considered. For each loading condition (low, medium, high), two PV penetration levels are analyzed: first, with one PV source, and second with one PV source per feeder (17 feeders \times 500 kVA = 8.5 MVA). Position of the PV source was varied in the following manner:

- (1) installation at the sending end of the feeder,
- (2) installation at 2/3 of the feeder length, and
- (3) installation at the end of the feeder.

Total composite load measured (modeled) at the 110/20 kV power transformers is given in Table 2. In the same table the power losses and the number of transformers in operation can be observed.

Table 2. Active and reactive power levels, and total losses at the substation for three loading conditions.

Loading	P_{tr} (MW)	Q_{tr} (MVar)	P_{loss} (kW)	Nr. Transformers
Low	9.4	-2.8	52	1
Medium	39	5.5	353	2
High	79	20.7	1308	2

Various simulations have been performed in order to compare PV inverters' specific reactive losses and system losses decrease (savings) due to reactive power generation. Comparing losses in PV inverters, Figure 1, and power savings due to reactive power generation, conditions in which power savings are larger than losses in inverters can be determined and thus there is net overall power savings in the system.

Firstly, overall system losses are determined for various loading conditions. It was shown in Section 3 that for every analyzed network element there is a quadratic relationship between power flow and losses. As can be seen from Figure 3, the quadratic relationship is preserved when considering the system as a whole: in fact, an approximately quadratic relationship between overall system loading and system losses can be observed. In a manner similar to the one presented in Section 3, overall losses (P_{loss}) are separated to losses due to active power ($P_{loss,P}$) and losses due to reactive power ($P_{loss,Q}$). The latter one will be further analyzed, since the focus of this research is to determine the viability of targeted reactive power generation by PV inverters in order to decrease overall system losses. Approximating the quadratic function between $P_{loss,P}$ and total system load P ($P_{loss,P} = aP^2$), results in a quadratic function coefficient a of 0.02%/MW.

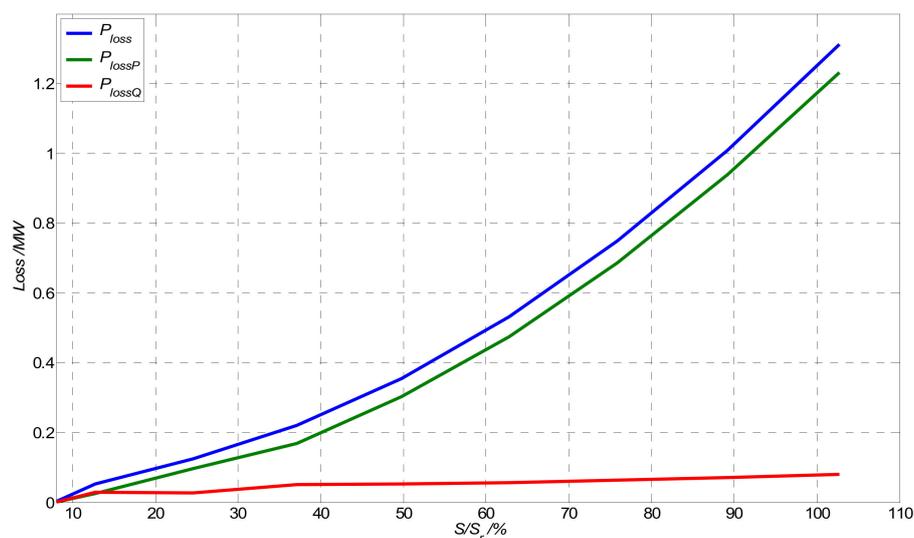


Figure 3. Losses as function of overall system load. Graph gives overall losses (P_{loss})—blue line, losses due to active power ($P_{loss,P}$)—green line, and losses due to reactive power ($P_{loss,Q}$)—red line.

It must be noted that not only is the absolute value of the $P_{loss,Q}$ important (both in the PV inverter and the system), but marginal losses/savings, or increment/decrement of losses due to reactive power generation is of great importance. In other words, it is the slope of the curve for a particular loading condition that will determine savings rate due to reactive power generation. With linear loading level increase a linear specific losses/savings increase can also be observed. Therefore the losses curve slope (increment/decrement) due to active power is greater than the losses curve slope due to reactive power. As a consequence, compensation of losses by reactive power generation will always be less efficient than compensation with active power generation in distribution networks.

