Performance Analysis of Power Quality Improvement in Distribution Network using an Inductively Active Filter

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Abstract*: With the widespread use of power electronics devices such as rectifier, inverter etc. in power system causes serious problem relating to power quality. One of such problem is generation of current and voltage harmonics causing distortion of load waveform, voltage fluctuation, voltage dip, heating of equipment etc. Also presence of non-linear loads such as UPS, SMPS, speed drives etc. causes the generation of current harmonics in power system. They draw reactive power components of current from the AC mains, hence causing disturbance in supply current waveform. Thus to avoid the consequences of harmonics we have to compensate the harmonic component in power utility system. Among various method used, one of the effective method to reduce harmonic in power system is the use of Inductively Active Filtering (IAF). This method comprehensively improves the power quality (PQ) for not only the distribution network (public grid) but also the power-supply system (nonlinear load) connected to the network. At first, a new main-circuit topology for implementing the IAF method is presented. It consists of an inductively filtered transformer and a fully tuned branch controlled by an inverter. The control strategy of the FT branch and the impedance coordination for the inductively filtered transformer are designed based on theoretical analysis. A case study is investigated in detail to illustrate the operating characteristics of the IAF method. Both the theoretical and the case studies show that the IAF method can effectively prevent harmonic components from flowing into the primary (grid) winding of the transformer. Since the harmonic components are suppressed near the harmonic source, it is good for the power-supply system and especially good for the converter transformer. Besides, since the harmonic flow is limited to near the harmonic source, the PQ of the public network can be guaranteed completely.

Index Terms: Active filtering method, converter transformer, distribution network, harmonic, inductive filtering method, power Quality.THD.

I. INTRODUCTION

Electrical distribution systems are primarily designed to meet the consumer's demands for energy. The electrical distribution network is a power delivery system consisting of cables that deliver electric power from its point of generation to the end users. In recent years, more power electronics are being applied to distribution networks such as three phase voltage source inverter. The network also provides power supply to the non-linear loads such as three phase diodes or thyristor rectifiers for medium voltage drives or large power industrial applications.

Since the action of power electronic devices is inherently non-linear, there arises a Power-Quality problem in the distribution network and the power supply connected with that network. [1, 2]

The PQ problems can be solved through the filtering methods. Usually it involves APF, passive power filtering and Hybrid power filtering. [3-5] However, these methods are mainly used to implement the filtering and the reactive power compensation at the PCC; thus, they are effective 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 the rectifier/inverter system. Since there is no effective scheme on PQ improvement active on the power-electronics side of the transformer, all of the harmonic and the reactive power components flow freely in the windings of the transformer, which inevitably leads to a series of problems for the transformer, such as additional losses, temperature increase, vibration, and noise [6]–[9].

To overcome these problems, an inductive power filtering method was proposed in recent years [10], [11]–[15]. This method can prevent harmonic and reactive power components from flowing into the primary (grid) winding of the transformer, so it can effectively solve PQ problems of the power-supply system.

The Inductive filtering can only suppress the fixed order harmonics by the fixed impedance design for the Fully Tuned branch. The inductive filtering method is designed based on the harmonic characteristics of the nonlinear load. The FT branch can track the change of harmonic components at the load side. It consists of LC circuit, Voltage Source Inverter. The FT branch is connected to the winding tap of converter transformer. The IAF method can track online the change in harmonic generation of the nonlinear load and always maintain effective filtering performance.

This paper proposes an IAF method. It combines the advantages of inductive power filtering and active power filtering methods and can improve the PQ of the distribution network and the power-supply system itself. More important, it can track online the change in harmonic generation of the nonlinear load and always maintain effective filtering performance. This paper distributed in VI sections Introduction of complete system included in Section-I Section II presents the main circuit topology of the IAF method and describes the operating principle and technical features by comparison with the traditional APF method. Section III reveals the unique filtering mechanism in theory by detailed mathematical modelling. The controller structure, control strategy, and impedance coordination for the IAF method are designed in Section IV. A case study is performed in Section V to illustrate the filtering performance and operating characteristics of the IAF method. And in the last section conclusion of paper is addressed.

II. SYSTEM DEVELOPENT

Power filtering is an effective way to solve the PQ problems. Currently, it includes PPF, APF, and HAPF methods However, these methods are mainly used to implement the filtering and the reactive power compensation at the PCC; thus, they are effective in solving the PQ problems of the public network, but cannot provide an effective solution for the power-supply system connected with the network. To overcome these problems, an inductive power filtering method was proposed. In principle, this method uses the balance of a trans-former's harmonic magnetic potential to carry out the power filtering.

