DESIGN OF AUTOMATIC POWER FACTOR CONTROL SYSTEM

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Maintenance of the proper power factor is a very important matter for the industry and for the economy of any country. A study of the power factor values for a number of industrial plants in Botswana shows that they operate at power factors lower than the optimal values. If a plant power factor is different from its optimal value, this will cause considerable loses in terms of investments for larger power generation and supply equipment and in terms of heat dissipation from the supply lines and other equipment. To improve the power factor and keep it at an optimal value, there are a number of preventative measures, as well as corrective actions that could be implemented. The power factor of a plant changes, depending on the number of electrical units operating at a time. After a full analysis of the power factor issue and its optimal case, an automatic control is designed that may maintain the power factor of a plant within values close to optimal. Similar automatic power factor control system can be introduced for all industrial plants with unsatisfactory power factor throughout the country that can improve considerably the efficiency of power utilization

Keywords: Control system, power factor, power utilization, optimal value

1 INTRODUCTION

The utilization of electric energy is more economic when the phase shift φ between the current and the voltage is smaller. However, motors, transformers and other electromagnetic devices are peculiar in that they cause a significant and variable phase shift φ and therefore the power factor $\cos\varphi$ is very low. The effects of the low power factor operating plants may be any one or all of the following: overloaded supply cables, transformers and generators; increased losses in terms of heat dissipation; reduced load voltage level, resulting in sluggish motor operation; diminished illumination; and increased power costs, where a power-factor clause is enforced as a part of the rate structure [1,2].

It is well known that underloaded induction motors and transformers operate at lower power factors. Frequently a motor or a transformer is selected to handle the largest load, but usually operates at less than full load. Even if a motor or a transformer is fully loaded, its power factor is about $\cos\varphi = 0.8$, which in general is lower than an optimal targeted value. Since any low power factor puts a particular strain on power generation and transmission line, there is a standard requirement that customers must maintain a minimum power factor of $\cos\varphi = 0.9$ [3]. Although the best case would be to keep a maximum value of $\cos\varphi = 1$, in different countries the standard for optimal targeted power factor may vary within the limits from $\cos\varphi = 0.9$ to $\cos\varphi = 0.95$. This depends on the consideration if a country imports or produces equipment for correcting the power factor. Countries that import all the necessary corrective equipment have a targeted optimal power factor $\cos\varphi = 0.9$, while countries that produce all components of such equipment target $\cos\varphi = 0.95$. Any further increment beyond an optimal power factor causes unreasonable equipment capital costs as seen from Figure 1. The purpose of this paper is to show the design of a control system that maintains a targeted optimal power factor.

At Figure 1 is shown a typical graphical relationship between costs of corrective equipment, a loss due to poor power factor and the actual value of the power factor [1,3]. At one particular power factor the graph lines cross. This point gives the most economical level of power factor correction. As already discussed, this point may vary from $\cos\varphi = 0.9$ to $\cos\varphi = 0.95$ and for this particular case it is $\cos\varphi = 0.9$.

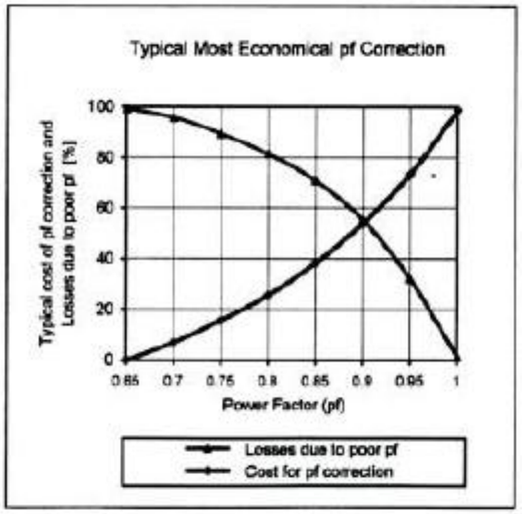

Figure 1. Typical Most Economical Power Factor Correction [1,3]

The three well-known methods for improving the power factor are: the preventive measures for full loading of motors and transformers; connecting shunt capacitors to loads and implementing synchronous motors in the case of very large loads [4]. The most effective and commonly used method is that of parallel power-factor correction, where shunt connected capacitor banks are implemented for proper compensation of the inductive load.

