A NEW POWER FACTOR COMPENSATION STRATEGY FOR HIGHLY UNBALANCED LOW VOLTAGE ELECTRICAL NETWORKS

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Abstract - Almost all bulk electric power is generated, transported and consumed in an alternating current (AC) network. Elements of AC systems produce and consume two kinds of power: real power (measured in watts) and reactive power (measured in volt-amperes reactive or VAr). Real power accomplishes useful work (e.g., running motors and lighting lamps); reactive power supports the voltages that must be controlled for system reliability. The industrial consumers normally contain high power single-phase receivers as mains frequency induction furnaces, welding transformers etc. If the load is unbalanced, the reactive power absorption on each phases are also unsymmetrical. In this case the three phase reactive compensation can have negative consequences; some phases may be over-compensating other less-compensating.

In this paper, the authors propose a new strategy to improve the power factor using single phase capacitor for strongly unbalanced loads. Every capacitor is connected through a static circuit breaker and the control strategy aims calculating the right value of the control signal on every phase according to the real amount of the consumed reactive power.

Key words: power factor, unbalance, low voltage electrical networks

1. INTRODUCTION

Almost all bulk electric power is generated, transported and consumed in an alternating current (AC) network. Elements of AC systems produce and consume two kinds of power: active power (measured in watts) and reactive power (measured in volt-amperes reactive or VAr). Active power accomplishes useful works (e.g., running motors and lighting lamps). Reactive power supports the voltages that must be controlled for system reliability.

Reactive power supply is essential for constantly operating the electric transmission system. Inadequate reactive power has led to voltage collapses and has been a major cause of several recent major power outages worldwide.

Reactive power is difficult to transport. Indeed at high loadings, relative losses of reactive power on transmission lines are often significantly greater than relative active power losses. Thus, reactive power consumption or losses can increase considerably with the distance transported. Losses in the power transmission systems lead to the expression that reactive power does not travel well. Never the less, when there is not enough reactive power supplied locally, it must be supplied remotely, causing larger currents and voltage drops along the path.

Reactive power needs are a critical part of the planning processes of a real power system. Supply chain management, the name often given to the developed transportation – storage – consumption process, is usually measured in days, weeks or months for most industries. For electricity this process takes less than a second – the ultimate just-in-time system. If there is a disruption in the system, corrective action is called for in seconds or minutes. As a result, the system must be planned so that it can respond to contingencies. Auctions can be employed to satisfy the procurement needs of the planning process. Reactive power requirements are determined in the planning process, which is part engineering, part economics and part judgment.

The engineering investigation requires running large, complex mathematical computer models of the electric system. The economic analysis requires putting costs or bids into the models to determine how to achieve an efficient, reliable system. The judgment arises due to the large number of modelling choices, expert assumptions and approximations that often are necessary.

Reactive power needs to be managed or compensated in a way to ensure sufficient amounts that have to be produced in order to meet the demand and so to ashore the electric power system efficient running. Significant problems (e.g., abnormal voltages and system instability) can occur if reactive power is not properly managed. Capacitors, which supply reactive power, can be switched into a system in real-time to compensate for the reactive power consumed by the power system during periods of heavy loading. Similarly, inductors, which consume reactive power, are added to compensate for the reactive power supplied by the electric power system during periods of light loading. Generators can also provide or absorb reactive power.

The above mentioned devices are installed throughout the power system to maintain an acceptable voltage profile for a secure and efficient power system operation. Reactive power compensation can be either static (e.g.

capacitors or inductors) or dynamic (e.g. generators) in nature.

Reactive power compensation can be well managed under predictable changes in load demands and generation balances, scheduled generation and transmission outages and contingencies that are within the operating criteria. A key characteristic of reactive power demand is the magnitude and speed at which it changes over time. Due to the varying nature of loads, reactive power requirements, both supplying and consuming, can change significantly (and sometimes unpredictably) during a day at the same location.

Generally, reactive power support is divided into two categories: static and dynamic. Capacitors and inductors (or reactors) supply and consume static reactive power, respectively. These are called static devices since they have no active control of the reactive power output in response to the system voltage. Synchronous generators, synchronous condensers, Flexible AC Transmission Systems (FACTS) including static VAr compensators (SVC), static compensators (STATCOM), and Dynamic VAr (D-var) are considered as dynamic reactive power devices capable of changing their output according to pre-set limits in response to the changing system voltages.

