

Enhancement of Power Quality for the Non Linear Distribution System Using Active Filter

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ABSTRACT: This paper imply an active filtering approach (AFA) to utterly augment the power quality (PQ) for the distribution network (grid) and the power supply system (non-linear load) linked to the network. At first, a recent main-circuit topology to inflict the proposed AFA is conferred, which consists of an inductively filtered transformer and a fully tuned (FT) branch controlled by an inverter. Its operating principle and features are received by correlating with the typical AFA which certainly brings additional losses such as temperature boost, vibration, and noise in transformers. Thus classical AFA contribute more harmonics in distribution system when compared to proposed AFA. Based on this, the unique filtering mechanism of the proposed AFA is affirmed in theory. Further, the control strategy of the FT branch is calculated based on theoretical analysis. A case study is explored in detail to portray the operating characteristics of the proposed AFA. Both the theoretical and the case studies show that the proposed AFA can cogently avoid harmonic components from flowing into the primary (grid) winding of the transformer. As harmonic components are concealed near the harmonic source, it is valuable for both power-supply system and converter transformer. Likewise, as the harmonic movement is restricted near the harmonic source, the PQ of the distribution system can be assured entirely.

I. INTRODUCTION

In modern trends, more power electronic devices are being applied in distribution networks. For example, wind power and solar energy are integrated into the network [1], [2] by means of current source converters (CSCs) and voltage source converters(VSCs)[3]-[5].

The network also often provides power supply to various types of non-linear loads such a s three phase diode/thyristor rectifiers for medium voltage(MV) motor drive[6] or larger power industrial electrolysis[7]. The non-linear characteristics are induced by the action of power electronics, which inevitably brings PQ problems to the distribution network [8] and to the power-supply system connected to the network [9], [10].

Power filtering is an efficient way to solve the PQ problems. Recently, it includes PPF (combination of passive components such as resistance, inductance, and capacitance), AFA (combination of power electronic devices and passive components) and HAPF (combination of active filter and passive filter) methods [11], [12]. However, these methods substantially used to implement the filtering and the reactive power compensation at the PCC [13]. Thus, they are powerful in solving the PQ problems of the public network, but cannot provide an effective solution for the power-supply system connected with the network.

For example, a converter transformer is generally used in rectifier/inverter system [14]. As there is no efficient scheme on PQ improvement on the power electronics side of the transformer, all of the harmonic and the reactive power components flow freely in the winding of the transformer, which evidently leads to a array of problems for the transformer such as additional losses, temperature increase, vibration and noise [15], [16].

To overcome these problems, an inductive power filtering method was proposed in present years [17]. This method can prevent harmonic and reactive power components from flowing into the primary (grid) winding of the transformer. Thus, it can effectively solve PQ problems of the power-supply system [18]. Basically, this method uses the balance of a transformer's magnetic potential to carry out the power filtering. That is to say, the current inductive filtering system is designed based on the harmonic characteristics of the non-linear load. If the load has different harmonic generation, then filtering performance cannot be fully guaranteed.

Unlike the aforementioned filtering methods, this paper deals about AFA. It combines the advantages of inductive power filtering and active power filtering and can improve the PQ of the distribution network and the power supply system itself. More important, it can track online changes in harmonic generation of the non-linear load and always maintain effective filtering performance [19]-[22].

The structure of this paper is organized as follows. Section II presents the main circuit topology of the proposed AFA and describes the operating principle and technical features by comparison with the classical AFA. Section III reveals the detailed block representation of controller structure for proposed AFA. Section IV deals with a case study performed to illustrate the filtering performance and operating characteristics of proposed AFA. The conclusion is presented in Section

II. MAIN CIRCUIT TOPOLOGY

The propagation of harmonics generated by non-linear loads in entire power systems is shown in below figure 1.

