Transformerless Single-Phase Universal Active Filter with UPS Features and Reduced Number of Electronic Power Switches

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Abstract - This paper presents an universal active power filter for harmonic and reactive power compensation with UPS (Uninterrupted Power Supplies) features. The configurations do not use transformer in the series part. Transformerless modern UPS systems have been rapidly replacing the old technology due to their performance and size attributes. Reducing the numbers of passive elements and/or switches in active power filters and UPS topologies not only reduces the cost of the whole system but also provides some advantages, such as great compactness, smaller weight, and higher reliability. However, the cost reduction requires the use of more complex control strategies. The model of the proposed system is derived and it is observed that the system can be reconfigurable to operate with four or three-leg depending on the issue. A complete control system, including the PWM (Pulse-Width Modulation) techniques, is developed and a comparison between the proposed filter and the standard one is done, as well. Simulated and experimental results validate the theoretical considerations.

Keywords – universal active power filter, single-phase structure, uninterrupted power supplies and PWM techniques.

I. INTRODUCTION

The requirements of quality at power grids and increased sensitivity of the loads has stimulated the use of power electronics in context of power line conditioning [1]. Different equipments are used to improve the power quality, e.g., transient suppressors, line voltage regulators, uninterrupted power supplies, active filters, and hybrid filters [1], [2], [3], [4], [5], [6]. The continuous proliferation of electronic equipments either for home appliance or industrial use has the drawback of increasing the non-sinusoidal current into power grid. So, the need for economical power conditioners for single-phase systems is growing rapidly [2], [7], [8], [9], [10], [11]. Different solutions are currently proposed and used in practice applications to work out the problems of harmonics in electric grids. In the last decades, the use of active filtering techniques has became more attractive due to the technological progress in power electronic switching devices and more efficient control algorithms.

The issue of reducing the cost has been attracting the attentions of researchers. Generally, the largest cost reduction is achieved by reducing the number of switches employed in power converter or developing topologies that employ switches with lower voltage stresses. Cost reduction is also achieved by eliminating passive components such as inductors, capacitors and transformers. Reducing the numbers of switches and passive elements in Active Power Filters (APF) and Uninterrupted Power Supplies (UPS) topologies not only reduces the cost of the whole system but also provides some other advantages such as great compactness, smaller weight, and higher reliability [12], [13], [14], [15], [16], [17]. However, the cost reduction requires the use of more complex control strategies.

Uninterrupted power supplies are widely used to supply critical loads and provide reliable and high quality energy to the load [15], [18], [19], [20]. Static UPS systems are the most commonly used UPS systems. They have a broad variety of applications from low-power personal computer and telecommunication systems, to medium-power medical systems, and to high-power utility systems. The main advantages are high efficiency, high reliability, and low THD (Total Harmonic Distortion). The static UPS systems are classified into on-line, off-line and line-interactive.

This work will focus on the study of series-parallel line-interactive UPS topology, also known as delta converter, with reduced number of switches. The idea consists in developing a reconfigurable structure where one of the converter-leg can be used to charge the battery bank without having a dedicated d.c./d.c. converter, e.g., buck-boost converter. So, the configuration composed by four-leg converter can operates with three-leg leaving one leg to charge the battery bank. When the battery bank is charged, the system returns to its original form. A mathematical modelling and complete control system, including the PWM techniques, is presented. Simulated and experimental results validate the theoretical considerations.

II. SYSTEMS MODELLING

The proposed configuration shown in Fig. 1 (a) comprise the grid \( (e_g, i_g) \), internal grid inductance \( (L_g) \), load \( (v_l, i_l) \),
converters $S_e$ and $S_h$ with a capacitor bank at the d.c.-link and filters $Z_e$ ($L_e$, $L'_e$ and $C_e$) and $Z_h$ ($L_h$, $L'_h$ and $C_h$). Converter $S_e$ is composed by switches $q_e$, $q'_e$, $q''_e$ and $q'''_e$. Converter $S_h$ is composed by switches $q_h$, $q'_h$, $q''_h$ and $q'''_h$. The conduction state of all switches is represented by an homonymous binary variable, where $q = 1$ indicates a closed switch while $q = 0$ an open one.

