Hybrid system of power factor correction

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Abstract. The paper reviews research data of hybrid of reactive power compensation for Metro electric power substations. Comparative compensation analysis has been made and the control system for the suggested device has been developed; besides, mathematic simulation has been carried out, as a result of which the power factor of substation has been increased from 0.5 to 0.97-0.99.

1. Introduction

One of the energy users converting AC electric energy into DC in great amounts is the electric transport system, particularly Mass Rapid Transit (MRT Metro). Arising high-frequency distortions thus and the actively inductive type of load, which is the cause of current phase shift in terms of voltage, are the reason for a low value of Metro substation power factor. All energy users of Metro can be roughly divided into two groups. The first group is loads having low but constant power factor within 24 hours. They are such users as escalators, ventilation, lighting, pumps etc. (Figure 1a). Up to 40-50% of energy consumed by Metro is for this user group [5]. The key factor affecting negatively the energy quality in the present group is the current phase shift in terms of voltage. The second group is electric trains, the feeders wherein have a higher but variable over wide range power factor [Figure 1b].

Figure 1. Histogram of statistical density probability and the graph of statistical functions for the power factor of two groups of electricity consumers.

The great width of density probability of the power factor is due to an abruptly variable type of
energy consumption and availability of high-frequency components of consumption current because of using 6-pulse (the 5th and 7th harmonics) or 12-pulse (the 11th, 13th harmonics) rectification circuits. Traditional ways of reactive power compensation, such as applying capacitor banks (CB), passive filters etc. except for slow response, could be the cause of emerging electromagnetic resonance processes [7]. Higher-end static thyristor compensators (STC) and STATCOMs do not provide the shaping of compensation impact in real-time and distortion power compensation [6]. Because of these reasons, there is a shift to active power correction by the active power filter (APF) in recent years (Table 1). In the device, the generation of the compensation impact, reciprocal to a harmonic component value due to compensation, is implemented.

Table 1. Power factor compensation matching

| Function:                             | Type of compensators |
|--------------------------------------|----------------------|
|                                      | CB       | STC     | STATCOM | APF     |
| Regulation of compensation on the main harmonics | –        | step    | 10ms    | 0.2ms   |
| Higher harmonics reactive power compensation | –        | –       | –       | 50 harmonics |
| Adequation of phase load             | –        | –       | +       | +       |
| Smoothing active power peaks         | –        | –       | –       | +       |

2. Problem definition
The goal of this research is the design of hybrid reactive power compensation conforming to specifications of target user. To fulfill a set goal the following tasks are solved in research: to offer and describe the operation of hybrid reactive power compensation, to consider the question of developing control system of hybrid filter, to fulfill mathematic simulation the device as suggested in Matlab Simulink.

3. Theory
To date, APF is connected to grid by two main ways: in-series and in parallel. In the first case, APF is calculated by total current of a consumer and controlled by the phase to earth voltage resulting in high capacity, which is equivalent of high cost. APF connection in-parallel is more common because of a more flexible approach to choosing nominal power, compensation possibility of various pulse types, imbalance and phase shift, and harmonic distortions of converter units [8].

APF consists of three-phase inverter, the crucial components of which are Insulated Gate Bipolar Transistor (IGBT), smoothing – inductors, capacitor bank (CB) which is a source of reactive energy, and also control microprocessor generating control signals for assigning compensation action based on the information from current and voltage sensors. The initial charge of capacitor bank is constructed without using supplementary power supply.

A self-excited inverter is usually actualized using two-level circuit of IGBT-inverter. The inductance value of smoothing-inductor is calculated due to smoothing conditions of pulse width modulation (PWM) and the possibility to secure high current range.

APF could solve several parallel tasks simultaneously. Besides reactive power compensation in main harmonic and higher harmonic compensation caused by nonlinear distortions, APF could accomplish load distribution between phases. This capability allows decreasing greatly difference of potential between neutral conductor and ground in four-wire system. APF is insensitive to great changes of grid impedance which can occur for instance when switching from mains supply to generating set feeding. The use of digital controllers provides reliability, versatility and system accuracy.

For reactive power compensation in supply system of Metro, the hybrid reactive power compensator, containing CB with step regulation for compensation current phase shift with regard to
phase voltage and APF for compensation high-frequency distortions, can be considered (Figure 2). Moreover, it is necessary to increase CB part because of a high cost of APF devices.

![Connection diagram](image)

**Figure 2.** Connection of APF and CB to grid: C - capacitor bank; L - three-phase inductor; AVI - autonomous voltage inverter; CS - control system; VSU1, VSU2 - ventilating supply units; IU - indicating unit; UPS - uninterruptable power source.

