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A Hybrid Active Power Filter Comprising an Active Electromagnetic Filter

***Abstract**. A hybrid active power filter comprising a b-shape C-type hybrid active power filter and an active electromagnetic filter is proposed in this paper. The active electromagnetic filter of the proposed topology consists of a three-phase Zig-Zag transformer and a half-bridge single-phase inverter connected in parallel with the b-shape C-type hybrid active power filter and the loads. The zero sequences of the load currents due to unbalancing and the triple order harmonics are compensate by the active electromagnetic filter. In this topology, compensation of the zero sequences is independent of the Zig-Zag transformer location. The b-shape C-type hybrid active power filter consists of a double tuned parallel passive filter and a half-bridge three-phase inverter. Using the active electromagnetic filter reduces rated power of the active part of the b-shape C-type hybrid active power filter effectively. The proposed configuration is applicable in high voltage grid (up to 20kV) due to the series capacitor of the b-shape C-type hybrid active power filter and the Zig-Zag transformer of the active electromagnetic filter. The steady state compensation and the resonance-damping characteristics of the proposed topology are analyzed in this paper. The hybrid active power filter is simulated and the simulation results are provided to validate effectiveness of the topology and the design considerations.*

***Streszczenie.** W artykule analizuje się aktywny filtr mocy wykorzystujący aktywny filtr elektromagnetyczny. Filtr elektromagnetyczny składa się z trójfazowego transformatora w topologii Zig-Zag i półmostkowego jednofazowego przekształtnika połączonego równolegle do hybrydowego filtru aktywnego typu C. (**Hybrydowy filtr mocy z elektromagnetycznym filtrem aktywnym**)*

Keywords: hybrid/active power filter, Zig-Zag transformer, electromagnetic filter, resonance damping
Słowa kluczowe: hybrydowy filtr aktywny, filtr elektromagnetyczny.

Introduction

Nowadays, unbalanced and nonlinear loads, such as three-phase or single-phase diode and thirystor rectifiers, are widely used in electrical network. Therefore, without harmonic and unbalancing compensation, the power quality of electrical systems is degraded. There are several solutions to improve power quality. The simplest solution is parallel passive filters (PPFs). The PPFs are widely used to decrease the harmonic components of utilities due to their low cost and high efficiency. The PPFs have some drawbacks, such as effects of the source impedances on their characteristics, the series and the parallel resonance, and Over-voltage under no-load or light load conditions [1-3]. Another solution is active power filter (APF). Some papers such as [4] and [5] employ the shunt active power filter to compensate reactive and harmonic components of the source currents, but construction of a large rated current of the APF with rapid current response is costly and difficult [1, 3].

Combination of the passive and the active filters, named hybrid active power filter (HAPF), is economic solution. The HAPFs have the advantages of the PPFs and the APFs without their disadvantages. In other words, they are cost effective, small size, easy protection, and low rated power [1, 3].

Three-phase four-wire distribution power systems are widely employed to supply low voltage system of office buildings, commercial complexes, manufacturing facilities and etc. These systems may consist of unbalanced and non-linear single-phase and three-phase. These loads produce fundamental and harmonic components of zero sequences (third, sixth, ninth and etc.). The zero sequence components of the load currents are injected into electrical systems through neutral conductors. They may cause overload of the neutral conductors, transformers, and unbalancing of the voltages of the loads. There are several methods to decrease zero sequence components of the load currents [1, 6]:

- Passive filters
- Active filters
- Electromagnetic filters

These methods are presented by some papers. In [1] a three-phase four-wire active power filter which comprises a three-phase three-wire APF and a Zig–Zag transformer is proposed. The Zig-Zag transformer is connected in parallel with load, but it must be located as near as possible to the load [1]. Therefore the place of the Zig-Zag transformer is so important in the presented topology in [1]. A passive three-leg electromagnetic filter with Zig-Zag connection is presented by paper [6]. In this configuration, compensation of the unbalanced currents is dependent on location of the Zig-Zag transformer too. Also, magnetic reactances of the phases are asymmetrical in three-leg core configuration [7-8]. In paper [9], a hybrid neutral harmonic suppressor employing a Zig-Zag transformer is presented. In this topology, a single-phase inverter connected in series with the neutral conductor [9]. Whereas, the series inverter is employed, the reliability of the presented topology will be decreased. In some papers such as [10] and [11], a three-phase four-wire active power filter is employed to compensate the harmonic currents and the neural current.

This paper presents a topology of the HAPF which consists of a b-shape C-type hybrid active power filter (bCHAPF) and an active electromagnetic filter (AEMF). The bCHAPF consists of a double tuned parallel passive filter (PPF) and a three-phase three-leg inverter. The AEMF comprises a three-phase Zig-Zag transformer and a single-leg inverter too. Therefore the active part of the HAPF is a four-leg inverter as shown in figure (1). The PPF of the bCHAPF is tuned on 5th order harmonic and fundamental frequency for absorption of 5th order of harmonic of the load current, and compensation of reactive power. Also capacitors of $C_{f1a,b,c}$ degrade the rated voltage of the three-leg inverter. The AEMF compensates zero sequences of the load currents comprising the zero sequences of the fundamental and the triple orders of harmonic components (3^{th}, 6^{th}, 9^{th} and etc.). Therefore the PPF and the AEMF decrease the rated power of the three-leg inverter effectively. The compensation of the zero sequences is independent of the Zig-Zag transformer location due to the presence of the single-leg inverter of the AEMF. This paper focuses on the principles of the proposed topology and pays attention to the control system design of the bCHAPF and the AEMF finally. The proposed HAPF is simulated and the simulation results show that the proposed HAPF works effectively.

