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# HYBRID ANTI–RESONANCE CAPACITOR SYSTEM FOR POWER FACTOR CORRECTION

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**ABSTRACT**
This paper presents a hybrid compensator as a combination of three-phase shunt *LC* passive compensator connected in series with a small-rating active compensator. The main objective of the presented hybrid capacitor system is to compensate reactive power. The active part of the filter is used to prevent the resonance amplifications of current harmonics. As a result, no harmonic resonance occurs under any system condition. The effectiveness of the hybrid compensator is presented in a real industrial network and verified by digital simulation.

**KEY WORDS**
Power factor correction, impedance characteristics, resonance damping, hybrid compensator.

## 1. Introduction

Due to the introduction of the electricity market and the increasing sensitivity of consumers to power quality also the awareness of problems caused by harmonic distortion is growing. In the last decade a great increase in the number of large adjustable-speed motor drives and a vast variety of other nonlinear loads used in industrial networks has been witnessed. Nonlinear loads are known to be a major source of current harmonics. In addition to that, the basic component of the reactive power is required for operation of most of these loads. Both can contribute greatly in reducing the electrical power quality and the performance of the power system. Operation of these devices may therefore prove to be very problematic [1].

To limit negative effects of harmonic distortion, recommended guidelines determine the levels of permitted harmonic distortion in the supply voltage [2]. Limiting the harmonic distortion to meet EN 50160 standard and also to prevent devices to be overloaded with excessive harmonic currents is very important to industrial customers. Equally important, if not even more, is reactive power compensation, as utilities charge the customer with penalties for poor power factor at the customer-utility point of common coupling (PCC).

The key role in providing the appropriate parameters of the quality of electricity is played by modern compensation devices. With regard to basic structure, compensators can be classified into passive and active, of which the latter are based on power electronics. Passive compensators represent established technology. However, there are some problems regarding their operation due to the growing number of electronic devices in the network. Beside their fundamental task of reactive power compensation they may cause unwanted resonance conditions and amplification of harmonics. Their other most notable limitations are their inability to adapt to the changing conditions in the network and their size. With the development of power electronics, active compensators are growing in importance, because they do not cause resonance with the system and they also enable fast dynamic responses to changing conditions.

The central part of these devices is a power converter, which is controlled in such a way that the device improves the selected power quality parameters. Today, the most problematic parameters, apart from the already mentioned harmonics and poor power factor, are voltage fluctuations, fliker, unbalanced voltages, etc. These can all be successfully addressed with active compensators. They have a major advantage over passive compensators due to their operation not depending on the impedance characteristics of the system. This gives them the ability to operate in complex situations, where, due to resonance problems, the use of passive compensators is not possible. The most notable disadvantage of active compensators is their high investment and operational costs [3].

By combining passive and active compensators into one device, their individual disadvantages are mitigated. These devices are named hybrid compensators. The purpose of the active part of hybrid compensator is not a standalone operation, but improving operational characteristics of the passive part. This allows us to considerably reduce the necessary power ratings of the active part – typically up to 5 % of the rating of passive part [4].

Topologies of hybrid compensators, which are frequently discussed in the literature are a series connected active compensator with passive compensator connected in parallel [5], and parallel connected passive compensator with active compensators added in series [3], [4]. Some other topologies are summarized in [6]. It is clear that all topologies are not equally effective in carrying out specific tasks. Thus, in the planning process of the hybrid compensator it is necessary to accurately define the requirements for a specific operation.

The main goal of this paper is to propose a hybrid active filter, which will allow a passive compensator to be insensitive to network impedance. It also has to be suitable for retrofit application to the existing passive reactive power compensators. Following this objectives, the requirements for the hybrid capacitor system are set as follows:

- reactive power compensation at 50 Hz,
- preventing series resonance,
- preventing parallel resonance,
- voltage distortion at the compensator PCC should be minimal and
- minimal power ratings of active part.

Given the above requirements the topology of series coupling of active and passive part which operates parallel to the system has proved to be the most suitable.

The following section presents the frequency characteristics of the discussed industrial network with integrated hybrid compensator, the connection topology and the principle of operation of the hybrid compensator.

