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Impacts of photovoltaic plants on the power factor correction: the cat head curve

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Universidade Federal de Viçosa
Departamento de Engenharia Elétrica
Curso de Graduação em Engenharia Elétrica

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IMPACTS OF PHOTOVOLTAIC PLANTS ON THE POWER FACTOR CORRECTION: THE CAT HEAD CURVE

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Dedico este trabalho a todas pessoas que acreditaram em mim,
e que ajudaram a tornar deste sonho, uma realidade.

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"The superior man is modest in his speech,
but exceeds in his actions."
(Confucius)

Resumo

Com a crescente utilização de usinas fotovoltaicas, principalmente em ambientes industriais os quais necessitam de grande quantidade de energia elétrica para seu funcionamento, impactos na distribuição de energia devem ser pesquisados de forma a obter-se um melhor entendimento das novas características do sistema elétrico. Um fator importante a ser observado é o fator de potência, visto que o mesmo possui um limite inferior o qual gera tarifas extras sob potência reativa excedente caso esteja abaixo deste limite. Este trabalho mostra os efeitos do fator de potência com a instalação de uma usina fotovoltaica em determinados perfis industriais e como a correção deste fator de potência deve ser realizada neste caso. Isto deve ser propriamente avaliado visto que o fator de potência cai para aproximadamente zero nos pontos onde a potência ativa liquida é cancelada, causando um incremento em torno de 80% do banco de capacitores previamente instalado. A potência para correção tem um formato semelhante a uma cabeça de gato, sendo denominado dessa forma.

Keywords: Potência Reativa; Usinas Fotovoltaicas; Fator de Potência; Qualidade de Energia.

Abstract

With the increasing utilization of photovoltaic plants around the world, some impacts on the energy distribution must be researched for a better understanding of the system in general. An important issue is the power factor value, since it has an inferior limit that can create extras charges on exceeding reactive power if under its determined limit. This paper works on showing the influence on exceeding reactive power by adding a photovoltaic plant in different industries and how the power factor correction should be made, since it falls to almost zero in points where the liquid active power is canceled, therefore causing an increment of almost 80% of the nominal installed capacitor bank. In fact, the extra capacitive reactive power has a dynamic profile that reminds a cat head, being called that way.

Keywords: Reactive Power; Photovoltaic Plants; Power Factor; Energy Quality.

List of Figures

List of abbreviations and acronyms

ANEEL	Agência Nacional de Energia Elétrica
EPE	Empresa de Pesquisas Energéticas
PV	Photovoltaic
GCPS	Grid-Connected Photovoltaic Systems
RES	Renewable Energy Sources
SEPIC	Single-Ended Primary Inductor Converter
MPPT	Maximum Power Point Tracking
ISO	Independent System Operator
pf	Power factor

List of symbols

P	Nominal active power of the industry
Q_L	Nominal inductive reactive power of the industry
P_{PV}	Active power generated by the PV panels
Q_{PV}	Capacitive reactive power generated by the PV panel
Q_C	Capacitive reactive power given by the capacitor bank
P_{grid}	Active power drawn from the grid
Q_{grid}	Reactive power drawn from the grid
X_C	Capacitive reactance
V_g	Line to line RMS voltage
ω	Angular frequency of the grid
f_g	Frequency of the grid
C_Y	Capacitance of the capacitor bank in star connection
C_Δ	Capacitance of the capacitor bank in delta connection
S	Apparent power of the industries
$\Delta Q_{C,max}$	Maximum value of the capacitive power from the cat head curve
$\Delta Q_{C,min}$	Minimum value of the ”belly” created by the cat head curve
$\Delta Q_{C,mean}$	Mean value between $\Delta Q_{C,max}$ and $\Delta Q_{C,min}$

Contents

1 Introduction

Nowadays, the distributed generation has been attractive for various economical interests. Instead of using dispersed generation based on high power plants, each consumer has the possibility to use various sources for generating energy (such as solar, wind and thermal power)(DULăU; BICă, 2017). By using the local generated power, it is expected a reduction in the electricity bill.

In fact, this economy comes from the active power generation, such as by photovoltaic panels. By producing an amount of active power, less will be required from the grid to feed the industry loads and the consumed active power will be reduced to its minimum value. This causes the electricity bill to fall to the minimum cost possible (that is specified in the Resolution n°414/2010 from ANEEL(ANEEL, 2010)). In three-phase systems, this minimum value is the cost of 100kWh in a month, for example.

The Figure 1 shows the distribution of the Brazilian electrical energy sources in contrast with the world in 2015. Renewable energy corresponded to 82% of the total produced electrical energy. Of this amount, 5.2% corresponded to the eolic and solar contribution(EPE, 2016). In the year of 2018, this value has increased to 5.8%(EPE, 2018).

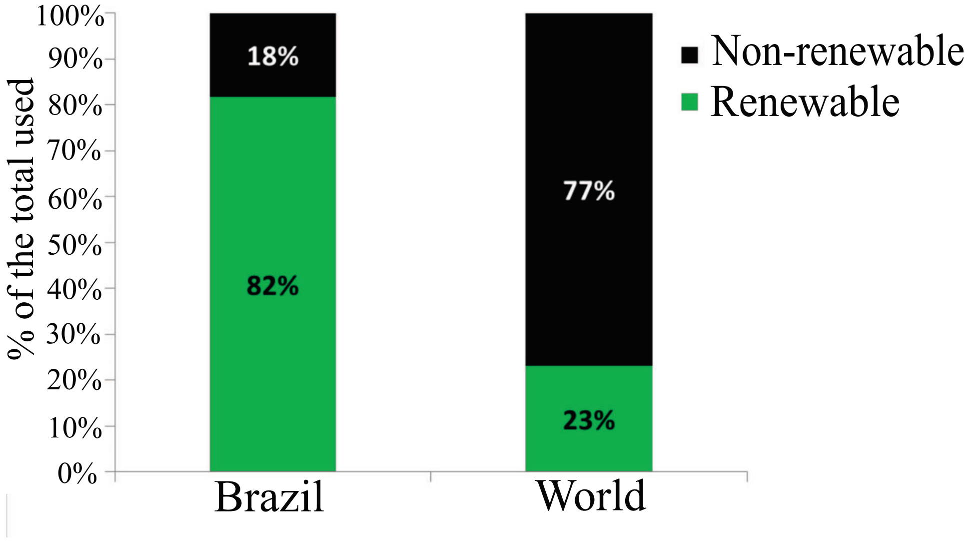

Figure 1 – Electrical brazilian matrix against the world matrix in 2015(EPE, 2016).

With better technologies, the installation of eolic and photovoltaic power plants is becoming viable. Furthermore, the Brazilian energy offer of photovoltaic generation increased 875.6% from 2016 to 2017(EPE, 2018).