The power factor of a plant varies, depending on the loading and number of units connected at a time. Usually, there are three methods for connection of capacitor banks for power factor correction: individual (for individual loads), group (for a group of identical load) and central (for all the loads of a plant). In the central power factor correction, a joint bank of capacitors compensates the reactive power of inductive loads, each with varying power and with varying operating times. Since power factor varies in time during operation, the central power-factor correction is preferable. A study of a number of industrial plants in Botswana shows that they operate at quite low power-factors. For example, a case study at the Botswana Water Utilities Corporation shows that the average power factor is $\cos\varphi = 0.6$. Similar low power-factors are observed at other plants in the Botswana [5]. Since in this country, all the required power factor corrective equipment is imported and therefore is more costly, the targeted optimal power factor is $\cos\varphi = 0.9$ [5].

To maintain any targeted optimal plant power factor, the authors designed and simulated an electronic control system, implementing a central power factor correction approach. It automatically switches on or off the capacitive reactive power required to compensate the respective inductive reactive power. The electronic control system tracks continuously the load current and the voltage and automatically determines the phase difference between them. Therefore it closely follows the value of the load power factor [6]. Accordingly, the control system switches on just the necessary capacitance to maintain power factor close to the targeted optimal value $\cos\varphi = 0.9$. It is estimated that the investment in the automatic control system will yield reasonable long-term savings. Such control systems can be implemented in all industrial plants, operating with unsatisfactory power factors.

2 DEMONSTRATING THE EFFECT OF A TYPICAL POWER FACTOR CORRECTION

To demonstrate the effect of power-factor correction, a typical case of a motor operating under-loaded is suggested. After testing, the following results were taken: Supply voltage: $V = 240V$; Operating frequency: $f = 50Hz$; Motor current $I_1 = 8A$; Motor power: $P = 1.2kW$. To improve the power factor, a parallel capacitor is connected [3,6]. The equivalent circuit for the motor including the parallel corrective capacitor is shown in Figure 2.

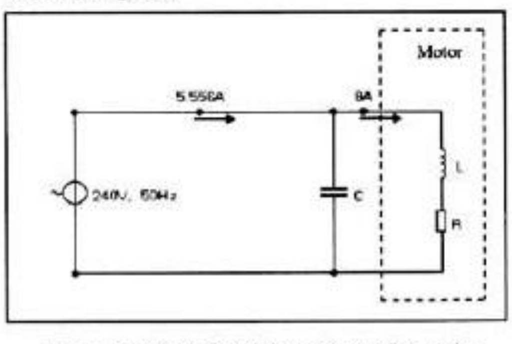

Figure 2. Principle of Power Factor Correction

The apparent power of the motor is:

$$S = IV = 8A \times 240V = 1920VA = 1.92kVA \tag{1}$$

In this case the active power of the motor is:

$$P = VI\cos\varphi = 1.2kW \tag{2}$$

The power factor of the motor is determined as:

$$\cos\varphi_1 = \frac{P}{S} = \frac{1.2kW}{1.92kVA} = 0.625 \tag{3}$$

The phase angle between the motor current and the voltage is:

$$\varphi_1 = \cos\varphi_1^{-1} = 51.32^\circ \tag{4}$$

The motor reactive power is:

$$Q = VI\sin\varphi = 1.5var \tag{5}$$

When a capacitor $C = 51\mu F$ is connected in parallel to the motor, the current I_C flowing in the capacitor has the effect of reducing the phase angle between the supply voltage and the supply current from $\varphi_1 = 51.32^\circ$ to $\varphi_2 = 25.84^\circ$ and the power factor becomes $\cos\varphi_2 = 0.9$. Also as a result, the supply current $I_1 = 8A$ is reduced to $I_2 = 5.556A$, as seen from the phasor diagram in Figure 3. From the phasor diagram the current I_C can be determined as:

$$I_C = \frac{P(\tan\varphi_1 - \tan\varphi_2)}{V} = 2\pi fCV \tag{6}$$

Then the required capacitance is be determined as:

$$C = \frac{P(\tan\varphi_1 - \tan\varphi_2)}{2\pi f V^2} \tag{7}$$

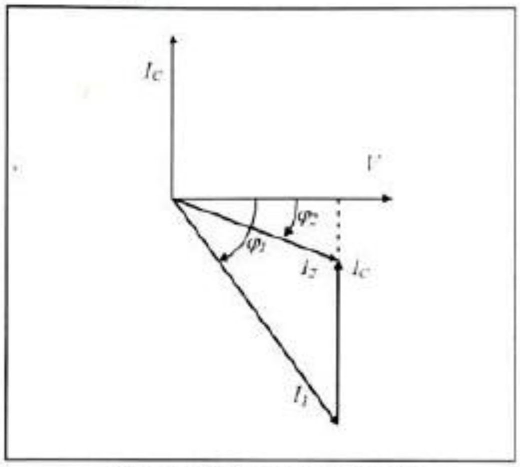

Figure 3. Current Phasor Diagram

Depending on the value of the capacitive reactive power Q_C, the inductive reactive power Q_L taken from the mains supply is thus wholly or partly compensated and reduced from Q_1 to Q_2, as seen from Figure 4.

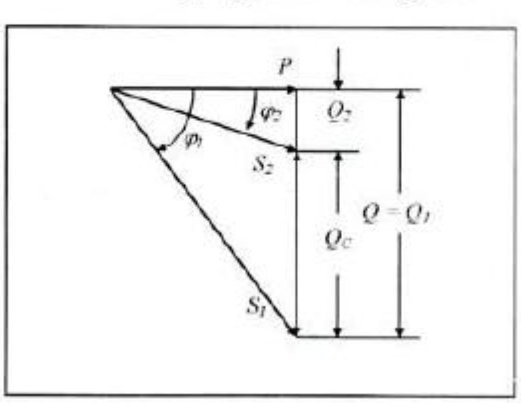

Figure 4. Power Phasor Diagram

The test is performed for different power factors and the results are placed in Table 1. Theoretically the best power factor correction occurs at the maximum value $\cos\varphi_2 = 1.0$. In this case the suggested targeted optimal power factor is $\cos\varphi_2 = 0.9$, since its corrective effect is very close to the best case, but the capacitance required is reduced from $83\mu F$ to $51\mu F$ (more than 60%), as seen from Table 1. The power- factor correction described for a single motor can be applied in a similar way to a whole industrial plant or for an entire region of a country.

Table 1

Power Factor	Supply Phase Angle	Capacitor Current (A)	Supply Current (A)	Capacitance Connected (μF)
0.65	51.32°	0	8	0
0.7	45.57°	1.144	7.143	15
0.8	36.87°	2.495	6.25	33
0.9	**25.84°**	**3.823**	**5.556**	**51**
1.0	0°	6.245	5	83

3 METHOD OF CENTRAL POWER-FACTOR CORRECTION

In installations with many loads of unequal power and with varying operating times, individual power-factor correction is usually too expensive. Also, in such cases, group power factor correction can only be realized in certain circumstances of predictable performance of the load. As a result, central power factor correction is mostly preferable. A joint bank of capacitors for all the loads is set up at a central point that is located at the low-voltage main distribution board. The capacitor's (leading) reactive power, required for operation at specific time and in each individual case is automatically switched on or off in steps by a control mechanism [5,6]. The plant's power factor can thus be kept approximately constant and independent of the fluctuating reactive power.

