Power factor improvement in three-phase networks with unbalanced inductive loads using the Roederstein ESTAmat RPR power factor controller

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Abstract. The paper presents the analysis of a power factor with capacitors banks, without series coils, used for improving power factor for a three-phase and single-phase inductive loads. In the experimental measurements, to improve the power factor, the Roederstein ESTAmat RPR power factor controller can command up to twelve capacitors banks, while experimenting using only six capacitors banks. Six delta capacitors banks with approximately equal reactive powers were used for experimentation. The experimental measurements were carried out with a three-phase power quality analyser which worked in three cases: a case without a controller with all capacitors banks permanently parallel connected with network, and two other cases with power factor controller (one with setting power factor at 0.92 and the other one at 1). When performing experiments with the power factor controller, a current transformer was used to measure the current on one phase (at a more charged or less loaded phase).

1. Introduction

The paper presents the analysis of a power factor improvement in three-phase network with unbalanced inductive loads using capacitors banks, without series coils.

Power factor (PF) is an important power engineering parameter. PF measured must be greater than neutral PF (0.92 for low voltage, and 0.95 for medium and high voltages). An artificial solution to increase the PF is to connect capacitors banks (CBs) in parallel with electric loads, which create capacitive reactive power (opposite with inductive reactive electric power), so, the overall reactive power decreases. CBs can be connected on the low or medium voltage. Capacitors values must be calculated and chosen to improve PF [1-4].

Increasing of the PF in industry can be achieved by natural means (e.g. choosing the right electric motors and transformers, reducing free running time, achieving high quality repairs of electrical equipment, changes of induction motors with synchronous motors) and/or by artificial means (using of synchronous compensators, static VAR compensators, CBs controlled by power factor controller - PFC). The use of CBs is a common solution to improve PF in low voltage electrical installations [3-6].

To improving of PF in the low voltage substation, CBs connection can be done manually or automatically (e.g. with a PFC).

To improve PF with CBs (for a single large power electric motor or for a group of electric motors), the effect of nonlinearity becomes significant and current waveforms deviate more from sine shape [4-11]. Electric waveforms (current or voltage) can be decomposed into fundamental (frequency 50
Hz) and harmonics, through Fast Fourier transform. Passive, active, or hybrid filters, can be used with CBs to improve power quality of the grid [6, 7, 9].

Experimental measurements were performed on the network with three-phase inductive loads (two three-phase induction motors) and, also single-phase inductive loads (low-pressure mercury lamps and high-pressure mercury lamp with inductive ballast) that are connected on the same phase [4, 5, 11, 12].

It is observed that the PFC controls the power factor close to the set value, for the phase on which the phase shift is measured, and on other phases, the power factor is not adjusted properly.

Operation limitations of the three-phase controller that measures the power factor on a single phase will be evaluated. It is also noted that the improvement of the power factor will increase the deformation of the phase currents.

2. Power quality and harmonics effects

The main disruptive phenomena of the power quality are:

- frequency variations;
- long-term interruptions;
- transient over-voltages;
- harmonic and inter-harmonic;
- slow variations in the effective voltage value;
- voltage shocks, short-term interruptions;
- voltage fluctuations/flicker;
- unbalances of the three-phase voltage system.

In an ideal energy system (perfectly clean), the voltage and current curves are perfectly sinusoidal. In practice, non-sinusoidal currents occur if the load is non-linear in relation to the applied voltage [13-15].

2.1. Some indicators of power quality

The power quality analyser CA 8334B can computes up to 50 harmonics rank [16, 17].

The RMS values of voltage and currents are:

\[
V_{RMS} = \sqrt{\frac{1}{N} \sum_{j=0}^{N-1} (V_{ji})^2}
\]

\[
I_{RMS} = \sqrt{\frac{1}{N} \sum_{j=0}^{N-1} (I_{ji})^2}
\]

where \( i \) is L1, L2 or L3.