Topology of the proposed HAPF

Figure (1) shows the proposed HAPF comprising a bCHAPF and an AEMF. In order to reduce, rated voltage of the three-leg inverter, the capacitors of $C_{f1a,b,c}$ are connected in series with the inverter. Also to degrade the rated power of the three-leg inverter, the passive filters comprising $C_{f2a,b,c}$ and $L_{f1a,b,c}$ are connected in parallel with the three-leg inverter. Capacitors of $C_{f1a,b,c}$, $C_{f2a,b,c}$ and inductors $L_{f1a,b,c}$ are tuned in 5^{th} order of harmonic, and capacitors of $C_{f2a,b,c}$ and inductors of $L_{f1a,b,c}$ are tuned in fundamental frequency too. Therefore, the capacitors of $C_{f1a,b,c}$ are employed to compensate the reactive power. The system parameters are listed in table (1).

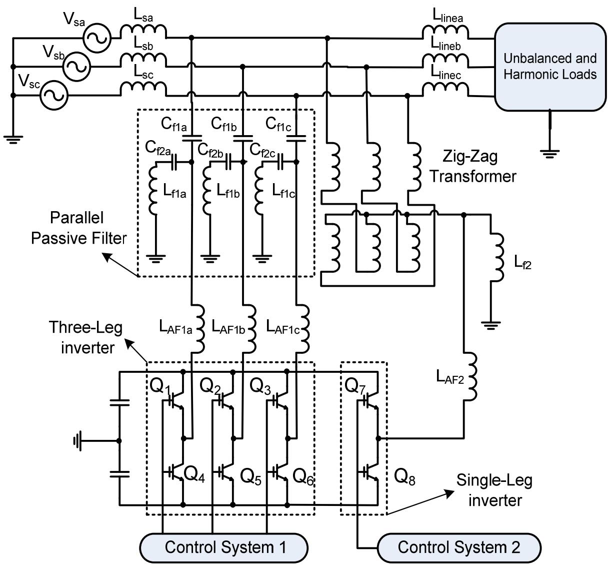

Fig.1.The proposed circuit of HAPF

Table1. The system parameters

The inductances of the source	L_{sa}=L_{sb}=L_{sc}=0.2mH
The parameters of the filters	$C_{f1a,b,c}$=179.2uF $C_{f2a,b,c}$=4296.5uF $L_{f1a,b,c}$=2.36mH
The inductances of the line	$L_{line\ a,b,c}$=0.1mH
The inductances of the AEMF	L_{ZT}=2.5mH, L_{f2}=10mH

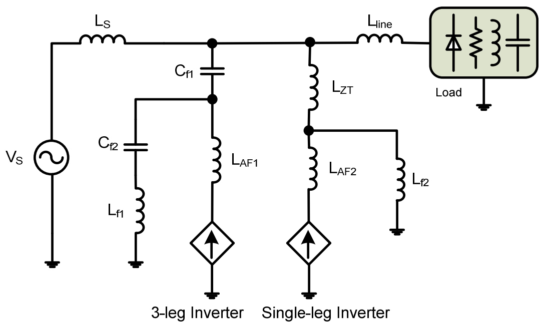

Fig.2.The single-phase equivalent circuit of the proposed HAPF

The principles of the proposed HAPF

To clarify the compensation principles of the proposed HAPF, a single phase equivalent circuit of it is demonstrated in domains of fundamental, harmonic and zero-sequence frequencies in figure (2). As shown, the three-leg inverter is considered as controlled current source i_{AF1} and the single-leg inverter is considered as controlled current source i_{AF2} , where V_s and L_s are voltage and equivalent inductor of the network respectively, and the inductors of L_{ZT} and L_{line} denote for Zig-Zag transformer leakage inductance and the line inductance respectively.

The equivalent circuit in zero sequence frequency domain

To compensate the zero sequence currents of the loads, a Zig-Zag transformer and a single-leg inverter are employed as shown in figure (1).

The zero sequence impedances of the three-phase Zig-Zag transformer are low respect to other transformers that are usually used in the electrical grids. The shape and the configuration of the core are important parameters in the magnitude of the zero sequence impedances. 3- Leg cores are usually used in the transformers, but the magnetic reluctances of the three phases are unequal in them, because of the asymmetrical magnetic fluxes of the phases. This paper uses a Zig-Zag transformer that the zero sequence impedances are equal and symmetrical. Figure (3) shows a configuration which the magnetic reluctances of phases are equal and the magnetic fluxes are symmetrical.