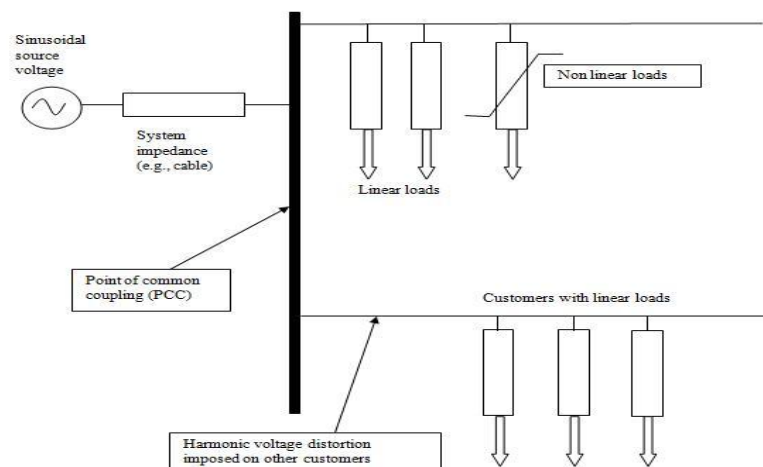


Fig. 1. Propagation of harmonics provoke by nonlinear loads in power system.

Furthermore, the aforementioned schematic can also be expressed by different circuit topology with transformers. Fig. 2 compares the topologies of the classical AFA and the proposed AFA. As shown in Fig. 2(a), the classical AFA is generated configured at the PCC, and it usually adopts a coupling transformer to interface with the power system. For non-linear loads, such as large power industrial DC load, it needs the converter transformer to isolate the DC supply system from distribution network. A power transformer with MV/LV windings is generally used to connect the nonlinear load with the MV distribution network.

For this customarily used wiring design, when interpreting the harmonic flow, it can be found that the load current i_L flows into the PCC through the converter transformer and the power transformer. These transformers have to bear all of the harmonic and reactive power components from i_L , which leads to supplementary losses, temperature increase, vibration and noise for these two transformers. In addition, these transformers are generally sited in diverse areas and the harmonic flows in the absolute power-supply system which may wipe out the electromagnetic surroundings of the systems and the neighboring areas. Besides, Fig. 2(b) shows equivalent arrangement where AFA is positioned at the secondary side of the power transformer, that is, the primary side of the converter transformer. Even though this

arrangement can effectively solve the PQ problems of the power transformer, the converter transformer still has to face all the PQ problems created by the non-linear load.

Here, it should be noted that the commutation process of CSC needs the support of commutation reactance afforded by the converter transformer. When AFA is directly parallel with the converter bridge, the commutation process may be afflicted by the impedance of the AFA. Thus, in a classical scheme, the PQ problems cannot be bypassed for the converter transformer.

Unlike the classical AFA arrangement, Fig. 2(c) shows the topology of the proposed AFA. In this figure, there is an inductively filtered converter transformer between the non-linear load and the power transformer. This converter transformer has a unique wiring design. Its secondary winding follows extended delta wiring. Between the extended windings and the delta windings, there is a connecting point linked to the FT branch. The FT branch is restrained by an inverter and it can draw virtually all of the harmonic components flowing into this branch. Based on these conditions, the harmonic magnetic potential is stabilized between the extended windings and the delta windings. Thus, there are very minor harmonic components in the primary winding of the converter transformer. Under this way, the harmonic components are quenched near the non-linear load (harmonic source). It means the path of harmonic flow is restricted in a small area which appreciably reduces the impact of harmonics on the supply system.

Furthermore, since the current in the primary winding exhibit a good sinusoid, we may even combine the MV winding of the power transformer with the primary winding and there is no requirement to configure an independent power transformer to connect the distribution network.