1. The p-q theory

In 1983, Akagi et al. [16, 17] have proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as instantaneous power theory, or p-q theory. It is based on instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms. The p-q theory consists of an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in the a-b-c coordinates to the α-β-0 coordinates, followed by the calculation of the p-q theory instantaneous power components:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{3}{\sqrt{2}} & -\frac{3}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{3}{\sqrt{2}} & -\frac{3}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (1)$$

$p0 = v_0.i_0$ instantaneous zero-sequence power (2)
$p = v_\alpha.i_\alpha + v_\beta.i_\beta$ instantaneous real power (3)
$q \equiv v_\alpha.i_\beta - v_\beta.i_\alpha$ instantaneous imaginary power (4)

The power components p and q are related to the same α-β voltages and currents, and can be written together:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

These quantities are illustrated in Fig. 1 for an electricai system represented in a-b-c coordinates and have the following physical meaning:

$\overline{p0}$ = mean value of the instantaneous zero-sequence power – corresponds to the energy per time unity which is transferred from the power supply to the load through the zero-sequence components of voltage and current.

$\widetilde{p0}$ = alternated value of the instantaneous zero-sequence power – it means the energy per time unity that is exchanged between the power supply and the load through the zero-sequence components. The zero-sequence power only exists in three-phase systems with neutral wire. Furthermore, the systems must have unbalanced voltages and currents and/or 3rd harmonics in both voltage and current of at least one phase.

$\bar{p}$ = mean value of the instantaneous real power – corresponds to the energy per time unity which is transferred from the power supply to the load, through the a-b-c coordinates, in a balanced way (it is the desired power component).

$\tilde{p}$ = alternated value of the instantaneous real power – It is the energy per time unity that is exchanged between the power supply and the load, through the a-b-c coordinates.

q= instantaneous imaginary power – corresponds to the power that is exchanged between the phases of the load. This component does not imply any transference or exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases. In the case of a balanced sinusoidal voltage supply and a balanced load, with or without harmonics, q (the mean value of the instantaneous imaginary power) is equal to the conventional reactive power ($q = 3.V.I_1.\sin\varphi_1$).

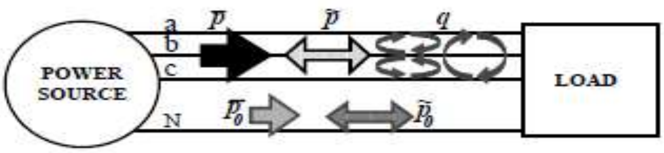

Fig 1 Power components of the p-q theory in a-b-c coordinates

2. Main circuit topologies

The comparison of circuit topologies for APF and proposed IAF method is shown in below Fig. Usually the APF is configured with the coupling and converter transformer which is interfaced with non-linear loads of power system. The converter transformer is used to isolate the dc supply from the distribution network. A power transformer with MV/LV windings is generally used to connect the nonlinear load with the medium voltage distribution network.

A. Active Power Filtering:

The control method with APF shown in fig 2 mainly focused on the harmonic reduction and also on the voltage unbalance enhancement. The generated real power from distributed resources is injected to the grid by the inverter interfaced with grid. The inverter works like shunt APF and injects power to the grid. The current at the grid is balanced and sinusoidal with power factor at unity, by compensating the unbalanced nonlinear load effects connected near point of common coupling like unbalance current, harmonic current, and reactive power of load. Hence the power quality improvement of distribution network that is only public grid is possible.

During the analysis of harmonic flow, the load current flows into point of common coupling through the converter transformer and power transformer and Hence these transformers is affected by harmonics and reactive components from load current resulting in temperature increase, noise, poor power factor. Since the PQ problems is solved only to public grid but not to power supply system, for non-linear load, the APF circuit is altered and configured with the proposed IAF method.

