POWER FACTOR COMPENSATION OF PHOTOVOLTAIC POWER PLANT

František Bernáth

Doctoral Degree Programme (2), FEEC BUT

E-mail: xberna07@stud.feec.vutbr.cz

Supervised by: Petr Mastný

E-mail: mastny@feec.vutbr.cz

Abstract: Handling with photovoltaic power plant (PVE) from point of view of its reacting with network is a key factor considering its integration into electricity supply system (ESS). PVE is a special form of dispersed sources which affects electric parameters far from point of common coupling. This paper presents the importance of power factor regulation of photovoltaic plants and possible technical solution with the practical outcome.

Keywords: Power Factor, Reactive Power compensation

1. INTRODUCTION

Monitoring and controlling voltage in ESS is a key aim of power engineering. Method is based on reactive power control in chosen nodes of network. Large photovoltaic plants should be included into controlled nodes but the manner depends on legislative background. For example photovoltaic plant in Czech Republic above 400 kWp must be equipped by dispatching reactive power control unit which enables to system operator to modify power factor from 0,85ind to 0,95cap [1]. On the other hand in Slovak Republic there is prescribed only general PF within 0,95ind – 1.

It means that designing power factor compensation unit underlies to legislative expectations and reactive power balance within power plant.

2. BALANCE SHEET OF REACTIVE POWERS WITHIN PHOTOVOLTAIC PLANT

Whole photovoltaic plant has several elements which determine the final character of installation from point of view of reactive power. It is necessary to take into account following components which are present after pcc:

2.1. INVERTORS

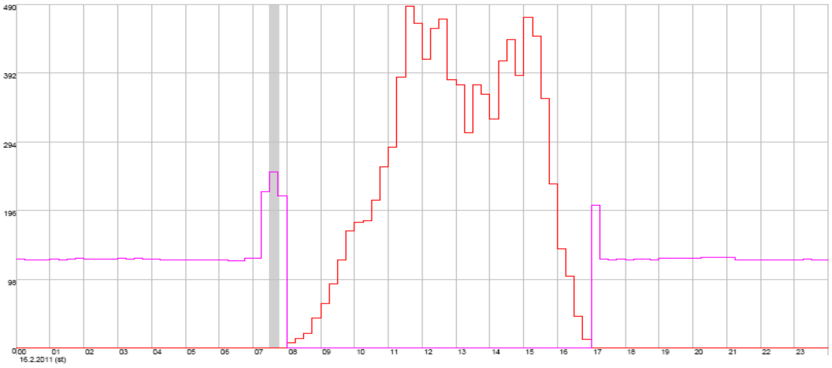

Figure 1: Typical characteristic of reactive power (pink curve) of classical inverter – capacitive power teeth during start/stop process.

There is a large variety of products considering its way of dealing with reactive power. The best inverters are able to provide reactive power according to the request even as automatic control of power factor.

However investors seek for economical optimization and therefore they choose rather classical inverters. They are most frequently set to power factor $0{,}99_{ind} - 1$ if output active power is above 20% of its nominal value. And especially the low output part causes problem of reactive power balance. At no-load running the output LC filter dominates which is capacitive at nominal frequency. Experiences have also shown that higher reactive capacitive power is provided by invertors during start/stop process (see *Fig.1- capacitive power teeth during start/stop process*).

Evaluation of reactive power of inverters underlies to producer's data sheet or verification by measurement of running installations.

2.2. LOW VOLTAGE CONDUCTORS

Low voltage cables are connecting inverters and power transformers. They are very little of capacitive behavior during no-load state. However this capacitive power is essential only in case of long distances which is a case of decentralized power plants.
Evaluation can be made by measurement or by using catalogue data of cable to calculate capacitive power according equation (1).

$$Q_{cap\_cable} = 3 \cdot \frac{U_f^2}{X_C} = 3 \cdot U_f^2 \cdot 2\pi f C_k \cdot l \qquad (1)$$

Where:
U_f – phase voltage, X_c – capacitive reactance, C_k - capacity per km of length, l – distance.

2.3. TRANSFORMERS

Transformers are inductive in no-load state and inductive reactance grows by loading. Values of reactive power can be obtained from catalogue list or calculated using equation (2).

$$Q_T = {}_\Delta Q_0 + {}_\Delta Q_K \cdot \left(\frac{S}{S_n}\right)^2 = i_0 \cdot S_n + u_k \cdot S_n \cdot \left(\frac{S}{S_n}\right)^2 \qquad (2)$$

[cit. 2]

Where:
Q_T – inductive reactive power of transformer (T), Q_0 – no-load reactive power of T, Q_0 –loading reactive power of T, S - loading of T, S_n – nominal load of T, i_0 –no-load current, u_k – short circuit voltage of T

2.4. MEDIUM VOLTAGE CABLES

Medium voltage cables connect plant to the supply system. They are strongly capacitive and in case of higher distances (few hundred meters) they are dominant considering reactive power of power plant. The exact values can be obtained by using calculation (1).

