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Comparison of Various Configurations of Hybrid Active Filter With Three Different Control Strategies

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Abstract-This paper presents a comparative analysis of various configuration of Hybrid Active filter with three control strategies which involves instantaneous p-q theory, d-q method, and the conventional method. A comparative evaluation of three control strategies for shunt active filter and hybrid active filter is carried out. A PI controller is used to control the dc capacitor voltage in all cases. The modeling of different configurations of hybrid active filter topologies is done using MATLAB/Simulink.

Keywords- Active filters (AF), Passive filters, Instantaneous reactive power theory (p-q)

I. INTRODUCTION

Large number of power electronic applications is used nowadays in industrial as well as for household applications. Accompanying with various advantages these devices also suffers with the problem of poor power quality [4, 7]. They draw harmonic currents as well as reactive power. To mitigate these problems various types of filters are designed [5]. These filters are classified into mainly two categories- passive filters and active filters. Passive filters are the integration of resistance, inductance and capacitance placed in such a fashion that it acts as a frequency discriminator. Accompanying with advantages of low maintenance cost, high efficiency and easy to implement, they suffer from various drawbacks such as changing system conditions then they are unsuitable. The source impedance changes with the change in system parameters and it affects its filtering characteristics. Due to problem of ageing and temperature effects detuning of filter occurs. There is a problem of parallel resonance between filter and system [6]. Due to these problems of passive filters development of power electronic devices based filter is encouraged known as Active filters. Active filters also suffer from some of the disadvantages like they are more expensive than the passive filters. High rating of active filters also leads to high cost. Therefore, attention of researchers is shifted to hybrid active filters. There are several topologies of hybrid active filters such as combination of shunt active and shunt passive filter, combination of shunt active and series passive filter, active filter is in series with the parallel passive filter.

II. CONFIGURATIONS OF HYBRID ACTIVE FILTERS [8, 9, 11]

Hybrid1: Combination of shunt active and shunt passive filter

This configuration is most commonly uses because this provides the excellent compensation characteristics. The main advantage with this configuration is relative independence between active and passive filters. Passive filter always provides filtering action even if active filter is out of service. The presence of passive type filter alters the impedance characteristics of the whole system, therefore proper coordination between the two needs to be maintained. The other advantage is that the rating of the active filter is reduced and hence the configuration is more economical compared to shunt active filter used alone [11].

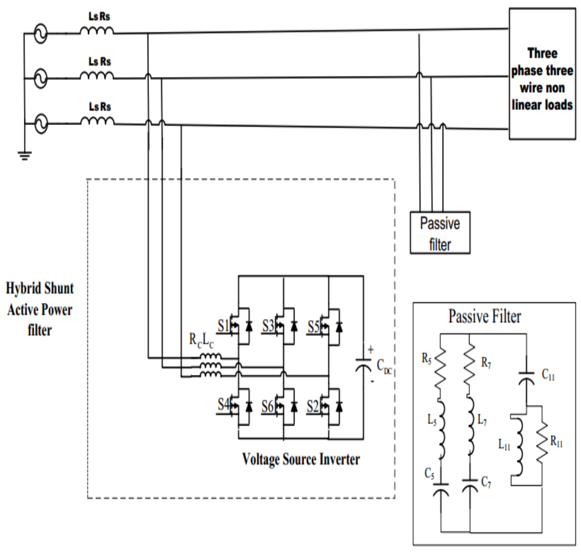


Figure 1 Combination of a shunt active and shunt passive filter

The passive filters are mainly employed to filter the lower order harmonics and for reactive power compensation. The rest of higher order harmonics is compensated by the active filter. But due to the presence of passive filter impedance characteristics of the system changes and there is a possibility that passive filter could start taking current by the active filter. This will make both active and passive filters overloaded.

Hybrid2: Combination of shunt active and series passive filter

In this configuration a series passive filter and a shunt passive filter are connected. The operating principle of this configuration is almost same as that when the shunt active filter is connected in parallel with the shunt passive filter [8]. This is generally used when the source voltage is contained with some harmonic contents.