## 2. Resonance between the Compensator and the Network

Figure 1 shows a simplified scheme of the industrial network with integrated hybrid compensator. The

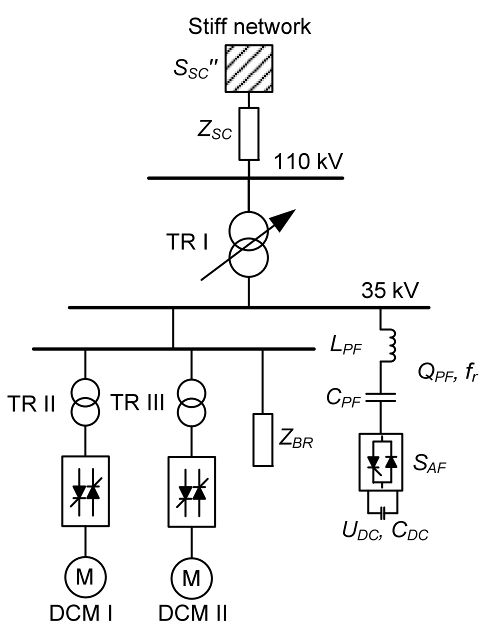


Fig. 1. A simplified industrial network scheme.

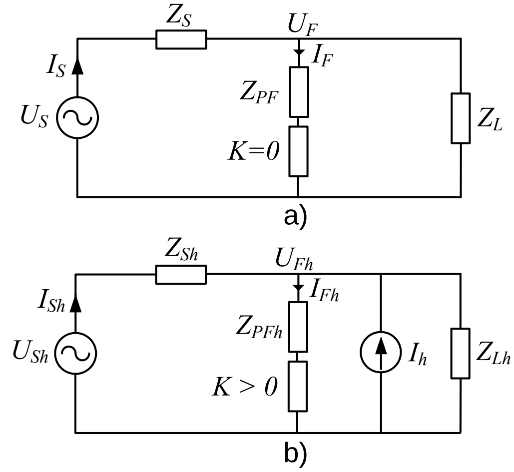


Fig. 2. A simplified scheme of the network with integrated hybrid compensator; a) circuit for the base frequency, b) circuit for harmonics.

equivalent circuit of the network is presented in Figure 2, separately for the base frequency 50 Hz (a) and for harmonics (b). The symbols used are as follows: $U_S$ supply voltage, $Z_S$ supply impedance (short-circuit impedance $Z_{SC}$ and transformer TR 1 impedance connected in series), $Z_L$ load impedance, $Z_{PF}$ passive compensator impedance, $U_F$ voltage at compensator PCC and $I_F$ compensator current. The active part of the hybrid compensator is presented with a proportional gain $K/\Omega$.

According to Figure 2 b) the equivalent impedance of the network from the point of view of the harmonic current source $I_h$ can be written as:

$$\frac{U_{Fh}}{I_h} = Z_{N,p} = \frac{1}{\frac{1}{Z_{Sh}} + \frac{1}{Z_{Bh}} + \frac{1}{Z_{PFh} + K}}, \tag{1}$$

where $Z_{Sh}$, $Z_{Lh}$ and $Z_{PFh}$ are, respectively, the system, load and passive filter equivalent impedances at harmonic $h$.

Assuming that only the passive part of hybrid compensator is connected to the network, the equivalent impedance at the parallel resonance point $f_{r\text{-}p}$ simplifies to:

$$Z_{N,p}^{f_{r-p}} \approx \frac{X_{PF}^{\ 2}}{R_S} = \frac{X_S^{\ 2}}{R_S} = Q \cdot X_S = Q \cdot X_{PF}\,. \tag{2}$$

$X_S$ and $R_S$ are the system reactance and resistance at the compensator PCC. Quality factor $Q$ gives the sharpness of the resonant response [7]. Since $X_S >> R_S$, impedance $Z^{fr\text{-}p}_{N,p}$ becomes very high near the parallel resonance frequency. Thus, even a very low harmonic current can cause a very large voltage drop on the equivalent impedance $Z^{fr\text{-}p}_{N,p}$. Harmonic component of the voltage at the compensator PCC will in turn greatly increase.

$$U_{Fh}^{f_{r-p}} = Q \cdot X_{PF} \cdot I_h \tag{3}$$

Similar relation applies for the harmonic current flowing in the compensator.

$$I_{Fh}^{f_{r-p}} = \frac{U_{Fh}}{X_{PF}} = Q \cdot I_h \tag{4}$$

The active part of the hybrid compensator is controlled in a way to represent resistance $K$ to the compensator harmonic current $I_{Fh}$. The expression (2) is thus transformed into:

$$Z_{N,p}^{f_{r-p}} \approx \frac{X_{PF}^2 - j \cdot K \cdot X_{PF}}{K + R_S} \approx \frac{X_S^2 + j \cdot K \cdot X_S}{K + R_S}. \tag{5}$$

For large values of gain $K$, the above expression simplifies to:

$$Z_{N,p}^{f_{r-p}} \approx X_S. \tag{6}$$

Equivalent impedance from the harmonic current point of view is therefore represented only by system reactance.

