A Full Compensating System for General Loads, Based on a Combination of Thyristor Binary Compensator, and a PWM-IGBT Active Power Filter

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Abstract: A full compensating system for distribution networks which is able to eliminate harmonics, correct unbalanced loads and generate or absorb reactive power is presented. The system is based on a combination of a Thyristor Binary Compensator (TBC), and a PWM-IGBT Active Power Filter (APF) connected in cascade. The TBC compensates the fundamental reactive power and balances the load connected to the system. The APF eliminates the harmonics and compensates the small amounts of load unbalances or power factor that the TBC cannot eliminate due to its binary condition. The TBC is based on a chain of binary-scaled capacitors and one inductor per phase. This topology allows, with an adequate number of capacitors, a soft variation of reactive power compensation and a negligible generation of harmonics. The capacitors are switched-on when the line voltage reaches its peak value, avoiding inrush currents generation. The inductor helps to balance the load, and absorbs reactive power when required. The APF works measuring the source currents, forcing them to be sinusoidal. The two converters (TBC and APF) work independently, making the control of the system simpler and more reliable. The system is able to respond to many kinds of transient perturbations in no more than a couple of cycles. The paper analyzes the circuit proposed, the way it works and the results obtained under operation with different types of loads.

I. INTRODUCTION

Load compensation, in distribution networks, is oriented to solve three different problems: reactive power compensation, unbalanced loads correction, and harmonic elimination.

For reactive power compensation, different strategies and topologies have been used: capacitors banks, Static VAr Compensators (SVC) [1], and PWM compensators [2]. However, most of them have disadvantages: capacitor banks have inrush problems during connection and disconnection, SVCs are harmonic polluters and PWM compensators are still expensive and complicated for high power levels. On the other hand, unbalance problems and harmonic elimination can be solved again using PWM converters, but at a high cost when the system is going to be used in high power applications.

This paper presents a simple topology, which is shown in figure 1. This topology can be used in high power for full compensation of the aforementioned problems. The system consists on a combination of Thyristor Binary Compensator (TBC) [3] operating in cascade with an Active Power Filter (APF) [4]. In this configuration the TBC solves the power factor and unbalance problems for high power levels, by producing pure sinusoidal currents while the APF, working in medium power level, gives the solution for harmonics cancellation problem.

The proposed topology has the following distinctive characteristics: 1) it compensates power factor, unbalanced loads, and harmonics; 2) it can compensate three phase loads in a minimum of two cycles; 3) the APF and TBC work independently, and an individual control strategy is used for each equipment, and 4) inrush problems during connection and/or disconnection are avoided by keeping the appropriate conditions of “null initial current” and “null voltage” between connection terminals.

II. PROPOSED TOPOLOGY DESCRIPTION

The proposed topology for the interconnection between TBC and APF is shown in figure 1. This configuration ensures that each equipment can work independently in the satisfaction of well-delimited objectives.

![Fig. 1. Proposed topology](image-url)
The TBC equipment measures the fundamental components of the load line currents “IL”, and calculates the value for the susceptances, necessary to connect between each phase of the electrical system, to get unity power factor operation, and a balanced load referred to the main voltage source.

By the other hand, the FAP [4] measures the line source currents “IS” and injects the harmonic components “IF” necessary to obtain a sinusoidal waveform in the main source current. Additionally, “IF” contains the small amounts of reactive power that the TBC cannot eliminate due to its binary operation.

The operation principle for each equipment is analyzed in the following sections.

2.1 Thyristor Binary Compensator (TBC).

The topology of the TBC is shown in figure 2, and consists on variable susceptances, connected in delta configuration, through common cathode, anti-parallel, thyristor-diode connection. The variability of each susceptance is based on a chain of binary-scaled capacitors and one inductor, whose value is chosen according to the reactive power that the capacitors can generate if they are all connected.

The presented topology allows to inject or absorb the amounts of reactive power \( B^{(ab)} \), \( B^{(bc)} \), and \( B^{(ca)} \) that are required in a three-phase electrical system to obtain unity power factor operation, and a balanced load in the main source terminals. Additionally, the configuration allows having a dynamic compensation range of \([-Q,Q]\) in each phase where \( Q \) is the maximum reactive power that the capacitors can generate.

Since the values of capacitors are selected as binary scaled, it is possible to obtain a linear regulation of compensating reactive power, by connecting or disconnecting them in the appropriate sequence. The precision of regulation is established by the lowest capacitor value [3].

The appropriate conditions for the connection of capacitors or inductances must keep the requirements of “null initial current” and “null voltage between connection terminals” to prevent inrush currents.