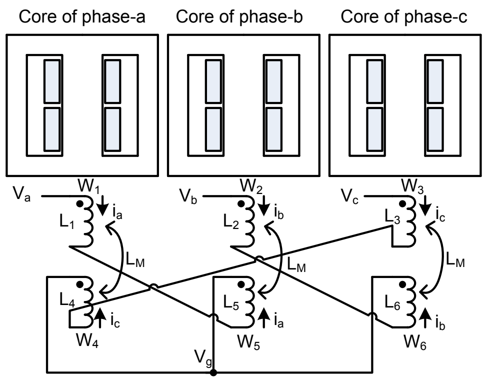

Fig.3.The configuration of the Zig-Zag Transformer and its equivalent circuit

In the configuration of the Zig-Zag transformer, there is no mutual inductance between phases of a-b, a-c and b-c. Assuming that the magnetic reluctance of each core is defined as $\Re$, the inductance of the each phase can be written as:

(1) $$L=\frac{N^2}{\Re}$$

where N is turns of each winding. The core and the winding of each phase are similar. Considering figure (3), the self and mutual inductances can be expressed as:

(2) $$L_1=L_2=L_3=L_4=L_5=L_6=L_M=L$$

From equations (1) and (2), the winding voltages of the Zig-Zag transformer can be computed as follows:

(3) $$\begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix}=\begin{bmatrix} 2L+L_l & -L & -L \\ -L & 2L+L_l & -L \\ -L & -L & 2L+L_l \end{bmatrix}\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix}+R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

where inductance of L_l and resistance of R are the leakage inductance and the winding resistance respectively. Therefore, the equivalent inductor matrix can be written as:

(4) $$\left[L_{eq}\right]=\begin{bmatrix} 2L+L_l & -L & -L \\ -L & 2L+L_l & -L \\ -L & -L & 2L+L_l \end{bmatrix}$$

It is observed that, $[L_{eq}]$ is symmetrical and $[L_{eq}]=[L_{eq}]^T$. If the 3-Leg core is used, the equivalent inductance matrix is asymmetrical and $[L_{eq}] \neq [L_{eq}]^T$.

In fundamental frequency, the zero sequence currents are in-phase and equal:

$$(5) \qquad \begin{cases} i_{ao} = i_{bo} = i_{co} = i_o \\ v_{ag} = L_1 \dfrac{di_o}{dt} + Ri_o \end{cases}$$

Thus, in the configuration of the Zig-Zag transformer, the zero sequence impedance is independent of the mutual inductances, and it can be written as:

$$(6) \qquad Z_{ZTo} = (L_1 + R)$$

where Z_{ZTo} is the zero sequence impedance of the Zig-Zag transformer. The zero sequence impedance of the 3-Leg core transformer is bigger than equation (6) and it depends on the mutual inductances [6-7].

In the domains of the zero sequence frequencies, the three-phase three-leg inverter is considered as open circuit, but the single-phase inverter is considered as the controlled current source i_{AF2}. Figure (4) shows equivalent circuit in the domains of the zero sequence frequencies.

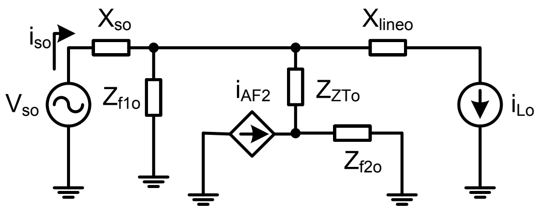

Fig.4.Equivalent circuit in zero sequence frequency domain

Considering figure (4), X_{so}, Z_{f1o}, Z_{ZTo}, Z_{f2o} and X_{lineo} are the source impedance, the passive filter impedance, the Zig-Zag transformer impedance, the impedance of the inductor paralleled with the single-leg inverter and the line impedance in domains of zero sequences frequencies respectively. Voltage source Vso is the zero sequence of the system voltage and iLo is the load zero sequence components. The single-leg inverter of the active part is considered as controlled current source injecting currents to decrease the zero sequence current of the source. Considering figures (3) and (4), the zero sequence impedance of the passive filter can be computed as:

$$(7) \qquad \begin{cases} Z_{f1o} = \dfrac{1}{jC_{f1}h\omega_o} + \dfrac{1}{jC_{f2}h\omega_o} + jL_{f1}h\omega_o \\ h = 1, 3, 6, 9, \ldots \end{cases}$$

where ω_o is the fundamental angular frequency.

In this paper, to decrease the zero sequence of the current source, i_{AF2} is considered as:

$$(8) \qquad i_{AF2} = k_o i_{so}$$

If the background zero sequences of the voltage sources are neglected, the zero sequence of the source current can be given as:

(9)

$$\frac{i_{so}}{i_{Lo}} = \frac{(Z_{f1o}Z_{f2o} + Z_{f1o}Z_{ZTo})}{Z_{so}(Z_{f1o} + Z_{ZTo} + Z_{f2o}) + Z_{f1o}Z_{ZTo} + (1+k_o)Z_{f1o}Z_{f2o}} = G_1$$

Considering equation (9), if coefficient of ko is sufficiently selected large, iso comes near to zero. The presence of the single-leg inverter causes that the compensation of zero sequences of the load currents is independent of the Zig-Zag transformer location.

The equivalent circuit in fundamental and harmonic frequency domain

Figure (5) shows single-phase equivalent circuit of the system demonstrated in figure (1) and (2) in fundamental frequency for negative and positive sequences, where i_{AF1}, i_{AF2} and the Zig-Zag transformer are considered as open-circuit.

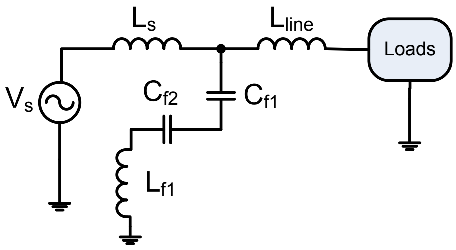

Fig.5.Equivalent circuit in fundamental frequency

Not only the double tuned parallel passive filter absorbs the fifth order of harmonic of the load currents, but also it supplies reactive power of the load currents. Also capacitor of C_{f2} and inductor of L_{f1} are tuned in fundamental frequency to bypass the three-leg inverter from fundamental frequency. Therefore, the relations of the passive filter can be written as:

$$(10) \qquad \begin{cases} V_S^2 C_{f1}\omega_o = Q_{load} \\ L_{f1}C_{f2}\omega_o^2 = 1 \\ 25L_{f1}\, C_{f1}C_{f2}\omega_o^2 / (C_{f1} + C_{f2}) = 1 \end{cases}$$

where, V_s and Q_{load} are the source voltage and the load reactive power respectively.