In particular, the photovoltaic generation system is often called photovoltaic (PV) plants for high nominal powers. On the other hand, they are called grid-connected photovoltaic systems (GCPS), for medium to low powers. This generation utilizes photovoltaic cells that generates d.c. voltage when exposed to solar irradiance. They are characterized by a high initial capital cost and can be utilized in residential and commercial/industrial places (ISE, 2018).

The technology used in PV panels is actually focused on improve the conversion (of solar irradiance in electricity) efficiency, reducing the cost per watt and the energy payback time (the necessary period of time to equal the economy obtained with the initial capital utilized).These improvements can be achieved with low cost crystalline silicon cells, which has better conversion efficiency, and it is expected to approximately 26% in the 2020's. In this scenario, the photovoltaic generation will be even more competitive with other forms of generation(MANN et al., 2014).

However, the PV panels generate d.c. electricity, which is not suited for the a.c. voltage grid levels(MANN et al., 2014). It is demanded a system to convert this energy, to make possible the power injection by the PV plant in the grid, by using power converters(SINGH; GAUTAM; FULWANI, 2017). This conversion demands an increasing care about the energy quality(ACKERMANN; ANDERSSON; SöDER, 2001).

In low power cases, the energy produced by the PV panel is commonly regulated by a d.c.-d.c. converter (such as Buck/Boost converters or more complex and effective topologies, like a SEPIC converter). Those converters are necessary in order to achieve a DC-Link bus with higher voltage and to extract the maximum power from the PV panels through a maximum power point tracking (MPPT) algorithm (PRADHAN; SUBUDHI, 2016).

The d.c. voltages are then exchanged to a.c. voltages by using power inverters (d.c.-a.c. converters), which have specific control loops to regulate the d.c. bus voltage, active and reactive power injection and voltage/current levels. Thus, the power generated by the PV panels can be injected into the grid(WANG; WANG, 2013). In high power systems, the d.c.-d.c. step can be ignored because there is already an high DC-Link voltage level and the MPPT algorithm can act directly in the external loop control of the inverter.

With the increasing utilization of distributed generation, some problems on the entire electrical grid begin to appear. In fact, a problem rising in electrical power system is described by the Duck Chart, which can be seen on Figure 2(ISO, 2016). This Chart represents the net active power delivered, which is the power supplied by the grid minus the power generated by all distributed generations on analysis. This particular Chart comes from a day in the city of California.(ISO, 2016)

The Independent System Operator (ISO), that is the operator that controls the actions and distribution on electrical grids must have attention to the net production.

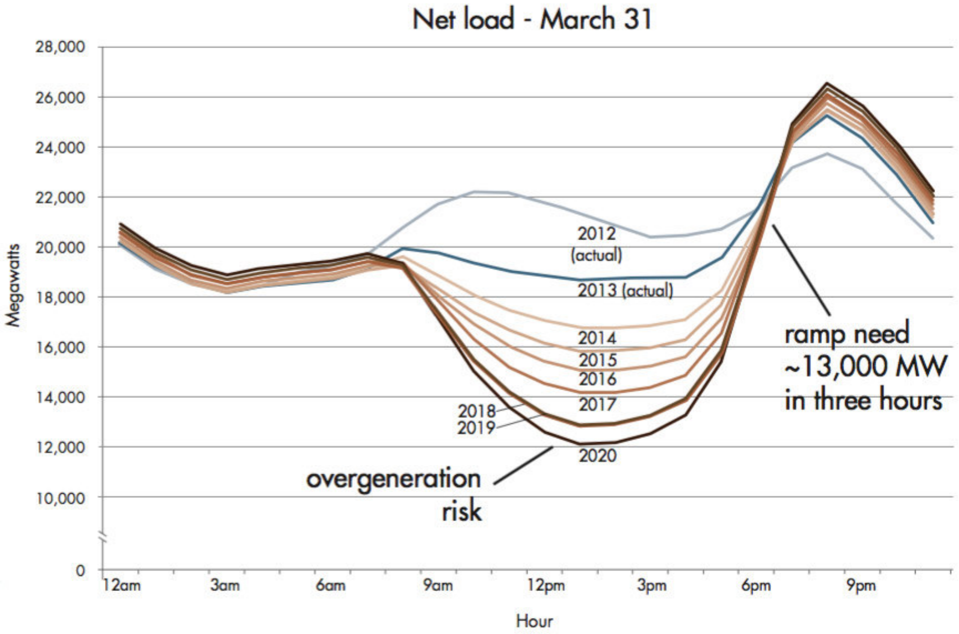

Figure 2 – The representation of load net active power along a day: the Duck Chart(ISO, 2016).

Along the chart, it can be seen that the ISO supplies the power starting on 3 a.m. in a rising ramp until 6 a.m. where the photovoltaic and other distributed generations start. Along the day, the generation pushes the curve to lower levels and in the end of the afternoon, at 6 p.m., the ISO must supply the active power again in a rising ramp behavior.

The entire problem is the rising ramp at the end of afternoon, which have high inclination (as an example, it is predicted that in 2020, shall be needed a ramp of approximately 13GW in only 3 hours). Furthermore, if the curve falls too much, it will be needed an oversupply of the ISO and, if the operator is not able to attend this demand, there will be an overgeneration, and the owners of the distributed generations will have to pay extra charges.

This Chart shows one of the problems caused by the distributed generation in a large electrical power system. On the other hand, this work shows and studies a problem caused by the photovoltaic generation in local terms.

Considering that there is no injection of reactive power (an unitary power factor PV plant), the plant will only support active power demands, being necessary to the industry to draw reactive power from the grid. Therefore, when there is solar irradiance, the PV panels will produce active power in order to supply the demanded energy in a day; in other hand, when there is no irradiance, the active power demanded will be given by the grid.

Since this work considers that the PV system does not inject reactive power at any time, a reduction on the active power reduces the industry power factor to limits that are lower than the indicated by the local standards. This results in additional charges by the energy distribution company. In many countries, e.g., Brazil, the power factor must be over 0.92 inductive (from 6 a.m. to 11 p.m) and 0.92 capacitive (from 0 a.m. to 6 a.m.) to prevent these charges on exceeding reactive power(ANEEL, 2010).

For instance, there are works related to these aspects. In electrical power systems in general, capacitor banks are studied as a part of the bus by delivering reactive power and increasing the voltage levels. The work made on (LONG; OCHOA, 2016) shows the project of a tapped capacitor bank and a tapped transformer to regulate the voltage levels on safe limits. The association of control in power factor and voltage level (or Voltage/VAr control) is greatly studied nowadays. The works on (WANG et al., 2014), (WANDHARE; AGARWAL, 2014) and (JAHANGIRI; ALIPRANTIS, 2013) show methodologies to find an optimum utilization of capacitor banks and inverters to make the Voltage/VAr control. All of these works consider a large system with several bus bars.