A specific circuit diagram of a central power factor correction, designed by the authors, is shown in Figure 5. The main switch connects the plant load to the supply line. The power factor of the plant varies, depending on the number of load units connected at a time. A sensor unit consisting of a voltage transformer and a current transformer continuously tracks the load current and the voltage. A feedback control system determines their phase difference and automatically switches on just the required number of capacitors from the capacitor bank to maintain power factor close to a targeted optimal value. The optimal value for Botswana is $\cos\varphi = 0.9$, since this country imports all the corrective equipment and any larger value, cannot be justified, because of unreasonable capital costs. By keeping the power factor at its optimal targeted value, the supply line current is maintained at a required designed value, while only the load current via the main switch changes according to the number of load units that are connected at a time. The reactive power is now exchanged mainly between the load units and the capacitor bank, rather than between the load and the source. Since the control system provides a full automatic maintenance of the desired power factor, no manual operation is required.

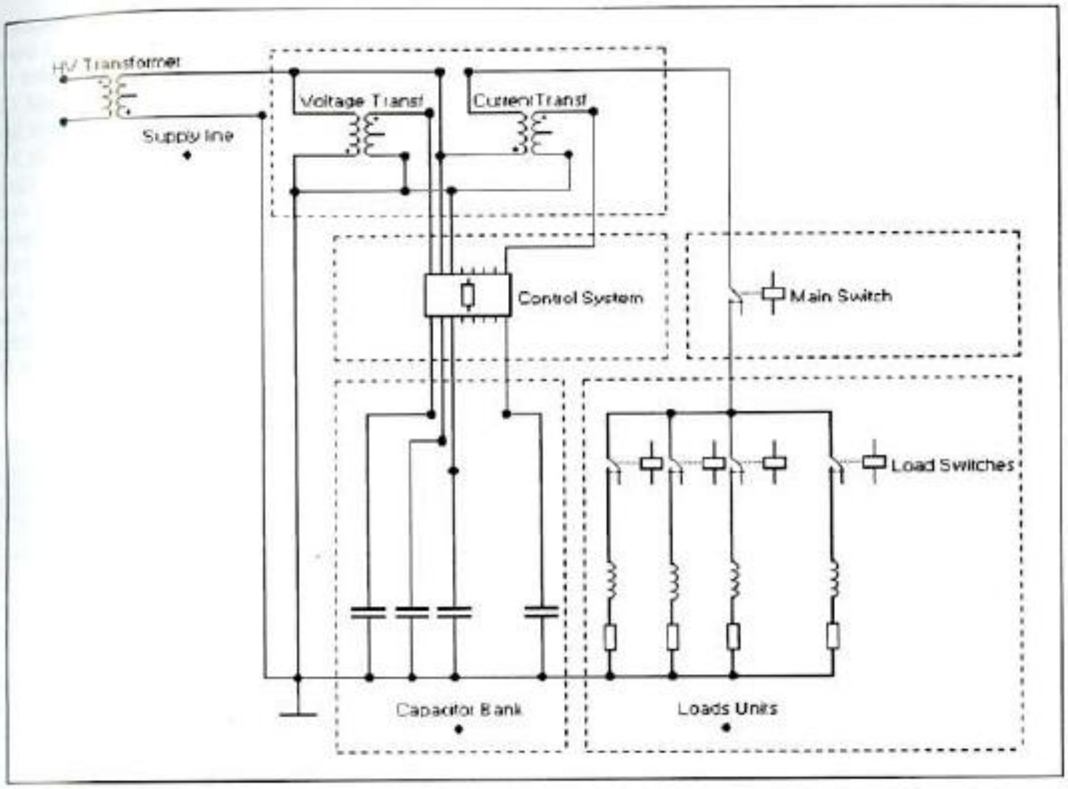

Figure 5. Circuit Diagram of a Central Power Factor Correction

4 PRINCIPLE OF FIVE-STEP SWITCHING CONTROL

With central power factor correction, the reactive power and the number of switching steps selected depend on the operating conditions [5,6,13]. The direct static thyristor switching of capacitor banks is considered as a very costly method, because of the much larger number of equipment involved. It is suggested that the five-step combination is providing the most favorable and less costly solution for the central power factor correction. For example, if the necessary capacitive (leading) reactive power is 50 kvar, a subdivision of kvar in the ratio respectively of 1:2:2 is applied. Only three capacitors can be used, providing 10, 20 and 20kvar accordingly. If connected in a five-step combination, a gradual increment of the capacitive reactive power is achieved, as show in Figure 6. In this way, the reactive power supplied, is a close match to the one required for obtaining