Reactive power compensation: a basic overview

Surnames, name	Antonino Daviu, Jose Alfonso (joanda@die.upv.es)
Department	Departamento de Ingeniería Eléctrica
Centre	Universitat Politècnica de València

1 Summary

The aim of this paper is to present a basic overview of the reactive power compensation. More specifically, we try to provide satisfactory responses to the following questions:

- Which are the problems caused by the generation and transmission of reactive power?
- How do the electric utilities penalize the reactive power consumption?
- How can the customers avoid these penalties?
- Which are the physical bases of the reactive power compensation?
- Which are the basic elements of a reactive power compensation system?
- Which are the modalities of reactive power compensation?
- Which are the guidelines for the basic design of a reactive power compensation system?

This work is devoted to students or researchers interested in obtaining a basic and quick vision of the area, without deepening in complex or accessory details.

2 Introduction

In the industrial environments, we can find two main types of loads. On the one hand, there are pure resistive loads (R) that only demand active power (P) due to their pure resistive characteristic (e.g. heaters, incandescent lamps…). On the other hand, there are also resistive-inductive loads (R-L) that demand a certain amount of active power (P) but also consume reactive power (Q) during their normal operation; this is the case of induction motors, most discharge lamps or transformers.

Hence, an industrial customer will demand two 'types' of energy: active and reactive. Both of them must be supplied by the electric utility. As a consequence, the phasor of the current circulating through the transmission and distribution lines (*I*) (from the generation plants toward the customers) will have two components: a real component (active current, I_a) and an imaginary component (reactive current, I_L), as depicted in Fig. 1.

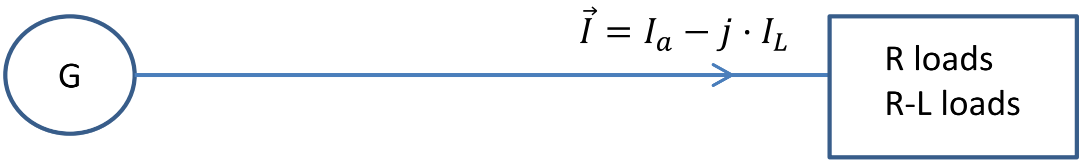

Figure 1. Schematic representation of the line current phasor

The generation, transmission and distribution of the reactive power (Q) cause several problems to the electric utility:

- First, it limits the active power (P) generation capacity: in the power plants, the generators have a limited apparent power (S) generation capacity. Indeed, the maximum apparent power of a three-phase generator ($S=\sqrt{3}\cdot U\cdot I$) is limited by the maximum line voltage (V) and current (I) that the generator can withstand; the first is determined by the generator insulations, while the second is determined by the cross-sectional areas of its conductors.

  Therefore, taking into consideration the basic Equation 1, we can conclude that, for a certain apparent power S, the higher the reactive power (Q) to be generated (in order to the supplied to the customers), the lower the active power (P) that the generator can produce. In other words, the generation of Q limits the capacity of generating P.

$$S = \sqrt{(P^2 + Q^2)}$$

Equation 1. Basic power equation.

- Second, the transmission and distribution of Q, increases the Joule losses in the lines as well as the voltage drops. Indeed, if the customers only demanded P, the line current would only have an active component ($I=I_a$) and, then, the Joule losses ($R\cdot I_a^2$) as well as the voltage drops would only be a function of I_a. However, since the electric utility must also supply Q, the line current is higher (see Equation 2) and, hence, the Joule losses and the voltage drops.

$$I = \sqrt{\left({I_a}^2 + {I_L}^2\right)}$$

Equation 2. Total line current as a function of its active and reactive components

Due to all these problems, the electric utility takes into consideration the reactive power demanded by the industrial customers, increasing their electricity bill as their Q consumption does. Years ago, in Spain, the way to include this penalty in the bill was clear: industrial customers with power factors (cos φ) higher than 0,9 were credited in the electricity bill, whereas customers with power factors lower than 0,9 were penalized, reaching surcharges of up to 47% [1]. Nowadays, due to the liberalization of the electricity market in Spain, the reactive power consumption penalization is still carried out, but in an indirect manner; the reactive power consumption is included in the price that the retailer must pay to the distributor, undergoing high increments as the demanded Q increases [1].