2.5. MEDIUM VOLTAGE LINES

Medium voltage lines are capacitive, too. However compared with medium voltage cables they are much less capacitive. Calculation method is more complicated and depends from mechanical suspension of line. These methods are out of subject of this text. However for purposes of power balance we can assume this reactive power as one tenth of cable's capacitive power.

2.6. CAPACITOR COMPENSATING TRANSFORMER LOSES

It is important to consider capacitors installed with the aim to compensate inductive power loss of transformer at no-load running. Installation of these capacitors is very frequent and sometimes it is contra productive solution. The reason is that designers do not take into account general power balance of power plant. Resulting reactive power of plant can be capacitive and capacitor will make situation even worse.

To obtain total reactive power it is necessary to sum up mentioned power elements with appropriate sign. Final value corresponds with no-load state (when the power flow from power plant to grid equals zero).

Particular reactive power elements within PVE installation change by escalation of electricity production. And therefore final reactive power of PVE at pcc changes with active power variations.

It is practically impossible to draw the specific characteristic of PVE reactive power. Generally the following processes are valid.

Cables and lines become less capacitive by loading and from specific point – natural loading of line – they are inductive. Transformers are more inductive by loading. These elements are describable however the most problematic for description are inverters. They are able to keep constant power factor except low loading when the most of them are capacitive.

Typical characteristic of centralized photovoltaic power plant of size 3 MW is on *Fig. 2*.

This was measured in medium voltage side of transformers. Involvement of MV cable would cause off-set of reactive power curve to more capacitive values.

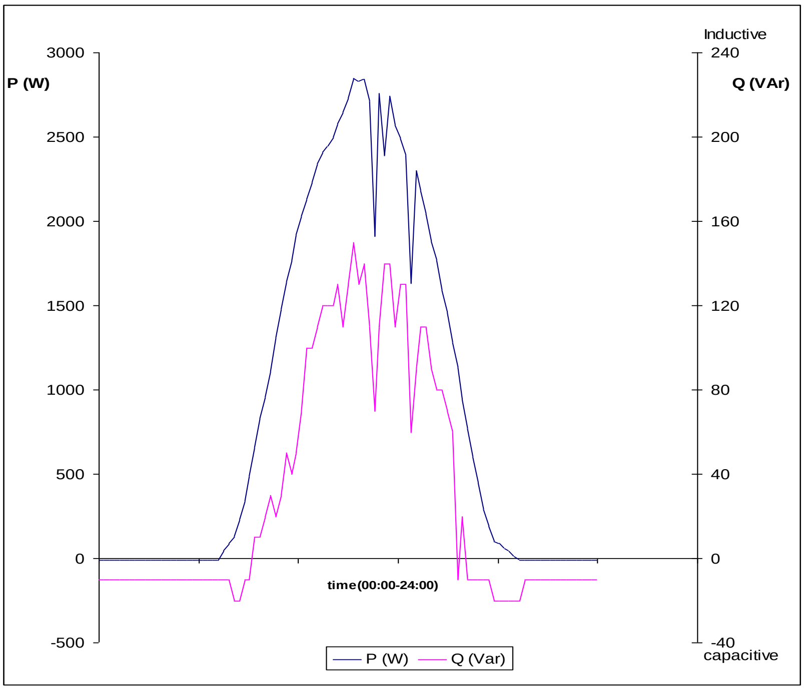

Figure 2: Typical characteristic of powers - photovoltaic plant 3 MW.

3. DESIGNING COMPENSATION UNIT

As it was mentioned technical requirements for power factor control of photovoltaic plant underlies to operational rules of distribution network in particular countries.

This text is suited mainly for legislative background of Czech Republic.

The importance of power factor compensation is double-sided considered customer - supplier relation in the pcc. For distribution network operator (DNO) it is a good way how to continually reach voltage limits and for the operator of photovoltaic plant it is a tool for fulfill requirement of DNO and prevent penalization. Basic accounting and controlling tool is six quadratic electrometer which registers following parameters:

P_+	**P_-**
Q_{ind} (if P_+)	Q_{ind} (if P_-)
Q_{cap} (if P_+)	Q_{cap} (if P_-)

Particular powers are illustrated on *Fig. 3* which refers to possible operational modes of power plant.

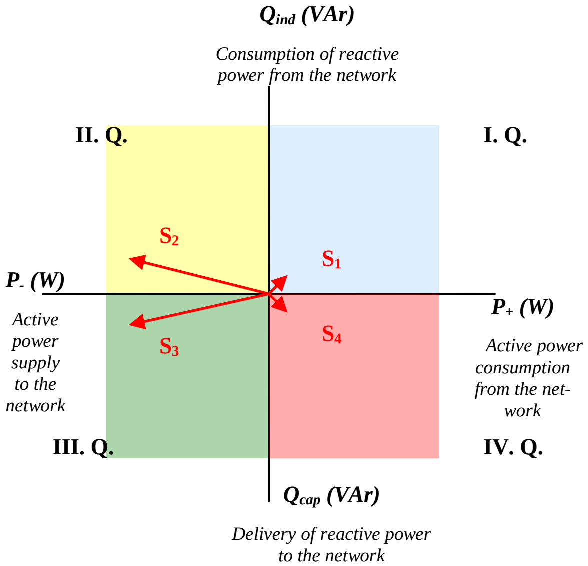

Figure 3: *Operational quadrants of electric powers.*

Mentioned powers on the last figure are related to power plant. Therefore it is possible to note that plant is inductive in case of consumption of reactive power from the network.