Analogue derivation can also be applied for the series resonance. Equivalent impedance of system and compensator impedances coupled in series becomes very small near the series resonance point and, assuming that the active part does not operate ($K = 0$), limited downward only by the system resistivity $R_S$.

$$Z_{N,s} = R_S + j \cdot X_S + j \cdot X_{PF} + K \tag{7}$$

$$Z_{N,s}^{fr-s} \approx R_S + K \tag{8}$$

Harmonic currents, which are close to the resonance frequency, will therefore be freely running in this part of the network. Consequently, the harmonic voltage at the compensator PCC greatly increases:

$$U_{Fh}^{f_{r-s}} \approx \frac{j \cdot X_{PF} + K}{R_S + K} \cdot U_{Sh}. \tag{9}$$

The harmonic current is given by:

$$I_{Fh}^{f_{r-s}} \approx \frac{U_{Sh}}{R_S + K}. \tag{10}$$

Figure 3 shows the impact of the size of proportional gain $K$ on the impedance characteristics of the network. As it can be seen, resonance occurs very close to the 5th harmonic – more specifically at 244 Hz series resonance and at 245 Hz parallel resonance. Clearly, even a small value of parameter $K$ significantly contributes to the resonance damping. Impedance amplification from the network and the load side drops from the original -26 dB and 30 dB for $K = 0$ to -9 dB and 14 dB for $K = 25$. In the case of $K = 150$, the impedance characteristic is very close to the case, when there is no compensator connected to the network.

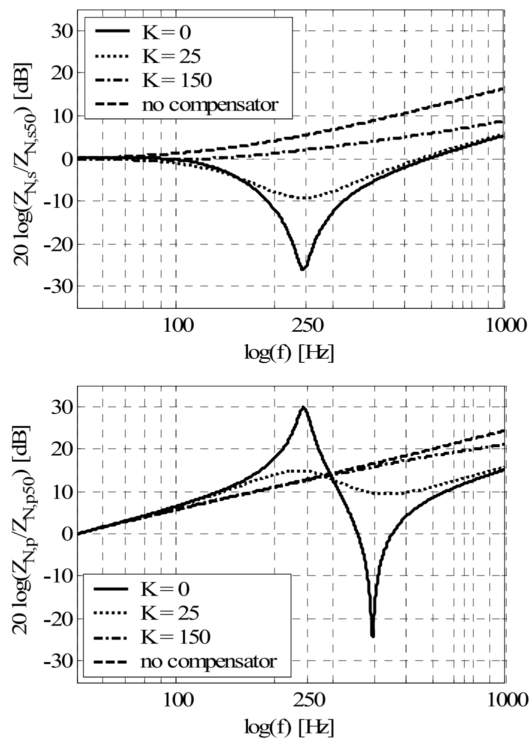

Fig. 3. Impedance frequency characteristic from the system and the load view point, respectively.

# 3. Hybrid Capacitor System

## 3.1 Circuit Topology

Figure 4 shows a detailed scheme of the hybrid compensator. It consists of a three-phase bridge converter and a combination of inductance $L_{PF}$ and capacitance $C_{PF}$ connected in series. Both parts of the compensator are directly connected without a transformer. The central unit

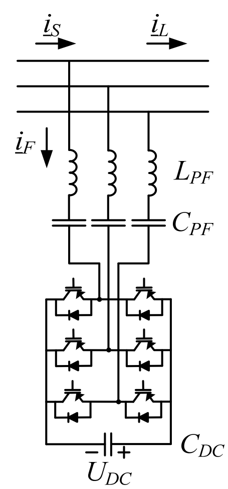

Fig. 4. Basic circuit of a shunt-connected hybrid capacitor system.

of the active compensator represents the voltage-source converter. It is comprised of the appropriate connection of semiconductor switches and of the controlling part which generates switching pulses on the basis of the objectives of compensation. According to the selected type of converter, the device can be described as a controllable voltage source [1].