Figure (6) shows the single-phase equivalent circuit of the figure (1) and (2) in domains of the harmonic frequencies. Controlled current source i_{AF2} and the Zig-Zag transformer are considered as open-circuit.

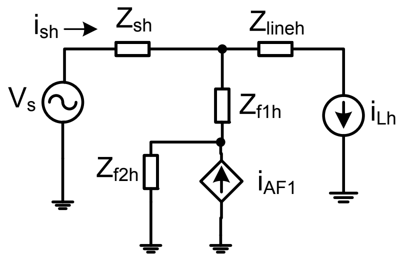

Fig.6.Equivalent circuit in harmonic domain

In figure (6), Z_{sh} , Z_{lineh} and Z_{f1h} are the harmonic impedances of the source, the line and capacitor of C_{f1} respectively. Impedance of Z_{f2h} consists of summation of the impedances of capacitor C_{f2} and inductor L_{f1}.

There are two strategies for controlling of i_{AF1}, load current detection and supply current detection. In this paper, to decrease the harmonic components of the source currents, the controlled current source i_{AF1} is considered as [3]:

$$(11) \qquad i_{AF1} = k_h i_{sh}$$

If the back ground harmonic voltages of the source are neglected, the ratio of the source harmonic currents to the load harmonic currents can be obtained as:

$$(12) \qquad \frac{i_{sh}}{i_{Lh}} = \frac{(Z_{f1h} + Z_{f2h})}{Z_{f1h} + Z_{sh} + (1+k_h)Z_{f2h}} = G_2$$

If k_h is sufficiently selected large, the source harmonic currents are effectively decreased.

Investigation of k_o and k_h effects

According to the appendix, it is observed that:

$$\frac{i_{sho}}{i_{Lho}} = \frac{G_1 G_2}{G_1 + G_2} \tag{13}$$

where i_{sho} and i_{Lho} are the zero sequence and harmonic components of the source and the loads respectively.

The effects of K_o and K_h are investigated under two conditions, with and without active parts.

If the active parts are off-state, K_o and K_h are zero. Figure (7) shows the amplitude-frequency characteristics of G_1 and G_2 where the parameters of the system are according to table (1). The passive filter causes occurrence of parallel resonance around 250 Hz in Both of the curves. Many non-linear loads such as six-pulse rectifiers produce 5^{th} order of harmonic of the current, thus avoiding of the parallel resonance is difficult. Therefore, using the active part is necessary for damping of parallel resonance.

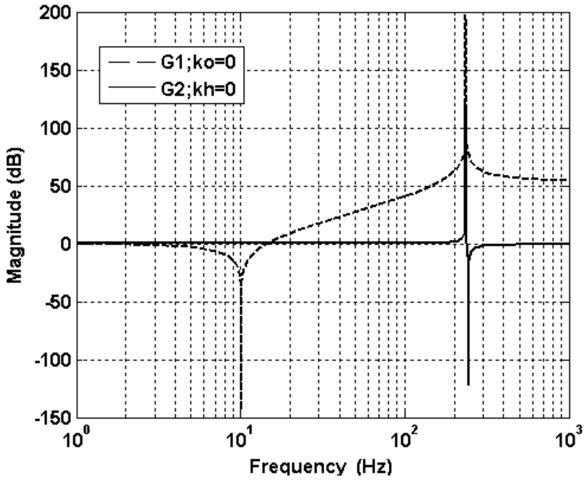

Fig.7.Amplitude-frequency characteristics of $G_1=i_{so}/i_{Lo}$ and $G_2=i_{sh}/i_{Lh}$

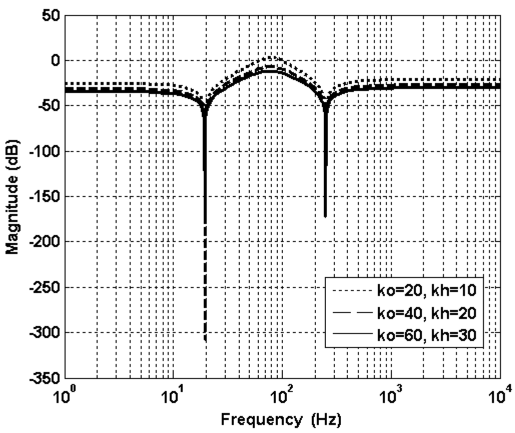

Fig.8.Amplitude-frequency characteristics of i_{sho}/i_{Lho}

If the active parts are off-state, the inverters can be considerd as two dampers. Figure (8) shows current ratio i_{sho}/i_{Lho} with different coefficients (k_o and k_h) in domains of frequencies, where the parameters of the system are according to table (1). The three-leg inverter of the bCHAPF and the single-leg inverter of the AEMF reduce the current ratio in all of frequencies as compared with the value obtained without them as shown in figure (8). Since the inverters of the bCHAPF and the AEMF act as damping resistors, no amplification occurs in the amplitude-frequency characteristics.

