Advanced Research in Electrical and Electronic Engineering
Print ISSN: 2349-5804; Online ISSN: 2349-5812 Volume 2, Number 3 January-March (2015) pp. 286-291

http://www.krishisanskriti.org/areee.html

Design of MLI Based Active Power Filter to Reduce the Harmonics Presented in a Three Phase Load with Direct Power Control

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Abstract—*A cascaded H-bridge multilevel inverter based active power filter with a novel direct power control is proposed in this paper. It can be directly connected to medium/high voltage power line without using the bulky transformer or passive filter. Due to the limited switching frequency (typically below 1 kHz) of high power solid-state devices (GTO/IGCT), multiple synchronous/stationary reference frame current controllers are reviewed and derived. Based on this, a novel current controller is proposed for harmonic current elimination and system power factor compensation. Furthermore, a synchronous/stationary hybrid structure can be derived with fundamental de- coupling control. The instantaneous reactive power theory and synchronous reference frame based control are compared based on mathematical models. A direct power control concept is then derived and proposed. It is equivalent as the hybrid synchronous/stationary frame current controller, but has a simpler implementation. It has clear physical meaning and can be considered as a simplified version of the hybrid frame current controller.*

Keywords: *Active power filter; Current control; Direct power control ;Low switching frequency; Medium voltage*

1. INTRODUCTION

Voltage source inverter based parallel active filter is known for current harmonic compensation of the power system and have been widely studied by using high switching power device (IGBT) [1]. For medium/high voltage application, a direct connected active filter can be more attractive by eliminating the bulky transformer or passive filter. Due to the limited switching frequency (typically below 1 kHz) of high power solid-state devices (GTO/IGCT), multilevel inverters have to be used [2]. This paper proposed a cascaded H-bridge multilevel inverter based active filter.

Multiple techniques are studied to increase the system bandwidth at low switching frequency:

- First, a software based multiple-sampled phase shifted PWM.
- Secondly, among most current controller designed for active filters, multiple synchronous referenceframe based current controller is proven to have the highest bandwidth with modest feed forward gain.
- Thirdly, an equivalent stationary frame based current controller is easily derived based on complex vector theory. The results are similar as that derived from convolution [3] or physical concept [4] in recent literature.
- Fourthly, to remove the fundamental cross- decoupling term in synchronous reference frame, a synchronous/stationary hybrid frame based current controller is proposed.
- Finally, instantaneous reactive power (IRP) theory [5] and synchronous reference frame (SRF) [6] based methods are briefly compared. Based on these, an instantaneous reactive power theory based direct power control is derived from the synchronous/ stationary hybrid frame based current controller.

This new concept combines the IRP theory and current control into one controller called direct power controller. The power reference is created by the IRP and a linear direct power controller is designed accordingly. It is similar to the multiple reference frame current controllers, which are suitable for high.

2. CASCADED H-BRIDGE MULTILEVEL INVERTER

In medium voltage/high voltage power electronics system design, there is a strong tendency to modularize the power pass and digital controller in order to reduce the price, simplify converter design and potentially increase the availability of applicable converters. There are three main voltage source multilevel converter topologies—diode clamped converter [7], flying capacitor converter [8] and cascaded H-bridge converter [9]. Among them, cascaded H bridge topology is presented to be the best candidate for medium voltage active power filtering application due to its modular feature of offering the least component with easy extension to higher level system.

3. PWM METHOD

Natural sampled PWM [10] is the best choice for applications modulation, such as active power filtering. It does not attenuate or distort the modulating signal, even when the frequency of that signal is similar to the switching frequency. Carrier based PWM [11] is also easily adapted to multilevel converter modulation by phase shifting the carriers. Although it appears more promising in theory, in practice as the number of converters increases, the variation between the analog generated carriers makes it increasingly difficult to achieve good carrier cancellation.

A digital implementation [12] is preferred for multilevel modulation. Switching edges with high accuracy and more importantly repeatability are needed to give the best carrier cancellation in a multilevel converter. Digital control is more easily modularized and is more noise immune.

As shown in Fig. 2(a and b), a software based multiple sampled phase shifted carried based PWM is usedfor PWM control. This PWM method allows using high sampling control rates at low switching frequency. It can be considered as an extension either from a naturally sampled carrier based PWM or a uniform carried based PWM, which builds a connection between these two, therefore it has the benefits of both analog and digital implementations.