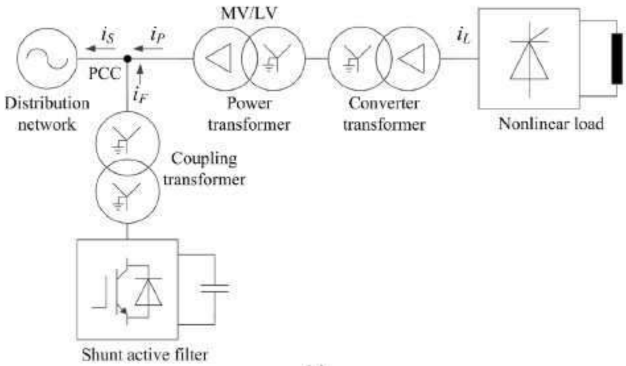

Fig 2 Traditional APF located at the PCC side

Fig 3 shows that APF is located at the secondary side of the power transformer, that is, the primary side of the converter transformer. Although this configuration can effectively solve the PQ problems of the power transformer, the converter transformer still has to face all of the PQ problems caused by the nonlinear load. Here, it should be noted that the commutation process of CSC needs the sup-port of commutation reactance provided by the converter trans-former. When APF is directly parallel with the converter bridge, the commutation process may be affected by the impedance of the APF. Thus, in a traditional scheme, the PQ problems cannot be avoided for the converter transformer.

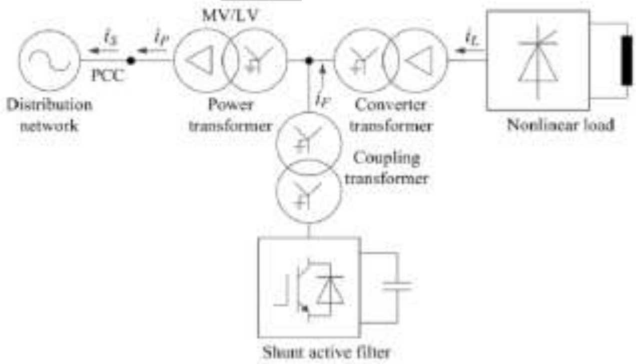

Fig 3 Traditional APF located at the primary side of the converter transformer

Converter Transformer

The converter transformer is an integral part of HVDC system. High AC and DC voltages put specific requirement on dielectric insulation. Non sinusoidal current give rise to additional losses, which are to be considered. Winding adopts prolonged-delta wiring. To facilitate our discussion, the winding of Ai - ai, Bi - bi, Ci - ci (i=1, 2) is called a prolonged winding, and the winding of a1-b1, b1-c1, c1-a1, a2-c2, b2-a2, c2-a2 is called common winding. (b) Shows the transformers voltage Phasor diagram, which is used to discuss the phase-shifting of the new transformer. Fig 4 shows the new converter transformer and the corresponding inductive filtering system, in which, (a) shows the wiring mode of the transformer, and its secondary [18]

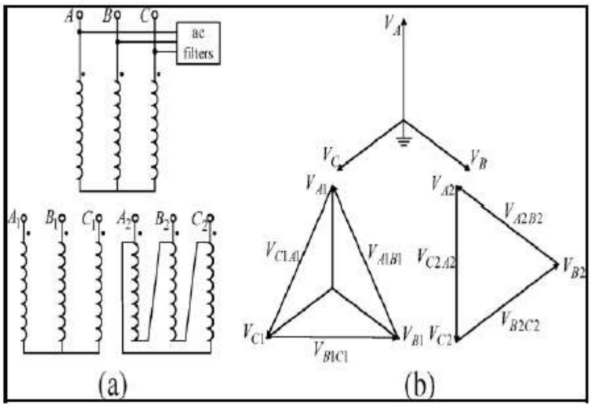

Fig 4 Traditional converter transformer with ac filter
(a) Wiring mode, (b) Voltage Phasor diagram

B. Inductive Active Filtering:
In fig 5, there is an inductively filtered converter transformer between the nonlinear load and the power transformer. This converter transformer has a special wiring scheme. Its secondary winding adopts extended delta wiring. Between the extended windings and the delta windings, there is a linking point connected to the fully tuned branch. The fully tuned branch is controlled by an inverter, and it can attract almost all of the harmonic components flowing into this branch. Under these conditions, the harmonic magnetic potential is balanced between the extended windings and the delta windings; thus, there are very few harmonic components in the primary winding of the converter transformer. In this way, the harmonic components are suppressed near the nonlinear load (harmonic source).

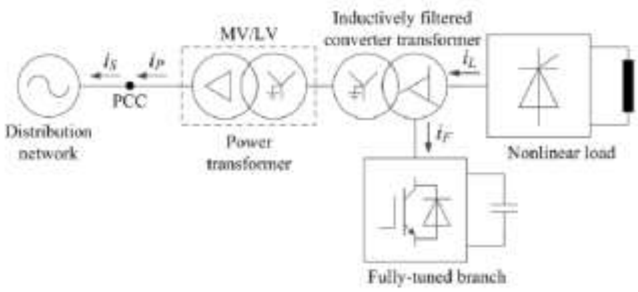

Fig 5 Proposed IAF coordinated with the converter transformer.