From figure (8), it is observed that coefficient k_o and k_h should be selected more than 20 and 40 respectively, for effective decreasing of the zero sequence and harmonic components.

Investigation of the source inductance effects

Figures (9) shows the amplitude-frequency characteristics for different values of the source inductances. Without the inverters of the bCHAPF and the AEMF, the parallel resonance occurs with every value of the source inductance around 250Hz, because of the presence of the passive filter.

Without damping, the magnitudes of the resonances are more than 100db and these over voltage may damage equipment as shown in figure (9).

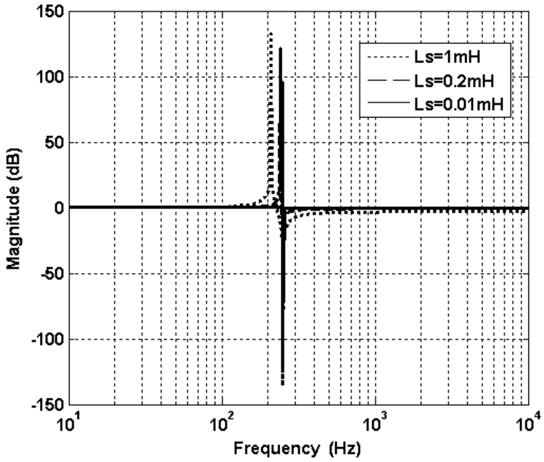

Fig.9.Amplitude-frequency characteristics of $G_2=i_{sh}/i_{Lh}$

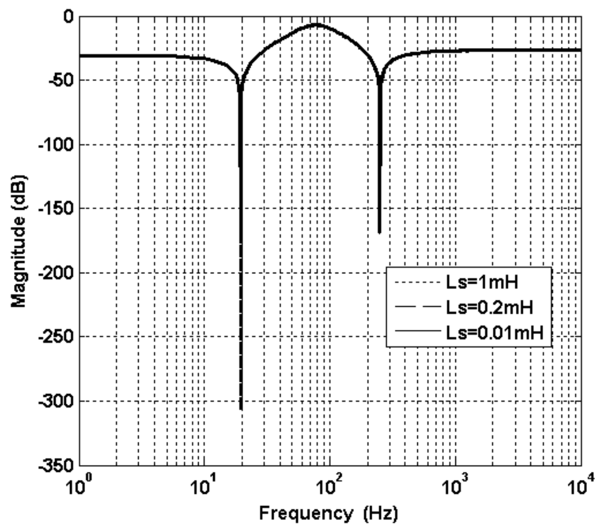

Fig.10. Amplitude-frequency characteristics of i_{sho}/i_{Lho}

As seen in figure (10), when the bCHAPF and the AEMF work with k_o=20 and k_h=40, no parallel resonance occurs and the curves pushed down in all frequencies as compared with the values obtained without them. It is observed that the bCHAPF and the AEMF act as two dampers. The variations of the source inductance values have no effect in amplitude-frequency characteristics and all of the curves are same approximately. In other words, when the bCHAPF and the AEMF are adopted, the amplitude-frequency characteristics aren't almost influenced by the variations of the source inductances.

Reference signals and control method

The control system of the HAPF is divided into two units. The first unit is for three-phase three-leg inverter of the bCHAPF and the second unit is for the single-phase single-leg inverter of the AEMF. The control systems of them are shown in figure (11).

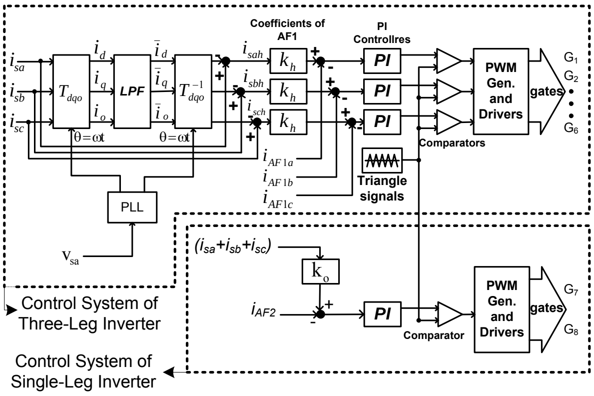

Fig.11.Schematic of the HAPF control system

The control system of the three-phase inverter

In this paper, the reference signals are extracted by SRF method [3, 12, and 13]. Three-phase current signals of the source are changed in to d-q coordination by equation (14):

$$i_{dqo}=\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix}=\begin{bmatrix}T_{dqo}\end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}=\begin{bmatrix} \bar{i}_d+\tilde{i}_d \\ \bar{i}_q+\tilde{i}_q \\ \bar{i}_o+\tilde{i}_o \end{bmatrix} \quad (14)$$

where T_{dqo} is transform matrix as follows:

$$\begin{bmatrix}T_{dqo}\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} \cos\omega t & \cos\left(\omega t-\frac{2\pi}{3}\right) & \cos\left(\omega t+\frac{2\pi}{3}\right) \\ -\sin\omega t & -\sin\left(\omega t-\frac{2\pi}{3}\right) & -\sin\left(\omega t+\frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (15)$$

The voltages of the source are used in PLL for obtaining of ωt used in d-q transform as shown in figure (12).