3.1 Current control

Current controller design is very critical for the current controlled voltage source inverter system, especially for non sinusoidal low switching frequency application such as medium voltage active power filter design. Existing current control techniques [13] can be classified into two main groups, linear and non-linear controllers.

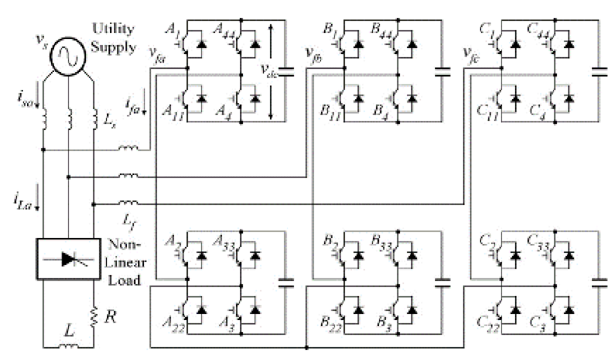

Fig. 1: The topology of proposed medium voltage multilevel inverter based active power filter. *V*s (line-line) = 4160V, *R*=26_, *L* = 0.15 H, *L*s = 0.002 -0.004H (5–10% per unit), *L*f = 0.002H (5% per unit),*C*= 1000_F.

Non-linear controller is not suitable for low switching frequency applications and will not be discussed. In the linear group, there are four controllers that are generally studied for active filtering application: P stationary, PI stationary, PI synchronous and predictive(deadbeat) with constant switching frequency.

In the linear group, there are four controllers that are generally studied for active filtering application: P stationary, PI stationary, PI synchronous and predictive (deadbeat) with constant used current controllers of active power filters have been extensively studied [14,15], but most methods are not suitable for low switching frequency applications. The conventional current controller can be summarized as:

- When the reference current is a dc signal, zero steady-state error can be secured by using a conventional proportional integral (PI) controller.
- When the reference current is a sinusoidal signal, straightforward use of the conventional PI controller would lead to steady-state error due to finite gain at the operating frequency.
- A synchronous-frame PI controller is popularly used which guarantees zero steady-state error.
- When the reference current is a non-sinusoidal signal, as in active power filters, predictive/deadbeat controller is often used as a viable solution

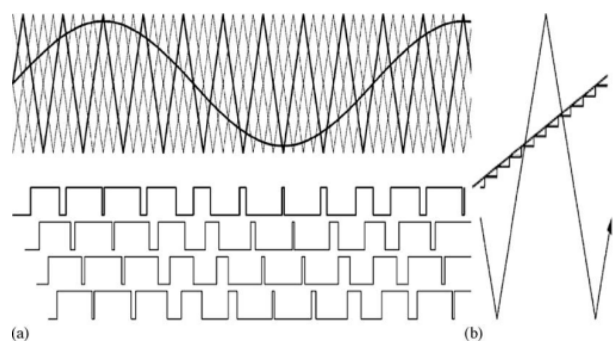

Fig. 2: Multi-sampled phase shifted carrier based PWM for multilevel inverter"

Actually, the requirements of designing a non-sinusoidalcurrent controller for active power filter can be considered as designing a multiple frequency current controller, which is compared with generally studied single frequency current controller.

Generally, the dominant harmonics in medium voltage line are the 5th, 7th, 11th, 13th harmonics. A multiple synchronous reference frame based current control method [16] can be designed to reach zero steady state error for multiple harmonics, therefore it has superior benefits in low switching frequency application where feedforward gain has to be kept modest to limit the switching frequency at the carrier frequency. To simplify the complex rotation frame transformation, an equivalent stationary frame current controller can be developed by convolution derivation [3] or the direct physical concept [4].

In this paper, a different method is used to derive the stationary counterpart of the multiple synchronous reference frame by using the complex vector theory. First, a complex vector based mathematical model (Fig. 4a) is used to represent the multiple synchronous reference frame based current controllers; then a simple and straightforward derivation is used to find the equivalent stationary frame based current controller, as shown in Eqs. (1)–(5) and Fig. 4b. Eq. (5) shows the same result as the ones in [3,4], and Eq. (2) gives the general relationship between rotationframe and stationary frame.