The difference between the two systems, Fig. 1, relates to components reduction. The proposed configurations, Fig. 1 (a), is transformerless and presents less power switches than the conventional, Fig. 1 (b). The idea of the proposed system is to utilize one of the converter-leg to charge the battery bank - when d.c. voltage level at the battery bank is beyond the preset tolerance - avoiding the necessity to have a dedicated d.c./d.c. buck-boost converter for it. The buck-boost converter of the conventional topology is composed by switches $q_{b1}$ and $q_{b2}$. The filter inductance $L_{cc}$ is common to both configurations. The system description with the power converter operating with four and three-leg is addressed.

### A. Four-leg converter operation mode

The converter pole voltages $v_{e0}$, $v'_{e0}$, $v_{h0}$ and $v'_{h0}$ depend on the conduction states of the power switches, that is

$$v_{e0} = (2q_e - 1) \frac{v_c}{2}$$  \hspace{1cm} (1)

$$v'_{e0} = (2q'_e - 1) \frac{v_c}{2}$$  \hspace{1cm} (2)

$$v_{h0} = (2q_h - 1) \frac{v_c}{2}$$  \hspace{1cm} (3)

$$v'_{h0} = (2q'_h - 1) \frac{v_c}{2}$$  \hspace{1cm} (4)

where $v_c$ is the d.c.-link voltage.

From Fig. 1(a), assuming that the switches $S_1$ and $S_2$ are on and $S_3$ and $S_4$ are off, the following equations can be derived considering the system operating with four-leg:

$$v_{e0} - v'_{e0} = v_g + \left[ \frac{r'_e}{2} + \frac{r_c}{2} + \left( \frac{l_e}{2} + \frac{l'_e}{2} \right) p \right] i_e - v_l - \left( \frac{r'_e}{2} + \frac{l'_e}{2} \right) i_o$$  \hspace{1cm} (5)

$$v_{h0} - v'_{h0} = \left[ \frac{r_h}{2} + \frac{r'_h}{2} + \left( \frac{l_h}{2} + \frac{l'_h}{2} \right) p \right] i_h + v_l + \left( \frac{r'_h}{2} + \frac{l'_h}{2} \right) i_o$$  \hspace{1cm} (6)

$$v'_{e0} - v'_{h0} = \left( \frac{r'_e}{2} + \frac{l'_e}{2} + p i_e \right) i_e + \left( \frac{r'_h}{2} + \frac{l'_h}{2} \right) i_h + v_l + \left( \frac{r'_e}{2} + \frac{l'_e}{2} \right) i_o$$

$$+ \left[ \left( \frac{r'_e}{2} + \frac{l'_e}{2} \right) + \left( \frac{l'_e}{2} + \frac{r'_h}{2} \right) \right] p i_o$$  \hspace{1cm} (7)

$$v_{e0} - v_{h0} = v_g - v_l = \left( \frac{r_c}{2} + \frac{l_c}{2} \right) i_e - \left( \frac{r_h}{2} + \frac{l_h}{2} \right) i_h$$  \hspace{1cm} (8)

$$e_g - v_{ee} - v_l = (r_g + l_g p) i_g$$  \hspace{1cm} (9)

$$p v_{ee} = \frac{1}{C_e} (i_g + i_e)$$  \hspace{1cm} (10)

$$p v_l = \frac{1}{C_h} (i_g - i_l + i_h + i_o)$$  \hspace{1cm} (11)

where $p = d/dt$, $v_g = e_g - r_g i_g - l_g p i_g$, $v_l = v_{ce}$ and $i_l$ is calculated using the load model which can be linear or nonlinear; and symbols like $r$ and $l$ represent resistances and inductances of the inductors $L_p$, $L_c$, $L_e$, $L_h$ and $L'_h$. The circulating current $i_o$ is defined by

$$i_o = i_e + i'_e = -(i_h + i'_h)$$  \hspace{1cm} (12)