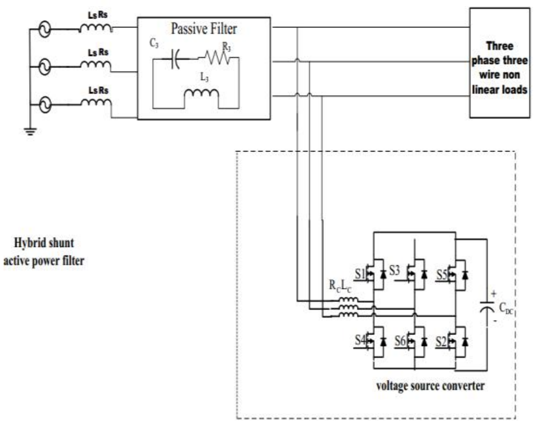


Figure 2 Combination of a shunt active and series passive filter

Hybrid3: Active filter in series with the parallel passive filter

This is one of best scheme of hybrid filters. In this the active filter is connected in series with the passive filters. There are two ways by which this connection can be made, one is either by using transformer [1] and other is transformerless. Initially, configuration was implemented with transformer but it was not cost effective so transformer-less configuration was designed.

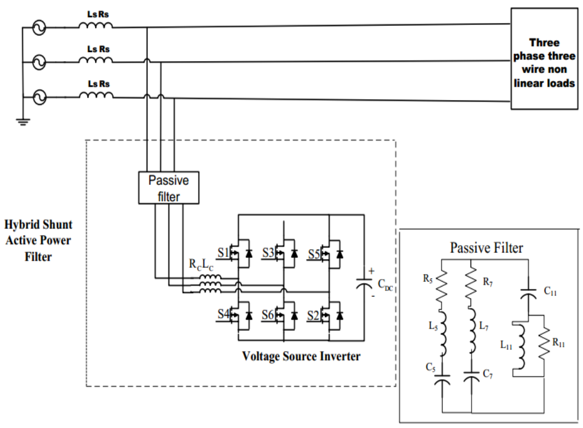


Figure 3 Active filter is in series with passive filter

The main advantage of this configuration is that the rating of active filter is greatly reduced because the value of dc capacitor is of very less value. In this configuration the active filter acts as voltage source. Damping resistance to all the harmonics is imposed and zero impedance is posed for the fundamental component. The use of the capacitor shows high impedance to the fundamental frequency components and minimum impedance to the harmonic components for which it is tuned. The fundamental voltage exclusively comes on the capacitor and hence no fundamental voltage appears across active filter. Therefore, there will be a reduction in the rating of the switches [2, 3].

III. EXPLANATION OF THREE DIFFERENT CONTROL STRATEGIES

There are number of control strategies to generate the required gate pulse for the inverter operation. In this paper three strategies are considered. These are instantaneous p-q Theory, conventional method (calculating reference value of source current) and d-q Theory [10, 12].

1. Instantaneous p-q Theory

It is based on instantaneous power defined in time domain. The p-q theory is applicable to both three phase three wire system as well as three phase four wire system. Since it is based on instantaneous power calculation, it is valid both in steady state as well as transient state. This theory uses the concept of Clark's transformation [10]. In this transformation the three instantaneous voltages in abc is transformed in $\alpha\beta\gamma$ axes.

The Clarke Transformation for the three phase voltage is represented in matrix form as

$$\begin{pmatrix} V_o \\ V_\alpha \\ V_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (1)$$

Similarly the Clarke Transformation for three phase current is represented as

$$\begin{pmatrix} i_o \\ i_\alpha \\ i_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \quad (2)$$

If the load is balanced then V_o and i_o can be neglected in the equation represented above in the matrix form and the instantaneous voltage vector can be define as

$$e = V_\alpha + jV_\beta \tag{3}$$

$$i = i_\alpha + ji_\beta \tag{4}$$

The instantaneous complex power can be defined as product of voltage vector and conjugate of current vector and it can be represented as

$$s = e * i^* = (V_\alpha + jV_\beta) * (i_\alpha + ji_\beta) = (V_\alpha i_\alpha + V_\beta i_\beta) + j(V_\beta i_\alpha - V_\alpha i_\beta)$$
(5)