When it comes to industrial power plants, there are few works about power factor impacts due to the installation of PV plants. The work made on (LO; LEE; WU, 2008) shows the implementation of a control loop to use the inverter as a parallel power factor corrector, without considering a capacitor bank. Furthermore, in (BANUELOS et al., 2016) is showed a double loop to use the system to compensate reactive power at night (the often called multifunctional PV inverter), since there is no active power production in this period. Also, the work on (LO et al., 2009) shows a power factor correction of the grid with a switching device to regulate the power supply on a d.c. load with a PV system operating in parallel.

1.1 Objectives

There are few works in literature that concern about capacitor bank correction for local industrial RL loads with the presence of a PV power plant. Thus, the contributions of this work are:

- An overall analysis about the effects of a PV plant on the industry power factor;
- Show the dynamic variations of the additional capacitive reactive power, which is called here “cat-head curve”;
- Proposing a solution based on tapped capacitor banks.

1.2 Text organization

In chapter 2, a literature review is made to show the schematics of the system, about power factor corrections and the effects that the PV active power production should cause. Furthermore, in chapter 3, generalized profiles of power consumption are tested as a case study applying the methodology proposed, theoretically. Also, in chapter 4, the results about the new demanded capacitive power is explored. Finally, in chapter 5, the conclusions about this work are discussed.

2 Literature Review

2.1 An overview of the system

A PV plant usually works on parallel with the utility grid, as shown in Figure 3. With this configuration, the PV active power can support the industrial demand, being the energy produced by the PV plant along the day equal to the energy used by the industry. The consumer draws active power from the grid when there is low power generated by the PV plant. On the other hand, it injects power generated by the plant when there is exceeding power generation. For the implementation of the PV system, the consumer energy demand should be known in a determined period of time, such as a year or a month.

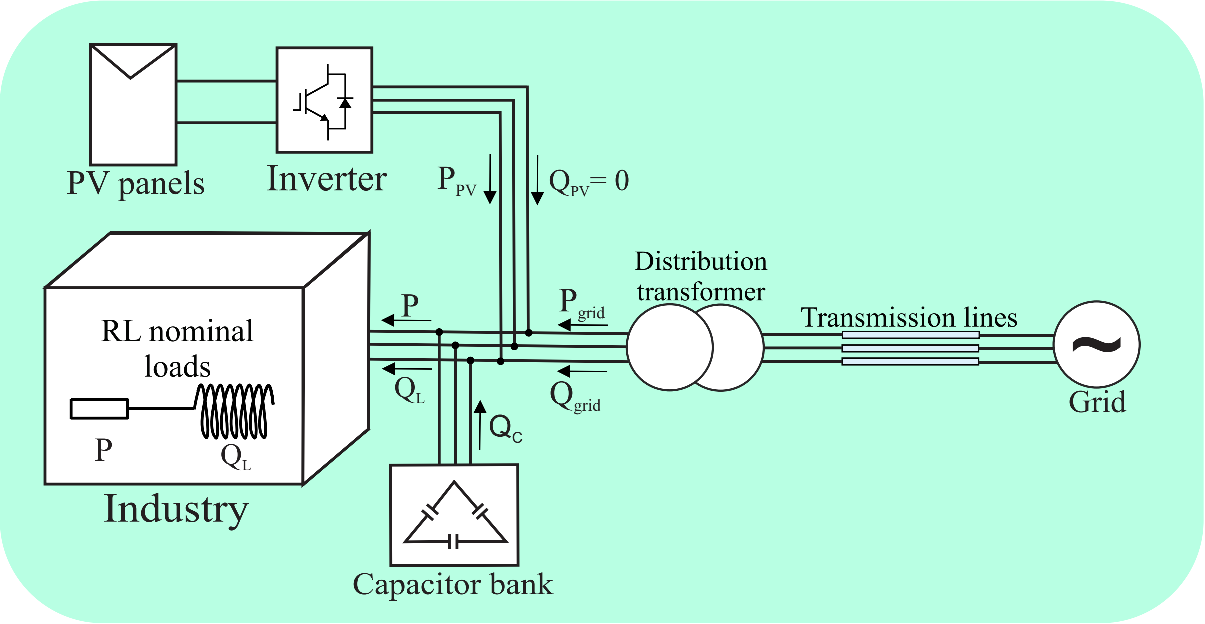

Figure 3 – Diagram of the industry, PV plant and grid connections.

When there is no PV plant connected to the industry, the active and reactive power drawn from the grid must be equal to the nominal powers of the industry. That means:

$$P_{grid} = P, \tag{2.1}$$

and:

$$Q_{grid} = Q_L. \tag{2.2}$$

The values of P and Q_L correspond to the nominal load power values, i.e., the relation of active and reactive power of all equipments in the industry, such as pumps, motors, etc.

Normally, in the industrial ambient, large inverters are used in a centralized configuration, which has multi strings inputs and a certain number of MPPTs for maximum power tracking. Figure 4 shows some types of central inverters produced by ABB.

Figure 4 – Central inverters produced by ABB(ABB, 2018).

2.2 Industrial capacitor banks and power factor correction

As can be seen in Figure 3, there is a capacitor bank which is used in order to correct the actual power factor of the industry to the limit of 0.92. With the presence of a capacitor bank, the power factor can be calculated as follows:

$$pf = \cos\left[\tan^{-1}\left(\frac{Q_L - Q_C}{P}\right)\right]. \tag{2.3}$$

By isolating Q_C in (2.3), the necessary capacitive reactive power for correction can be calculated as:

$$Q_C = Q_L - P\tan(\cos^{-1}(pf)), \tag{2.4}$$

for any value of power factor, such as 0.92 established in Brazil.

Given the value of the necessary capacitive reactive power, the value of each capacitor can be calculated directly by 2.5.

$$X_C = \frac{V_g^2}{Q_C} \tag{2.5}$$

where X_C is the capacitive reactance and V_g is the root mean squared (RMS) value of the voltage across the capacitor. Considering that:

$$X_C = \frac{1}{\omega C}, \tag{2.6}$$

where $\omega = 2\pi f_g$ is the angular frequency of the grid and C is the capacitance value. The equation (2.5) can be expanded as:

$$\frac{1}{\omega C} = \frac{V_g^2}{Q_C} \tag{2.7}$$

therefore,

$$C = \frac{Q_C}{2\pi f_g V_g^2}. \tag{2.8}$$

The last equation shows how to calculate the capacitance given the reactive power that is demanded. This formula is deduced considering a single-phase parameter. However, since it is a three phase system, there are two ways to connect the capacitor bank to the grid: either in a delta or a star configuration. As can be seen that in Figure 3, it was chosen to use a delta connected one. That shall be explained by seeing the Figure 5, which considers a voltage V_a as line to neutral.