The resultant circulating voltage model is obtained by
adding (5)-(8):

\[
v_o = v_{e0} + v_{e0} - v'_{h0} - v_{h0}
\]

\[
v_y = \left(\frac{r_c}{2} + \frac{l_c}{2} \right) + \left(\frac{r_l}{2} + \frac{l_l}{2} \right) p i_o
\]

\[
+ \left(\frac{r_h}{2} + \frac{l_h}{2} \right) p i_e
\]

\[
- \left(\frac{r_h}{2} - \frac{l_h}{2} \right) p i_h
\]

(13)

The voltage \(v_o\) is used to compensate the circulating current \(i_o\). The demonstration of this current can be seen in appendix of [16].

From the point of view of the controllers, the voltages: \(v_e = v_{e0} - v'_{e0}\) (converter \(S_e\)) is used to regulate and compensate the load voltage \(v_l\), \(v_h = v_{h0} - v'_{h0}\) (converter \(S_h\)) regulates and controls the grid current in order to maintain the power factor close to one and \(v_o = v_{e0} + v_{e0} - v_{h0} - v_{h0}\) (converter \(S_e + S_h\)) is used to cancel or gather the circulating current \(i_o\) near to zero.

In the balanced case, filter inductors are equal (\(L_c = L'_c\) and \(L_h = L'_h\)) and the circulating voltage model become more simple, that is,

\[
v_o = v_y + \left(\frac{r_c}{2} + \frac{l_c}{2} \right) + \left(\frac{r_l}{2} + \frac{l_l}{2} \right) p i_o
\]

(14)

Thus, it can be noted that to minimize the circulating current \(i_o\), the voltage \(v_o\) must be equal to \(v_y\), i.e.

\[
v_o = v_y
\]

(15)

When \(i_o = 0\) (\(i_e = -i'_e\), \(i_h = -i'_h\)) the system model becomes:

\[
v_{e0} - v'_e = v_y + (r_c + i_c) i_e - v_l
\]

(16)

\[
v_{h0} - v'_{h0} = (r_h + i_h) i_h + v_l
\]

(17)

\[
ev - v_{ce} - v_l = (r_g + i_g) i_g
\]

(18)

\[
pv_{ce} = \frac{1}{C_e}(i_g + i_e)
\]

(19)

\[
pv_{l} = \frac{1}{C_h}(i_g - i_l + i_h)
\]

(20)

This model is quite similar to the model of the conventional filter with an ideal transformer. Therefore, we can use \(v_e = v_{e0} - v'_{e0}\) (converter \(S_e\)) to regulate the load voltage and \(v_h = v_{h0} - v'_{h0}\) (converter \(S_h\)) to control the power factor and harmonics of \(i_g\) as in the conventional filter.

B. Three-leg converter operation mode

The system composed by three-leg works similar but, in this case, it has a shared-leg used by both converters (series and parallel filter) and a free-leg which is used to charge the battery bank when needed. The converter pole voltages \(v'_{e0}\), \(v'_{h0}\) and \(v'_{h0}\) depend on the conduction states of the power switches and may be expressed as

\[
v'_{e0} = (2q_e - 1) \frac{v_e}{2}
\]

(21)

\[
v'_{o} = (2q_e - 1) \frac{v_e}{2}
\]

(22)

\[
v'_h = (2q_e - 1) \frac{v_e}{2}
\]

(23)

Assuming that the system operates with three-legs, considering the switches \(S_1\) and \(S_3\) are on and \(S_2\) and \(S_4\) are off, can write the following equations:

\[
v_{e0} - v'_{e0} = v_g - v_l + (r_c + l_c) i_e - (r'_h + l'_h) p i'_h
\]