2. SOME ASPECTS REGARDING THE POWER FACTOR

The economic effects determined by the functioning at a low power factor (PF) have to be considered in the process of establishing the electrical energy tariff. Thus in this way is followed the compensation of energy losses that this functioning state is causing. Taking into account that the reduced value of the power factor is a consequence of several local phenomenon (causes), the technical and financial measures that are adopted in order to raise this value are particularly referring to the power system node in which is connected the consumer that causes this power factor reduction.

A low power factor means a higher load current than necessary and accompanying higher line losses. Determining the power factor for a given element of a distribution power system is complicated by the variety of loads typically connected. Different loads present different PF components [2]:

- *Lighting*. The power factor for most incandescent lamps is unity. Fluorescent lamps usually have a low power factor: 50 percent is typical. Fluorescent lamps sometimes are supplied with compensation devices to correct the low power factor. Mercury vapour lamps have a low power factor: 40 to 60 percent is typical. Again, such devices can be supplied with compensation devices.
- *Electric motors*. The power factor of an induction motor varies with the load, as shown in Fig 1. Unloaded or lightly loaded motors exhibit a low PF. Fig. 2 illustrates the variation of power factor and reactive power for varying loads on a three phase induction motor. Synchronous motors provide good power factor when their excitation is adjusted properly. Synchronous motors also can be over-excited to exhibit a leading power factor and, therefore, can be used to improve the power factor of a facility.

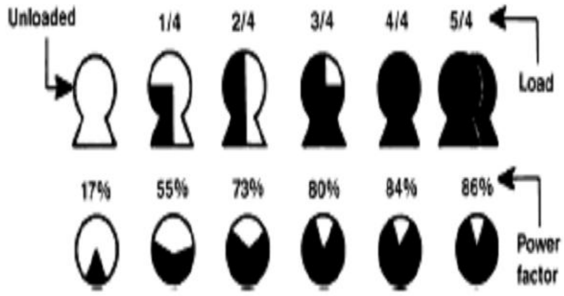

Fig. 1. Power factor for an induction motor as a function of motor loading

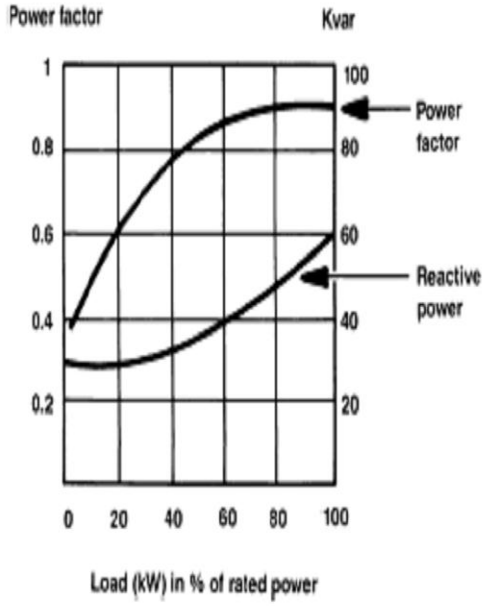

Fig. 2. The relationship of reactive power and power factor to percentage of load for a 100 kW, three-phase induction motor.

- *Heating systems*. Most heating systems used in ovens or dryers present a power factor of close to unity.
- *Welding equipment*. Electric arc welders usually have a low power factor: 60 percent is typical.
- *Distribution transformers*. The power factor of a transformer varies considerably as a function of the load applied to the device, as well as the design of the transformer. An unloaded transformer would be highly inductive and, therefore, would exhibit a low power factor.

A low power factor needs additional investments for the over-dimension of the production, transport and distribution installations of electrical energy. Indeed, if it is thought an installation that functions with a power factor of 0.7, the considered rating is 40% higher than in the case of a unitary factor and the installation design is made in accordance with this value. Also the functioning under a low power factor leads to the growing of conductors' cross-section and to the raising of supplementary investments in the transport and distribution grids.

3. POWER FACTOR COMPENSATION

The effects of a low power factor existence have led to the use of specific equipments. Thus, in order to avoid a low power factor there can be used either over-excited synchronous compensators or capacitor banks.