Total harmonic distortion of voltages and currents:

\[
V_{THD} = \sqrt{\frac{\sum_{n=2}^{50} (V_{ni})^2}{V_1}} \cdot 100
\]

\[
I_{THD} = \sqrt{\frac{\sum_{n=2}^{50} (I_{ni})^2}{I_1}} \cdot 100
\]

Crest factor voltage and current can be compute with:
\[ V_{CFi} = \max \left( \frac{\left| V_{pp \; i} \right|}{\sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N-1} \left( V_{ni} \right)^2}} \right) \] (5)

\[ I_{CFi} = \max \left( \frac{\left| I_{pp \; i} \right|}{\sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N-1} \left( I_{ni} \right)^2}} \right) \] (6)

Positive voltage and negative voltage are given by relations:

\[ V_+ = \frac{V_1 + aV_2 + a^2V_3}{3} \] (7)

\[ V_- = \frac{V_1 + a^2V_2 + aV_3}{3} \] (8)

The unbalance voltage and currents are calculated with:

\[ V_{unb} = \frac{V_-}{V_+} \cdot 100 \] (9)

\[ I_{unb} = \frac{I_-}{I_+} \cdot 100 \] (10)

Power factor (including harmonics) is given by:

\[ PF = \frac{P}{S} \] (11)

3. **Power factor improving with capacitor banks**

The role of capacitor banks is to provide the reactive power required for inductive loads. The goal of the capacitor banks are:

- decreasing of the phase current;
- increasing the voltage level for electric loads;
- reduction of the active and reactive power losses;
- improving the power factor of the source;
- reduction total consumption at power source.

Compensation of reactive power with capacitors banks also has the following advantages:

- the installations are static, have no wear parts, so there is no need for expensive improvement or surveillance;
- it has a relatively low gauge and can be located at any point;
- the active power losses are relatively low (2-6 W/kVAr).

4. **Power factor improving in electrical networks with power factor controllers**

In the experimental installation, a 12-steps ESTAmat RPR power factor controller (from VISHAY, Germany) and three phase power quality are used (Figures 1, 4, 5, 6) [12], [17].
Figure 1. Electrical setup with ESTAmat RPR controller

- K1.....K6 - power relays, RI 13 type;
- CT – current transformer, with transformation ratio 15A/5A connect on the phase L1.
Inductive three-phase loads used in experiments are two induction motors:
- Motor 1 (M1): power: 0.75 kW; current: 2.1 A; efficiency: 0.72; power factor: 0.76; rotation: 1350 rpm; shaft diameter: 19 mm – Figure 2;
- Motor 2 (M2): power: 0.25 kW; current: 0.85 A; efficiency: 0.62; power factor: 0.72; rotation: 1350 rot/min; shaft diameter: 14 mm – Figure 3.

Figure 2. Induction motor M1
Figure 3. Induction motor M2

Figure 4. Power switch S1
Figure 5. Power quality analyser CA 8334 B

Figure 6. ESTAmat RPR controller
Single-phase inductive loads are lamps:
H1 – Hg fluorescent lamp with magnetic ballast, 2 x 20 W;
H2 – Hg high pressure lamps, 125 W;
H3 – Hg fluorescent lamp with magnetic ballast, 2 x 20 W.

In experiments, where used six capacitor banks, in delta connection (Figure 7, two capacitor banks in one box). The electrical parameters for capacitor banks, delta connection, are:
- Capacitors bank 1, B1: C1=3x3.78µF/400V, Qb1=571 VAr;
- Capacitors bank 2, B2: C2=3x4µF/400V, Qb2=616 VAr;
- Capacitors bank 3, B3: C3=3x3.71µF/400V, Qb3=560 VAr;
- Capacitors bank 4, B4: C4=3x3.9µF/400V, Qb4=588 VAr;
- Capacitors bank 5, B5: C5=3x4.12µF/400V, Qb5=622 VAr;
- Capacitors bank 6, B6: C6=3x3.6µF/400V, Qb6=542 VAr.

**Figure 7.** Capacitors banks used in experiments

### 5. Experimental measurements
In the following experiments with the current transformer, the current was measured on phase L1. The current transformer connected to the PFC input. The single-phase loads were connected between L1 and null, at experiments 1, 2 and 3. At experiments 1 and 2 the single phase consumers were connected between L1 and null, and at experiment 3 between L2 and null.

#### 5.1. Experiment 1, power factor controller with DPF set=1
The stages at experiments 1 are shown in Table 1.

**Table 1.** Stages at first experiment DPF set = 1

| Measuring stages | DPF (-) |
|------------------|---------|
| 1. Motor M1 connected | 0.12 i |
| 2. Capacitors banks B1, B2 connected | |
| 3. Motor M2 connected | 0.64 i |
| 4. Lamp H1 connected | 0.6 i |
| 5. Capacitors bank B3 connected | 0.6 i |
| 6. Lamp H3 connected | 0.91 i |
| 7. Lamp H2 connected | 0.48 i |
| 8. B4, B5, B6 connected | 0.98 c |
9. Motor M1 disconnected  0.58 i
10. Capacitors banks B1, B2 disconnected  1
11. Lamps H1, H3 disconnected  0.64 i
12. B3 disconnected  0.92 i
13. B4 disconnected  0.94 c
14. Motor M2 disconnected  0.88 c
15. Lamp H2 lamp disconnected  0.06 c
16. Capacitors bank B5 disconnected  -
17. B6 disconnected  -

M2 and H1 were connected, and then PFC connected capacitors banks B1 and B2, DPF = 0.6 (Figures 8-11).