Considering the topology shown on figure 3 for each capacitor, when the thyristor T is “off” the diode D keeps the capacitor C charged at the peak negative value of the main supply (-\( V_m \)) which in this case corresponds to the negative peak of phase-to-phase voltage. The optimal firing moment for the capacitor is given by the following equations:

\[
\nu^{Th}(t) = \nu(t) - V_c = V_m \sin(\omega t) - V_c 
\]

where:
- \( \nu^{Th} \): Thyristor voltage
- \( \nu(t) \): Main source phase to phase voltage
- \( V_c \): Capacitor’s voltage
- \( V_m \): Peak value of \( \nu(t) \)

In the connection moment:

\[
\nu^{Th}(t) = \nu(t) - V_c = V_m (\sin(\omega t) + 1) = 0
\]

According to equation (2) a soft connection is obtained when the main supply reach its maximum negative voltage (\( \omega t=270^\circ \)). Then, the capacitor current will increase from zero following equation (3):

\[
i_c = C \cdot V_m \frac{d}{dt} (-\cos(\omega t)) = C \cdot V_m \sin(\omega t)
\]

A similar analysis could be made for the current in the inductance connected between each phase. In this case, the
configuration is given by figure 4, where two thyristors are required instead. In this case, it is required to fire each thyristor, T1 and T2, in the negative and positive peak of the supply voltage (phase-to-phase voltage) respectively.

The value of the susceptances that must be connected, to obtain the power factor correction and load balance, can be calculated by an analysis of the zero, positive and negative-sequence of the current set. The compensation objective can be stated as to eliminate the negative-sequence component (balancing) and to cancel the reactive component of positive-sequence, considering a null zero-sequence phasor [1].

The expressions for the reactive requirements $B_{ab}^{(c)}$, $B_{bc}^{(c)}$ and $B_{ca}^{(c)}$, that are obtained from the aforementioned method, are given by eqs. (4) to (6).

$$B_{ab}^{(c)} = k \left( -\frac{1}{\sqrt{3}} \cdot \text{Im}(I_{al}) - \frac{1}{\sqrt{3}} \cdot \text{Im}(I_{jl}) + \text{Re}(I_{al}) \right)$$  \hspace{1cm} (4)$$

$$B_{bc}^{(c)} = k \left( -\frac{1}{\sqrt{3}} \cdot \text{Im}(I_{ai}) + \frac{2}{\sqrt{3}} \cdot \text{Im}(I_{aj}) \right)$$  \hspace{1cm} (5)$$

$$B_{ca}^{(c)} = k \left( -\frac{1}{\sqrt{3}} \cdot \text{Im}(I_{ci}) - \frac{1}{\sqrt{3}} \cdot \text{Im}(I_{cj}) - \text{Re}(I_{ai}) \right)$$  \hspace{1cm} (6)$$

where:

$$k = \frac{1}{\sqrt{3} \cdot V}$$

Equations (4)-(6) can be expressed as the following time variation equations [1]:

$$B_{ab}^{(c)} = -\frac{1}{\sqrt{3} \cdot V_{ff \text{ peak}}} \left[ \frac{d}{dt} i_a(t) \frac{dV_{al}(t)}{dt} \right]_{V_{al}(t)=0} + \frac{d}{dt} i_b(t) \frac{dV_{jl}(t)}{dt} \right]_{V_{jl}(t)=0} - \frac{d}{dt} i_c(t) \frac{dV_{al}(t)}{dt} \right]_{V_{al}(t)=0}$$  \hspace{1cm} (7)$$

$$B_{bc}^{(c)} = -\frac{1}{\sqrt{3} \cdot V_{ff \text{ peak}}} \left[ i_c(t) \frac{dV_{ai}(t)}{dt} + i_a(t) \frac{dV_{aj}(t)}{dt} - i_b(t) \frac{dV_{aj}(t)}{dt} \right]_{V_{aj}(t)=0}$$  \hspace{1cm} (8)$$

$$B_{ca}^{(c)} = -\frac{1}{\sqrt{3} \cdot V_{ff \text{ peak}}} \left[ i_a(t) \frac{dV_{aj}(t)}{dt} + i_b(t) \frac{dV_{cj}(t)}{dt} - i_c(t) \frac{dV_{cj}(t)}{dt} \right]_{V_{cj}(t)=0}$$  \hspace{1cm} (9)$$

Where $i_a(t) \frac{dV_{al}(t)}{dt} > 0$ represents the measure of current $i_a$ in the instant where the line voltage $V_a$ has its zero crossing point (positive slope).