an optimal power factor correction. In case of larger plants, with considerable variation of load operating times and requirement for more accurate power factor correction, larger number capacitors are used. For example, if the required capacitive reactive power is 100 kvar, a subdivision of kvar in the ratio of 1:1:2:2:2:2 can be applied. Six capacitors provide 10, 10, 20, 20, 20 and 20kvar accordingly. The five-step combination shown in Figure 6 is applied repeatedly as follows:

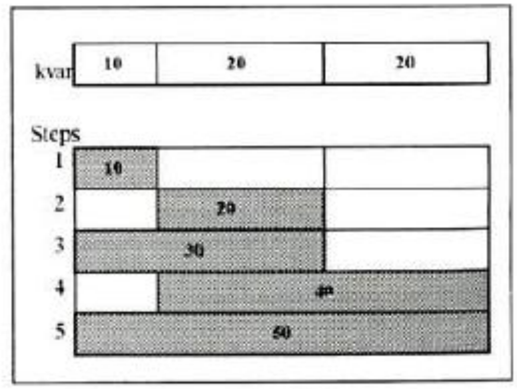

Figure 6. Five-Step Combination of Capacitive Reactive Power Control

In case of larger plants, with considerable variation of load operating times and requirement for more accurate power factor correction, larger number capacitors are used. For example, if the required capacitive reactive power is 100 kvar, a subdivision of kvar in the ratio of 1:1:2:2:2:2 can be applied. Six capacitors provide 10, 10, 20, 20, 20 and 20kvar accordingly. The five-step combination shown in Figure 3 is applied repeatedly as follows:

Step 1 1×10 = 10kvar
Step 2 1×20 = 20kvar
Step 3 1×10+ 1×20 = 30kvar
Step 4 2×20 = 40kvar
Step 5 1×10 + 1×20 + 1×20 = 50kvar
Step 6 2×10 + 1×20 + 1×20 = 60kvar
Step 7 1×10 + 2×20 + 1×20 = 70kvar
Step 8 2×10 + 2×20 + 1×20 = 80kvar
Step 9 1×10 + 2×20 + 2×20 = 90kvar
Step10 2×10 + 2×20 + 2×20 =100kvar

Using this approach, additional reactive power increment may be achieved if required. Also, any other reactive power values can be used, but for each set of 1 to 5 steps, always the subdivision of kvar in the ratio of 1:2:2 is applicable.

5 THE CONTROL SYSTEM DESIGN

The block shown in Figure 5, labeled as "Control System" is represented in detail as a full electronic circuit in Figure 7. The control system circuit is entirely designed by the authors and is unique in its way of automatic tracking of the actual power factor value, comparing it with a reference targeted optimal value and accordingly implementing the five-step control method of correction. The purpose of the control system is to monitor the phase difference between the voltage and the load current of the plant so as to achieve the corresponding combination of capacitive reactive power connection or disconnection. The operation of the real system was simulated with the aid of the software package "Electronics Workbench" [7].