III. ANALYSIS OF FILTERING MECHANISM AND MODELING

1. Equivalent Circuit Model
The three-phase equivalent circuit model for the inductively filtered converter transformer and the FT branch can be constructed in this model; each winding of the transformer is equivalent to impedance and the FT branch as controlled impedance. For The analysis of fundamental and harmonic currents from load to grid can be seen in Fig 6.

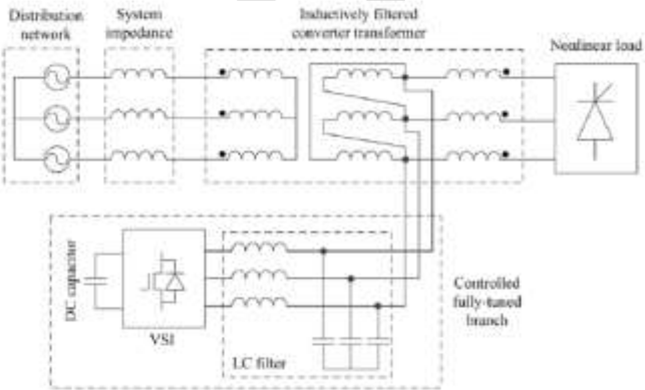

Fig 6 Wiring scheme of IAF

2. Mathematical Modeling
According to the theory of multi winding transformers and combining the equivalent circuit model shown in Fig. 7, the voltage equations at the fundamental and the harmonic frequencies can be obtained as follows:-

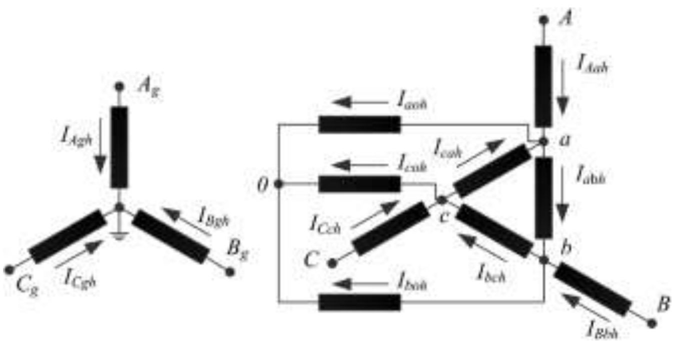

Fig 7 Three-phase equivalent circut

Voltage equations at the fundamental and the harmonic frequencies can be obtained as follows

$$\left.\begin{aligned}
V_{Aah} - k_{12}^{-1}V_{Agh} &= -k_{12}I_{Agh}Z_{h21} - k_{32}I_{abh}Z_{2h}\\
V_{Aah} - k_{32}^{-1}V_{abh} &= -k_{32}I_{abh}Z_{h23} - k_{12}I_{Agh}Z_{2h}\\
V_{Bbh} - k_{12}^{-1}V_{Bgh} &= -k_{12}I_{Bgh}Z_{h21} - k_{32}I_{bch}Z_{2h}\\
V_{Bbh} - k_{32}^{-1}V_{bch} &= -k_{32}I_{bch}Z_{h23} - k_{12}I_{Bgh}Z_{2h}\\
V_{Cch} - k_{12}^{-1}V_{Cgh} &= -k_{12}I_{Cgh}Z_{h21} - k_{32}I_{cah}Z_{2h}\\
V_{Cch} - k_{32}^{-1}V_{cah} &= -k_{32}I_{cah}Z_{h23} - k_{12}I_{Cgh}Z_{2h}
\end{aligned}\right\} \quad (1)$$

Where (Z_{h21}) and can be obtained by the short-circuit test, and Z_{2h} is calculated based on Z_{h21}, Z_{h23}, Z'_{h13} and (here the superscript means the impedance value is reduced into the side of the secondary extended winding), that is to say

$$Z_{2h} = \frac{1}{2}(Z_{h21} + Z_{h23} - Z'_{h13}) \quad (2)$$

According to the principle of transformer magnetic pote lance and ignoring very few exciting currents, the current equations at the fundamental and the harmonic frequencies can be obtained as follows:

$$\left.\begin{aligned}
I_{Aah} + k_{12}I_{Agh} + k_{32}I_{abh} &= 0\\
I_{Bbh} + k_{12}I_{Bgh} + k_{32}I_{bch} &= 0\\
I_{Cch} + k_{12}I_{Cgh} + k_{32}I_{cah} &= 0
\end{aligned}\right\} \quad (3)$$