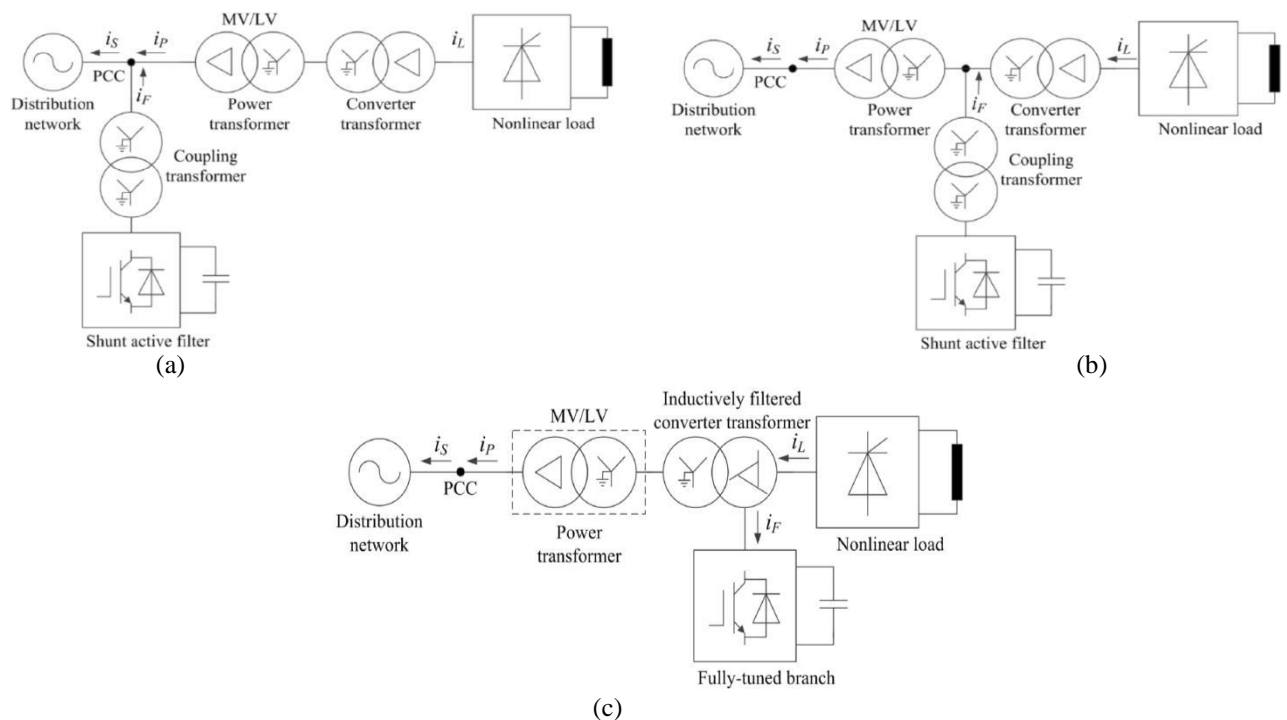


Fig. 2. Comparison of topologies: (a) classical AFA located at the PCC, (b) classical AFA located at the primary side of the converter transformer, and (c) proposed AFA coordinated with the converter transformer.

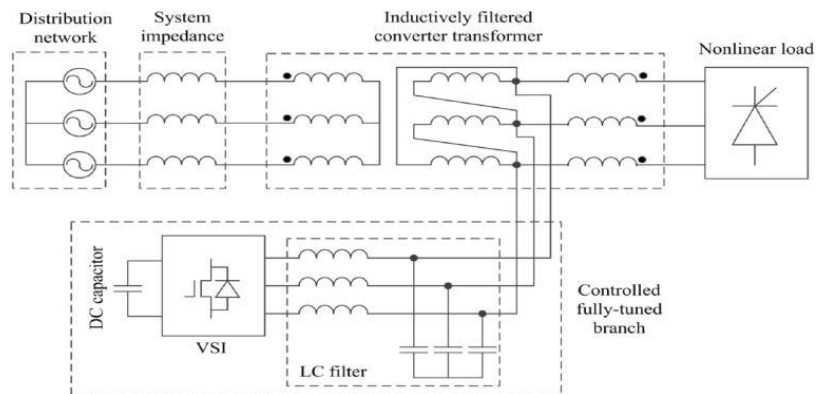


Fig. 3 Wiring arrangement of proposed AFA.

Fig. 3 shows the wiring arrangement of the proposed AFA. In this arrangement, the secondary winding of the converter transformer adopts extended delta wiring. For every phase, there is a connection point, which is connected with the controlled FT branch between the extended and the delta windings. This unique wiring on the secondary winding aims at balancing harmonic magnetic potential nearby the secondary winding. Thus, harmonic currents cannot be inducted into the primary (grid) winding.