Two ac sources (Voltage Transformer and Current transformer) are used to simulate the voltages obtained at the secondary windings of the voltage and the current transformers, connected to the main supply line respectively. The operational amplifiers OA1 and OA2 operate as Zero Comparators [8,9]. When the input voltages at OA1 or OA2 become larger than 0V, their outputs switch to logic high level. Since the supply line voltage has a sine waveform, the two output signals obtained at the output terminals 1-1' and 2-2' of the Zero comparators have square waveforms. Their phase difference is equal to the phase difference between the line voltage and the plant load current. The circuits C1, R5, D1, D3 and C2, R6, D2, D6 convert the square waveforms signals into positive pulses that can be observed at the terminals 3-3' and 4-4' respectively. These pulses control a Latch Circuit, operated by Q1 and Q2 [10,11,12]. At each period of the line voltage, it produces a positive square waveform pulse at terminals 5-5'. The width of this pulse represents exactly the phase difference between the line voltage and the plant load current. The circuit R13, R14, C6 converts this pulse into a ramp voltage, which change within the phase difference considered and can be observed at terminals 6-6'.

The ramp voltage is next applied to an Angle Detector, which consists of five amplifiers: OA3, OA4, OA5, OA6 and OA7 operating as different voltage level comparators. A voltage divider, consisting of R20, R21, R22, R23, R24, R25, provides five different reference voltages: 0.6V, 1.2V, 1.8V, 2.4V and 3V respectively. Each one of them is applied to the corresponding comparator. These voltages are compared at each period of operation with the linear ramp voltage that is applied simultaneously to all comparators [11,12]. Depending on the phase difference between the line voltage and the load current, the ramp voltage may reach different levels. If the phase difference is 10°, the output of comparator OA3 switches to logic high level, but the output voltages of all other comparators are zero. If the phase difference becomes 20°, OA3 and OA4 switch to logic high level, while all the others have zero outputs. Only when the phase difference becomes 50°, or more, then all the comparators have logic high level. The Zener diodes D5, D6, D7, D8 and D9 limit the output voltages of the angle detecting comparators to 3.5V, which corresponds to a digital logic high level of 1. This voltage level is made suitable for application to the digital electronic circuit element that is the Priority Encoder. The set of capacitors C7, C8, C9, C10 and C11 operate as sample-and-hold circuits at the outputs of the angle detection comparators. They keep the achieved final comparator output voltage for a time larger than the period of the line voltage. Every next line voltage cycle restores and confirms the real comparator output, depending on the load power factor. Hence, an input to the Priority Encoder keeps its magnitude if there is no change in the power factor. It may drop from logic level 1 to logic level 0 only if there is a change in the power factor and hencee in the longer-term logic level condition of the comparator output.