Some of the synchronous compensators disadvantages can be mentioned:

- The specific cost in Lei/kVAr is much higher than the capacitor banks cost;
- They are realized for high powers;
- They need additional equipments;
- It is necessary a specialized exploitation personal;
- It contribute to the raising of the short-circuit power in the consumers electric installations.

In the paper is studied the power factor compensation using capacitor banks. From their advantages it can be mentioned:

- They are realized for LV and MV grids;
- It is not necessary special connection equipments;
- It is not needed a specialized exploitation personal;
- The specific cost, Lei/kVAr, is much lower than the synchronous compensators price;
- They don't contribute to the growing of short-circuit power.

Several disadvantages of capacitor banks use are:

- It can appear sudden voltage variations due to their functioning in ranks;
- It can grow the no-load voltage and resonance phenomenon can appear;
- The Capacitor banks repair is difficult.

The equipments used today for the automatic power factor control – Fig.3 – most of the times in the low voltage installations, are utilizing the information regarding the diphase of the voltage and current waveforms of one phase. The command block BC establishes the power factor value (cosφ) and by knowing the capacities of the 6 or 12 bank capacitors rungs, it connects the necessary elements to realize the prescribed power factor. The exceeding of the prescribed value of the power factor leads to the disconnecting of the capacitor bank rungs [3].

From practical point of view, the solution presented in Fig. 3 is not in concordance with the real functioning state of the power system, which is a non-sinusoidal and unbalanced operating state. This is because in the real situations the solution that takes in consideration only a phase can increase the gravity of the powers unbalance.

Taking in consideration these aspects, regarding the permanent unbalanced operating states are proposed two alternatives for the compensation of the power factor:

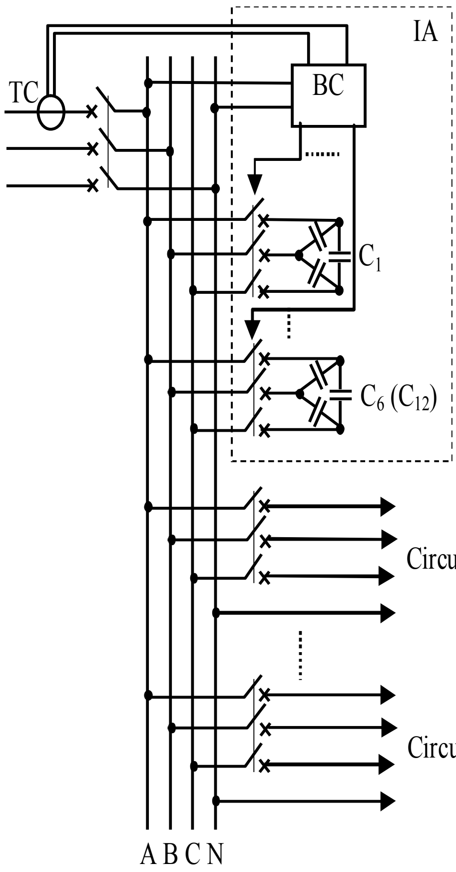

Fig. 3. The fundamental scheme of an automatic control of the power factor installation (cosφ) [4].

A. Power factor compensation using 3-phase capacitor banks

In the control scheme of the power factor from Fig. 3 it is controlled the phase angle between the current and the voltage on a single phase. In the case that the connected consumers through circuit 1 – circuit N are unbalanced, this reactive power control method is no more efficient. This is because on one of the non-monitored phases the power factor is possible to have a value much higher or much lower than the imposed value, so that the 3-phase power factor won't be between the desired thresholds. Consequently, it is proposed the control of the compensation capacitor bank based on the power factor – Fig. 4 – that is determined starting from the mathematical relationship:

$$\lambda = \frac{P}{S} \qquad (1)$$

where λ represents the power factor;
P is the active power absorbed in the common coupling point (PCC), in kW;
S – the real power in the PCC, in kVA.