According to Kirchhoff's current law (KCL), the following equations can be obtained to illustrate the relationship between the load-side current and the winding current, between the winding current and the FT branch current, respectively, that is

$$\left.\begin{aligned}
I_{Aah} &= I_{ALh}\\
I_{Aah} &= I_{abh} + I_{a0h} - I_{cah}\\
I_{Bbh} &= I_{BLh}\\
I_{Bbh} &= I_{bch} + I_{b0h} - I_{abh}\\
I_{Cch} &= I_{CLh}\\
I_{Cch} &= I_{cah} + I_{c0h} - I_{bch}\\
I_{abh} + I_{bch} + I_{cah} &= 0\\
I_{Aah} + I_{Bbh} + I_{Cch} &= 0
\end{aligned}\right\} \quad (4)$$

Where I_{ALh}, I_{BLh}, and I_{CLh} can be used to express the harmonic characteristics of the nonlinear load Furthermore, according to Kirchhoff's voltage law (KVL), the equations which express the relationship between transformer windings and FT branch voltage, can be obtained as follows:

$$\left.\begin{aligned}
V_{abh} &= -V_{b0h} + V_{a0h}\\
V_{bch} &= -V_{c0h} + V_{b0h}\\
V_{cah} &= -V_{a0h} + V_{c0h}\\
V_{a0h} &= I_{a0h}Z_{Fah}\\
V_{b0h} &= I_{b0h}Z_{Fbh}\\
V_{c0h} &= I_{c0h}Z_{Fch}
\end{aligned}\right\} \quad (5)$$

Where Z_{Fah}, Z_{Fbh}, and Z_{Fch} are controlled by the VSI. Equations (1)–(5) construct the mathematical model for the inductively filtered transformer and the FT branch. Based on this model, it is easy to investigate the operating characteristics and the special filtering characteristics that the IAF method has. It also provides a guideline for the impedance coordination and the controller design of the IAF system.

IV. CONTROL STRATEGIES

For the control strategy of the IAF method, a very important task is how to attract all of the harmonic components flowing from the load side into the FT branch. Unlike the existing APF method, in the IAF method, the control object of the FT branch includes the following parts:

1) Track the change of harmonic components at the load side;
2) Predict the amount of harmonic components that should flow into the FT branch
3) Generate the opposite harmonic components to eliminate them.

1. Control Flow

The control flow of the FT branch includes the following parts which is shown in fig 8.

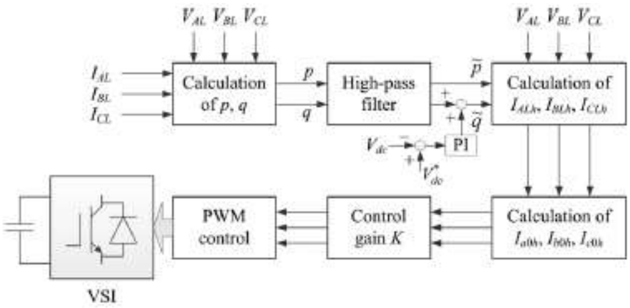

Fig 8 Control diagram for the fully tuned branch.

a) Calculation of p and q

Based on the detected three-phase voltage (V_{AL}, V_{BL}, and V_{CL}) and current (I_{AL}, I_{BL}, and I_{CL}) at the load side, the instantaneous real power (p) and reactive power (q) are obtained by using the p–q theory. [17]

High-Pass Filter (HPF)

The HPF is used to filter the dc and the low-frequency components in p and q; thus, converting to high frequency components. The performance of the HPF highly depends on the proper setting of the characteristic frequency f_c. Here, in order to attract the full harmonic components from the load-side current to the FT branch and, at the same time, prevent the fundamental component f_c is set as 100Hz.

b) Calculation of Harmonic Components of the Load-Side Current

The harmonic components of the load-side current are extracted by $\tilde{p}$, $\tilde{q}$, and the load-side voltage (V_{AL}, V_{BL}, and V_{CL}). Besides, the dc voltage of the VSI is controlled by a proportional- integral (PI) controller. The output of the PI controller is an additional component to the filtered reactive power at the q-axis.

c) PWM Controller

To control the shunt active filter a PWM logic controller is developed. The difference between the injected current and the reference current determine the modulation wave of the reference voltage. This voltage is compared with two carrying triangular identical waves shifted one from other by a half period of chopping and generate switching pulses. [12]

d) Calculation of Harmonic Components Attracted to the FT Branch.