As noticed, the voltage across the capacitor is higher in the delta configuration, meaning a smaller capacitance by (2.8). In this way, the capacitance for a star connection is given as:

$$C_Y = \frac{Q_C}{2\pi f_g V_a^2}. \tag{2.9}$$

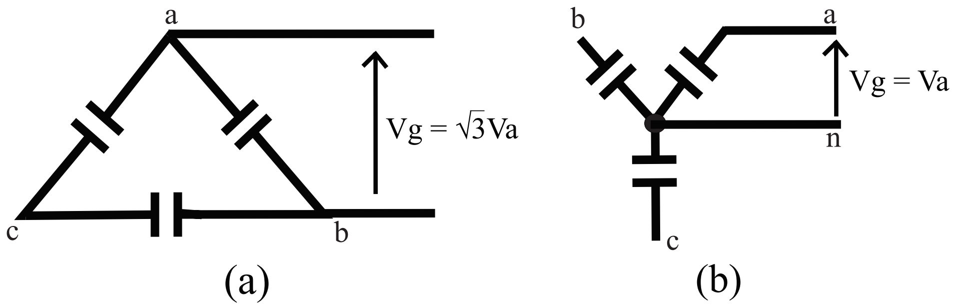

Figure 5 – A capacitor bank. (a) Delta connected. (b) Star connected.

In the same way, the capacitance of the delta connection is:

$$C_\Delta = \frac{Q_C}{2\pi f_g(\sqrt{3}V_a)^2} = \frac{1}{3}C_Y. \tag{2.10}$$

C_Δ is three times smaller than the star configuration for the same reactive power. Furthermore, no zero sequence current can flow into the bank, since there is no ground connection and these harmonics does not appear on line to line voltages in three phase systems, increasing the lifetime of the capacitors by decreasing the value of the True RMS current flowing on them(JINTAKOSONWIT; SRIANTHUMRONG; JINTAGOSONWIT, 2007).

Even though the voltage across the capacitor is slightly higher than in the star configuration (such as the difference between 220V and 380V, for example), it does not increase drastically the cost. Thus, it is economically better to use a delta-connected capacitor bank instead of a star configuration.

In practical terms, Figure 6 shows a capacitor bank available and produced by WEG. It has inductors to limit the in-rush current and de-tune the resonance frequency.

2.3 Effects of adding a PV plant

The PV plant injects active power when there is solar irradiance, injecting energy into the grid or feeding the industry. By doing this, less active power will be needed from the grid, i.e.,

$$P_{grid} = P - P_{PV}, \tag{2.11}$$

and

$$Q_{grid} = Q_L, \tag{2.12}$$

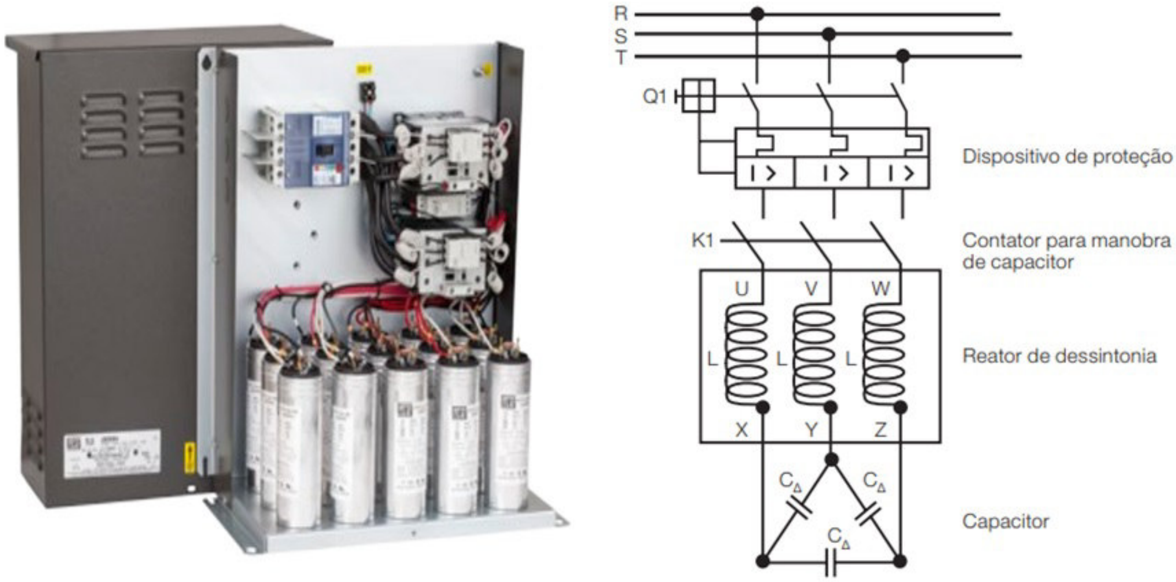

Figure 6 – WEG capacitor bank(WEG, 2018). (a) Practical device. (b) Diagram of contacts.

since the PV plant does not inject reactive power. With an unitary power factor industry, the same amount of reactive power must be drawn from the grid. Equation (2.11) means that the active power profile with a PV plant is represented by a bidirectional power flux, i.e., the industry with a PV plant can either draw ($P_{grid} > 0$) or inject($P_{grid} < 0$) active power from the grid, depending on the actual production.

In order to determine the impacts on the power factor by the implementation of a PV plant, the power profiles of the system must be obtained, being these:

- The nominal active power demanded by the industry (P);
- The nominal inductive reactive power demanded by the industry (Q_L);
- The capacitive reactive power of the capacitor bank to correct the power factor (Q_C);
- A common daily active power active power profile produced by the PV plant (P_{PV}), considering a day with a high level of solar irradiance.

The actual power factor, that was corrected by the capacitor bank, is now represented by:

$$pf = \cos\left[\tan^{-1}\left(\frac{Q_L - Q_C}{P_{grid}}\right)\right]. \tag{2.13}$$

Since P_{grid} has lower values than the original active power profile P, it is expected, by (2.13), that the power factor falls as well. This variable has to remain controlled and, thus, the reactive capacitive power must be increased. The capacitive power correction can be made using the expression:

$$Q_{C,new} = Q_L - |P_{grid}| \tan\left(\cos^{-1}(pf)\right), \tag{2.14}$$

where, given the profiles of the active power P, inductive reactive power Q_L and the reference power factor pf, the capacitive reactive power profile can be calculated. Observe that it is counted the absolute value of the difference between the active power of the load and the produced power from the PV plant, because negative values for the capacitive power is not physically significant. The variation of capacitive power can be expressed as

$$\Delta Q_C = Q_{C,new} - Q_C. \tag{2.15}$$

Expanding the expression in equation (2.15) by using (2.14) and (2.4), it becomes:

$$\Delta Q_C = Q_L - |P_{grid}| \tan\left(\cos^{-1}(pf)\right) - \left(Q_L - P \tan\left(\cos^{-1}(pf)\right)\right). \tag{2.16}$$

The terms of Q_L are canceled in (2.16), since the inductive reactive power remains unchanged with the addition of a unitary power factor PV plant. By simplifying the expression in (2.16), ΔQ_C can be represented by:

$$\Delta Q_C = (P - |P_{grid}|) \tan\left(\cos^{-1}(pf)\right), \tag{2.17}$$

which can be expressed as a piecewise function:

$$\Delta Q_C = \begin{cases} P_{PV} \tan\left(\cos^{-1}(pf)\right), & if \quad P > P_{PV} \\ (2P - P_{PV}) \tan\left(\cos^{-1}(pf)\right), & if \quad P < P_{PV} \end{cases} \tag{2.18}$$

The last expression shows a very interesting description of a grid-connected photovoltaic system that is not often observed. If the active production of the PV plant is zero, it will be needed no extra capacitive reactive power for power factor correction, i.e., there is no change on the previous corrected pf. However, when there is production of active power, an extra amount of capacitive power will be demanded in order for further correction.