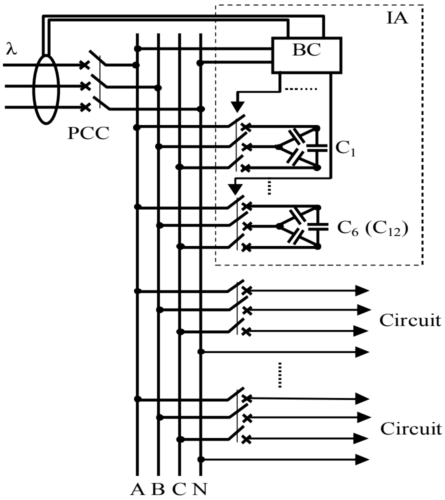

Fig. 4. The fundamental scheme of an installation for the automatic control power factor (λ)

B. Power factor compensation using single-phase capacitor banks

In the case that the consumers connected in the common coupling point are heavy unbalanced, the authors propose the power factor compensation with the help of single-phase capacitor banks set like in Fig. 5.

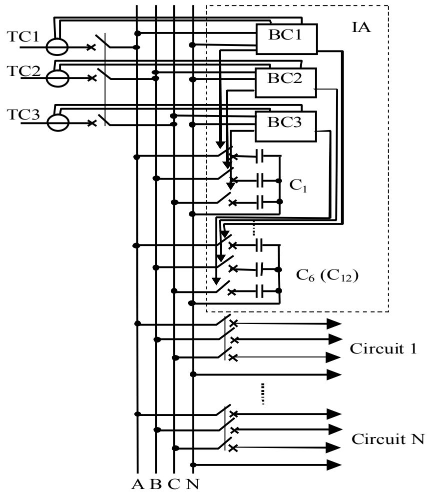

Fig. 5. The fundamental scheme of an installation used for the single-phase automated power factor control

In this case, the power factor compensation is made on each phase so that in the system is injected the amount of reactive power needed and every capacitor is connected through a static circuit breaker. The difference between this solution and the former one is the introduction of more two command blocks, in this way each phase is practically compensated independently from the other ones.

4. STUDY CASE

In order to underline the previous presented solutions for the power factor compensation, in the next paragraphs is presented a study case. Thus, it is considered a 3-phase unbalanced consumer. The absorbed powers and the power factors on each phase are:

$$P_1 = 19\ [\text{kW}], \qquad \lambda_1 = 0.48;$$
$$P_2 = 12.76\ [\text{kW}], \qquad \lambda_2 = 0.71;$$
$$P_3 = 25\ [\text{kW}], \qquad \lambda_2 = 0.91;$$

In order to determine the differences between the three compensation solutions described in the preceding section initially was chosen the power factor value to reach. In the first case was elected 0.92 that is the Romanian imposed power factor value, then the calculus was made in order to reach the unity.

In table 1 are presented the values obtained in the case of the power factor compensation in order to reach the value of 0.92. In table 2 are synthesized the values that were obtained in the case the power factor was compensated to reach the unitary value.

Table I. Power factor compensation in the PCC to the value of 0.92

Case I – figure 3			
Q_{BC} = 75 [kVAr]			
λ_1	0.923	$\lambda_{3\text{-phase}}$	0.953 cap
λ_2	0.719 cap		
λ_3	0.878 cap		
Case II – figure 4			
Q_{BC} = 33 [kVAr]			
λ_1	0.655	$\lambda_{3\text{-phase}}$	0.921
λ_2	0.99		
λ_3	1		
Case III – figure 5			
Q_{BC} = 33.25 [kVAr]			
λ_1	0.923	$\lambda_{3\text{-phase}}$	0.923
λ_2	0.927		
λ_3	0.92		

Table 2. Power factor compensation in the PCC to the unitary value

Case I – figure 3			
Q_{BC} = 99 [kVAr]			
λ_1	1	$\lambda_{3\text{-phase}}$	0.8 cap
λ_2	0.53 cap		
λ_3	0.76 cap		
Case II – figure 4			
Q_{BC} = 57 [kVAr]			
λ_1	0.807	$\lambda_{3\text{-phase}}$	1
λ_2	0.895 cap		
λ_3	0.957 cap		
Case III – figure 5			
Q_{BC} = 57.5 [kVAr]			
λ_1	1	$\lambda_{3\text{-phase}}$	1
λ_2	1		
λ_3	1		

With the purpose to underline the advantages of the power factor compensation, there have made also an economic investigation. Firstly were calculated the invoices in the case of no compensation. In table 3 are synthesized the monthly costs before the compensation and the annual spending considering a constant loading, respectively.