3 Objetives

Once the problems of reactive power generation, transmission and distribution have been exposed, we will proceed to describe the actions that the customers can adopt in order to avoid or minimize the corresponding penalization in the electricity bill. These actions are covered by the denomination '*reactive power compensation*'. In this context, three main goals are pursued:

- To explain the physical process underlying the reactive power compensation process.

- To describe the industrial modalities for reactive power compensation, commenting their respective advantages and drawbacks.
- To design a basic reactive power compensation system.

4 Development

4.1 Reactive power compensation: foundations

The intuitive idea underlying the reactive power compensation process is the following one: to avoid the penalties that the electric utility imposes due to the consumption of reactive power (Q) by the R-L loads, the customer installs capacitor banks. In that way, the customer can produce the reactive power that his plant needs, hence avoiding the supply of Q by the electric utility.

More rigorously, the physical process taking place when the customer installs capacitor banks in parallel with the loads is described next:

Let us suppose that there is no reactive power compensation (the customer does not install capacitor banks). The line current circulating through the distribution lines (I) will be equal to the total current demanded by the loads in the industrial plant and it will have two components; an active (I_a) and a reactive component (I_L), as depicted in Fig. 1. The phasor diagram corresponding to this situation is depicted in Fig.2.

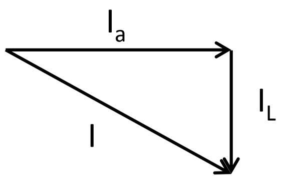

Figure 2. Phasor diagram of the line current in the situation of Figure 1

Let us suppose now that the customer installs capacitor banks (Fig. 3). Since the capacitor (C) is also a load, it demands a certain current for its operation. However, the phasor of the current demanded by a capacitor (I_C) —unlike the one demanded by a coil— is forwarded 90° versus its voltage phasor. As a consequence, since the total current circulating through the distribution lines is the addition of the current demanded by the loads in the installation (I_a-$j \cdot I_L$) and the current demanded by the capacitors ($j \cdot I_c$), the resulting phasor diagram will be the one depicted in Fig.4.

Note there is a 180° phase displacement between the phasor of the reactive component of the current demanded by the loads ($-j \cdot I_L$) and that of the capacitor current ($j \cdot I_C$). Therefore, if the capacity (C) of the capacitor is selected in such a way that the magnitudes of I_L and I_C are equal, these two components would cancel each other in the phasor diagram and, hence, the total current circulating through the distribution lines would be $I=I_a$. In conclusion, the electric utility should only supply the active component (i.e. active power P), so we avoid the supply of the reactive one and, hence, the supply of Q from the grid.

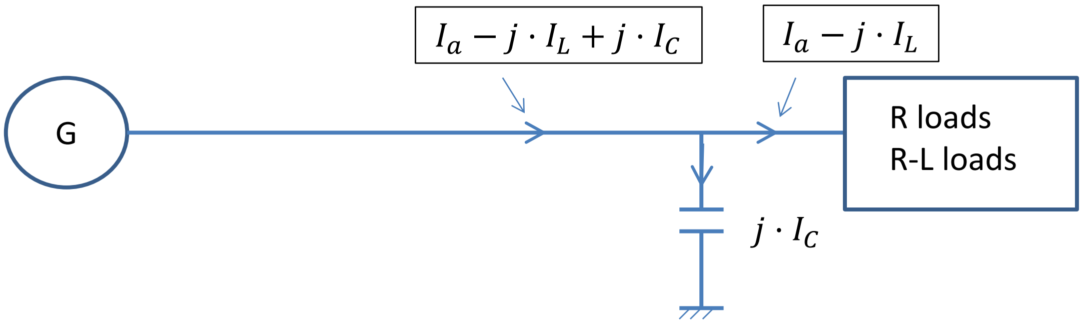

Figure 3. Schematic representation of the line current phasor when there is reactive power compensation