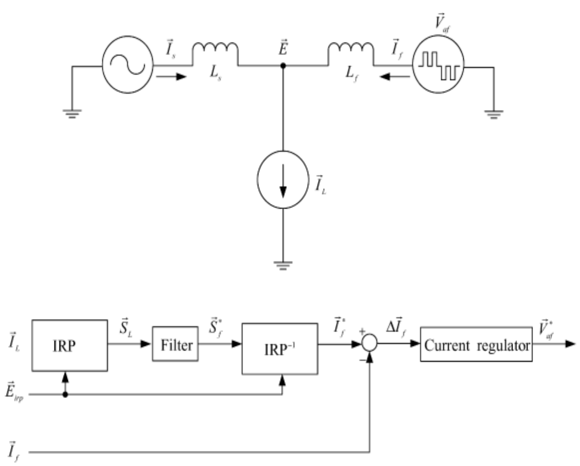

Fig. 3: Typical current controlled voltage source inverter based parallel active power filter.

$$\vec{Y}(s) = \vec{X}(s) * H_w(s - jwt) \rightarrow (1)$$

If consider $\pm w$ rotating frame transformation when

$$H_w(s) = \frac{1}{s} \rightarrow (2)$$

Then

$$\vec{Y}(s) = \vec{X}(s)\left[\frac{1}{s - jwt} + \frac{1}{s + jwt}\right]$$

$$= \vec{X}(s)\left[\frac{s + jwt}{s^2 + w^2} + \frac{s - jwt}{s^2 + w^2}\right]$$

$$= \vec{X}(s)\left[\frac{2s}{s^2 + w^2}\right] \rightarrow (3)$$

In unbalanced load conditions, both positive sequence harmonics and the negative sequence harmonics are presented and need to be compensated. Item $\omega 2$ in Eq. (3) shows that it can control both positive sequence and negative sequence components. This means that the derived controller can deal with unbalanced load conditions by nature.

It is well known that the decoupling synchronous reference frame [12] can improve the current controller bandwidth, due to the existence of the system cross- coupling term on the synchronous reference frame. Therefore, a hybrid synchronous stationary frame current controller with de-coupling scheme is then proposed with improved bandwidth (Fig 4 c and d).

For a three phase balanced system as shown in Fig

4.1, the lowest four dominant harmonics are the −5th, +7th,−11th, +13th. In fundamental synchronous rotation frame, they become equivalent as ±6th and ±12th harmonics Therefore, applying the multiple stationary reference frame on first rotation frame results in the proposed hybrid frame current controller as shown in Fig 4.3c and d. In this synchronous/stationary hybrid structure, current reference is generated by the well-known instantaneous reactive power (IRP) theory, and then transformed into synchronous reference frame (SRF) for the current control. These two-step transformations make the system complicated and a merging of these two transformations can be found. This is based on a brief review of IRP and SRF based system models in the next section.

$$L_f \frac{d\vec{I}_f}{dt} * e^{-jwt} + L_f \vec{I}_f * \left(-jw^{-jwt}\right) \rightarrow (4)$$

4. SYSTEM MODEL BASED ON IRP AND SRF THEORIES

Instantaneous reactive power [6] based and synchronous reference frame based active filtering theories have been popularly studied. To investigate the difference and connection between instantaneous reactive power theory and synchronous reference frame based control, mathematical models are derived separately. By using complex vector, Eqs. (4)-(11) give the mathematical equations of synchronous reference frame based control; Eqs.(12)-(24) give the mathematical equations of instantaneous reactive power based control.