Simulations of different scenarios always start with PV inverter generating only active power i.e., with unity power factor. Then, reactive power is gradually increased, until it reaches the reactive power limit given by Equation (1), similar to References [4,6]. The difference of power losses in the case with and the case without reactive power generation equals power savings due to reactive power generation [4]:

$$p_{sav,Q} = \frac{P_{loss,0} - P_{loss,Q}}{|Q_{gen}|}, \quad (21)$$

where $p_{sav,Q}$ are the specific reactive power savings, $P_{loss,0}$ are the overall power losses when the generated reactive power equals zero, $P_{loss,Q}$ are the power losses when reactive power has been generated and thus inverter's power factor is below 1, and Q_{gen} is the reactive power generated by the PV inverter. Absolute value of Q_{gen} is introduced in order to obtain correct results for both inductive and capacitive reactive power.

5.1. One PV Source Per Distribution Network

One PV source of 500 kVA rated power is considered to be the case with minimum PV dispersion rate. In the first scenario a low loading condition is considered (9.8 MW, 25% of transformer's rated power; $\cos\phi = 0.75$). In this case, only one 110/20 kV power transformer is in operation, while the other transformer is switched off. Owing to a large number of underground cables a high capacitive reactive power is generated (-2.8 MVar). The total system losses are around 0.5%.

Figure 4 presents the results for low loading conditions scenario and one PV source installed at the beginning of a feeder.

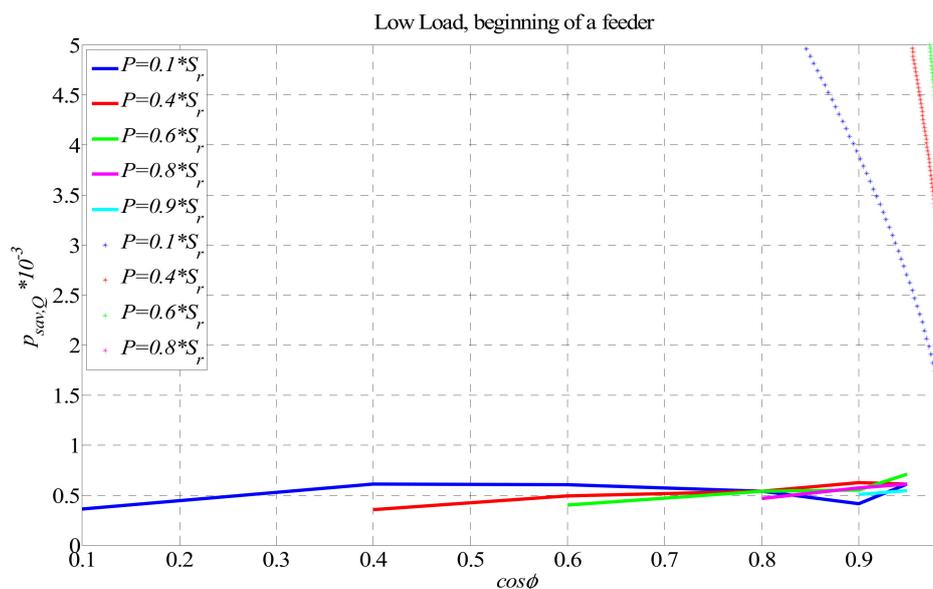


Figure 4. Specific reactive power savings as function of PV inverter's power factor for low loading conditions and PV inverter installed at the beginning of a feeder. '*' marks PV inverter losses with color corresponding to the same active power level.

Although overall system losses are around 0.5%, it can be observed that specific power savings vary between 0.3 and 0.7‰, with maximum savings at $P_{gen} = 0.6 \cdot S_n$ and $\cos\phi = 0.95$. Furthermore, from Figures 4 and 5 it is evident that maximum specific savings are achieved for inverter's high power factor, while at lower power factor the savings are also lesser.