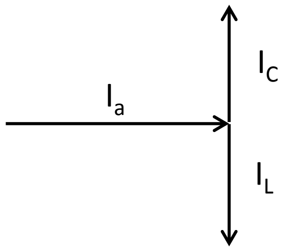

Figure 4. Phasor diagram of the line current in the situation of Figure 3

Of course, the theoretical situation described above is not usual in practice. In real life, the magnitudes of I_L and I_C are not exactly the same. This is due to the fact that the capacity of the real capacitor banks is rarely changed in a continuous way, since these banks are typically based on several capacitor steps with predefined reactive powers that are connected or disconnected according to the Q necessities. This provokes that I_L is 'compensated' in steps, depending on the capacitor steps connected in each moment.

Instead of using capacitor banks, there is a different alternative to compensate the reactive power that is based on the use of synchronous compensators. These are synchronous machines that, operating with null active power, can behave either as variable capacitors or coils, by simply changing their excitation current [1]. However, their use in the industry is very uncommon, being restricted to large electric power grids.

4.2 Reactive power compensation: modalities

There are two main types of reactive power compensation: a) *individual* and b) *centralized*. These two modalities are schematized in Fig. 5 (a) and (b), respectively. There is a third modality that can be considered an intermediate case: c) the *compensation in group*. These three modalities can coexist in the same installation.

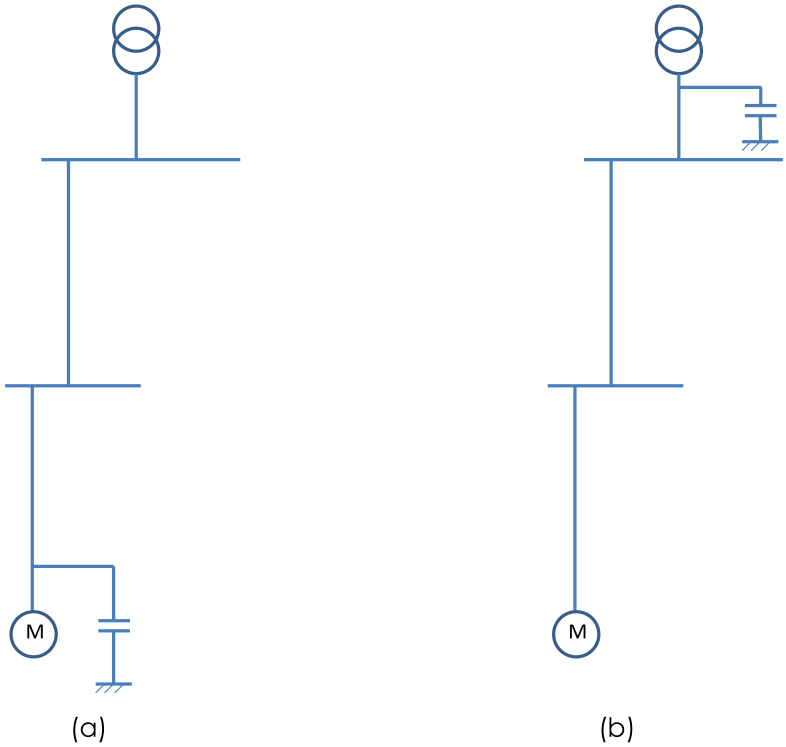

Figure 5. (a) Individual and (b) centralized reactive power compensation

The *individual reactive power compensation* relies on installing capacitor banks in an individual way, in parallel with each single load. This modality is represented in Fig. 5(a) that shows the individual reactive power compensation for a motor. This modality is usually suitable for large machines (e.g. motors) operating under continuous duty cycles. In that situation, is the user knows the Q demanded by the load, he can easily calculate the capacity of the capacitor needed and install it in parallel with the load. Moreover, this reactive power compensation modality is carried out in manual way, i.e., the user connects or disconnects the capacitor manually by using normal switches or, more commonly, contactors.