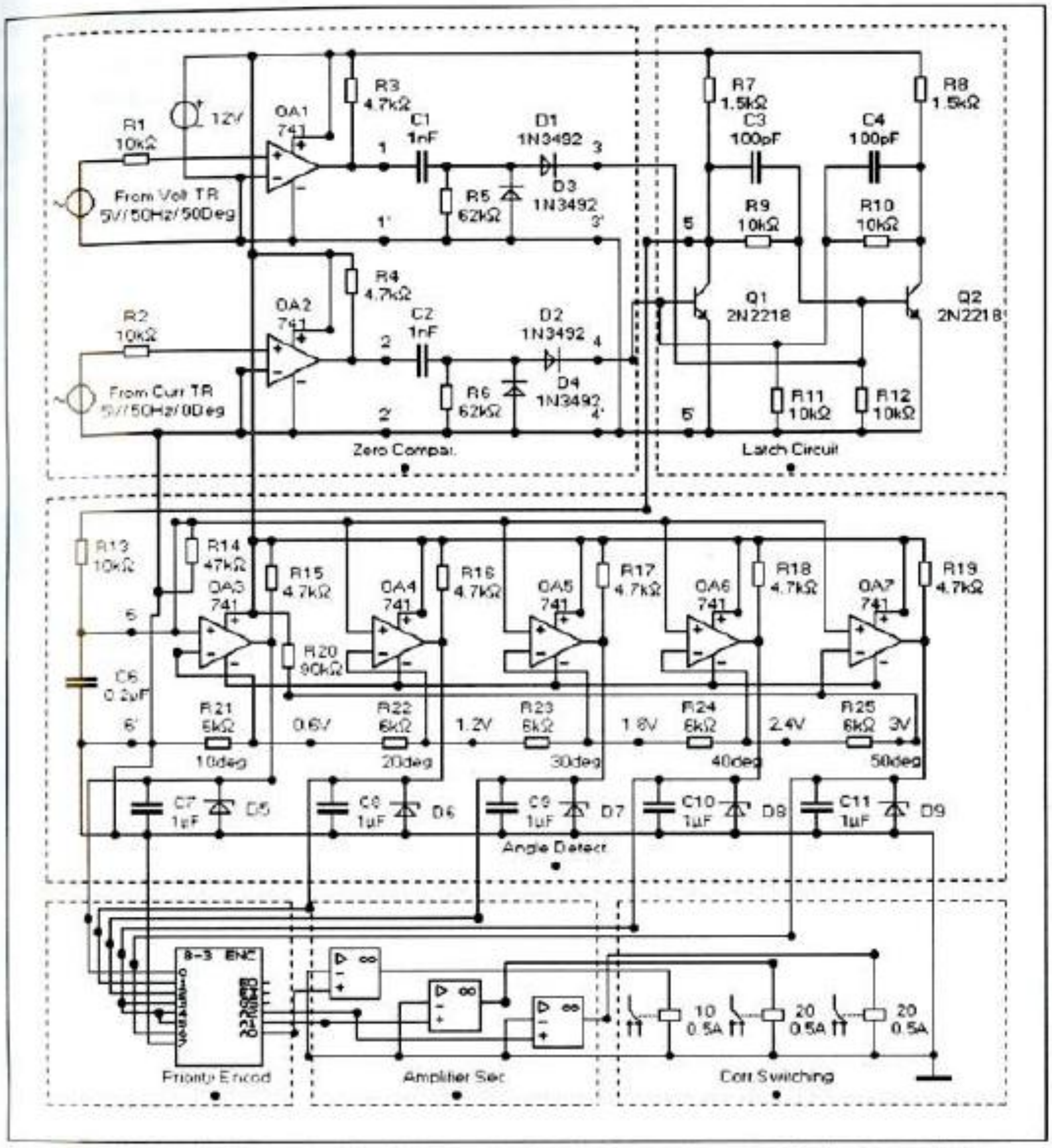

Figure 7. Control System for Automatic Control and Maintenance of a Targeted Optimal Power Factor

The Angle Detector unit can be used for a direct switching of five power-factor correcting capacitors, but this would cause much larger investments for the power-factor correcting system. As already described, a proper five-step switching combination of corrective reactive power can use only three capacitors instead of five. It will be less costly, but equally effective. To achieve the five-step combination for the required capacitive reactive power connection, a Priority Encoder is employed. For better flexibility the control system is designed to operate for a phase difference between voltage and current from 10° to 50°, approximately corresponding to power factor from 0.95 to 0.6 respectively [13].

The truth table, for the operation of the Priority Encoder [14,15] is shown in Table 2. The five output conditions, useful for the five-step control of the power factor correction system are highlighted in the table. Only some of the combinations of the Priority Encoder can be useful for the five-step switching of reactive power, as seen from Table 2, [13,14,15]. These are the combinations **B**,**C**,**D**,G and **H**. They correspond to the successive five steps of corrective reactive power switching, described in Figure 6.

If the phase difference is less than 10°, combination **B** causes no active output of the Priority Encoder. All corrective capacitors are switched off. When the phase difference is larger than 10°, but less than 20°, the comparator OA3 activates combination **B**, the Priority Encoder output A0 becomes logic level 1 and step one of the five-step switching is performed. A 10kvar capacitive reactive power is switched in parallel to the load.

When phase difference is larger than 20°, but less than 30°, combination **C** is activated. Outputs of comparators OA3 and OA4 are logic level 1. The Encoder output A1 becomes logical level 1 and a 20kvar is switched on, thus increasing the required leading reactive power accordingly.