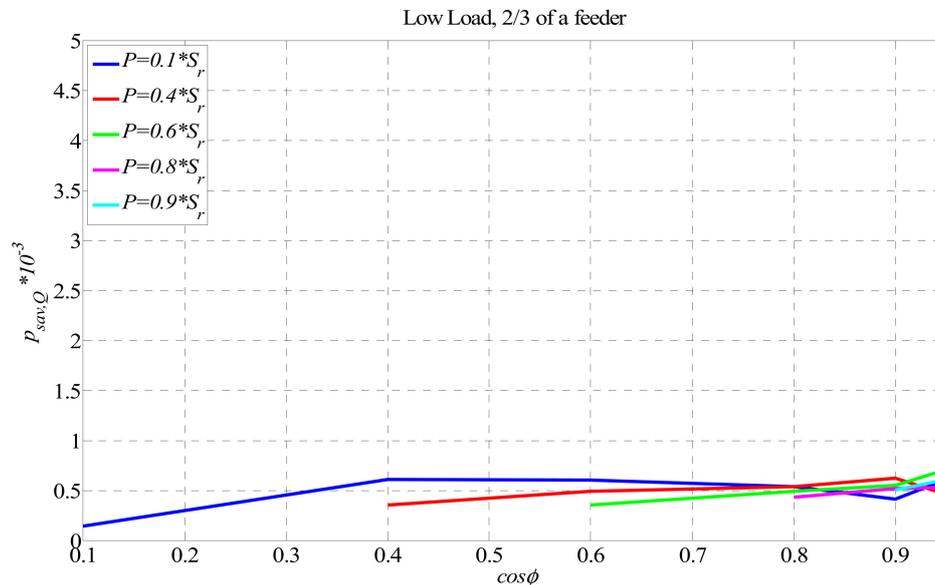


Figure 5. Specific reactive power savings as function of PV inverter's power factor for low loading conditions and PV inverter installed at 2/3 of a feeder.

In order to easily compare system and PV inverter losses, PV inverter losses are also given in Figure 4. It is important to point out that savings on the system level due to reactive power generation are always lower than specific reactive losses in the PV inverters. Therefore, for the analyzed scenarios of low system loading and low DER installation levels, energy savings with PV inverters are practically not feasible. This is also true for passive reactive power compensation (i.e., compensation with shunt inductors in this case), where losses are one order of magnitude higher than possible savings.

During low system loading conditions there is obviously no need for congestion reduction, however benefits from voltage regulation capabilities by reactive power generation with PV inverters could justify inherent additional losses. This could be particularly important in systems with high proportion of underground cables (as in the system considered in simulations). In fact, MV cables loaded below their natural power produce capacitive reactive power thus raising terminal voltages for a prolonged period of time, which in turn stresses equipment insulation and shortens its expected lifetime.

When the PV source is installed near 2/3 of a line, slight variation of results is observed, although savings could be potentially maximized, since maximum compensation of cable capacitive reactive power is achieved [23]. Obtained results for the described case are presented in Figure 5.

Varying PV source position along the feeder almost no difference in specific power savings has been detected. Therefore, it can be concluded that for this case calculated specific power savings are not sensitive to the position of the PV source along the feeder.

Minor variation of specific savings for different loading conditions are also observed, Figure 6. Between low and medium loading conditions specific savings range from 0.05 to 0.8‰

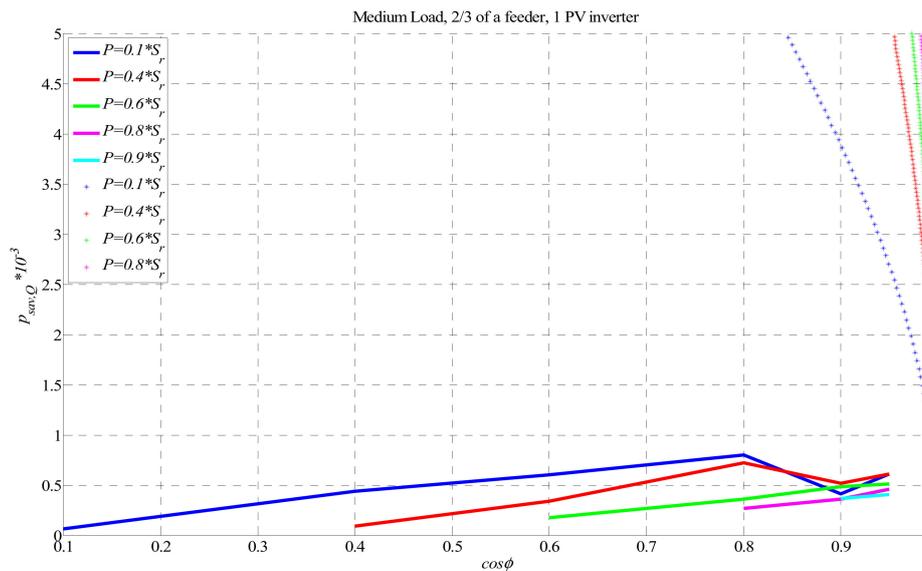


Figure 6. Specific reactive savings as function of PV inverter’s power factor for medium loading conditions and PV inverter installed at 2/3 of a feeder. ‘*’ marks PV inverter losses with color corresponding to the same active power level.