This last curve expressed in (2.18) is called “cat head curve” in this work, for its shape. The curve acts like the curve P_{PV} while $P - P_{PV} > 0$ and has critical values where the liquid active power (P_{grid}) is zero, being necessary the compensation of the entire reactive inductive power, and that is a risky situation, for the large size of the necessary extra capacitor bank for correction.

A graphical representation of the cat head curve is shown in Figure 12. The demanded capacitive power is given by the difference between the actual triangle to the red triangle, which represents 0.92 power factor. From t_0 to t_3, the demanded power increases until it reaches the point where $P_{PV} = P$ and it is necessary all the supply all of the inductive power to maintain the power factor unitary. After that, the triangle changes to the region where $P_{PV} < P$ and the necessary capacitive power begins to fall until t_6. From t_6 to t_12, there is a congruency between triangles caused by the symmetric pattern of the active PV power generation.

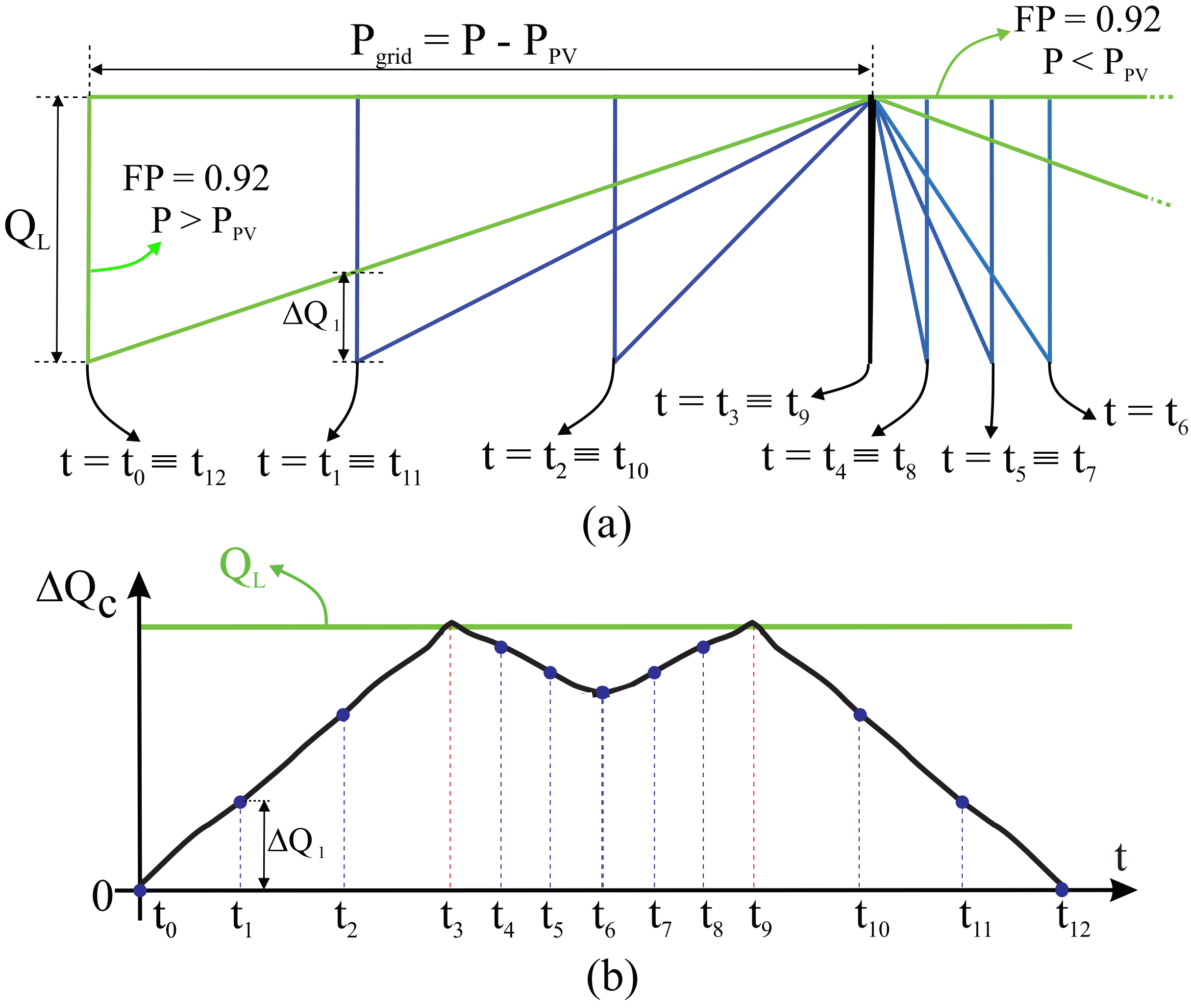

Figure 7 – Effects of the PV plant on power factor compensation. (a) Power triangles changing on time. (b) Demanded capacitive power for correction (cat-head curve).

3 Methodology

3.1 Case Study

This work proposes two case studies based on different consumers load profiles to show how the cat head curve shall appear for distinct and generalized cases . Both of them have an apparent power (S) of 1 p.u., different nominal power factors (0.8 and 0.7) and a capacitor bank for correction to 0.92.

The Figure 8 shows the nominal characteristics of the industry. In both cases, the industrial loads have an individual power factor relating their resistive parameters with the inductive ones. That means there is an necessary value of total active and reactive power for the full operation of the industry.