To connect the device to the network no coupling transformer is needed. The capacitor represents high impedance for the basic component of the voltage, thus most of the voltage drop occurs on the capacitor.

### 3.2 Control Algorithm

The control algorithm is essential for a proper and efficient operation of the active compensator. The criteria for the operation were given in the introduction. The control algorithm can be divided into three parts:

- currents and voltages detection,
- reference currents and voltages determination and
- determination of control pulses for driving the semiconductor switches.

When determining the reference values of signals to be generated by the compensator the transformation into the frequency or the time domain is being used. The reference values are determined on the basis of the objectives of the compensation.

Control in the frequency domain is based on Fourier analysis, by which the current and voltage components to be compensated are determined. The active compensator switching frequency should be at least twice higher than the highest harmonic which is supposed to be compensated [8]-[10].

Control in the time domain is a determination of the reference signals from the reference currents and voltages. In this area there are several controlling strategies, e.g. instantaneous active and reactive power theory (PQ theory) [11], [12] and the synchronously rotating dq reference frame theory (the dq transformation) to mention only the most common ones [13]. In subsequent derivations the latter will be used.

### 3.3 Dq Reference Frame Transformation

When using the dq reference frame transformation, nominal frequency ac quantities transform into dc quantities. The reference signals are then determined by filtering the converted quantities. In doing so, all the information from the original system must be maintained.

Assuming a balanced three-phase system ($I_0$ = 0), the transformation can be written as [14]:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = [T] \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (11)$$

$$[T] = \frac{2}{3} \cdot \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t + \frac{2}{3}\pi) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2}{3}\pi) & -\sin(\omega t + \frac{2}{3}\pi) \end{bmatrix}. \quad (12)$$

If $\omega$ in the matrix $\boldsymbol{T}$ is equal to the nominal angle speed $\omega_S$, the nominal frequency ac quantities of the original three-phase system transform into dc quantities of the dq coordinate system. Harmonic components of the original system remain ac. It can therefore be written:

$$\begin{aligned} i_d &= \bar{i}_d + \tilde{i}_d \\ i_q &= \bar{i}_q + \tilde{i}_q \end{aligned}. \quad (13)$$

A dc component of the current $\bar{i}_d$ represents a basic component of active current, $\bar{i}_q$ the basic component of reactive current and the alternating components $\tilde{i}_d$ and $\tilde{i}_q$ represent the harmonic components of the compensator's current. All it remains is to filter them with the appropriate filter (low-pass) and transform them back to the three-phase system (dq inverse transformation).

### 3.4 Reference Currents And Voltages Determination

The voltage at the output terminals of the active compensator (desired voltage) is defined as follows:

$$U_{AF}^{*} = K \cdot I_{Fh}, \quad (14)$$

where $I_{Fh}$ represents current harmonics flowing in the compensator. Current is given by the described dq transformation and filtering.

The expression (14) can be interpreted as follows: the active part of the hybrid compensator acts as a resistor of $K > 0$ for the harmonic components of the compensator current. So, the device acts as a current-controlled voltage source.

According to (14), if the gain $K$ is high enough, no harmonic current flows into the compensator. Furthermore $K$ has no effect on the basic component of the current. Therefore, the hybrid compensator can compensate the reactive power without reaching resonance. However one must be aware, that high values of gain $K$ may cause a system to become unstable. There should therefore be a compromise between the damping of the harmonics and the stability of the system. As a compromise $K$ is set to 150.

### 3.5 DC Voltage Control

It is very important for the effective operation of the hybrid compensator that the voltage on the DC side of the converter is as constant as possible. Fluctuations in the dc voltage are reflected as a voltage harmonic distortion on the AC side. The PI controller with proportional and