An then, after a period of time, PFC was connected capacitors bank B3 (Figures 12, 13).
After a while were connected all electrical loads (M1, M2, H1, H2, H3), and the power factor controller was connected all capacitors banks: DPF = 0.98 capacitive (Figures 14, 15).
H1 and H3 were disconnected and, after a short time, B3 and B4 were disconnected by PFC, \( \text{DPF}_m = 0.63 \) inductive.

5.2. Experiment 2, power factor controller with DPF set = 0.92

The stages at experiments 2 are shown in Table 2.

| Measuring stages                        | DPF (\( \cdot \)) |
|-----------------------------------------|------------------|
| 1. Motor M1 connected                   | 0.12 i           |
| 2. Capacitors bank B1 connected         | 0.29 i           |
| 3. Capacitors bank B2 connected         | 0.79 i           |
| 4. Motor M2 connected                   | 0.63 i           |
| 5. Lamp H1 connected                    | 0.59 i           |
| 6. Capacitors bank B2 connected         | 0.99 i           |
| 7. Lamp H3 connected                    | 0.9 i            |
| 8. Lamp H2 connected                    | 0.47 i           |
| 9. Capacitors banks B4, B5 connected    | 0.9 i            |
| 10. Motor M1 disconnected               | 0.74 i           |
| 11. Capacitors banks B1, B2 disconnected| 0.92 i           |
| 12. Lamps H1, H3 disconnected           | 0.86 i           |
| 13. Capacitors bank B3 disconnected     | 0.95 i           |
| 14. Motor M2 disconnected               | 0.82 i           |
| 15. Capacitors bank B4 disconnected     | 0.9 i            |
| 16. Lamp H2 is connected                | -                |
| 17. Capacitors bank B5 disconnected     | -                |

M1 and M2 were connected, and in a short time B1 and B2 were connected, \( \text{DPF}_m = 0.63 \) inductive (Figures 19, 20).
H1 was connected and after a short period of time, B3 was connected by PFC, $\text{DPF}_m = 0.99$ inductive (Figures 21-23).

Then H3 and H2 were connected, and, after a short period of time, B4 and B5 were connected by PFC, $\text{DPF}_m = 0.9$ inductive (Figures 24-26).
Figure 24. Phases’ currents and the null current

Figure 25. Fresnel diagram for currents

Figure 26. Harmonic spectra for currents

H1 was connected and then, immediate, B3 was connected by PFC, $\text{DPF}_m = 0.99$ inductive (Figures 27, 28).

Figure 27. Voltage and current on phase L1

Figure 28. Voltage and current on phase L2

And then, H3 and H2 were connected, and then immediate B4 and B5 were connected by PFC, $\text{DPF}_m = 0.9$ inductive. It was disconnected M1 and then B1 and B2 were disconnected by PFC, $\text{DPF}_m = 0.92$ inductive. H1 and H3 were disconnected, B3 was disconnected by PFC, and $\text{DPF}_m = 0.95$ inductive.
M2 was disconnected and B4 was disconnected by PFC, DPF\textsubscript{m}=0.9. Finally, H2 was disconnected and B5 was disconnected by PFC.

5.3. Experiment 3, power factor controller with DPF set =0.92

At experiment 3, all single-phase loads were connected at phase L2, and the current was measure by current transformer on phase L1. The stages at experiments 3 are shown in Table 3.

| Measuring stages          | DPF (-)  |
|---------------------------|----------|
| 1. Motor M1 connected     | 0.12 i   |
| 2. Capacitors bank B1 connected | 0.29 i  |
| 3. Capacitors bank B2 connected | 0.77 i  |
| 4. Motor M2 connected     | 0.61 i   |
| 5. Lamp H1 connected      | 0.62 i   |
| 6. Lamp H3 connected      | 0.62     |
| 7. Lamp H2 connected      | 0.61 i   |
| 8. Motor M1 disconnected  | 0.24 c   |
| 9. Capacitors bank B1 disconnected | Low current |
| 10. Lamps H1, H3 disconnected | Low current |
| 11. Motor M2 disconnected | 0.11 c   |
| 12. Capacitors bank B2 disconnected | - |
| 13. Lamp H2 disconnected  | -        |