The main advantage of this individual modality is the fact that the conductors located upstream in the installation must only carry the active component of the current (I_a), hence, decreasing the Joule losses and limiting the voltage drops [1, 3]. This is illustrated in Fig. 6, where, once again, we suppose that the magnitudes of I_L and I_C are equal.

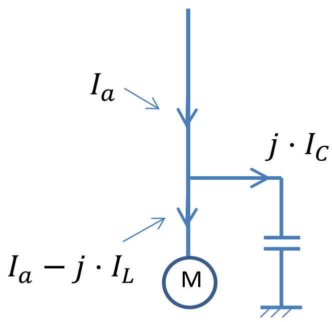

Figure 6. Currents in the installation in the case of individual Q compensation

The _centralized reactive power compensation_ modality is based on installing capacitor banks but for the whole industrial installation (Fig. 5 (b)). Usually, these banks are installed in the Transformer Substation (T.S.) containing the transformer through which the whole industrial electric installation is supplied. This modality is usually suitable when there are many loads in the installation that have diverse sizes and operate under different duty cycles. Moreover, this compensation modality is carried out in an automatic way; the system measures the reactive power demanded by the installation and automatically connects or disconnects capacitors accordingly.

A typical automatic reactive power compensation system is based on the following elements (Fig. 7) [3]: 1) a *measurement device* that measures the power factor of the installation (i.e. the Q that the installation is demanding from the grid), 2) a *regulator* that compares the power factor of the installation with the reference power factor (the one that the user wishes to obtain), 3) a group of *switching devices* (usually contactors), through which the regulator connects or disconnects the: 4) *capacitor steps*.

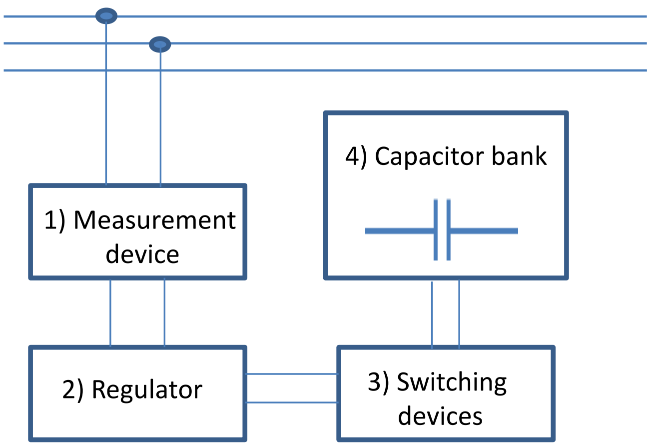

Figure 7. Elements of an automatic Q compensation system

Some advantages of this compensation modality are: its easier maintenance, its higher flexibility for installation extensions, it is a better option when there is no space beside the loads, it takes more advantage of the capacitor capacities at each moment…

However, this modality does not avoid the circulation of the reactive component (I_L) through the installation conductors.

Finally, the third modality, the _compensation in group_ is based, as its name indicates, on compensating the Q of a group of loads by installing, for instance, capacitor banks in the secondary or tertiary panelboards that supply this group of loads. This modality is common is certain parts of the installation with specific loads of the same nature or involved in the same part of the process.

4.3 Reactive power compensation: basic design

4.3.1 Determining the Q of the capacitor bank for centralized compensation

Let us suppose that a certain industrial premise demands certain amounts of active power (P) and reactive power (Q1) from the grid (the installation has an initial power factor, cos φ_1). Imagine that the owner of the installation considers that the amount of demanded reactive power is too high; he wants to reduce it, demanding a lower reactive power (let us call it Q2). In other words, he wants to have a higher power factor, cos φ_2. The question is: which is the value of the reactive power of the necessary capacitor bank to be installed (Q_c)? This question can be answered considering the power diagram in Fig. 8. This diagram enables to easily determine the expression to calculate Q_c (Equation 3).