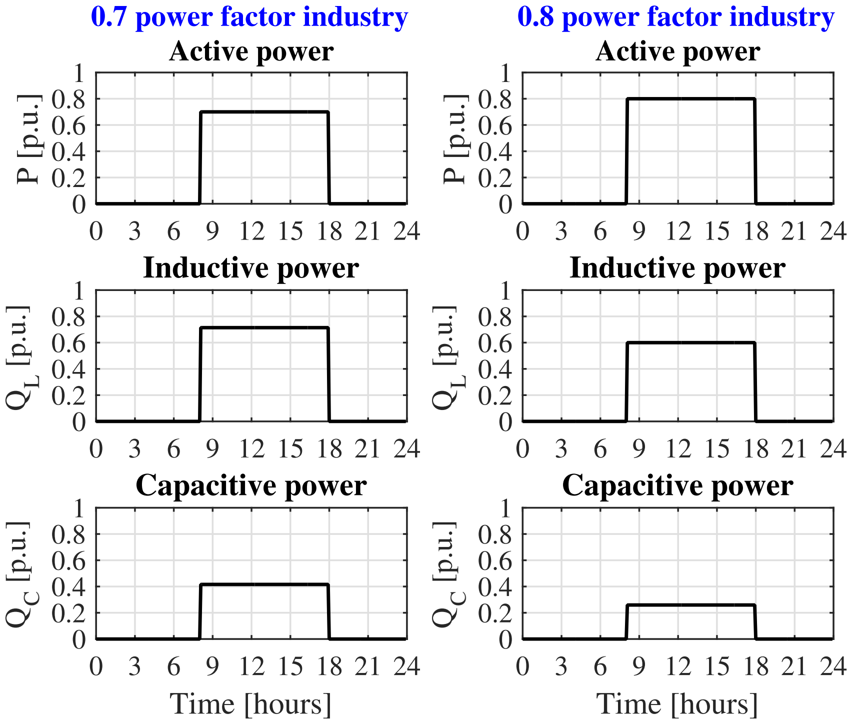

Figure 8 – Power profiles of the two consumers.

The power profiles of these industries are calculated as:

$$P = S.pf, \tag{3.1}$$

$$Q_L = S.\sin[\cos^{-1}(pf)] \tag{3.2}$$

and the capacitive reactive power can be calculated as shown in (2.4).

These profiles represent ideal profiles in industries, being the nominal power (represented by 1 p.u.) turned on at 8 a.m., kept constant all day long until the system shut down at 6 p.m.. The nominal power factor represents the installed nominal power of the consumer (the relation between all reactive power by the active power of the equipments).

With a power factor of 0.7, there is less active power demanded while the inductive reactive power is increased. This means that the industry needs more capacitive reactive power in order to regulate the power factor. In other hand, a power factor of 0.8 means an industry more resistive and less inductive and, thus, less capacitive reactive power is needed.

A PV plant is projected for both consumers. The PV active power profile was projected in order to make its area equal to the nominal active power profile. By doing this, it is possible to balance the energy produced by the PV plant with the energy demanded by the industry in a day, what makes the total liquid energy taken from the grid equals to zero and, thus, make the electricity bill price falls to its minimum value.

The Figure 9 shows the adjusted active power PV profiles.

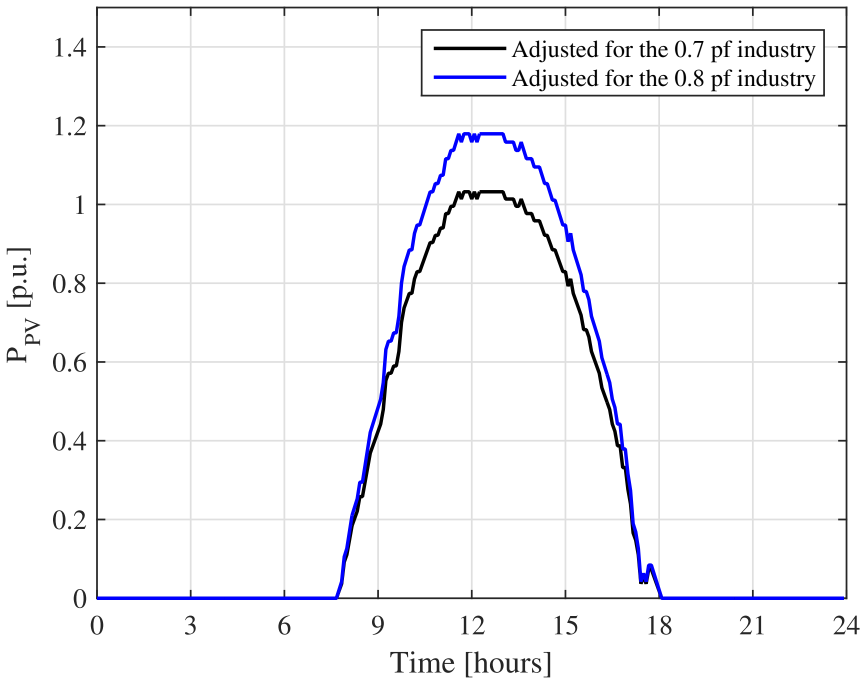

Figure 9 – Adjusted photovoltaic active power profiles.

The characteristic curve of a PV plant is well known, being the maximum produced power around 12 a.m., when the solar irradiance is on its maximum level. In fact, as the power produced is increased, P_{grid} falls as shown in (2.11) until the power flow reverts (go from the PV plant to the grid). In this situation, the liquid active power has negative values, representing this reverse flow. After the solar irradiance falls at the end of the day, the liquid active power starts to increase again.

The Figure 10 represents the dynamic power profiles of the industry after the implementation of the PV plant. It can be notice that the inductive reactive power does not change along the day, since the photovoltaic plant does not have the capacity of inject any of this kind of power. The PV plant can only inject capacitive reactive power by regulating the amount of energy between load and the capacitor from the DC-Link bus.

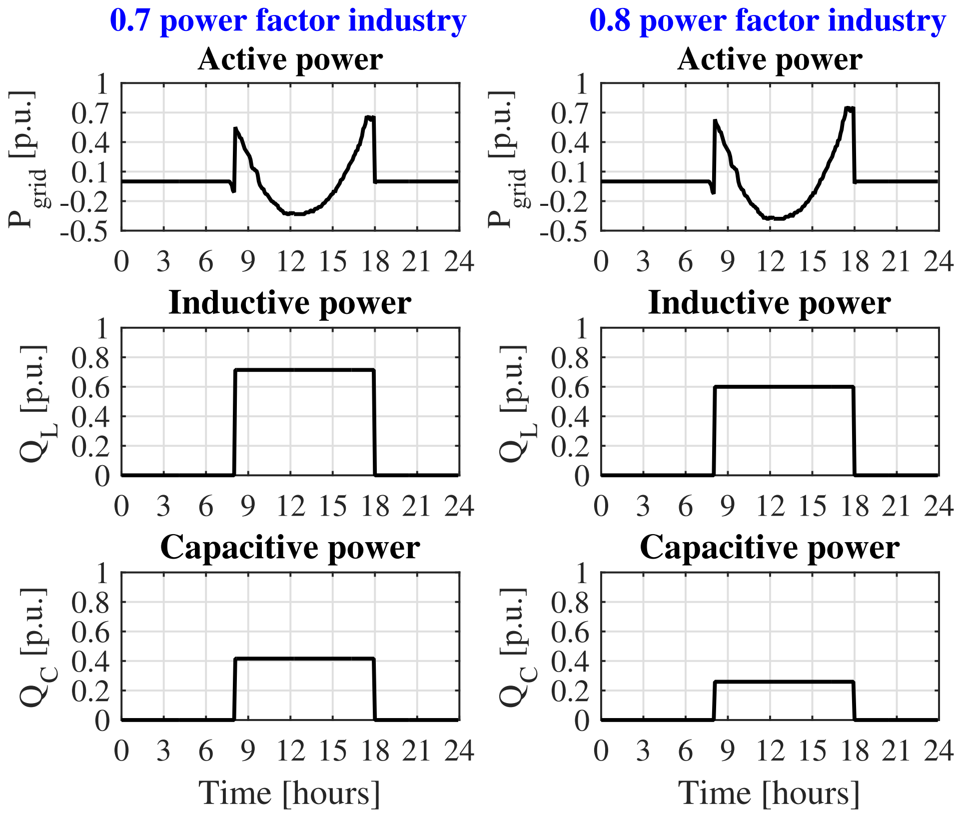

Figure 10 – Power profiles of the two consumers in the presence of a PV plant.