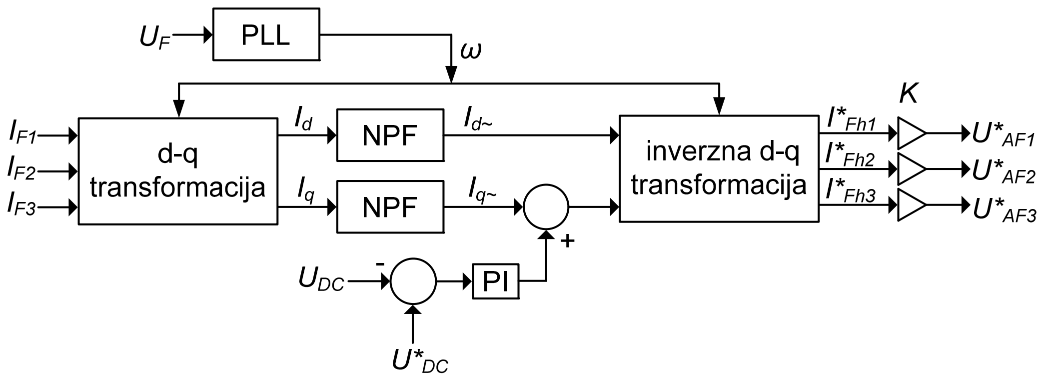


Fig. 5. Control circuit of the active compensator.

integral gains set to 0.5 $\Omega^{-1}$ and 20 $\Omega$/s is used to control the voltage. Active compensator is capable of regulating voltage independently, without external power supply.

Figure 5 shows the control circuit of the active compensator. The compensator detects three-phase compensator current $I_F$ and three-phase voltage at compensator PCC $U_F$ for feedback control.

### 3.6 Determination of Control Pulses to Drive Semiconductor Switches

When the reference values are determined, the next step is to determine the control pulses to drive the semiconductor switches (IGBT). The pulse-width modulation (PWM) was used. There the reference signals are compared to the triangle signal and according to the comparison pulses are triggered with a frequency of 5 kHz.

## 4. Simulation Results

To illustrate some practical implications of the hybrid capacitor system a detailed model was constructed in the PSCAD software. The simulated system was shown in Figure 2 and presents an actual industrial power network. Network parameters are given in Table 1 and the parameters of the hybrid compensator in Table 2. 35 kV distribution network is powered through a 110 kV transmission system, which is presented by a stiff network, with short-circuit power rating of 3750 MVA. The hybrid compensator is connected on the secondary side of the transformer TR I. The compensator's passive part is rated at 5.4 MVAr and the active part at 200 kVAr. Two large adjustable-speed thyristor-supplied motor drives DCM I and DCM II are also connected to the network, rated at 2.5 MW and 2.15 MW. These motors are a main source of harmonic distortion in the network. Linear load is modelled with impedance $Z_L$.

Table 1. Industrial network parameters.

| | |
|---|---|
| Stiff network | 3750 MVA |
| Tr I | 110/ 35 kV, 20 MVA, 10,82 % |
| Tr II | 35/0,676 kV, 3,25 MVA, 7,41 % |
| Tr III | 35/0,675 kV, 3,5 MVA, 6,62 % |
| DCM I | 2,5 MW, 690 V, 350/450 min$^{-1}$ |
| DCM II | 2,15 MW, 690 V, 750 min$^{-1}$ |
| Other load | 6,1 MW, 0,96 MVAr |

Table 2. Hybrid compensator parameters.

| Passive *LC* compensator | |
|---|---|
| $Q_{PF}$ | 5,4 MVAr |
| $L_{PF}$ | 11,8 mH |
| $C_{PF}$ | 13,81 μF |
| $f_{r-p}$ | 395 Hz, 1,6 % |
| Active compensator | |
| $S_{AF}$ | 200 kVA (3,7 %) |
| $C_{DC}$ | 6900 μF |
| $U_{DC}$ | 1,5 kV |

Table 3 shows the THD and harmonic values of voltage at compensator PCC $U_F$, compensator current $I_F$ and load current $I_L$. As it can be seen, the 5$^{th}$ harmonic in particular is problematic. It reaches values above 70 % of the compensator fundamental current. Consequently, the voltage $U_F$ is also highly distorted with the 5$^{th}$ harmonic which exceeds the limit value of 6 % by the standard. The maximum allowed voltage THD (i.e. 8 %) is also exceeded and is 8.8 % [2]. After the starting of the active compensator, the voltage and current distortions decrease significantly.

The compensator current has the current THD reduced to 3.3 %. The PCC voltage THD is now only 1.8 % and thus well below 8 %.

The waveforms of the observed quantities are shown in Figure 6. At first, only a passive compensator is operating and after 300 ms the active compensator starts. Reduction in distortion is obvious. Compensator current and voltage waveforms become almost sinusoidal.

Figure 7 shows compensator active and reactive power outputs. It can be seen that the active compensator does not affect the reactive power generation. It remains almost the same after putting the active part in the operation.