The harmonic currents I_{a0h}, I_{b0h}, and I_{c0h} attracted from load side to the FT branch, are determined by the harmonic currents in secondary winding of converter transformer.

e) Control Gain K

The calculated currents I_{a0h}, I_{b0h}, and I_{c0h} are multiplied by K to generate 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 produce the PWM waves for the independent current control of the VSI.

V. SIMULATION RESULTS AND DISCUSSION

The simulation of the proposed IAF method is done through MATLAB/Simulink. The model diagram of IAF is shown in fig.9 and filtering configuration is shown in fig.10 and the output is observed in MATLAB software.

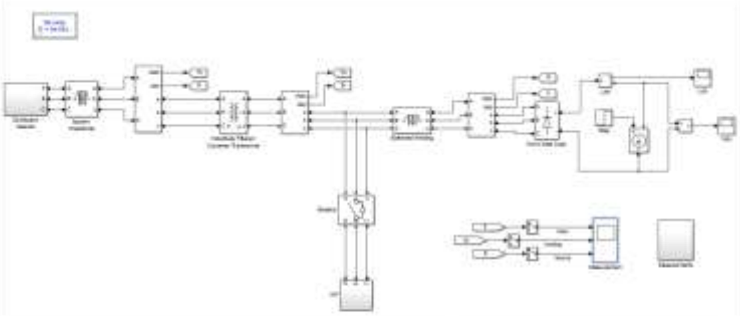

Fig 9 Simulink model for IAF

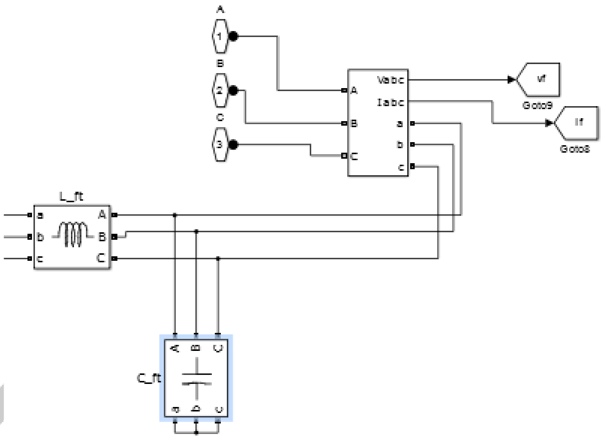

Fig 10 filtering configuration

Fig. 11 shows the steady state response of the proposed IAF method. It shows the current at the load side has a harmonic characteristic,which is determied by non linear load. Also the grid winding current as a good sinusoidal after 0.2 sec.this IAF filtering methods can effectively suppress the harmonic currents at the ac grid side, thus improving the power quality of the public distribution network.

From Fig.12, it can be seen that when switching the FT branch, which means the implementation of the IAF method, the branch can attract the harmonic components from the load side; thus, the harmonic currents in the grid winding are reduced significantly. The results coincide with the theoretical analysis.