Based on the new power profiles, the methodology can be applied in order to study the new dynamics of the power factor and the changes that must be made to the capacitor bank.

4 Results and Discussion

The profiles in the case study have been generalized so the results can be applied to every PV plant installed by knowing the nominal conditions of the consumer. By using (2.13), and considering the capacitor bank that was already implemented, it is possible to show how the power factor falls harshly under the limit in Figure 11, generating increasing charges on the consumer.

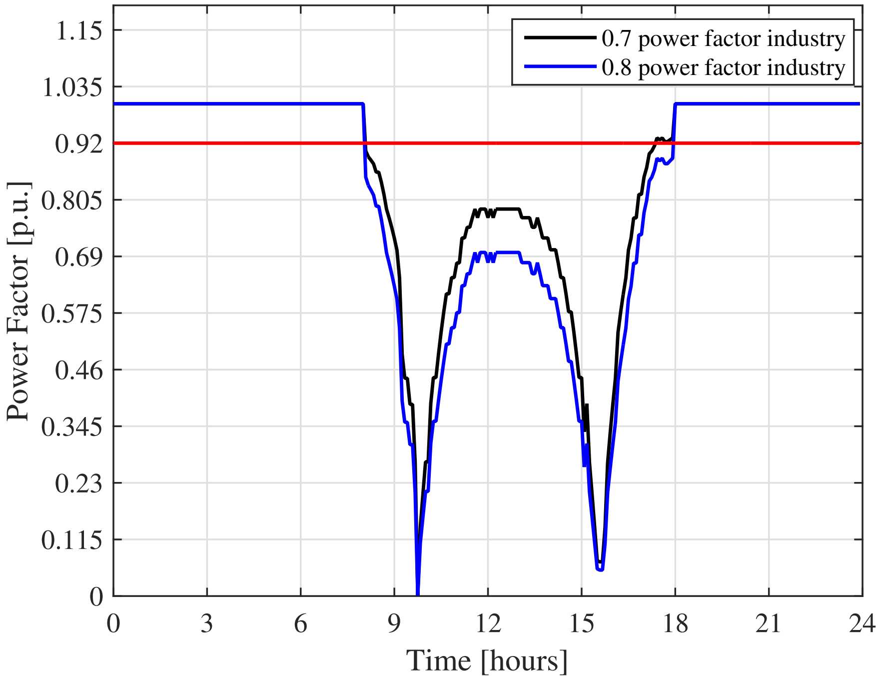

Figure 11 – New power factor of both consumers.

A constant capacitor bank is unable to correct the new power factor, since it is not constant along the day. Since the power factor is no longer constant in time, it is needed a capacitor bank that changes its capacitive reactive power in order to make the proper correction in the correct time. These variable power capacitor banks can be implemented by using taps that are programmed to open or close at the specific time with help of PLCs.

The new incremental capacitive power that must be added is calculated by (2.17). It shows how the variations should be made along the day in order to correct the power factor fall caused by the implementation of the PV plant.

In fact, this curve shows how the capacitive power should be increased for the optimum correction of the consumer power factor. This curve has a peculiar cat head shape, being called the cat head curve, or cat curve for shortens. Each industry that install a PV plant will have its own cat curve, that must be considered in order to avoid extra charges. The Figure 12 shows the cat curve for both industries.

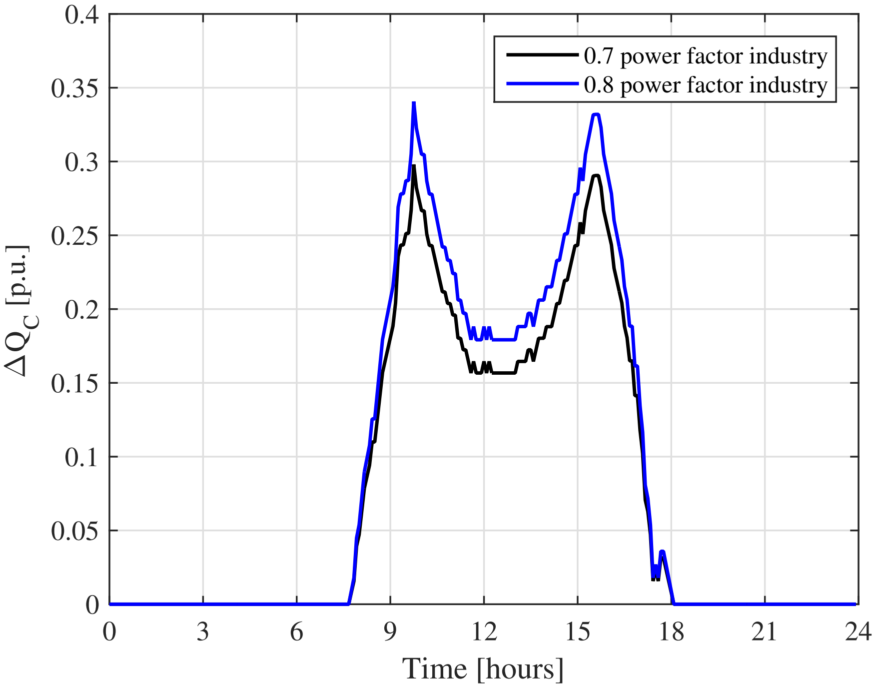

Figure 12 – Additional capacitive reactive power for both consumers: the cat head curve.

By following this curve, a perfect correction of the power factor with a PV plant can be made. However, it is a difficult task to make capacitor banks follow this profile, since they work with discrete tap values. It is necessary a great number of taps, what makes the design of a new bank to be more expensive and less effective.

Another thing should be noticed: the increase that must be made on the capacitive reactive power is very large compared to the previous installed bank. For example, the 0.7 pf industry needed a original maximum 0.4 p.u. power bank for correction and now is needed an extra 0.3 p.u., which gives a total of 0.7 p.u. for the new power bank. This is an increasing of 75% on the previous capacitor bank, almost doubling the necessary power.