(24)

\[
v'_{e0} - v'_{h0} = v_l + (r'_e + l'_e) i'_e - (r'_h + l'_h) p i'_h
\]

(25)

\[
v_{e0} - v'_{h0} = v_g + (r_e + l_e) i_e - (r'_h + l'_h) p i'_h
\]

(26)

\[
ev - v_{ce} - v_l = (r_g + l_g) i_g
\]

(27)

\[
pv_{ce} = \frac{1}{C_e}(i_g + i_e)
\]

(28)

\[
pv_{l} = \frac{1}{C_h}(i_g - i_l + i_h)
\]

(29)

where \(p = \frac{d}{dt}\), \(v_g = e_g - r_g i_g - l_g i_g\), \(v_l = v_{ch}\) and \(i_g\) is calculated using the load model which can be linear or nonlinear. For this case, it is noted by the equations that there is no circulation current \(i_o\).

III. PWM STRATEGY

This section presents the PWM Strategy for different modes of operations. Firstly, the system starts as four-leg converter and when is need to charge the bank of batteries it is reconfigurable to operate as three-leg. The descriptions of these modes of operations are presented as following.

A. Four-leg converter operation mode

Pulse-widths of gating signals can be directly calculated from the pole voltages \(v'_{e0}\), \(v'_{h0}\), \(v'_{h0}\) and \(v'_{h0}\).

Considering that \(v^*_{e0}\), \(v^*_{h0}\) and \(v^*_{h0}\) denote the reference voltages requested by the controllers (see Section IV), it comes

\[
v'_{e0} - v'_{e0} = v^*_{e0}
\]

(30)

\[
v'_{h0} = v'_{h0} = v^*_{h0}
\]

(31)

\[
v_{e0} + v_{e0} - v_{h0} - v_{h0} = v^*_{h0}
\]

(32)

Such equations are sufficient to determine the four pole voltages \(v_{e0}, v'_{e0}, v'_{h0},\) and \(v'_{h0}\). Introducing an auxiliary variable \(v^*_{e0}\) and choosing \(v'_{e0} = v^*_{e0}\), it can be written

\[
v_{e0} = v^*_{e0} + v^*_{e0}
\]

(33)

\[
v'_{e0} = v^*_{e0}
\]

(34)

\[
v'_{h0} = \frac{v^*_{h0} + v^*_{h0} - v^*_{h0} + v^*_{h0}}{2}
\]

(35)
The algorithm for this case is given by:

1) Choose the converter side to be the THD optimized and calculate \( v_{e\,s} \) between \( v_{e\,s_{\max}} \) and \( v_{e\,s_{\min}} \) or \( v_{e\,save} = (v_{e\,s_{\max}} + v_{e\,s_{\min}})/2 \).
2) Calculate the limits \( v_{e\,max} \) and \( v_{e\,min} \) from (37) and (38).
3) Do \( v_{e\,s} = v_{e\,max} \) if \( v_{e\,s} > v_{e\,max} \) and \( v_{e\,s} = v_{e\,min} \) if \( v_{e\,s} < v_{e\,min} \).
4) Do \( v_{e\,s} = v_{e\,s} \).
5) Determine the pole voltage and the gating signal as in previous method.

B. Three-leg converter operation mode

The pulse-widths of the gating signals can be directly calculated from the voltage referred to the d.c.-bus midpoint, which is given by the desired voltages for the grid and loads. If the desired phase voltages are specified as \( v_e \) then the reference midpoint voltages can be expressed as

\[
v_e^{i\,0} = v_e + v_{e\,0}
\]

\[
v_e^{h\,0} = v_e + v_{e\,0}
\]

Note that these equations cannot be solved unless \( v_{e\,0} \) is specified. Relations (43) and (44) can be formulated as

\[
v_e^{i\,0} = v_e + v_{e\,i}
\]

\[
v_e^{h\,0} = v_e + v_{e\,h}
\]

The problem to be solved is to determine \( v_e^{i\,0} \), \( v_e^{h\,0} \) and \( v_{e\,0} \) from (45) - (47), once the desired voltage \( v_e \) and \( v_{e\,0} \) have been specified. In the following, two techniques will be presented for generating the PWM gating signals for the converters.