On the other hand, for high loading conditions (Figure 7), significantly higher savings are detected, independently of PV source position. This is in accordance with Equations (10) and (12), since specific reactive losses in cables and transformers depend on relative reactive power q . Although total system savings are higher, they are still lower than PV inverter losses. The only exception occurs for the case of low PV inverters active power generation ($0.1S_r$), where positive power balance exists for power factor in the range 0.97–1.00 (extrapolated from the graph). In terms of reactive power, only modest levels of reactive power ($2.5\% \cdot S_r$) generation are acceptable in order to have a positive energy balance. Therefore, for low PV dispersion rates, no practical conditions, where positive energy balance is achieved, are found. This is also true for passive compensation methods, since savings in the simulated cases are below the assumed losses of 0.5%.

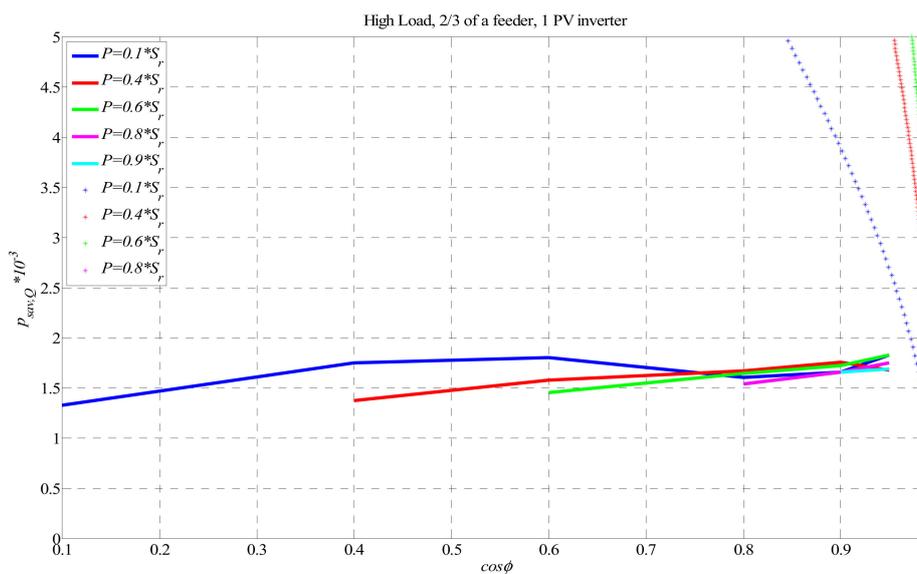


Figure 7. Specific reactive power savings as function of PV inverter’s power factor for high loading conditions and PV inverter installed at 2/3 of a feeder. ‘*’ marks PV inverter losses with color corresponding to the same active power level.

5.2. One PV Source per Each Feeder

One PV source per each feeder is considered to be the case of medium PV dispersion rate (8.5 MVA total peak power). Although different control schemes are proposed for finding the optimum level of reactive power generation (e.g., [2,11,22,26–28]), in this research, uniform reactive power generation of individual PV sources is assumed. In fact, the focus of the research was to investigate reactive power generation influence on the overall system behavior. Additionally, it is our intention to find the technical limits for reactive power generation when simple strategies for reactive power generation is assumed.

In medium PV dispersion rate scenarios, an increase in savings for higher loading conditions is possible (Figure 8). However, only a narrow range of power factors, i.e., reactive power levels exists with positive energy balance. The allowable power factor for the case of low active power generation by PV inverters ($0.1S_r$) is 0.88 or higher (i.e., maximum reactive power equals $5.4\% \cdot S_r$). For scenarios with higher generation of active power, the allowable power factor varies in the range of 0.97–0.99 thus allowing reactive power delivery in the range of 10–12% S_r . For low and medium loading (Figure 9) conditions, there is again a very narrow range of operating conditions with positive energy balance.

Maximum $p_{sav,Q}$ is achieved for PV inverters operating at a higher power factor. The savings gradually decrease when power factor deviates from unity. This is due to the fact that with system's total reactive power decreasing, marginal losses also decrease (see Equations (10) and (12) and Figure 3).