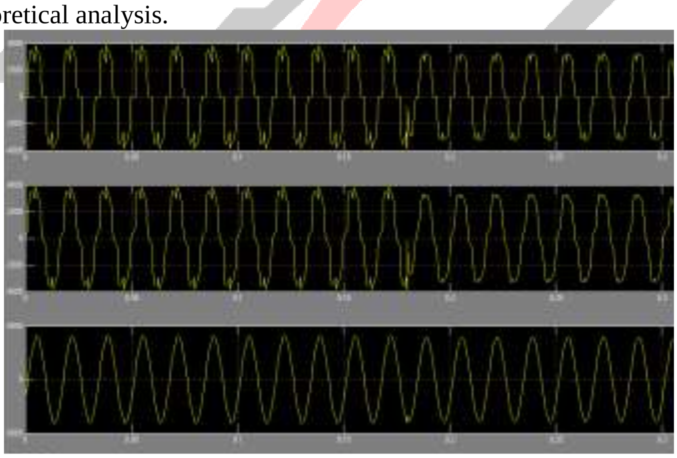

Fig 11 Steady state response with IAF method

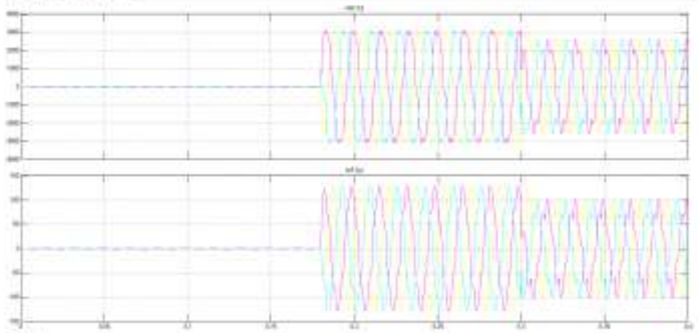

Fig 12 Dynamic response when switching on FT branch

The amount of distortion in the voltage or current is quantified by means of Total Harmonic Distortion (THD). It is defined as the ratio of root-mean-square of root of harmonic content to the root-mean square value of fundamental quantity and expressed as the percentage of fundamental. The THD is the most common indicator to determine the quality of AC waveforms. Using the Fast Fourier Transform (FFT) the harmonic spectrum of the source current under different compensation condition is presented. Then, the THD comparison is carried out for the simulation results and from the plot, it can be seen that source current contains large amount of harmonic current components. Here the comparison of APF and proposed IAF method for calculation of THD is shown in fig 13 and 14. It can be seen that with APF, the value of THD is 17.27% and for IAF, value of THD is 9.18%. Hence it is purely sinusoidal.
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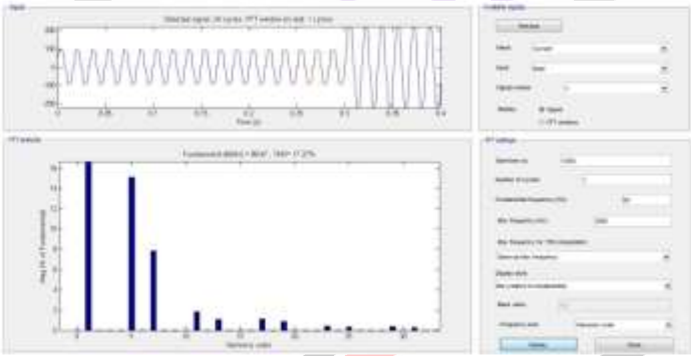

Fig 13 FFT results of traditional APF method

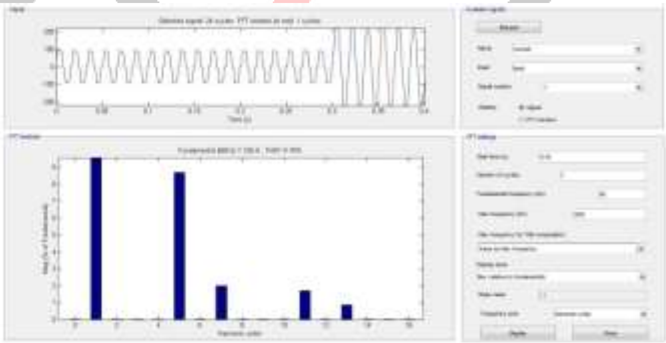

Fig 14 FFT results of proposed IAF method

VI. CONCLUSION

In this paper, an IAF method, which is characterized as an inductively filtered converter transformer and a controlled FT branch, is proposed to improve the PQ of the distribution network (public grid) and the power-supply system (power consumer side) connected with nonlinear loads. The three-phase equivalent circuit model and the basic mathematical model are established to express such a new power filtering method. Based on the extension of the mathematical model, the control method and controller structure for the FT branch are designed, which is used to create the precondition for the balance of the harmonic magnetic potential in the windings of the converter transformer. The theoretical results indicate that by means of the IAF method, 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 dynamic state (e.g., variation of the nonlinear load and the switching of the FT branch). The IAF method can contribute PQ improvement for the public network and the power consumer. It may also reduce the need for power transformers that isolate the nonlinear loads from the distribution network. It has potential application in industrial power-supply systems and distribution networks interfaced with distributed generation.

REFERENCES

[1] R. Oliva and J. C. Balda, “A PV dispersed generator: A power quality analysis within the IEEE 519,” IEEE Trans. Power Del., vol. 18, no. 2, pp. 525–530, Apr. 2003.

[2] M. Aiello, A. Cataliotti, S. Favuzza, and G. Graditi, “Theoretical and experimental comparison of total harmonic distortion factors for the evaluation of harmonic and inter harmonic pollution of grid-connected photovoltaic systems,” IEEE Trans. Power Del., vol. 21, no. 3, pp.