Method A: General approach

1) The voltage \( v_e \) can be calculated taking into account the general apportioning factor \( \mu \), that is

\[
v_e = E \left( \mu - \frac{1}{2} \right) - \mu v_{e_{\max}} + (\mu - 1) v_{e_{\min}}
\]

where: \( v_{e_{\max}} = \max(v_e, v_e, 0) \) and \( v_{e_{\min}} = \min(v_e, v_e, 0) \).

The apportioning factor \( \mu (0 \leq \mu \leq 1) \) is given by

\[
\mu = \frac{l_{o\,a}}{l_o}
\]

and indicates the distribution of the general free-wheeling period \( l_o \) (period in which voltages \( v_e^{i\,0}, v_e^{h\,0} \) and \( v_{e\,0} \) are equals) between the beginning \( l_{o\,a} = \mu l_o \) and the end \( l_{o\,f} = (1 - \mu) l_o \) of the switching period. The apportioning factor can be changed as a function of the modulation index (\( \mu \)) to reduce the THD of both converter voltages.

In this case, the proposed algorithm is:

1) Choose the general apportioning factor \( \mu \) and calculate \( v_e \) from (48).
2) Determine \( v_e^{i\,0}, v_e^{h\,0} \) and \( v_{e\,0} \) from (45) - (47).
3) Finally, once the midpoint voltage have been determined, calculate pulse-widths \( \tau_e, \tau_e^{i} \) and \( \tau_e^{h} \).

\[
\tau_e = \frac{T}{2} + \frac{T}{E} v_{e\,0}
\]
\[ \tau'_p = \frac{T}{2} + \frac{T}{E} v'_{c0} \]

\[ \tau'_h = \frac{T}{2} + \frac{T}{E} v'_{h0} \]

**Method B: Local approach**

The voltage \( v'_{\mu s} \) can be calculated taking into account the local apportioning factor \( \mu_s \):

1. for the grid \( \mu_s = \mu_e \), dividing (splitting) the period \( t_{oc_e} \), in which the voltages \( v'_{c0} \) and \( v'_{e0} \) are equal, at the beginning \( (t_{oc_e} = \mu_e t_{oc_e}) \) and at the end \( (t_{oc_e} = (1 - \mu_e) t_{oc_e}) \) of the switching period.

2. for the load \( \mu_s = \mu_h \), splitting the period \( t_{oh} \), in which the voltages \( v'_{h0} \) and \( v'_{e0} \) are equal, at the beginning \( (t_{oh} = \mu_h t_{oh}) \) and at the end \( (t_{oh} = (1 - \mu_h) t_{oh}) \) of the switching period.

Thus, the reference voltage \( v'_{\mu s} \) can be expressed by:

\[
v'_{\mu s} = E \left( \mu_s - \frac{1}{2} \right) - \mu_s v'_{\max} + (\mu_s - 1) v'_{\min}\]

where \( v'_{\max} = \max V_c \) and \( v'_{\min} = \min V_g \) if \( s = e \) or \( v'_{\max} = \max V_h \) and \( v'_{\min} = \min V_h \) if \( s = h \), where \( V_c = \{v'_{c0}, 0\} \) and \( V_h = \{v'_{h0}, 0\} \). Besides (53), the voltage \( v'_{\mu s} \) must also obey the other converter side. Then, from (45) and (46) the limits for \( v'_{\mu s} \) can be calculated

for \( s = e \):

\[
v'_{\mu s} = \frac{E}{2} - v'_{h}\]