The FT branch recognizes the harmonic components of the load side current, anticipates the harmonic components that flow into the branch, and shapes an opposite harmonic components to get rid of them. Meanwhile, once the harmonic components flow into the secondary extended winding, the secondary delta winding inducts analogous components to balance them, then there is none of these components in the primary winding.

III. CONTROLLER DESIGN FOR PROPOSED AFA

For the control scenario of the proposed AFA, a very essential task is how to draw all the harmonic components flowing from the load side into the FT branch and create the precondition for the harmonic magnetic potential balance between the secondary extended and delta winding. Unlike the classical AFA, in the proposed AFA, the objective of the FT branch includes the following functions: 1) predict the change of harmonic components at the load side; 2) track the amount of harmonic components that should flow into the FT branch; and 3) generate the opposite harmonic components to eliminate them. In this way, the FT branch represents a resonant state at the harmonic frequencies (zero impedance) which is the precondition for the implementation of the proposed AFA.

In the following subsections, the fundamental control flow will be presented and then the essential part, which is about how to calculate the amount of the harmonic current attracted to the FT branch, will be investigated in detail.

A. Control Sequence

The control block diagram for the FT branch is presented as shown in Fig. 4. In general, the control sequence of the FT branch includes the following parts:

- 1) Calculation of p and q : Based on the detected three-phase voltage (V_{AL} , V_{BL} , V_{CL}) and current (I_{AL} , I_{BL} , I_{CL}) at the load side, the instantaneous real and reactive power based on α and β quantities are retrieved using the $p-q$ theory [22]. Generally, the phase voltage at the AC valve side of the converter bridge represents nonsinusoidal. Thus, it is difficult to precisely convert the three-phase voltage into the α and β quantities. To conquer this problem, we can measure the voltage at the primary (grid) side of the converter transformer and indirectly obtain the voltage at the load side by using the potential transformer (PT) with the similar wiring to the converter transformer, or consider the phase shift factor of the converter transformer and indirectly compute the valve side voltage by using the grid side voltage.
- 2) High-Pass Filter (HPF): The HPF is used to filter the DC and the low-frequency components in p and q . The performance of the HPF highly rely on the proper setting of the characteristic frequency f_c . Here, in order to attract the

complete harmonic components from the load side current to the FT branch and at the same time avert the fundamental component, f_c is set as 120 Hz.

3) Estimation of Harmonic Components of the Load-Side Current: The harmonic components of the load-side current are extracted by \tilde{i} , \tilde{v} , and the load side voltage (V_{AL} , V_{BL} , and V_{CL}). In addition, the dc voltage of the VSI is controlled p q

by a proportional-integral (PI) controller. The output of the PI controller is an extra component to the filtered reactive power at the q-axis.

4) Calculation of Harmonic Components Attracted to the FT Branch: Due to the constraints among the harmonic currents in the secondary extended and delta winding, the harmonic components attracted to the FT branch, that is, I_{aoh} , I_{boh} , and I_{coh} shown in Fig. 4 are not from the load side straightly. The detailed calculation will be proposed in the equations 1, 2 and 3.

5) Control Gain (K): The estimated current I_{aoh} , I_{boh} and I_{coh} are multiplied by K to produce the current reference for the pulse width modulation(PWM) of the VSI. The reference is compared with the output of the AC current of the VSI, which is used to generate the PWM waves for the independent current control of the VSI.