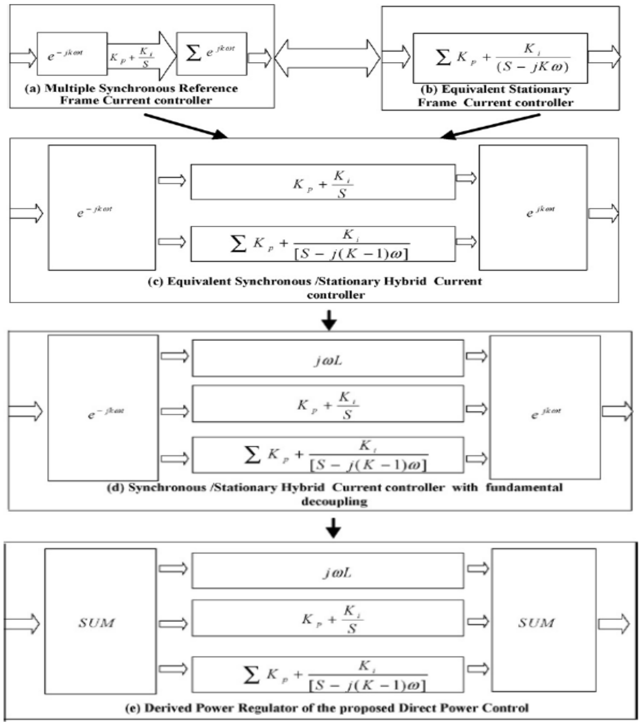

Fig. 4: Derivation of direct power controller.

The derivation of synchronous reference frame method is as follows.

$$\vec{V} = V_\alpha + jV_\beta ; \vec{I}_f = I_{f\alpha} + jI_{f\beta} ; \vec{E} = E_\alpha + jE_\beta$$

$$\vec{V} - \vec{E} = L_f \frac{d\vec{I}_f}{dt} \rightarrow (5)$$

$$L_f \frac{d}{dt}\left(\vec{I}_f * e^{-jwt}\right) = L_f \frac{d\vec{I}_f}{dt} * e^{-jwt} + L_f \vec{I}_f * \frac{de^{-jwt}}{dt}$$

$$= L_f \frac{d\vec{I}_f}{dt} * e^{-jwt} + L_f \vec{I}_f * \left(-jw^{-jwt}\right)$$

$$= L_f \frac{d\vec{I}_f}{dt} * E^{-jwt} \rightarrow (6)$$

$$\Rightarrow L_f \frac{d\vec{I}_f}{dt} * e^{-jwt} = L_f \frac{d\left(\vec{I}_f * e^{-jwt}\right)}{dt} + jwL_f \vec{I}_f * e^{-jwt}$$

$$\vec{V} * e^{-jwt} - \vec{E} * e^{-jwt} = L_f \frac{d\left(\vec{I}_f * e^{-jwt}\right)}{dt} + jwL_f * \left(\vec{I}_f * e^{-jwt}\right)$$

$$\vec{V}_w - \vec{E}_w = L_f \frac{d\vec{I}_f}{dt} + jwL_f \vec{I}_{fw} \rightarrow (7)$$

The derivation of instantaneous reactive power theory is :

$$\vec{V} = V_\alpha + V_{\beta;}\ \vec{I}_f = I_{f\alpha} + jI_{f\beta} ; \vec{E} = E_\alpha + jE_\beta$$

$$\vec{E}_{IRP} = E_\alpha + jE_\beta \rightarrow (8)$$

$$\vec{V} - \vec{E} = L_f \frac{dI_f}{dt} \rightarrow (9)$$

$$\vec{V} * \vec{E}_{IRP} - \vec{E} * \vec{E}_{IRP} = L_f \frac{d\vec{I}_f}{dt} * \vec{E}_{IRP} \rightarrow (10)$$

$$L_f \frac{d\left(I_f * \vec{E}_{IRP}\right)}{dt} = L_f \frac{dI_f}{dt} * E_{IRP} + L_f I_f \frac{d\vec{E}_{IRP}}{dt} \rightarrow (11)$$

$$\Rightarrow L_f \frac{d\vec{I}_f}{dt} * \vec{E}_{IRP} = L_f \frac{d(\vec{I}_f * \vec{E}_{IRP})}{dt} - L_f I_f \frac{d\vec{E}_{IRp}}{dt}$$

$$\vec{V} * \vec{E}_{IRP} - \vec{E}_{IRP} = L_f \frac{d(\vec{I}_f * \vec{E}_{IRP})}{dt} - L_f \vec{I}_f \frac{d\vec{I}_{IRP}}{dt}$$

$$\vec{V}_{IRP}^2 = \vec{V} * \vec{E}_{IRP} ; \vec{E}_{IRP} = \vec{E} * \vec{E}_{IRP} ; \vec{S}_f = \vec{I}_f * \vec{E}_{IRP} \rightarrow (12)$$

$$\vec{V}_{IRP}^2 - \vec{E}_{IRP}^2 = L_f \frac{d\vec{I}_f}{dt} - L_f I_f \frac{d\vec{E}_{IRP}}{dt} \rightarrow (13)$$