The real part of the complex power is defined as p and the imaginary part is represented as q. Because of the fact that instantaneous voltage and current values are used there is no restriction in s, so it can be applied during steady state or transient conditions. The matrix representation of p and q is given as
$$\begin{pmatrix} p \\ q \end{pmatrix} = \begin{pmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{pmatrix} \begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix}$$
(6)

The calculated value of p is separated into two parts. One is its average part represented as $\bar{p}$ and the other is the oscillating part represented as $\tilde{p}$. Similarly the load imaginary power q can be divided into two parts $\bar{q}$ and $\tilde{q}$. The undesirable components of real and imaginary power are chosen for the compensation. These compensated powers are known as $(-p_c)$ and $(-q_c)$. There is a reason of using the negative sign in powers. This is because active filter should draw a compensating current in such a way that it will produce exactly inverse of the undesirable powers drawn by non linear load. The α - β current calculation is done by using the following expression

$$\begin{pmatrix} i_\alpha^* \\ i_\beta^* \end{pmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{pmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{pmatrix} \begin{pmatrix} -p_c \\ -q_c \end{pmatrix} \tag{7}$$

Now, the inverse Clarke Transformation is carried out to get the value of three phase compensation current. It can be represented in the matrix form as

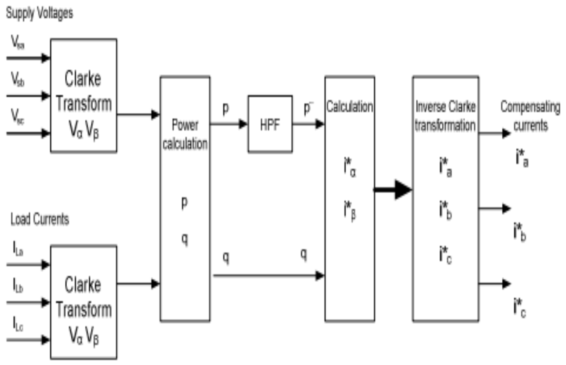


Figure 4 Block diagram of Instantaneous reactive power theory

2. d-q Method

In this method, in the first step the three phase currents are transformed into the $\alpha\beta$ axes with the use of Clarke Transformation and then $\alpha\beta$ axes current components are transformed into d-q axes current using the Park Transformation.

The Park Transformation to convert $\alpha\beta$ axes currents into d-q axes is as follows

$$\begin{pmatrix} i_o \\ i_d \\ i_q \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} i_o \\ i_\alpha \\ i_\beta \end{pmatrix} \tag{8}$$

The above equation can be rewritten in the form represented as

$$\begin{pmatrix} i_o \\ i_d \\ i_q \end{pmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{pmatrix} 1 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{pmatrix} \begin{pmatrix} i_o \\ i_\alpha \\ i_\beta \end{pmatrix} \tag{9}$$

The d-q reference frame is in synchronism with the AC voltage of main line. The d- q currents can be decomposed in to two parts- one is dc component and other one is the oscillating component. The dc component is considered as fundamental positive sequence current and the oscillating component represent the negative sequence currents. This can be represented as

$$i_d = \bar{i}_d + \tilde{i}_d$$
$$i_q = \bar{i}_q + \tilde{i}_q \tag{10}$$

Now the reference value for the compensating current (i.e., the oscillating component of the current in d-q reference frame) is obtained and again converted into abc frame by reverse operation. The dc component is considered as the reference source current [12].

$$i_{Sdref} = \overline{i_{Ld}}$$
$$i_{Sqref} = i_{S0ref} = 0 \qquad (11)$$

Where, $$i_{Ld} = \frac{V_\alpha i_{L\alpha} + V_\beta i_{L\beta}}{\sqrt{V_\alpha^2 + V_\beta^2}}$$