Initially, before introducing three phase and single phase consumers DPF\textsubscript{m} = 0.12 inductive (Figures 31, 32). Then M1 and M2 were connected, and in short time B1 and B2 were connected by PFC, DPF\textsubscript{m} = 0.61 inductive (Figures 33-35). Then the H1, H3 and H2 lamps are connected, but the PFC will no longer connect any CB, because the single phase consumers were connected to L2 phase and not to the current measuring phase, and DPF\textsubscript{m} = 0.61 inductive (Figures 36-38).

After disconnecting the motor M1, shortly after is disconnected the B1 by PFC, and after the motor M2 is disconnected the B2 is disconnected by PFC and DPF\textsubscript{m} = 0.11 (Figure 39). Also, the H1 and H3 lamps were disconnected from the second phase (L2).
It can be seen from this experiment that if the single phase consumers do not mount on the same phase as the current measure (with CT), they do not influence the insertion of the capacitors banks by the power factor controller, nor will the power factor reach the value set on the regulator, only a much lower value.
5.4. Experiment 4, capacitors banks permanently connected in the network
The all capacitors banks (CB1-CB6) are connected in the network and the PFC doesn’t use. Stages at experiments 4 are shown in Table 4. Three-phase and single-phase consumers were connected and disconnected in the same order as the other experiments. After disconnecting the motors and lamps H1 and H3, an inductive DPFm = 0.37 is obtained (Figures 40, 41).

| Table 4. Stages at fourth experiment, without controller |
|---------------------------------|------------------|
| Measuring stages               | DPF (-)          |
| 1. Motor M1 connected          | 0.35 i           |
| 2. Motor M2 connected          | 0.29 i           |
| 3. Lamp H1 connected           | 0.37 i           |
| 4. Lamp H3 connect             |                  |
| 5. Lamp H2 connect             |                  |
| 6. Motor M1 disconnect         |                  |
| 7. Lamps H1, H3 disconnected   |                  |
| 8. Motor M2 disconnected       |                  |
| 9. Lamp H2 disconnected        |                  |
Some aspects from experiments are shown in Figure 42.

As a result of the four experiments, it is noted that the six used capacitors banks only go into operation if the DPF is set to 1. If the DPF is set to 0.92, only five (from six) capacitors banks are used. If the single phase consumers are not mounted on the same phase on which the current is measured, the ESTAmat RPR controller does not take these into account when adjusting the DPF and fails to adjust the DPF to the set value. For this case (Experiment 3), only two capacitors banks from the six existing ones are used.

It is also noted that the insertion of capacitors banks by the controller in the circuit to improve the DPF leads to a significant increase in current deformation (increase THD currents) and increase, also, unbalance.
6. Conclusions
By using a power factor correction installation, there is provided: high power factor in the consumer supply network, thus maximum energy saving; low reactive energy costs; high efficiency of network connected electrical equipment and high power transfer capacity through cables. The results of the power factor improvement with the power factor controller are as follows: eliminates penalties; reduce load in transformer and equipment; reduces losses in transformers, cables and other equipment, and helps stabilize system voltage by increasing the apparent power available.

The power factor controller continuously measures the current and voltage, only one phase (e.g. L1). The current transformer is mounted on one phase, usually the most loaded, without taking into account the charging of the other phases. Very often, sub-compensation or over-compensation, with negative effects in the electricity network, occurs, on the other phases of the low-voltage electrical network.

Most controllers take into account the capacitor operating temperature and the resonance, but do not check at the same time the harmonic distortion of voltage and current on each phase.

There is an increase in the deforming regime with undesirable effects on the electrical network. Additional losses due to harmonic current circulation, reduced electrical machine efficiency, additional charge of capacitors banks, power cables heating, additional charging of null current, additional stresses of insulators.

Usually, currents from the power station are unbalance (there are a lot of single-phase consumers) and are strongly deformed (the total harmonic distortion for current may be 25-35 %). The currents have the following higher harmonics: 5th rank (<25%), 3rd rank (<20%) and 7th (<12%), with amplitudes higher than the other harmonics, 9-40 (<10 %).

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