After the d-q rotating coordination transform, the fundamental components of the source currents are changed into dc components, then they are extracted by low pass filters. The inverse d-q rotating coordination transformation produces the fundamental currents. The harmonic components (i_{sah}, i_{sbh} and i_{sch}) are obtained by subtracting of the fundamental components from input signals (i_{sa}, i_{sb} and i_{sc}). The harmonic components are multiplied by k_h (the coefficient of bCHAPF), and are compared with the output currents of three-phase three-leg inverter to produce error signals, the error signals input into PI controller.

$$i_h=i_S-i_f=\left(1-\left[T_{dqo}\right]^{-1}LPF\left[T_{dqo}\right]\right)i_S \quad (16)$$

where, i_s, i_f and LPF denote the source currents, the fundamental components of the source currents and the low pass filter respectively.

Finally, the PWM signals of the IGBTs' gates are produced by comparing the outputs of the PI controllers with a triangle waveform.

The control system of the single- leg inverter

The single-leg inverter is connected to the neutral of the Zig-Zag transformer to compensate the zero sequences of the source currents. For control of single-leg inverter, its output currents should be compared with the summation of the source currents, as follows:

$$e=k_o\left(i_{Sa}+i_{Sb}+i_{Sc}\right)-i_{AF2} \quad (17)$$

where e and i_{AF2} are the error signal and the output current of the single-leg inverter respectively.

In this control system, the output current of the single-leg inverter is compared with the zero sequences of the source current, and their error signal inputs into a PI controller. The output of the PI controller is compared with the triangle waveform and finally, the PWM signals of the IGBTs' gates are produced.

As mentioned before, the equivalent circuits of the zero sequence and harmonic components are different. In the other words, the control systems of the bCHAPF and the AEMF are independent. Therefore, the gain k_h is independent of the gain k_o. For this reason the implementation of the control system of the proposed HAPF is simple.

Control of DC-link voltage

Whereas the control systems of the three-leg inverter and the single-leg inverter are independent, a separate DC-link control system is employed. Figure (12) shows the DC-link control circuit of the bCHAPF and the AEMF. In the control system, the elements of $L_{dc\text{-}Link}$ and $R_{dc\text{-}Link}$ are employed to filter the current ripples and to limit of IGBT current respectively. The principles of the control system are based on voltage magnitude of DC-link. The voltage of the DC-link is detected and is compared with a reference voltage. The error of detected voltage and the reference voltage enters into a PI controller. The output of the PI controller is compared with a triangle waveform to produce the PWM signals of the IGBT. Rated power of the control circuit shown in figure (13) is very low.

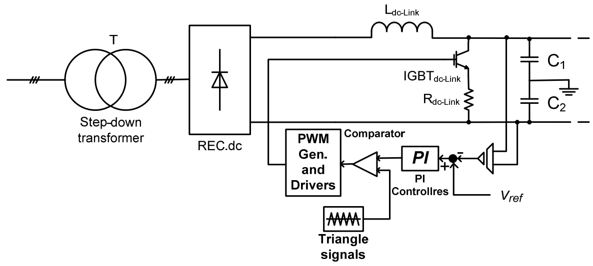

Fig.12. Control circuit of DC link of HAPF

Simulation results

To verify the effectiveness of the proposed topology, simulation based on MATLAB/Simulink has been carried out. The parameters of the system and the loads according to table 1 and 2 are used in simulation.

Table2. The parameters of the loads

Non-linear load	a three-phase full bridge rectifier L=1mH, R=40Ω
Unbalanced linear loads	R_a=50Ω , L_a=55mH R_b=40Ω , L_b=57mH R_c=50Ω , L_c=59mH

As shown in table 2, the loads consist of a three-phase non-linear load and unbalanced linear loads connected in parallel with together. The resistors and the inductors of the linear loads are parallel.

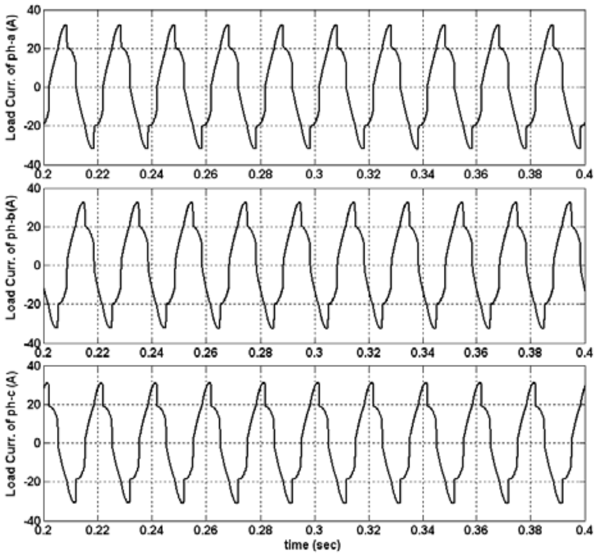

Fig.13. Load current waveforms

Figure (13) shows load currents. As seen in the figure, the non-linear load causes to inject harmonic currents to the source. Table (3) shows the harmonic components of load current of phase-a.

Table 3. Harmonic components of loads of phase-a load current (peak values)

Order of Harmonic	Amplitude (A)
1	28.83
5	3.35
7	1.67
11	1.33
13	1
17	0.8
19	0.64

According to the table (3), the total harmonic distortion (THD) of the load current of phase-a is 15.25%.

Simulation results of the voltage de-rating of three-leg inverter

As seen in figure (14), the active part voltage (the voltage of the three-leg and single-leg inverters) is very low because of capacitor C_{f1} connected in series with the active part. Therefore, capacitor C_{f1} plays its role effectively.