When $\vec{E}_{IRP} = \sqrt{E_\alpha^2 + E_\beta^2} * e^{-jwt}$; IRP based equation will become SRF based equation.

$$\vec{E}_{IRP} = \sum_{k=1}^{n} E_k e^{-jkwL} \rightarrow (14)$$

$$-L_f \vec{I}_f \frac{d\vec{E}_{IRP}}{dt} = L_f \sum_{k=1}^{n} \left[(jwE_k) * (\vec{I}_f e^{-jwt})\right] \rightarrow (15)$$

From eq (4) to (10), the derivation is done as follows:

Eqs (4) and (5) are the system model in stationary frame,Eq. (6) is transforming the system model from Stationary frame to the synchronous frame,Eqs. (7) and (8) is showing the origin of the cross- coupling term in current differential term.

Eqs.(9) and (10) lead the derivation to the system model in synchronous frame.From eq.(11) the derivation is conducted as follows:

- Eqs.(11)-(13) are the system model in current differential format.
- Eq.(14) is transforming the system model from current differential format to power differential format.
- Eq.(15) and (16) is showing the origin of the cross coupling term in power differential term

Based on the correlation between Eq.(4)-(10) and (11)-(21),the similarities between them show that IRP is equivalent as SRF when E_{IRP} only has one frequency component. The cross coupling term in IRP (shown in Eq.(18)-(21) reveals that the general nature of the cross coupling term in SRF is a cross differential phenomena,which can be explained as:

When a time domain signal is shifted in the frequency domain, the shifted frequency will be reflected back to the time domain with one more cross-differential term.If the shifting is non-linear (multiple frequency with different size), the size of the cross- differential term is not proportional to the distance(or frequency),which is how much the signal is shifted in frequency domain,but is the result of the sum of shifted distance (or frequency)multiplying their own size. In the non-linear situation, the portion of the different shifted frequency is not observable intime domain,so cross decoupling in this case cannot be realized for multiple frequencies.

However, de-coupling control can still be realized for one frequency and this is the case when E_{IRP} only has one frequency component (fundamental).

5. DIRECT POWER CONTROL

Based on the connection between IRP and SRF,

When E_{IRP} has one frequency component (fundamental) figs.4(d) and 3 can be simplified into figs. 4(c) and 5, which is proposed in this paper and can be called direct power control.Similar like Figs. 4(d) and 3, direct power control (Fig. 5) generates a power reference and feedback (controlled) power based on the IRP theory. The error is fed into a power regulator and the output of the power thevoltage reference of the inverter. This concept combines the IRP and current control into one controller called direct power controller. The power reference is created by IRP and a linear direct power regulator is designed accordingly.

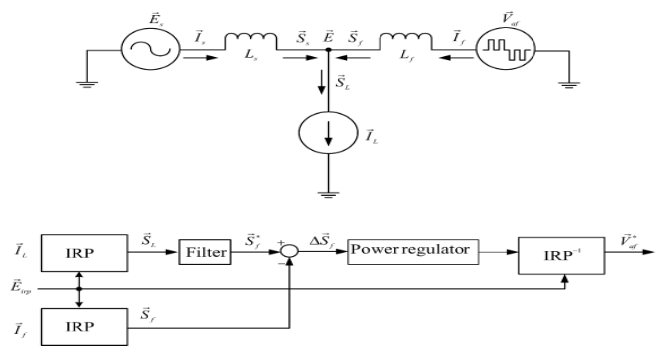

Fig. 5: The proposed direct power controlled voltage source inverter based active power filter”

6. SIMULATION RESULTS

The simulation results are as follows:

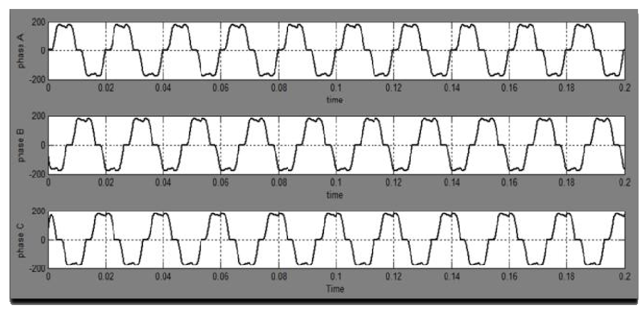

Fig. 6: Supply current without APF

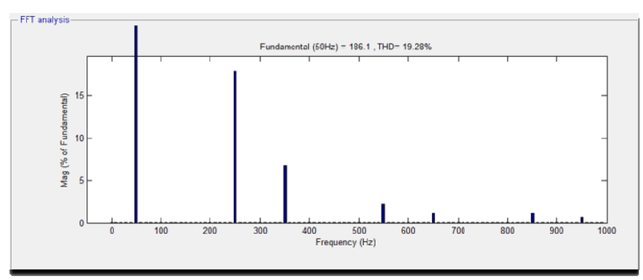

Fig. 7: THD for supply current without APF

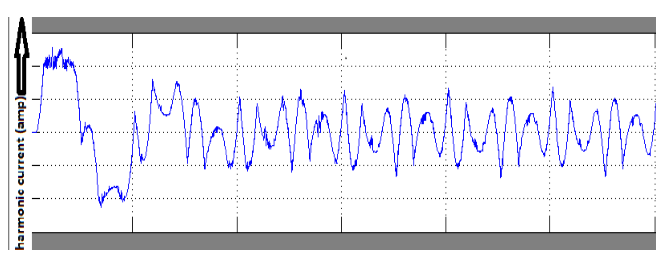

Fig. 8: Harmonic current to be compensated

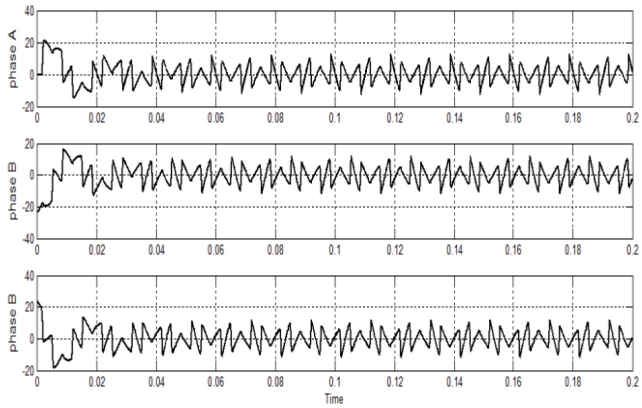

Fig. 9: Reference current signals generated for three phases

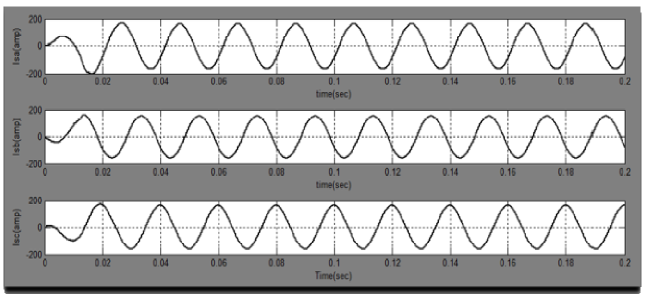

Fig. 10: Source current after filtering

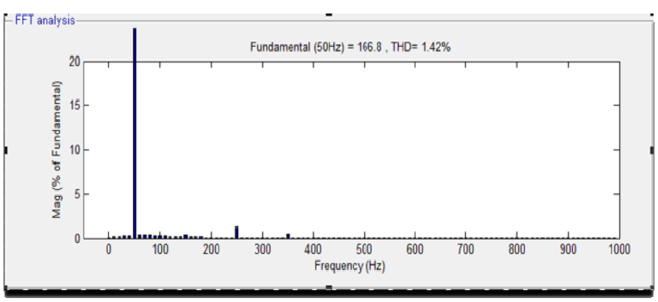

Fig. 11: THD for source current after filtering

7. SIMULATION PARAMETERS

Source voltage (V_s) = 1KV/phase.

Source inductance (L_s) = 1mH.

<u>RL load:</u>

Active power rating is = 1000W Reactive power rating = 100 Var Switching frequency = 1KHz

DC-link capacitor value = 2100 micro F.

8.Acknowledgements

This work was supported in part by GITAM UNIVERSITY.

8. CONCLUSION

An active power filter (APF) with five level cascaded H-bridge multilevel inverter was simulated using Matlab-Simulink software. A new hybrid current controller was proposed. Before using the APF the total harmonic distortion (THD) is about 19.50% and after filtering the THD reduces to 1.42%. The DC-link capacitor voltage was also maintained constant.

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