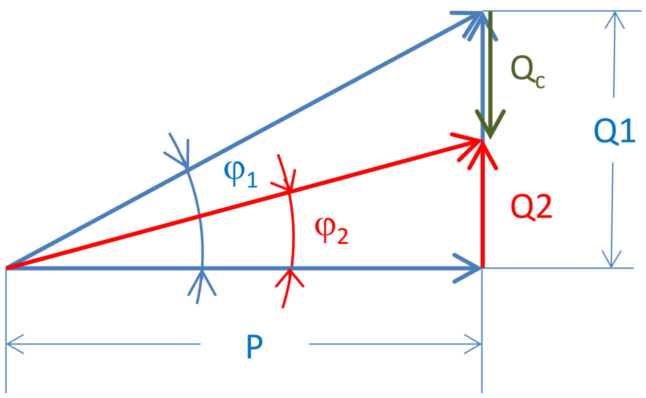

Figure 8. Power diagram that enables to obtain Q_c

$$Q_c = P \cdot (tg\,\varphi_1 - tg\,\varphi_2)$$

Equation 3. Calculation of Q_c

Once the reactive power capacity of the necessary capacitor bank, Q_c, has been calculated, we can determine the capacity of each capacitor of the bank, C. The expression that relates Q_c and C depends on the type of capacitor bank (single phase, three-phase with the capacitors connected in delta configuration or three-phase with the capacitors connected in star configuration). Table 1 shows the expression relating Q_c and C for each type of bank. These expressions are deduced from well-known circuit theory expressions [1-3].

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Type of capacitor bank	Expression
Single-phase	$Q_c = U^2 \cdot w \cdot C$
Three-phase (star)	$Q_c = U^2 \cdot w \cdot C$
Three-phase (delta)	$Q_c = 3 \cdot U^2 \cdot w \cdot C$

Table 1. Expressions relating Q_c and C for each type of capacitor bank

4.3.2 Individual Q compensation for a three-phase motor

Let us imagine that we want to calculate the necessary capacity of the capacitor to be installed in order to carry out the individual reactive power compensation of a certain three-phase motor.

Let us suppose that the rated characteristics of the motor, included in its characteristics plate are: rated power P_n (mechanical), rated current I_n, rated voltage U_n and rated power factor cos φ_n. With these data, we can calculate the reactive power demanded by the motor under rated operation, as indicated in Equation 6 (η is the efficiency of the motor). This Equation is easily deduced considering the usual expressions for calculating the active and reactive power of a three-phase load (Equations 4 and 5):

$$Q_n = \sqrt{3} \cdot U \cdot I \cdot sin\ \varphi$$

Equation 4. Reactive power of a three-phase load

$$P_{el} = \sqrt{3} \cdot U \cdot I \cdot cos\ \varphi$$

Equation 5. Active power of a three-phase load

$$Q_n = P_{el} \cdot tg\ \varphi = \frac{P_n}{\eta} \cdot tg\ \varphi$$

Equation 6. Reactive power of the motor under rated conditions

Taking into account this expression, we can determine the reactive power of the necessary capacitor (Q_c). Typically, in practice, it is recommended to take $Q_c=0,9 \cdot Q_n$. This is done to avoid the possibility of auto-excitation during overrun and the eventual appearance of overvoltages [1].

5 Conclusions

In this work, a basic introduction to the reactive power compensation has been presented. First, the most important problems caused by the generation, transmission and distribution of reactive power are explained. Then, the measures adopted by the electrical utility to discourage the consumption of Q are briefly commented.

The reactive power compensation mechanism is analyzed both under intuitive and under physical perspectives. Then, the different modalities for reactive power compensation (individual and centralized) are described and their respective elements, application scopes, advantages and drawbacks analyzed.

Finally, the last section is devoted to the basic design of the elements of a reactive power compensation system, both individual and centralized.

6 References

6.1 Textbooks:

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