Instead of using many taps, the curve can be approximated with precisely 2 taps, as follows. In the Figure 13, it is shown the values of $\Delta Q_{C,max}$, $\Delta Q_{C,min}$ and the mean value between them, $\Delta Q_{C,mean}$, for the 0.7 nominal power factor industry. The cat head curve can be rounded as a piecewise function in terms of these variables. This new function is called 2 tap cat head curve ($Q_{C,2T}$) and is represented by the equation below.

$$\Delta Q_{C,2T} = \begin{cases} \Delta Q_{C,max}, & if \quad \Delta Q_C > \Delta Q_{C,mean} \\ \Delta Q_{C,mean}, & if \quad 0 < \Delta Q_C \leq \Delta Q_{C,mean} \\ 0, & if \ \Delta Q_C \leq 0 \end{cases} \tag{4.1}$$

Using this equation, only two levels of reactive capacitive power will be necessary for the correction of the system, instead of many small steps, since the only requirement is that the power factor stays beyond 0.92, and not exactly on 0.92.

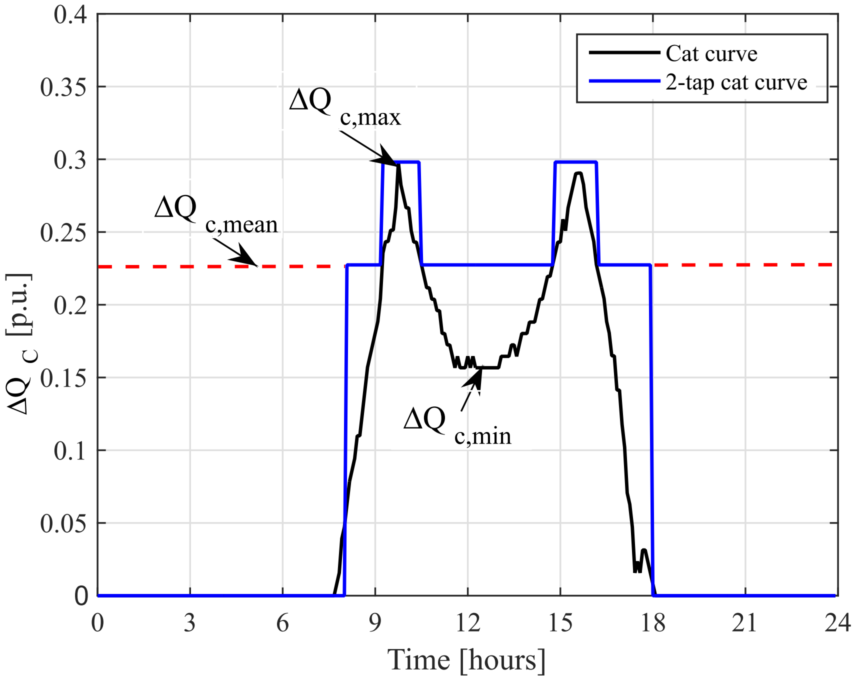

Figure 13 – 2-tap cat curve for the 0.7 pf industry.

The approximation with two taps make sure to correct the power factor to beyond 0.92, but any number of taps can be used for this.

An extra constant capacitor bank with the value of $Q_{c,max}$ is an one tap solution. Notice that the power factor is zero on the critical values ($P_{grid} = 0$) of the cat curve, what means that all the reactive inductive power must be canceled in order to obtain a pf $=$ 1, and hold this value for the entire day. However, that high value of capacitive reactive power will generate an over voltage in the system that may be dangerous for the equipments of the industry.

More than 2 taps can be also used meaning that each step will have smaller values and the over voltage problem will be fairly reduced compared to the one tap case. Besides, using many taps will increase the complexity of the system by using several relays that must be programed accordingly, what will increase the cost of this system and may be dangerous for the bank because of the in-rush current in each capacitor when they are added. For these reasons, a 2-tap capacitor bank is interesting.

The 2-tap cat curve for each industry and the corrected power factor is shown on Figure 14.

It is possible to notice the effect of the simplified correction. All of the power factor remain over the required limit by only using two taps of capacitive reactive power. Thus,

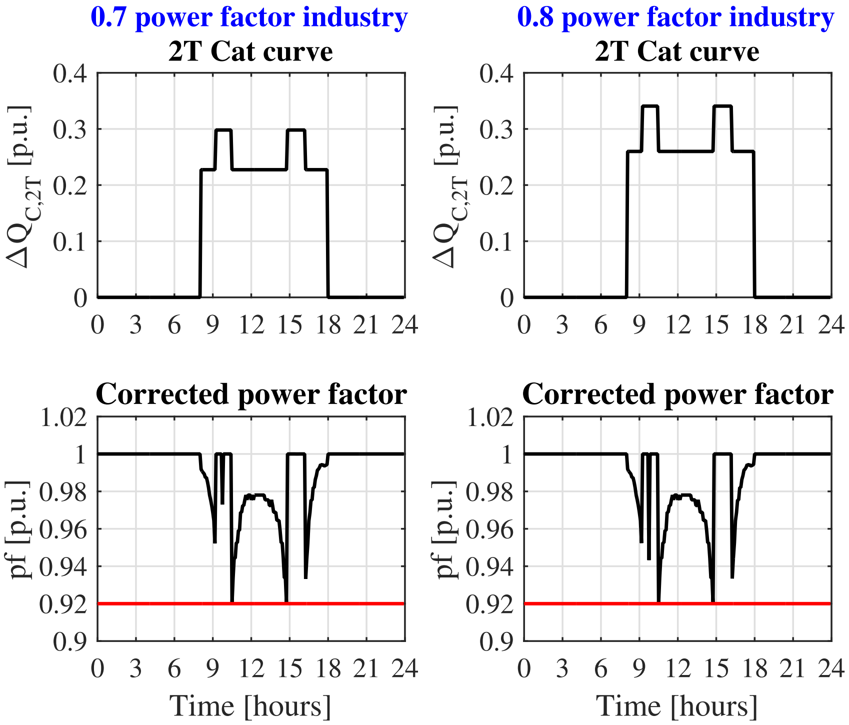

Figure 14 – 2 tap cat-head curve for both case studies and their corrected power factor.

a capacitor bank with only two taps can solve the problem of power factor correction, avoiding extra charges on the electricity bill.

5 Conclusion

This work made a study on how the inclusion of a PV plant can affect the power factor of the industries. In fact, with a reduction in the liquid active power of the consumer, there is a reduction on the power factor that must be solved in order to prevent the charges on this variable.

It is seen that the capacitive reactive power that must be added have a cat head shaped curve, in opposition of the constant reactive power that was used for correction. Thus, a industry that is going to install a photovoltaic plant, must be aware of this problem, design its own cat head curve and re-design the capacitor bank for an appropriate correction.

It can yet be analyzed how the reactive power compensation of the inverter can affect the cat-head curve. With a capacitive power factor, the inverter can decrease the demand of capacitive power for the curve, making the project of a capacitor bank easier and less expensive.

Besides, future studies should see the viability of making a good use of both capacitor bank and inverter, instead of using too much the inverter or designing a large capacitor bank for correction.

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