A phase difference between 30° and 40° activates combination **D**. Now the outputs of OA3, OA4 and OA5 are logical level 1, both A0 and A1 are logical level 1 and (10 +20) kvar are switched on. The total connected capacitive reactive power becomes 30kvar. Combinations A, E and F are not in use. For proper operation of the Priority Encoder input pin 3 is connected to pin 4 and pin 5, also pin 7 is grounded. [13,14]. From Table 2 and Figure 4 it can be seen that the comparator OA6 feeds simultaneously the Encoder inputs 3 and 4 and 5.

Further, for a phase difference between 40° and 50°, combination **G** is activated. The outputs of OA3, OA4, OA5 and OA6 are logical level 1. The Priority Encoder outputs A1 and A2 become logical level 1 and this switches on corrective reactive power (20 +20) kvar making it totally 40kvar.

Finally, for a phase difference larger than 50°, combination **H** activates. All angle detecting comparators: OA3, OA4, OA5, OA6 and OA7 have high logical level 1. The Encoder outputs A0, A1 and A2 become logical level 1. Then, a capacitive reactive power of (10+20 +20) kvar, or totally 50kvar is switched on in parallel to the inductive load.

It is evident that the switching combinations of the five-step control, shown in Figure 6, match exactly the highlighted five-step switching combinations of the Priority Encoder outputs, described in Table 2. The output terminals E0, EI and GS are not used in this control system and are left open. If necessary, they could provide system condition indication [13,14].

A three cannel Amplifier Section is applied for a proper buffering between the Priority Encoder and the Corrective Switching unit. Symbolically, the Corrective Switching unit is represented by a number of relays, but practically thyristor switches can achieve the switching electronically.

Table 2: Encoder in a five-step switching of reactive power

Input Comb.	Input Signals								Output Signals		
	7* Conn. to ground	6 From OA7	**5*** From **OA6**	**4*** From **OA6**	**3*** From **OA6**	2 From OA5	1 From OA4	0 From OA3	A2 Switching ON 20kvar	A1 Switching ON 20kvar	A0 Switching ON 10kvar
A	X	X	X	X	X	X	X	0	0	0	0
B	**X**	**X**	**X**	**X**	**X**	**X**	**0**	**1**	0	0	**1**
C	**X**	**X**	**X**	**X**	**X**	**0**	**1**	**1**	0	**1**	0
D	**X**	**X**	**X**	X	0	**1**	**1**	**1**	0	**1**	**1**
E	X	X	X	0	1	1	1	1	1	0	0
F	X	X	0	1	1	1	1	1	1	0	1
G	**X**	**0**	**1**	1	1	1	**1**	**1**	**1**	**1**	0
H	**0**	**1**	**1**	1	1	1	**1**	**1**	**1**	**1**	**1**

* Input pins **3**, 4 and **5** are connected together; 7 is grounded, as highlighted in the table

6 CONCLUSIONS

The described design for automatic control of an optimal power factor has been tested under normal laboratory conditions. The parameters of the simulated model are a scaled down equivalent of the actual system parameters. The power factor is tracked continuously by actually monitoring the phase difference between the load current and the supply line voltage. This is achieved by the Zero Comparator unit and the Latch Circuit. The suggested five-step combination for capacitance switching and hence corrective power switching involves considerable initial investment savings. It is operated through the applied logic solution, achieved by the Angle Detection unit and the Priority Encoder. The cost of the designed control system is around 500 Pula but its long-term implementation in practice can save hundreds of thousands Pula. Further considerable savings are achieved by using less capacitor banks, applying the five-step control.

The designed control system can be easily and directly applied for larger industrial plants. There might be a considerable variation of load operating times and also a probable requirement for more precise power factor correction. In such cases the five-step combination can be applied repeatedly as already described. For a two by five-step combination, ten comparators in the Angle Detector unit and two Priority Encoders are employed. If the number of the capacitors were increased, the savings would be even larger due to the suggested five-step combination of switching.

The implementation of the designed automatic control system for maintaining an optimal power factor definitely requires some initial investments. But once implemented, the system will deliver very shortly considerable long-term savings.

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