(54)

\[
v'_{\mu s} = \frac{E}{2} - v'_{h}\]

(55)

for \( s = h \):

\[
v'_{\mu s} = \frac{E}{2} - v'_{e}\]

(56)

\[
v'_{\mu s} = \frac{E}{2} - v'_{e}\]

(57)

In this case, it is possible to control how the harmonic distortion is divided by both converters. So, the proposed algorithm is:

1. Choose the local apportioning factor \( \mu_s \), so that grid or load converter is optimized, calculate \( v'_{\mu s} \) from (48).
2. Determine \( v'_{c0}, v'_{h0} \) and \( v'_{e0} \) from (45) - (47) using \( v'_{\mu s} = v'_{\mu s} \).
3. Use Step 3 of Method A.

**IV. OVERALL CONTROL STRATEGY**

As mentioned in the previous sections, the modes of operation of the converter are defined by the system functionality. The system can operate with four or three-leg depend on the need; or in case of grid voltage fault, the battery bank is used to supply energy to the d.c.-bus capacitor voltage and inverter in order to maintain the desirable voltage to the load.

The description of the operation mode of the proposed circuit can be observed in Fig. 2. The image in gray represents the section of the circuit that is not in use. Four operation modes are presented. In Fig. 2(a), the system operates with four-leg. In three-leg mode, presented at Fig 2(b), the free-leg denoted by \( h \) is not in use. At Fig. 2(c), the system is still operating in three-leg mode and the free-leg is used to charge the battery bank, operating as buck converter. Finally, assuming the battery charged, the Fig. 2(d) presents the condition in which the energy is transferred from the battery bank to the load via inverter, considering the failure at the a.c. input. At this mode, the leg \( h \) works as boost converter.

![Control block diagram of the proposed configuration.](image)

The proposed system control is shown in 3. The mode of operation of the converter is determined by the state of switch \( S_c \). If \( S_c \) is in position 1, the converter operates according to the four-leg mode. If \( S_c \) is in position 2, the selected mode is three-leg. The disconnection of the circulating current control block makes possible to use the shared-leg to charge the battery bank.

For the system operating with four-leg, switches \( S_a, S_b \) and \( S_c \) in position 1, the capacitor d.c.-link voltage \( v_c \) which is a standard PI type controller. This controller provides the amplitude of the reference current \( I_{c} \). For the power factor and harmonic control the instantaneous reference current \( I_{c} \) must be synchronized with voltage \( e_g \). This is performed by the block \( GEN-g \) from a P.I.L scheme. From the synchronization with \( e_g \) and the amplitude \( I_{c} \) the current \( I_{c} \) is generated. The current controller is implemented by using the controller indicated by block \( R_c \). The controller \( R_c \) is a double sequence digital current controller employed in [21]. Thus current controller defines the input reference voltage \( v_i \).

The instantaneous reference load voltage \( v_i \) can be determined by using the rated optimized load angle \( \delta_l \) plus the information \( \theta_g \) from block \( SYN \) and the defined load amplitude \( V_i^* \). The block \( GEN-l \) uses the input information to generate the desired reference load voltage \( v_i^* \). The homopolar current \( i_o \) is controlled by controller \( R_o \), that determines voltage \( v_o^* \) responsible to minimize the effect of the circulating current \( i_o \), maintaining this current near to zero. All these voltages are applied to \( PWM \) block to determine the conduction states of the converter’s switches.

When the switch \( S_c \) is in position 2, three-leg mode of operation occurs. The d.c./d.c. buck converter is used to charge the battery bank. The free-leg makes the d.c.-bus voltage \( V_{oc} \) to be stepped down in its average value to supply the d.c.-battery.
bank according to $V_{bat} = DV_{cc}$. The battery voltage $V_{bat}$ is directly proportional to duty ratio $D$. In the stored-energy mode of operation, when the a.c. input voltage is beyond the permissible tolerance range, the switch $S_1$ disconnects the a.c. input, transferring the energy from the battery bank to the load via inverter. Since the battery voltage is low, it is first requires to be boosted to high d.c. voltage for the proper operation of the d.c./a.c. inverter, now responsible to supply the load. The low battery voltage $V_{bat}$ is boosted to high d.c. voltage $V_{cc}$ according to $V_{cc} = V_{bat}/(1 - D)$.