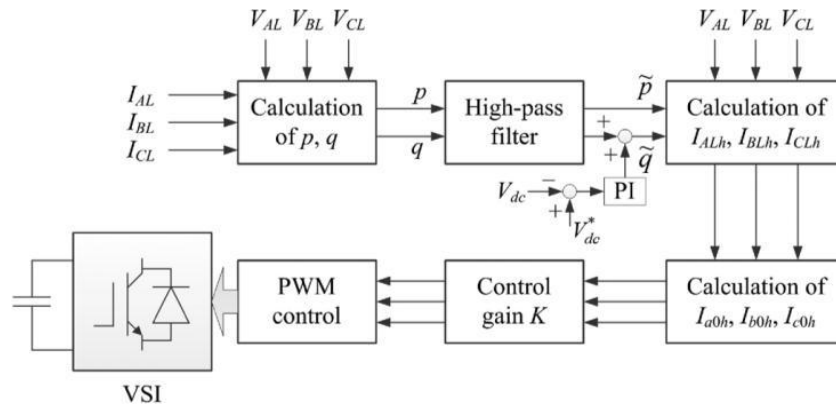


Fig. 4. Control block diagram for the fully tuned branch

B. Calculation of Harmonic Current Attracted to the FT Branch

As stated before, the harmonic currents I_{aoh} , I_{boh} and I_{coh} , attracted from the load side to the FT branch, are determined by the harmonic currents in the secondary windings of the converter transformer.

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$$Aah^1 Aah^1 Bbh^1 Bbh^1 Cch^1 Cch^1 abh I_{Aah}^1$$

$$^1 ALh$$

$$^1 abh^1 aoh^1 cah^1 BLh$$

$$^1 bch^1 boh$$

$$^1 abh$$

(1)

$$^1 CLh$$

$$^1 cah^1 coh^1 bch$$

$$^1 bch^1 cah^0$$

$$^1 Bbh^1 Cch$$

$$0$$

Where IALh, IBLh, and ICLh can be used to express the harmonic characteristics of the non-linear load. Similarly, the current from load side to the secondary delta winding side can be obtained as follows:

$$\left. \begin{array}{l}
 I_{abh} \\
 2 \\
 I_{bch} \\
 12 \\
 I_{cah}
 \end{array} \right\} \begin{array}{l}
 \frac{k^2 Z_{12} Z_{Fh}}{32 1h 12 Fh} I_{ALh} \\
 \frac{k^2 Z_{12} Z_{Fh}}{12 3h Fh 32 1h} I_{BLh} \\
 \frac{k^2 Z_{12} Z_{Fh}}{32 1h 12 Fh} I_{BLh} \\
 \frac{k^2 Z_{12} Z_{Fh}}{32 1h 12 Fh} I_{CLh} \\
 \frac{k^2 Z_{12} Z_{Fh}}{12 3h Fh 32 1h} I_{CLh} \\
 \frac{k^2 Z_{12} Z_{Fh}}{12 3h Fh 32 1h} I_{CLh}
 \end{array} \quad (2)$$

$$\frac{F_h}{2} = \frac{1}{2} \left(Z_{3h} + Z_{Fh} \right) I_k^{21h}$$

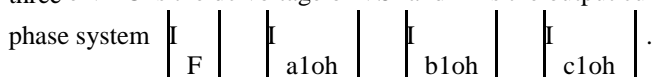
It can be seen from equation (1) and (2) that the attracted harmonic currents on the FT branch highly depend on the impedance parameters Z_{1h} , Z_{3h} , Z_{fh} . When considering the function of proposed AFA method, $Z_{3h} = Z_{Fh} = 0$ is satisfied. Under this condition, (2) can be simplified as follows :

$$\begin{cases} I_{aoh} \\ I_{boh} \\ I_{coh} \end{cases} = \begin{pmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} I_k \\ I_k \\ I_k \end{pmatrix} \begin{pmatrix} AL_h \\ BL_h \\ CL_h \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \quad (3)$$

In real, (3) exhibit the total amount of harmonic currents that flow into the FT branch. Subsequently, the FT branch should be controlled to generate the opposite harmonic currents to eliminate them, which means the K must be a negative value. In this manner, the FT branch represents a “short-circuit” state at the harmonic frequencies. It can attract the harmonic currents expressed by (3) to the FT branch. Besides, based on (3), the volt-ampere rating PFT of the controlled FT branch can be obtained as follows :

$$P_{FT} = \sqrt{3} \frac{D}{V_C} \frac{I_F}{\sqrt{2}} \quad (4)$$

Where V_C is the dc voltage of VSI and I_F is the output current of the controlled FT branch, for an ideal balanced



IV. CASE STUDY

In order to authenticate the theoretical results mentioned before and disclose the special operating characteristics of the proposed AFA method, a detailed case study on the distribution network with the nonlinear load, as shown in Fig. 5, was carried out by using MATLAB software. Here, we are concerned with the power quality of the public grid and the connected power-supply system for the nonlinear load. The classical AFA is also simulated to compare with the proposed AFA method.