[3] S. H. E. A. Aleem, A. F. Zobaa, and M. M. A. Aziz, “Optimal –type passive filter based on minimization of the voltage harmonic distortion for nonlinear loads,” IEEE Trans. Ind. Electron., vol. 59, no. 1, pp. 281–289, Jan. 2012.

[4] H. Akagi and K. Isozaki, “A hybrid active filter for a three-phase 12-pulse diode rectifier used as the front end of a medium-voltage motor drive,” IEEE Trans. Power Electron., vol. 27, no. 1, pp. 69–77, Jan. 2012.

[5] C.-S. Lam, W.-H. Choi, M. C. Wong, and Y. D. Han, “Adaptive dc-link voltage-controlled hybrid active power filters for reactive power compensation,” IEEE Trans. Power Electron., vol. 27, no. 4, pp. 1758–1772, Apr. 2012.

[6] G. Bhuvaneswari and B. C. Mahanta, “Analysis of converter transformer failure in hvdc systems and possible solutions,” IEEE Trans. Power Del., vol. 24, no. 2, pp. 814–821, Apr. 2009.

[7] J. A. C. Forrest and B. Allard, “Thermal problems caused by harmonic frequency leakage fluxes in three-phase, three-winding converter transformers,” IEEE Trans. Power Del., vol. 19, no. 1, pp. 208–213, Jan. 2004.

[8] M. J. Heathcote, J&P Transformer Book, 12th ed. Oxford, U.K.: Reed Educational and Professional Publishing Ltd., 1998.

[9] J. Biela, D. Hassler, J. Schönberger, and J. W. Kolar, “Closed-loop sinusoidal input-current shaping of 12-pulse autotransformer rectifier unit with impressed output voltage,” IEEE Trans. Power Electron., vol. 26, no. 1, pp. 249–259, Jan. 2011.

[10] Y. Li, L. Luo, C. Rehtanz, S. Rüberg, and D. Yang, “An industrial DC power supply system based on an inductive filtering method,” IEEE Trans. Ind. Electron., vol. 59, no. 2, pp. 714–722, Feb. 2012.

[11] Y. Li, L. Luo, C. Rehtanz, D. Yang, S. Rüberg, and F. Liu, “Harmonic transfer characteristics of a new HVDC system based on an inductive filtering method,” IEEE Trans. Power Electron., vol. 5, no. 5, pp. 2273–2283, May 2012.

[12] Y. Li, L. Luo, C. Rehtanz, S. Rüberg, and F. Liu, “Realization of reactive power compensation near the LCC-HVDC converter bridges by means of an inductive filtering method,” IEEE Trans. Power Electron., vol. 27, no. 9, pp. 3908–3923, Sep. 2012.

[13] Y. Li, Z. Zhang, C. Rehtanz, L. Luo, S. Rüberg, and F. Liu, “Study on steady- and transient-state characteristics of a new HVDC transmission system based on an inductive filtering method,” IEEE Trans. Power Electron., vol. 26, no. 7, pp. 1976–1986, Jul. 2011.

[14] Y. Li, L. Luo, C. Rehtanz, K. Nakamura, J. Xu, and F. Liu, “Study on characteristic parameters of a new converter transformer for HVDC systems,” IEEE Trans. Power Del., vol. 24, no. 4, pp. 2125–2131, Oct. 2009.

[15] Y. Li, L. Luo, C. Rehtanz, C. Wang, and S. Rüberg, “Simulation of the electromagnetic response characteristic of an inductively filtered HVDC converter transformer using field-circuit coupling,” IEEE Trans. Ind. Electron., vol. 59, no. 11, pp. 4020–4031, Nov. 2012.

[16] H. Akagi, Y. Kanazawa, A. Nabae, Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits, IPEC'83 - Int. Power Electronics Conf., Tokyo, Japan, 1983, pp. 1375-1386.

[17] H. Akagi, Y. Kanazawa, A. Nabae, Instanataneous Reactive Power Compensator Comprising Switching Devices without Energy Storage Compenents”, IEEE Trans. Industry Applic., vol. 20, May/June 1984.

[18] Yong Li, Tapan Kumar Saha Olav Krause, “An inductively active filtering methods for power quality improvement of distribution network with non-linear loads” IEEE Trans. On Power Delivery, VOL. 28, NO. 4, Oct 2013.