Table 3. The electrical energy invoice before the power factor compensation

Active energy cost	6015 [lei]
Reactive energy cost	475 [Lei]
Totally	6490 [Lei]

In tables 4 and 5 are presented the results obtained from the economic point of view considering the two cases of compensation: using a 3-phase capacitor bank and single-phase capacitor banks.

Table 4. The costs in the case of compensation to 0.92 in the PCC

Case I	
Active energy cost	6015 Lei/month
Reactive energy cost	191 Lei/month
Totally	6206 Lei/month
Capacitor bank investment	9600 Lei
Case II	
Active energy cost	6015 Lei/month
Reactive energy cost	0 Lei/month
Totally	6015 Lei/month
Capacitor bank investment	3590
Case III	
Active energy cost	6015 Lei/month
Reactive energy cost	0 Lei/month
Totally	6015 Lei/month
Capacitor bank investment	2900 Lei

Table 5. The costs in the case of compensation to unity in the PCC

Case I	
Active energy cost	6015 Lei/month
Reactive energy cost	446 Lei/month
Totally	6461 Lei/month
Capacitor bank investment	7400 Lei
Case II	
Active energy cost	6015 Lei/month
Reactive energy cost	0 Lei/month
Totally	6015 Lei/month
Capacitor bank investment	5057 Lei
Case III	
Active energy cost	6015 Lei/month
Reactive energy cost	0 Lei/month
Totally	6015 Lei/month
Capacitor bank investment	3800 Lei

By analysing the obtained results there can be observed the followings:

- In the case that the compensation is realized using the phase angle control on one phase, on the other phases can appear an over-compensation situation so that is reached a function under capacitive operating states.
- Also in the 1st case of compensation it can appear the situation in which the power factor in the common coupling point is capacitive. In this case, besides the electric effects that include the power networks that work under capacitive states there appear financial losses. This aspect is well proved in table 4;
- In the case in which the reactive power is compensated considering the power factor measured in the PCC, it can be observed that on some phases the system is working with an inductive power factor, under-compensated, and on others the power factor is capacitive, with the corresponding consequences from the electric point of view (on the phases that have inductive cosφ the voltages are lower than the nominal values, while on the capacitive ones the voltages grow);
- In the case of the 3rd alternative compensation, with single-phase capacitors banks, it is always obtained a framing between the desired thresholds;
- From the economic point of view, it can be observed that the 1st compensation alternative is the most unfavourable, because the investment is almost double in compare with the other two situations.

CONCLUSIONS

Taking in consideration that a low power factor needs supplementary investments for the over-dimension of the production, transport and distribution of electrical energy installations, it was tried to compensate it using special means.
In this paper, the authors propose a new strategy to improve the power factor using single phase capacitor. Every capacitor is connected through a static circuit breaker and the control strategy aims calculating the right value of the control signal on every phase according to the real amount of the consumed reactive power.
The advantages of using single-phase capacitor banks can be resumed as follows:

- The power factor compensation is realized individually on each phase so that there are avoid the capacitive operating states on some phases that can appear in the case of three-phase compensation (case 1 and 2);
- The voltage levels in the PCC are kept within the thresholds, thus no cases in with the voltage on a phase is higher than the one from the supply station have appeared;
- The investment made in the capacitor bank from case 3, according to the actual market prices, is lower than the ones from the other cases, consequently resulting a lower investment so a quicker investment recovery.

Taking in consideration these aspects, the use of single-phase capacitor banks can become a viable alternative for the compensation of strong unbalanced consumers.

REFERENCES

[1] Balaurescu D. and Eremia M. Imbunatatirea factorului de putere. Editura Tehnica, 1981.
[2]. Jerry C. Whitaker. AC Power Systems Handbook. Second edition. CRC Press, 1999.
[3] Golovanov N., Postolache P., Toader C., Eficienţa şi calitatea energiei electrice, Editura AGIR, Bucureşti 2007.
[4] Golovanov N. et all. Instalaţii electroenergetice si elemente de audit industrial. Editura Tipogal, Galaţi, 2008.
[5] Golovanov Carmen, Mihaela Albu, ş.a., Probleme moderne de măsurare în electroenergetică, Editura Tehnică, Bucureşti, 2001.
[6]. Cziker, A. şi Chindris, M. Compensarea regimului permanent dezechilibrat la consumator. Teorie. Aplicaţii. Editura Mediamira, Cluj-Napoca, 2003.