The calculated values for the susceptances must consider:

$$B_{ij}^{(c)} = \omega C_{ij}, \quad \text{if } B_{ij}^{(c)} \geq 0$$  \hspace{1cm} (10)$$

$$B_{ij}^{(c)} = (\omega L_{ij})^{-1}, \quad \text{if } B_{ij}^{(c)} < 0$$  \hspace{1cm} (11)$$

where $C_{ij}$ is the capacitor connected in the branch between phase “i” and “j”, and $L_{ij}$ is an equivalent inductance connected between phases “i” and “j”.

The equations stated in (7)-(11) make possible the implementation of a real time control methodology based on the measurements of line load currents.

The previously mentioned concepts are still valid if the TBC equipment is configured in star connection. In this case, it is necessary to consider the following expression to transform the delta susceptances in the star susceptances that must be connected between each phase and ground.

$$B_{in}^{-1} = B_{ij}^{-1} + B_{ki}^{-1} + B_{kj}^{-1}$$  \hspace{1cm} (12)$$

where:

$B_{in}^{-1}$: susceptance between phase “i” and ground

$B_{ij}^{-1}$: susceptance between phases “i” and “j”

$B_{ki}^{-1}$: susceptance between phases “i” and “k”

$B_{kj}^{-1}$: susceptance between phases “k” and “i”

2.2 Active Power Filter (APF).

The shunt configuration for an Active Power Filter, as shown in figure 5, is considered in the proposed topology. It is used as a current source, to generate sinusoidal current waveforms in the main voltage supply. The APF uses the current-hysteresis-controller method.

Therefore, the APF equipment is able to generate the current “$i_f$”, which contains three basic components (see equations (12) and (13)). The first component “$i_{fh}$” is in phase with the main voltage supply, the second component “$i_{fi}$” is in quadrature and the last, “$i_{fj}$”, have the harmonic components [4].

$$i_f = i_{fh} + i_{fi} + \sum_k i_{fj}$$  \hspace{1cm} (12)$$

$$i_f = I_{fh} \sqrt{2} \sin(\omega t) + I_{fi} \sqrt{2} \cos(\omega t) + \sum_k I_{fj} \sqrt{2} \sin(k \omega t - \phi_k)$$  \hspace{1cm} (13)$$

The APF, working in a medium power level, is connected to the high voltage network trough a three-phase transformer. This configuration allows reducing the cost associated to APF design, and avoids the utilization of force-commutated semiconductor at high voltage levels.
The inductance “\( L_f \)” is a current slope limiter of the currents injected to the network and it is essential in the protection of the semiconductor components (IGBTs), and in the absorption of the voltage differences between the system and the output of the APF.

The control strategy applied to the APF is based on the analysis of its electrical behavior. In fact, it is possible to obtain an expression that represents the power balance under the required conditions for line supply currents. That is, when the currents “\( I_s \)” are balanced, and have unity power factor and no harmonic components.

\[
p_s = P_s = P_{\text{load}} - P_f = 3V \cdot I_s = P_{\text{load}} - \frac{\Delta W_{\text{c}}}{T} \quad (14)
\]

\[
\hat{\Delta}f = \hat{\Delta} \text{load} \quad (15)
\]

where,

\( p_s \): Instantaneous power at source terminals
\( P_s \): Average active power at source terminals
\( P_{\text{load}} \): Average active power at load
\( \Delta W_{\text{c}} \): Average power in APF capacitor
\( \hat{\Delta}f \): Instantaneous VAr and harmonic power in APF
\( \hat{\Delta} \text{load} \): Instantaneous VAr and harmonic power at load

Therefore, the control of the APF must satisfy equation (14) and (15) to obtain the required operating conditions. Even more, from equation (14) it is possible to find an expression for the supply current “\( I_s \)” in terms of the average power variation in the APF capacitor:

\[
I_s = \frac{1}{3V} \left[ P_{\text{load}} - \frac{\Delta W_{\text{c}}}{T} \right] = \frac{1}{3V} \left[ P_{\text{load}} - \frac{C}{2T} \Delta V_{\text{DC}} \right] \quad (16)
\]

Then the control method can be based on a proportional integral (PI) close loop, which forces the line supply currents, “\( I_s \)” to be sinusoidal and in phase with the corresponding main voltages. The PI controller keeps the APF capacitor voltage “\( V_{\text{DC}} \)” according to a reference “\( V_{\text{REF}} \)” by manipulating the amplitude of “\( I_s \)” [4].

If the real value of “\( I_s \)” is different from \( P_{\text{load}}/(3V) \), the capacitor voltage will increase or decrease according to expression (16). The controller calculates the value the line supply currents must have, to keep a stable value in the APF capacitor. A second PWM control loop forces the line supply currents to be sinusoidal and with the value given by eq.(16).