When both switches $S_a$ and $S_b$ are in position 2, situation in what the a.c. input voltage failure, the load is supplied by battery bank and inverter. At this point, the converter $S_b$ who was responsible for regulating the grid current and the d.c.-bus voltage is now responsible for maintaining the voltage applied to the load.

V. SIMULATION RESULTS

The proposed configuration was simulated using PSIM software with the following parameters described in TABLE I. This configurations does not use transformer in the series connection and consist of four-leg converter. The converter can be reconfigured to work with three-leg in order to use the free-leg to charge the battery bank when needed. The free-leg is used to compose the buck converter controlling the duty ratio of the upper switch while the lower is idle.

Some simulation results are now presented in Figs. 4, 5, 6 and 7. In the simulation results, the capacitors were selected

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**TABLE I**

PARAMETERS OF THE SIMULATED SYSTEM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-bus voltage</td>
<td>300V</td>
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<tr>
<td>Battery bank voltage</td>
<td>45V</td>
</tr>
<tr>
<td>Inductance filter</td>
<td>5.0mH</td>
</tr>
<tr>
<td>Capacitor filter</td>
<td>70nF</td>
</tr>
<tr>
<td>Grid - voltage/frequency</td>
<td>110V/60Hz</td>
</tr>
<tr>
<td>Harmonic component - amplitude/frequency</td>
<td>0.2V/180Hz</td>
</tr>
<tr>
<td>Load voltage ($v_l$)</td>
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</tr>
<tr>
<td>Power</td>
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</tr>
<tr>
<td>RL load</td>
<td>155Ω/2.0mH</td>
</tr>
<tr>
<td>Diode bridge rectifier</td>
<td>153Ω/2.0mH/2.0mF</td>
</tr>
</tbody>
</table>

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as \( C = 2200 \mu F \) and the switching frequency employed was 15kHz. In each figures, there are four subfigures that describe the behavior of the system at certain intervals described as: (a) converter mode of operation of four-leg to three-leg (both switches \( S_2 \) and \( S_3 \) will be open) - the shared-leg is denoted by \( e \) and the free-leg is \( h \), (b) storing-mode of operation (switch \( S_3 \) will be close), (c) converter mode of operation of three-leg to four-leg (both switches \( S_2 \) and \( S_3 \) will be close) and (d) the fault at a.c. input grid voltage with its disconnection from switch \( S_1 \). In Fig 4 is presented the grid voltage, with a disturbance of 20\% of third harmonic, and current with power factor control near to unity. The THD of grid current is 3.91\% and the load current and voltage THD are equal to 31.02\% and 2.54\%. During the storing-mode of operation, when the d.c. voltage level at the battery bank is beyond the preset tolerance, it is observed a certain increase at the grid current amplitude \( i_g \), it happens because at this mode of operation the system needs to drain more current to maintain the voltage at d.c.-bus capacitors and to charge the d.c.-battery bank (Figs. 4 and 5). During this stage, the grid current THD increases a little to 4.36\%. The load and grid voltages are also shown in Fig 6. In all subfigures labeled as (d) are described the moment when the fault at a.c. grid voltage occurs and the load is supplied by boost converter via free-leg and inverter maintaining the load voltage at desired value.