Power factor will be increased arising from both current phase shift in terms of voltage and distortion power correction. Besides there will be an opportunity to implement equal phase load and to apply other possible improvements in quality of electric energy available with APF. Also hybrid reactive power compensator will have less cost than pure APF with the same power.

![Bargraphs](image)

**Figure 3.** Compensator operation areas.

Figure 3 shows bargraph changes of static density probability of power factor: a) prior to using filters; b) when using CB and APF. CB with step regulation shifts power factor toward great values, and APF decreases the width of distribution probability range by means of distortion power compensation of higher harmonics up to values 0.97-0.99. Load leveling between phases is also included in APF tasks and smoothing of fast active power peaks. Modern control systems of active power filters are based on the fastest design method of instantaneous power. One of the first scientists who graded instantaneous sinusoidal current into active and reactive component was S. Fryse [4]. His approach is based on calculations of root-mean-square and math integration device given the grave
impact on dynamics of high reactive power compensators. The instantaneous power theory was taken further in Japan in 1980s where the p-q theory was framed by the think tank chaired by H.Akagi. Some time later the theory was elaborated to the modified p-q theory \[1-3\]. The theory made a breakthrough in the field of active power filter design as it made possible to use active methods of power factor correction. The further development H. Akagi theory received as p-q-r, d-q formula \[10, 11\]. It increased the system response speed due to the decrease of calculation amount.

\[ S = \bar{p} + \bar{p} + \bar{q} + \bar{q} \]  

If total power could be presented as the sum: \( \bar{P} \) - active constant component; \( \bar{p} \) - active variable component; \( \bar{q} \) - reactive constant component; \( \bar{q} \) - reactive variable component. Then as a power compensation both all components of equation (1) except \( \bar{P} \) or its separate elements can be chosen e.g. the sum \( \bar{q} + \bar{q} \). In case of the hybrid filter, CB with step regulation compensates the reactive constant component:

\[ CB = \bar{q} \]

As steps of capacity connection to grid does not provide an opportunity to compensate accurately all reactive constant component, there is an uncompensated residue:

\[ \bar{q}^* = \bar{q} - \bar{q}_{CB} \]  

which will be compensated by APF in combination with \( \bar{q} \).

\[ APF = \bar{q} + \bar{q}^* \]

The control system of the hybrid reactive power compensator is functionally described as follows:

\[ P_{dq} = (u_d - j u_d) (i_d - j i_d) = P_p - j q_p \]

where \( P_p, \ q_p \) – real and fictitious power:

\[ P_p = \text{Re}(P_{dq}) = u_d i_d + u_q i_q \]  

\[ q_p = \text{Im}(P_{dq}) = u_d i_d - u_q i_q \]  

**Figure 4.** Functional scheme of control system.
Zero component power is:

\[ p_0 = u_0 i_0. \]  

(6)

A full–power at states dq0 equals S at states αβ.

\[ S_{dq0} = \sqrt{(Re(p_{dq}) + p_0)^2 + (Im(p_{dq}))^2} = S_{\alpha\beta}. \]  

(7)

4. Experimental results

Mathematical modeling of the hybrid filter operation was carried out in Matlab Simulink. Active-inductive load was energized from the three-phase three-wire source of the sinusoidal voltage and one also introduced higher harmonics into the grid. In parallel to this system, a passive capacitive filter, which performed a phase shift of the current, and an active power filter that smoothed high-frequency nonlinear distortions were connected.

Figure 5 shows the simulation results. Figure 5a shows the voltage and current of phase A without using filters, \( \cos \phi \) load is 0.6, and also the 5th, 7th, 11th and other harmonics are present. When a passive filter is connected, the phase of the current shifts to \( \cos \phi = 0.96 \), nonlinear distortions are present (Figure 5b).

Figure 5c shows the oscillogram of the active power filter correction current, its spectral analysis characterizes the operation of APF and shows that the active filter introduces higher harmonics into the grid, leveling the nonlinear distortions of the load current. Resulting current - the current of the grid (Figure 5d) has a sinusoidal shape with a fundamental harmonic equal to 96% of the first harmonic of the load current. Except correction of the current shape APF performs a more accurate shift of the phase current characteristic, as a result of which \( \cos \phi \) reaches values of 0.99. The compensation current is 56% of the load current. The higher harmonics constitute <1% of the fundamental.

5. Conclusion

During the research a hybrid device of reactive power compensation consisting of passive filter-capacitor bank with step regulation and active power factor corrector was proposed. The control system of this device and mathematic simulation of APF in Matlab Simulink are also represented. The
Simulation results show an increase of power factor system to the level of 0.97-0.99. The further research will be aimed to study the system of controlling filters with a focus on improving its dynamic properties and to develop a physical prototype to 250 kVA.

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