Table I shows the comparison on the basic design parameters of the proposed and the classical converter transformer. Table II shows the design parameters of the LC filter used by the classical AFA and the proposed AFA respectively. Both the classical AFA and the proposed AFA adopt the similar controller structure like Fig. 5. The difference is the calculation of the compensation current. For the proposed AFA, it uses (3) to calculate the amount of the harmonic currents generated by VSI.

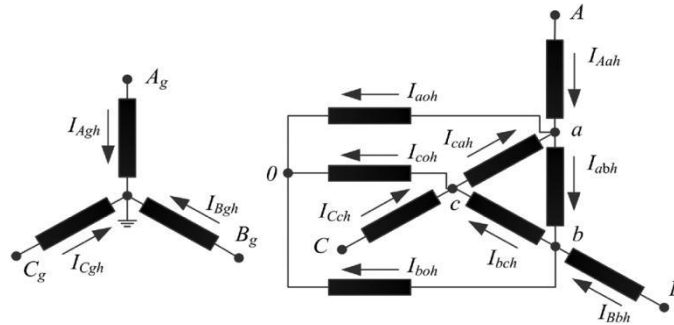


Fig. 5. Three-phase equivalent circuit

According to the design parameters shown in Table I and II, the rating of the controlled FT branch can be compared to that of the classical AFA. More particularly, in this case study, the VSI adopted by classical AFA and proposed AFA, has the same value DC voltage reference VDC. The primary side is star with neutral grounded and secondary side is provided with the star and extended delta connection. Table III shows the design specification of the non-linear load. For the proposed AFA ,

$$|IF| \left| \begin{matrix} I_{a10} \\ h \end{matrix} \right| \left| (1 - k^{-1} e^{j120})IL \right| \quad (5)$$

However, it should be noted that the rating is varied with the turns ratios of the converter transformer. This case study on the proposed AFA is performed from the following three aspects: 1) filtering performance with respect to the classical AFA and the proposed AFA; and 2) steady state response when switching on the FT branch.

DESIGN PARAMETERS OF THE NEW AND TRADITIONAL CONVERTER TRANSFORMER

	Rating/MVA	Wiring mode	Impedance /pu
Proposed converter transformer	0.02	Star/Extended-delta	Z ₁₂ =0.40 Z ₁₃ =0.02 Z ₂₃ =0.18
Classical converter transformer	0.02	Star/delta	Z ₁₂ =0.20

DESIGN PARAMETERS OF THE LC FILTER

	L(mH)	C(μF)
Proposed AFA	0.8	0.04
Classical AFA	1.0	0.1

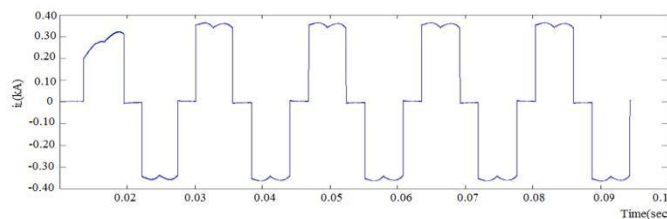
DESIGN SPECIFICATION OF THE NON-LINEAR LOAD

Non-Linear Load	Specification
Thyristor Rectifier	Six pulse
R(Ω)	30
Non-Linear Load	Specification
L(mH)	0.06