III. SIMULATION RESULTS

The figures 6, and 7 show the results obtained with this combined technology (TBC with Thyristors and APF with IGBTs). The first one shows three oscillograms: 6a) displays the three load currents, \( I_1^A \), \( I_2^B \), and \( I_3^C \), which are balanced but with a lagging power factor. After the step load change in the middle of the figure, these three load currents become completely unbalanced. It can be seen that the source currents shown in 6b), remain in phase with the voltage, and always balanced, even after the step change. The last oscillogram in figure 6c) shows the contribution of the TBC, and the APF, through the currents \( I_1^A \), and \( I_2^B \) respectively (only phase “a” is displayed).

The figure 7 shows now a step change from unbalanced load to polluted load. In the time indicated in the figure, a power rectifier is connected, and the load current (shown in 6a)) becomes completely distorted and unbalanced. However,
in 6b) the source currents $I_S$ remain clean, and in phase with the source voltage $V_S$. Finally, the figure 6c) shows the contribution of the TBC, and APF, to clean the current of the system. Only phase “a” is shown in this last oscillogram.

In the figures 6 and 7, the voltage $V_S$ has been scaled 30 times smaller. The values used in the power compensator for these oscillograms were: $V_S=220$ V (phase-to-neutral), 50 Hz. The TBC has the following compensating branches in each phase: $C1=1.25$ µF, $C2=2.5$ µF, $C4=5$ µF, $C8=10$ µF, $C16=20$ µF, and $L=260$ mH. These values allow compensation from $-1.76$ kVAR to $1.76$ kVAR. The load parameters were: Step 1) balanced load connected in delta,
with R=200 Ω, in parallel with L=500 mH. Step 2) unbalance load connected in delta with \( R_A = 400 \, \Omega \) in parallel with \( L_A = 500 \, \text{mH} \), \( R_B = 200 \, \Omega \) in parallel with \( L_B = 200 \, \text{mH} \), \( R_c = 150 \, \Omega \) in parallel with \( L_c = 500 \, \text{mH} \).

IV. EXPERIMENTAL RESULTS

An experimental prototype for the proposed topology was implemented for a nominal phase-to-phase voltage of 110 [V eff], and a 1650[VA] three-phase load. For simplicity, all the system was connected in star configuration. As in this case the star configuration of the TBC requires a return path to initialize thyristor anode currents, a neutral connection was included.

The TBC prototype includes two branches of binary scaled capacitors (see Table I). For economical reasons, the prototype did not include inductor branches. Then, it is only able to inject leading reactive power to the network.

### TABLE I

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{1i} )</td>
<td>15.00</td>
<td>[μF]</td>
</tr>
<tr>
<td>( C_{2i} )</td>
<td>30.00</td>
<td>[μF]</td>
</tr>
</tbody>
</table>

The APF equipment is connected in parallel to the voltage supply and their parameters are given in Table II.

### TABLE II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_f )</td>
<td>15.00</td>
<td>[mH]</td>
</tr>
<tr>
<td>( C )</td>
<td>4700</td>
<td>[μF]</td>
</tr>
<tr>
<td>( \text{Ref VC} )</td>
<td>150</td>
<td>[V dc]</td>
</tr>
</tbody>
</table>

The load is a lineal balanced R-L impedance in star configuration \((R_{\text{load}}=44[Ω], \, L_{\text{load}}=350[\text{mH}])\), which is connected in parallel with a half wave diode bridge rectifier. This rectifier has a R-L load \((R=80[Ω], \, L=20[\text{mH}])\) connected at the dc side.

Figure 8 illustrates an experimental result of the proposed topology, before and after the connection of the rectifier. The combined contributions of \( I_c \) and \( I_f \) achieve a sinusoidal waveform for \( I_s \), even when the load current \( I_L \) is highly polluted.

![Fig. 8. Experimental currents for a step change.](image)

V. CONCLUSIONS

A combined topology, using a Thyristor Binary Compensator (TBC), and a PWM-IGBT shunt Active Power Filter (APF), has been implemented. The TBC controls the power factor and corrects load unbalances. The APF eliminates the harmonics, and compensates the small amounts of power factor and unbalancing that the TBC, given its binary characteristic, is unable to correct. The two converters work independently, making the control system simple and more reliable. The system is able to compensate power factor, unbalanced loads, and harmonics, with a good dynamic response. Compared with other topologies able to do the same work, the one presented here is more economical, because the high kVAR stage has been implemented with thyristors, which are cheaper than GTOs. The results obtained, show an excellent behavior under both, steady-state and transient situations.

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