With the increase of PV dispersion rate a slight difference between relative system savings and PV inverter losses is possible, and consequently favorable energy balance is feasible, although for a very restricted range of PV inverter's operating power factors. This is in accordance with Reference [5], where a simplified assessment of savings due to reactive power compensation and hence lower losses is given. Although PV inverter losses and system power savings are compared taking into consideration energy costs in both cases, similar conclusions can be drawn: it is economically attractive to use PV inverters for reactive power compensation in scenarios with high network losses and/or substantial reactive power flows, as long as only a small amount of inverter's apparent power capacity is used for reactive power generation. Similar conclusions are reached in Reference [3], where more complex situations are considered. However, even in highly optimized microgrids with PV sources and batteries, reactive power delivery has diminishing technical benefits. Analyses presented herein try to give a technical comparison (i.e., detailed losses calculation) with a special emphasis on network losses that consequently narrow the set of operating scenarios with positive energy balance.

In the case of higher PV dispersion rate and a higher level of reactive power generation, a PV power factor level can be determined when reactive power at transformer reaches zero. As previously mentioned, this research was not focused on reactive power generation control schemes, therefore the optimum operation point, with maximum absolute power savings, was not determined. However, maximum relative power savings are achieved for PV source operating at a high power factor.

Finally, it must be stressed that there are other benefits apart from lowering system losses when reactive power generation is considered. The inclusion of PV sources, as well as other dispersed generation units, in a local/global distribution network voltage regulation system is the most important one. Therefore, when considering reactive power generation by PV inverters and their ancillary services to the distribution system operator, an economic justification for such operating regime (lower power factor) can easily be found.

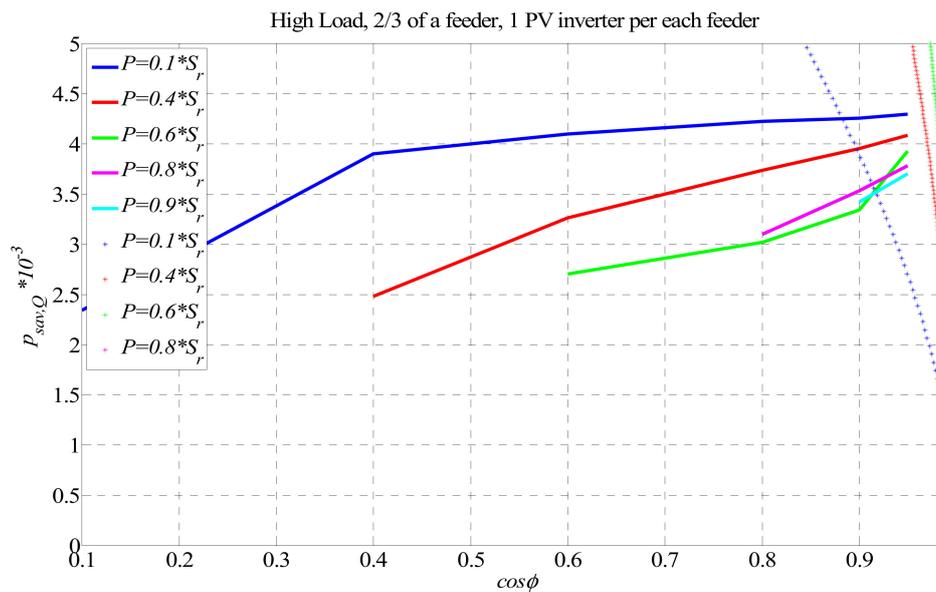


Figure 8. Specific reactive power savings as function of PV inverter's power factor for high loading conditions and PV inverters installed at 2/3 of each feeder. '*' marks PV inverter losses with color corresponding to the same active power level.