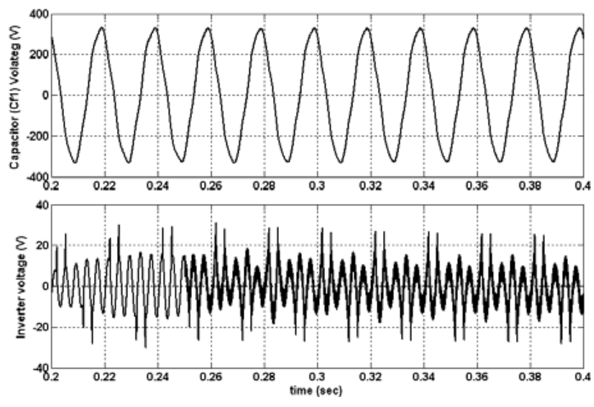

Fig.14.Capacitor C_{f1} and inverter voltage waveforms

As shown in figure (14), since the active part acts as a current source, the voltage magnitude of the active part doesn't change before and after 250ms (starting time of the active part). The magnitude voltages of the active part are less than 30V. Therefore, the active part voltages are almost one tenth of the system voltages (voltages of the electrical grid).

Simulation results of the PPF performance

Figure (15) shows the current of the PPF for phase-a. As seen in the figure, the current of the PPF contains the fundamental and the fifth harmonic component of the load current of phase-a.

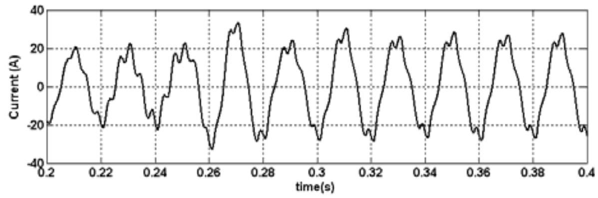

Fig.15. Current waveform of the PPF for phase-a

The PPF absorbs the 5th order of harmonic effectively. Before applying of the bCHAPF and the AEMF (before time of 250ms), the 5th order harmonic current peak value of the PPF is 3.18 A (around 95% of 5th order of harmonic of the load current). Also the phase-a fundamental current of the PPF is equal to load reactive current of phase-a (around 20A). Not only the PPF reduces the 5th order of harmonic of the source current, but also it supplies reactive current of the load.

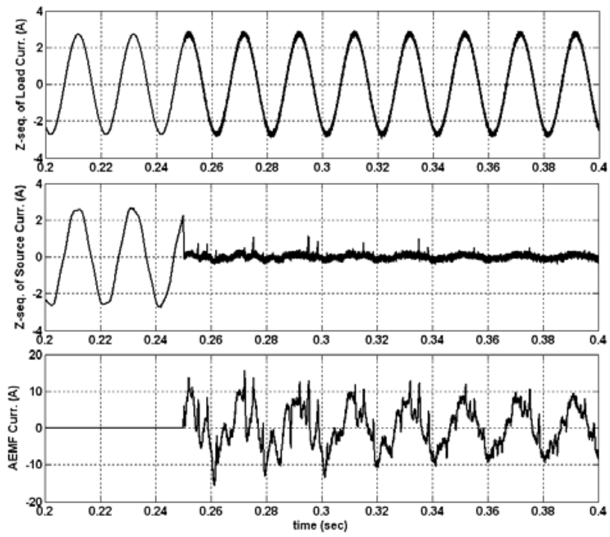

Fig.16. Zero-sequences of load, source and AEMF currents

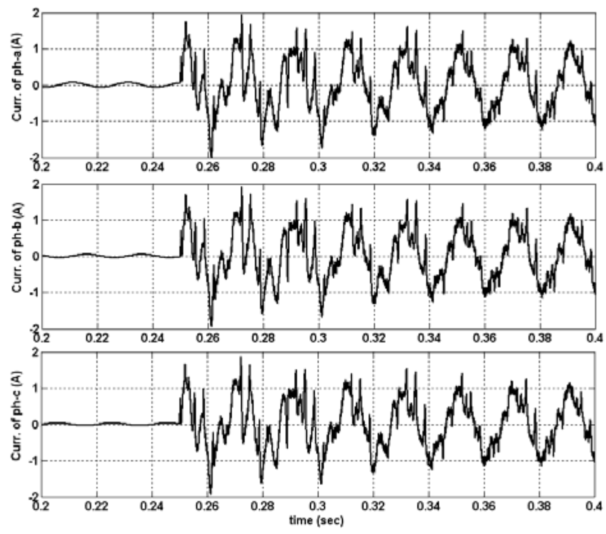

Fig.17. In-phase current waveform of Zig-Zag transformer

Simulation results of the AEMF performance

Figure (16) shows the zero-sequences of the load currents, the source currents and the AEMF current. The three-phase loads are asymmetrical (see table II) and the zero sequence component of the load currents is 2.73A. When the AEMF works (after time of 250msec), the zero-sequence of the source current comes near to zero, as shown in figure (16).

Figure (17) shows the currents of the Zig-Zag transformer. Before time of 250ms, the Zig-Zag transformer draws magnetizing currents from the source and its currents are near to zero, in other word, the Zig-Zag transformer acts as open circuit. After time of 250msec, the AEMF injects three in-phase currents and reduces the neutral current of the source effectively, as shown in figures (16) and (17).