During of the state P_+ is an operator of photovoltaic plant ordinary consumer of electrical power who is obligate to keep power factor within corridor $0{,}95_{ind} – 1$.

On the other hand if the photovoltaic plant (with installed power over 400 kW [1]) is producing energy (P_-) the one has to be equipped with remote dispatching control of PF ridden by distribution network operator who has possibility to vary PF from $0{,}95_{ind}$ to $0{,}95_{cap}$ in 5 steps. This requirement is given by operational rules of distribution network.

The aim of design process is to determine needed compensating reactive powers – inductive and capacitive. The mental process should be as following.

At first it is important to get reactive power balance. In the chapter 2 is described mathematical method. However it is more reliable to use measured data which better describe power characteristics (as *Fig. 2*). For designing is a key parameter maximal active power P_{max} with related maximal reactive power Q_{pmax} and maximal reactive power during the energy consumption (during night) – Q_0(without consideration of inverter's capacitive teeth).

The next step is calculation of needed reactive power of compensating unit. The extreme absolute value will be during P_{max} and during maximal power factor, e.g. PF = $0{,}95_{ind}$.

$$\cos\varphi = 0{,}95 \Rightarrow \varphi = 18{,}19^\circ \Rightarrow tg\,\varphi = \frac{Q}{P} = 0{,}328 \qquad (3)$$

According to the last figures following reactive power is needed:

$$Q_{p\max - needed} = 0{,}328 \cdot P_{\max} \qquad (4)$$

For the photovoltaic plant with installed power 3 MW - Q_{pmax_needed} = 0,984 MVAr (result of equation 4) of inductive and capacitive reactive powers are needed as dimension of compensation unit.

Now let's take reactive power Q_{pmax} during P_{max} and calculate differences between Q_{pmax} and Q_{pmax_needed}. This step is necessary for calculation of capacitive and inductive dimension of compensation unit.

This step can be demonstrated on example of 3 MW plant with needed coordinates $0{,}95_{ind}$ to $0{,}95_{cap}$. As it was shown plant has to be able to dispose with 984 kVAr inductive and capacitive reactive powers. Taking maximal reactive power from *Fig. 2* Q_{pmax} = 153 $kVAr_{ind}$ consequently compensation unit has to be equipped with following size of inductive reactive power:

$$Q_{comp\_ind} = Q_{p\max_{needed}} - Q_{p\max} = 984 - 153 = 831 kVAr \qquad (5)$$

and following capacitive reactive power:

$$Q_{comp\_cap} = Q_{p\max_{needed}} - Q_{p\max} = 984 - (-153) = 1137 kVAr \qquad (6)$$

Another aim of compensation unit is to avoid penalization during the time when plant is consumer of active energy. It is difficult to reach because of small value of P_+. If the denominator in relation (7) has very small value the result is as following:

$$\lim tg\,\varphi_{P\to 0} = \frac{Q}{P} = \infty \qquad (7)$$

From it depends that compensation corridor is narrow but on the other hand it is clear from *Fig.2* that reactive power Q_0 is stable during night which makes compensation easier by static elements.

3.1. TECHNICAL SOLUTION

To catch economical and functional optimization the stepwise compensation with total powers Q_{comp_cap} and Q_{comp_ind} is a good choice. For reaching good punctuality even during lower production of active power it is ideal to divide total power into steps with relation 1:2:4:8. The most important is power factor controller which is switching reactors / capacitors by contactors. Controller has to communicate by dispatching Centre of DNO.
For compensation during the night is appropriate to use individually tailored reactor or capacitor according demand.

4. CONCLUSION

Power factor compensation is an important step to reach voltage demand in connection point of photovoltaic plant. It is one of the ways that make integration of dispersed sources more performable.

Compensation unit has to be based on analyze of reactive power characteristics of photovoltaic plant. Some plant is pressed to dispose by compensation unit already before probation period. Then mathematical method to obtain reactive power balance can be realized. However the best solution is to measure powers and calculate needed powers according the connection conditions.

REFERENCES

[1] ERÚ. Pravidlá provozu distribučních soustav. *Příloha 4*. Energetický regulační úřad 2009

[2] HALUZÍK E. Řízení provozu *ES*. SNTL VUT Brno 1986

[3] BERNÁTH, F. Power Factor Compensation of Photovoltaic Power Plants. Energyspectrum - International e-Journal, www.energyspectrum.net, 2011, roč. 2011 (6), č. 1, s. 1-4. ISSN: 1214- 7044.