Table 3. Comparison of THD and harmonic values before and after the starting of the active part of the hybrid compensator, expressed in percentage of the fundamental current.

| | 5th | 7th | 11th | 13th | THD |
|---|---|---|---|---|---|
| **Passive compensator** | | | | | |
| $U_F$ | 8.7 | 0.2 | 0.1 | 0.1 | 8.8 |
| $I_F$ | 71.9 | 6.6 | 1.0 | 0.8 | 72.3 |
| $I_L$ | 8.15 | 3.1 | 0.7 | 0.6 | 8.8 |
| **Hybrid compensator** | 5th | 7th | 11th | 13th | THD |
| $U_F$ | 1.5 | 0.8 | 0.3 | 0.2 | 1.8 |
| $I_F$ | 2.0 | 2.5 | 0.6 | 0.5 | 3.3 |
| $I_L$ | 6.3 | 2.9 | 0.7 | 0.5 | 7.0 |

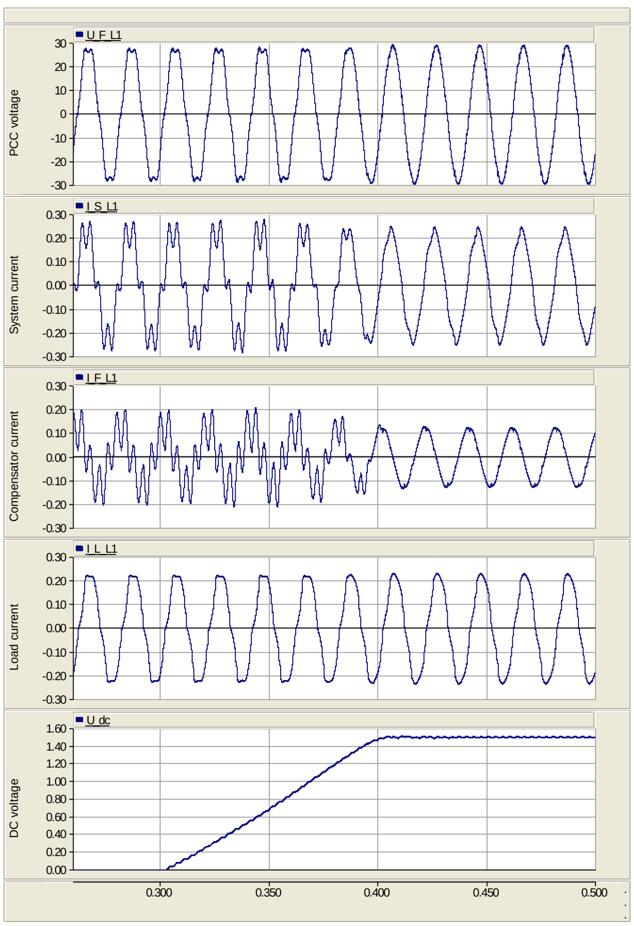

Fig. 6. Simulated waveforms of certain quantities.

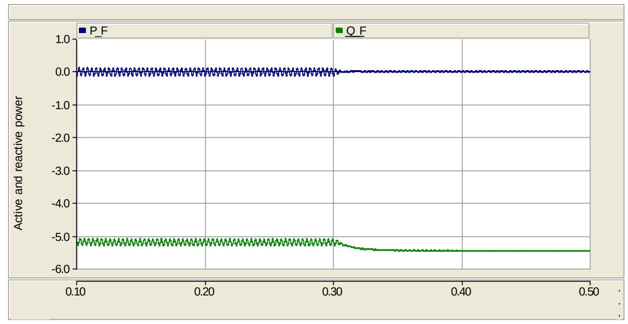

Fig. 7. Active and reactive power outputs.

## 5. Conclusion

In this paper a hybrid capacitor system has been presented. It is composed of a three-phase shunt *LC* passive compensator connected in series with a small-rating active compensator. For the connection to the network no transformer is needed. Since the rated power of the active compensator is relatively low, the hybrid compensator presents viable and effective solution to reactive power compensation. The cost comparison between the hybrid and stand-alone active compensator is excluded from this paper, although it is mandatory as a proof of cost efficiency of proposed solution.

The main advantage of the hybrid compensator over the passive one is the prevention of resonance conditions that may cause harmonics amplification. The proposed concept was validated with simulation.

## Acknowledgement


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