The d.c.-bus voltage is shown in Fig. 7. At time \( t_1 \), it is depicted converter mode of operation of four to three-leg. During \( t_2 - t_3 \), it observed the interval the battery bank is being charged. The change in the mode of operation of three-leg to four-leg occurs at \( t_4 \). The battery charging voltage is 48 \( V_{cc} \) as observed in Fig. 7 (b). The presented result illustrates only the interval the battery bank is being charged taking as reference the coupling point connection \( hB \), see Fig. 1(a). Finally, at \( t_5 \), where the a.c. grid voltage failure, it is show the instant the system is supplied by battery bank and inverter which keeps the voltage to the load at the desired value.
TABLE II
PARAMETERS OF THE TEST BENCH.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-bus voltage</td>
<td>250V</td>
</tr>
<tr>
<td>Battery bank voltage</td>
<td>48V</td>
</tr>
<tr>
<td>Inductance filter</td>
<td>7.0mH</td>
</tr>
<tr>
<td>Capacitor filter</td>
<td>70µF</td>
</tr>
<tr>
<td>Grid - voltage/frequency (e_g)</td>
<td>110V/60Hz</td>
</tr>
<tr>
<td>Harmonic component - amplitude/frequency</td>
<td>0.2e/180Hz</td>
</tr>
<tr>
<td>Load voltage (v_l)</td>
<td>110V</td>
</tr>
<tr>
<td>Power</td>
<td>1.2kVA</td>
</tr>
<tr>
<td>RL load</td>
<td>15Ω/2.0mH</td>
</tr>
<tr>
<td>Diode bridge rectifier connected to RLC</td>
<td>15Ω/2.0mH/2.0mF</td>
</tr>
</tbody>
</table>

VI. EXPERIMENTAL RESULTS

In this section, experimental results of the proposed system are presented. The system operates at four-legs mode which is reconfigurable to operate with three-legs in order to charge the battery bank performing voltage and current compensation. The proposed topology, Fig. 1(a), has been tested by using a microcomputer-based system which is equipped with dedicated boards, in order to generate the control signals. The system have twelve sensors (six current and six voltage sensors), interface card and data acquisition boards, and two static converters each one with three-leg, see Fig. 8. In the experimental tests, the capacitors were selected as $C = 2200$µF and the switching frequency employed was 15kHz. The system parameters are presented in TABLE II.

In Fig. 9 are shown the grid current ($i_g$), the grid voltage ($e_g$), the load current ($i_l$) and the load voltage ($v_l$). The grid voltage has been obtained from a disturbance voltage source and even in the presence of 20% of third harmonic voltage at grid; the grid current and the load voltage present the waveform characteristic close to sinusoidal and with power factor control close to one. The grid current THD is 4.36%, while the load current presents THD equal to 29.94%. The load voltage THD, for this case, is equal to 2.98%. The voltage of both d.c.-bus voltage and battery bank during the storing - mode of operation are indicated in Fig. 10. For the d.c.-bus voltage and battery bank control it was chosen 250Vcc and 48Vcc, respectively. After the fault at a.c. grid voltage the inverter via boost converter keeps the desired voltage to the load, as shown in Fig. 11.

VII. CONCLUSIONS

An universal active power filter for harmonic and reactive power compensation with UPS features for single-phase system has been presented. The proposed configuration is a transformerless delta converter with reduced number of components that that emulates the buck-boost converter from
the shared-leg. The system modelling of the proposed system shows that the circulating current can be controlled to a level near to zero. The control of the circulating current is accomplished by the voltage \( v_o = v_{o0} + v_{o1} - v_{o0} - v_{o1} \) (converters \( S_1 + S_2 \)) in order to control the \( i_o \) close to zero. In the three-legs mode of operation, the circulating current does not exist. A suitable control strategy for the proposed system, including \( P/I/M \) techniques has also been presented. The system can be reconfigurable to operate with four or three-leg leaving the free-leg to charge the battery bank without having a dedicated d.c./d.c. buck-boost converter. The configuration produces satisfactory results. The proposed solution has the advantage of reducing volume and cost in comparison to the conventional UAPF. Simulated and experimental results have been presented and validates the operation of the proposed system.

REFERENCES


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