Simulation results of harmonic components compensation

Before applying of the active parts of the bCHAPF and AEMF, the PPF supplies the load reactive power and absorbs 5^{th} order of harmonic of the load currents to reduce the THD of source currents. Therefore, before time of 250msec, THDs of the source currents are less than THD of the load currents. As seen in table (3) and (4), the PPF reduces THD of the source current for phase-a from 15.25% to 11.34%.

As shown in figure (18), before applying of the bCHAPF and the AEMF (before time of 250msec), the source currents contain the harmonic components, But after time of 250msec, the source currents are sinusoidal form. Therefore, the harmonic currents of the loads are effectively compensated by the HAPF.

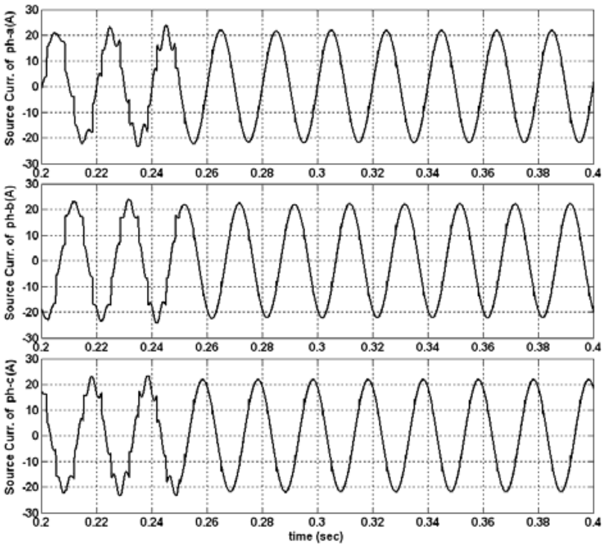

Fig.18. Source current waveform before and after compensation

Table (4) shows the peak of the source current values of phase-a before and after applying of the bCHAPF and the AEMF. As shown in the table, before applying of the bCHAPF and the AEMF, THD of the source current is 11.34%, but after applying of them, THD of the source current is 1.62%.

Table 4. Harmonic components of the source current of phase-a (peak values)

order of Harmonic	Peak of current (A)	
	Before applying of HAPF	After applying of HAPF
	Amplitude(A)	Amplitude(A)
1	21.4	21.79
5	1.92	0.01
7	1.41	0.05
11	1.19	0.08
13	0.83	0.07
17	0.73	0.07
19	0.55	0.07
THD	11.34%	1.62%

Simulation results of DC-Link voltage regulation

Figure (19) shows the DC-link voltage. To achieve desirable performance of the proposed topology, the DC-link of the bCHAPF and the AEMF must effectively control. As seen in the figure, after applying of the bCHAPF and the AEMF, the voltage of the capacitor of the DC link varies, but its variations is small.

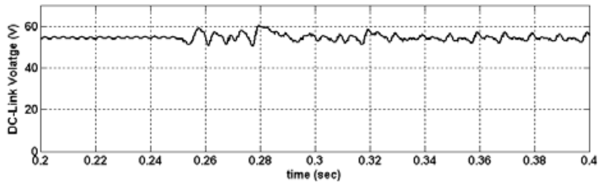

Fig.19. DC-link voltage variation

Conclusions

This paper proposed a hybrid active power filter which comprises a b-shape C-type hybrid active power filter (bCHAPF) and an active electromagnetic filter (AEMF) consisting of a Zig-Zag transformer and a single-leg inverter. The zero sequences of load currents are compensated by the AEMF connected in parallel with loads. Other harmonic components are compensated by the bCHAPF connected in parallel with loads too. The reactive power of the loads is supplied by a double tuned parallel passive filter of the bCHAPF. Also the PPF absorbs 5th order of harmonic of the load currents. The capacitor of the PPF reduces rated voltage of the three-leg inverter effectively. Therefore the proposed topology is appropriate for medioum voltage grids. Simulation results validate de-rating of the inverters of the bCHAPF and the AEMF, and shows that proposed topology can effectively compensate the harmonic components and zero sequences of the load currents. Also the proposed topology can damp parallel resonance compared with the case where only a power passive filter is used.

Appendix

This appendix provides an analysis of relationship between the zero sequence and the harmonic currents of the source and the loads. The zero sequence and harmonic currents of the source and the loads can be expressed as:

$$i_{Sho} = i_{So} + i_{Sh} \quad , \quad i_{Lho} = i_{Lo} + i_{Lh}$$

From equations (9) and (12), i_{sho} and i_{Lho} can be written as:

$$i_{Sho} = G_1 i_{Lo} + G_2 i_{Lh} \quad , \quad i_{Lho} = \frac{i_{So}}{G_1} + \frac{i_{Sh}}{G_2}$$

Substituting of above equations, the below equations can be obtained.

$$\begin{cases} i_{Sho}(G_1 + G_2) - i_{Sh} G_2 - i_{So} G_1 = G_1 G_2 i_{Lho} \\ i_{Sho}(G_1 + G_2) - i_{Lh} G_2^2 - i_{Lo} G_1^2 = G_1 G_2 i_{Lho} \end{cases}$$

If k_o and k_h are sufficiently selected large, G_1^2 and G_2^2 come near to zero approximately and, above equations can be written as:

$$\frac{i_{Sho}}{i_{Lho}} = \frac{1}{\dfrac{1}{G_1} + \dfrac{1}{G_2}}$$

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