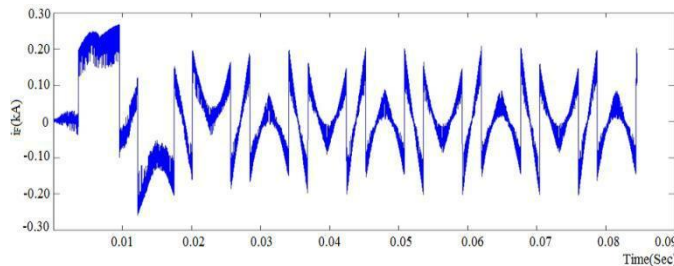
Filtering Performance with respect to Classical and Proposed AFA

Fig. 6 and Fig. 7 show the steady -state responses of the classical AFA and the proposed AFA respectively. It can be seen from Fig. 6(a) and Fig. 7(a) that regardless of whether using the classical AFA or the proposed AFA, the current at the load side has a similar harmonic characteristic, which is determined by the type of non-linear load. It can also be seen from Fig. 6(c) and Fig. 7(c) that both filtering methods can effectively suppress the harmonic currents at the ac grid side, thus improving the power quality of the public distribution network.

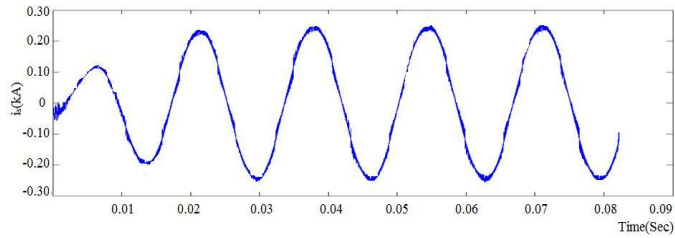
However, by comparing Fig. 6(b) and Fig. 7(b), it is clear that the classical AFA cannot carry out efficient harmonic suppression in the grid winding. Thus, there are heavy harmonic components. But the proposed AFA method can significantly reduce the harmonic content in the grid winding. Thus the waveform of the grid winding current is represented as a good sinusoidal. It means the proposed AFA cannot only solve the PQ problem to the public grid but also to the power supply system connected with the non-linear load. Furthermore, Fig. 8 gives more details about the harmonic magnitude in the grid winding without compensation, after implementing the classical AFA & proposed AFA. From this figure, it can be seen that the classical AFA cannot suppress harmonic currents significantly in the grid winding of the converter transformer. The total harmonic distortion (THD) is 7.11%. When using the proposed AFA, the harmonic currents in the grid winding are suppressed successfully and the THD is reduced to 2.97%.



(a)

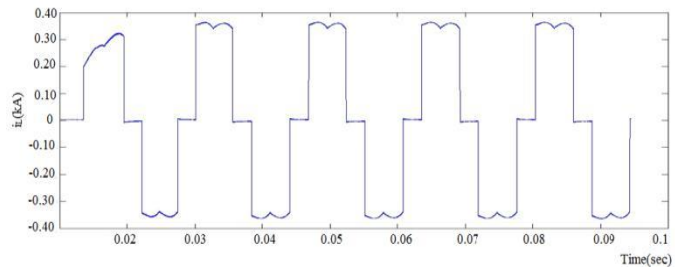


(b)

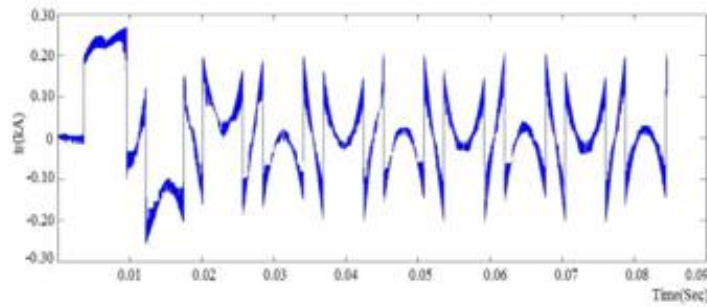


(c)

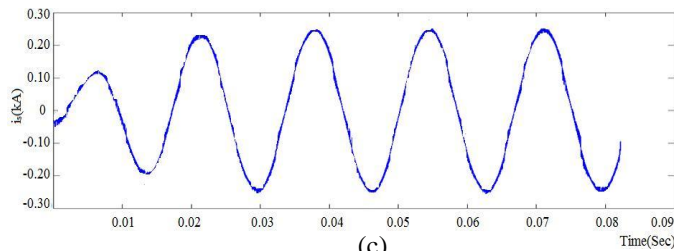
Fig. 6. Steady-state response of the system with the classical AFA : (a) Current at the load side, (b) Opposite harmonic current produced by filter, and (c) Current at the ac grid side.