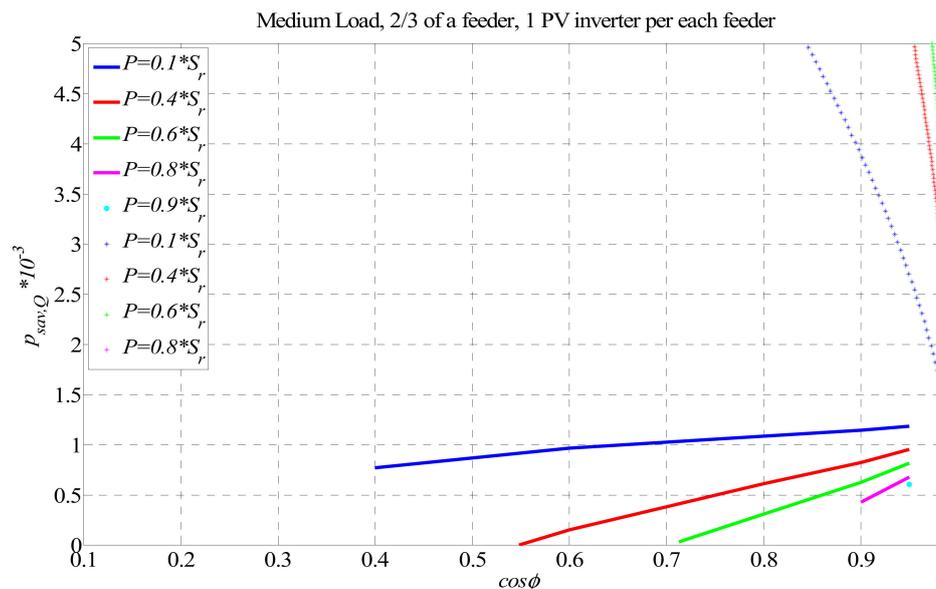


Figure 9. Specific reactive power savings as function of PV inverter's power factor for medium loading conditions and PV inverters installed at 2/3 of each feeder.

6. Conclusions

In this article, the influence of reactive power generation by PV inverters on overall system losses is analyzed. The comparison between savings and losses is based on specific reactive losses which are defined as part of overall losses that can be attributed to reactive power, divided by the reactive power. Presented research takes into consideration traditional distribution networks with low to medium PV dispersion rates and without the capability to determine the optimum operational point for the entire system (i.e., without corresponding communication media).

Theoretical analyses show that system specific reactive losses depend on underground cable type feeder length, its electrical characteristics and both active and reactive power loading levels. Therefore, losses in different systems will vary in a different manner and reactive power generation

will also cause different saving rates. On the other hand, specific reactive losses in PV inverters will depend on inverters' efficiency curves, generated active power and set power factor.

To compare specific reactive losses in PV inverters and savings due to reactive power generation, numerous simulations were performed. For simulation purposes a typical 20 kV radial distribution system (based on data from an actual Croatian distribution system) was modeled.

In general, PV inverters can provide reactive power during nighttime and during daytime. During nighttime, inverter losses are attributed entirely to the reactive power generation and are generally higher than specific losses due to reactive power flows in the distribution system. Therefore a negative power balance is observed (losses are larger than savings) and therefore nighttime operation was not further considered in simulations.

During daytime operation, only additional losses in PV inverter, caused by reactive power generation, are attributed to reactive power. This unlocks the possibility for reactive power generation by PV inverters thus lowering system losses and achieving savings greater than additional losses that occur in PV inverters. Therefore, different scenarios were simulated and analyzed to compare system savings and additional PV inverter losses during daytime operation.

Several parameters were considered and varied in performed analyses: overall system loading, PV inverters number, active power generation level and PV sources power factor, and inverter installation position. Among them, overall system loading conditions influence the most the value of specific savings due to reactive power generation. It was shown that the increase in overall system loading increases system savings when reactive power is generated by PV inverters. However, a positive energy balance is achieved only for cases when inverters operate with a high power factor. This means that overall system energy savings can be achieved only for high PV sources dispersion rates and high loading conditions. In low and medium loading conditions, additional losses in PV inverters lead to a negative energy balance.

Once more it must be emphasized that, apart from lowering system losses when reactive power generation is considered, there are other benefits. In fact, inclusion of PV sources, in a local/global distribution network voltage regulation system could provide a valuable asset to the distribution system operator, and an economic justification for such operating regime (lower power factor) can easily be found. These observations are the base for future research. In fact, our intention is to extend presented research and consider the capabilities and limitations of distribution network voltage regulation with the aid of dedicated PV inverters. Moreover, it will be investigated whether independent operation with simple control strategies for each PV inverter (readily applicable rules for reactive power generation) could provide satisfactory results at the distribution system level, or whether more complex control strategies are needed.

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Appendix A

Table A1. Considered cable parameters: cross section, cable's unit resistance R_1 , cable's unit inductance L_1 , and cable's unit capacitance C_1 [29].

Cable (mm ²)	R_1 (Ω /km)	L_1 (mH/km)	C_1 (μ F/km)
150 (Cu)	0.124	0.39	0.251
150 (Al)	0.206	0.39	0.251
185 (Al)	0.164	0.39	0.272
240 (Al)	0.125	0.36	0.302

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