(a)



(b)



(c)

Fig. 7. Steady-state response of the system with the proposed AFA : (a) Current at the load side, (b) Opposite harmonic current produced by filter, and (c) Current at the ac grid side.

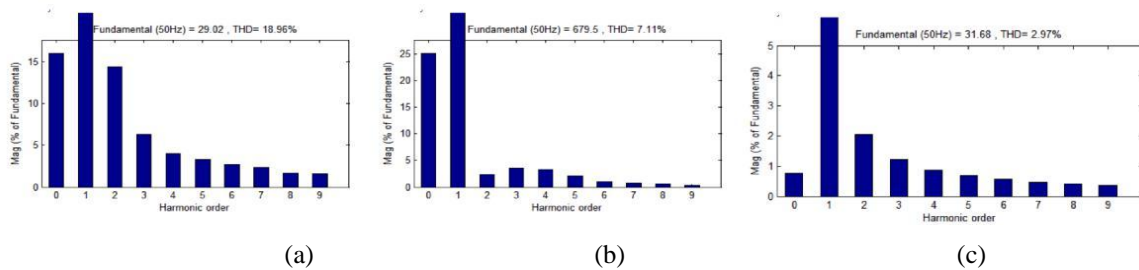


Fig. 8. FFT results on the current waveform in the grid winding a) without compensation b) when using classical AFA, c) when using proposed AFA.

COMPARISON OF THD

	Without Compensation	With Classical AFA	With Proposed AFA
THD	18.96	7.11	2.97

Steady State Response When Switching on the FT branch

In order to assess the impact of the proposed AFA on the operation of the non-linear load, the following case is considered before $t = 0.01$ s, the load and also the related power supply system operate without the proposed AFA and at $t = 0.01$ s, the FT branch is switched on to implement the IAF method. Fig. 7 shows the steady state response of the test system. Both currents at the DC side and the AC valve side are stable before and after the switching of FT branch, which means that the proposed AFA does not affect the operation of the load and the connected power supply system. On the other hand, from Fig. 7(b) and Fig. (c), it can be seen that when switching the FT branch, which means the implementation of the proposed AFA, the branch can attract the harmonic components from the load side; thus, the harmonic currents in the grid winding are reduced significantly. The non-linear load generates more harmonic components. However, the proposed AFA can track the load variation successfully and the FT branch attracts more harmonic currents [see Fig. 7(b)]. Thus, the current waveform in the grid winding of the converter transformer can always maintain a good sinusoid, as shown in Fig. 7(c) from time instant $t = 0.01$ s.

V. CONCLUSION

In this paper, an proposed AFA, which is characterized as an inductively filtered converter transformer and a controlled FT branch, is anticipated to enhance the PQ of the distribution network (public grid) and the power supply system (power consumer side) connected with non-linear loads. The three phase equivalent circuit model are established to express such a new power filtering method. The controller structure for the FT branch are designed, which is used to generate the precondition for the balance of the harmonic magnetic potential in the windings of the converter transformer with extended delta connection.

The theoretical results indicate that by means of the proposed AFA , the harmonic currents are balanced out in the secondary winding of the converter transformer; thus, there are not any or only a few harmonic currents inducted into the primary (grid) winding. The case results coincide with the theoretical analysis and illustrate the good filtering performance under a steady state and dynamic condition. The proposed AFA can contribute PQ enhancement for the public network and the power consumer. It may also reduce the need for power transformers that isolate the non-linear loads from the distribution network. It has prospective application in industrial power supply systems and distribution

networks interfaced with distributed generation. The performance of this system can be further improved by means of interfacing with any one of the soft computing tools for better results.

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