And, $$\overline{i_{Ld}} = \left(\frac{V_\alpha i_{L\alpha} + V_\beta i_{L\beta}}{\sqrt{V_\alpha^2 + V_\beta^2}}\right)_{DC} \qquad (12)$$

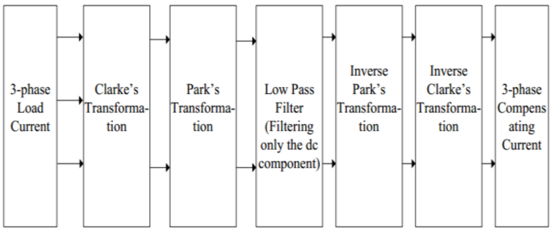


Figure 5 Block Diagram of d-q Method

3. Conventional Method (Calculating reference value of source current)

This is one of the simplest control strategy involved in the shunt active filter. In this method, the three phase reference source current is calculated using dc capacitor voltage balance and unit current templates and then compared with the actual ones with the use of hysteresis or other controller to generate the firing pulses for the devices [12].

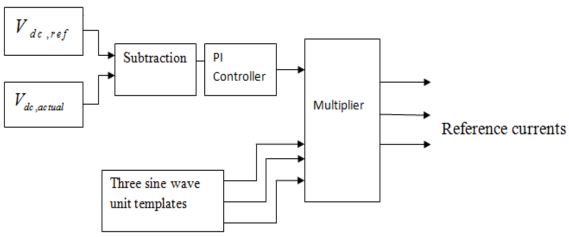


Figure 6 Block Diagram of Conventional Method

The step by step process to develop these reference values of source currents as shown in the figure. The first step is to calculate the sine wave unit templates. To develop the unit templates three phase voltages are sensed and then these three voltage signals will be passed through a phase locked loop. The phase locked loop will directly give us the three sine wave unit templates. The second step is to decide the peak value of the reference value of the source current. This is done by taking the difference of actual DC voltage across capacitor and the reference value of DC capacitor voltage. The final step is to achieve the three phase reference source current by multiplying peak value of reference source current and the sine wave unit templates. Now the actual source current and the calculated reference value of source current is given to any of the control schemes to generate the gating pulse for the switches. The limitation of this scheme is that there is no independent control on reactive power compensation and harmonic compensation that can be achieved in Instantaneous reactive power theory.

IV. SIMULATION RESULTS

For the simulation analysis of active hybrid filters the following parameters of the system are selected:

Supply phase voltage= 230V peak

Source impedance: Rs=1 ohm, Ls=0.01 mH
Coupling inductance=8 mH
Load resistance=20 ohm
Load inductance=10 mH
The simulation results are shown in figures from 7 to 13. When a non linear load (diode bridge rectifier) is connected alone the waveform of the source current is as shown in the figure 7 and the THD of the source current is 25.49%.

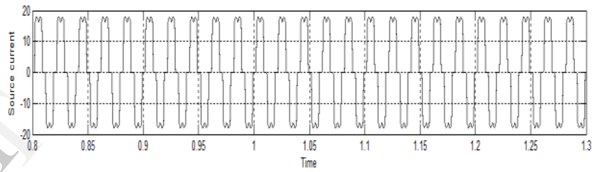


Figure 7 Source current when a non linear load is connected

Now to eliminate these harmonics filters are used. First passive filters are used. The waveform of source current when a shunt passive filter is used alone with load is as shown in figure 8 and the corresponding THD becomes 14.23%.

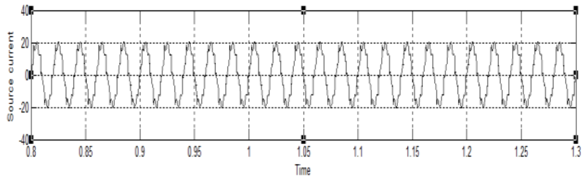


Figure 8 Source current when shunt passive filter is connected alone

The passive filter is tuned for the fifth harmonic. The waveform of source current when series passive filter is used alone is also shown in figure 9 and the corresponding THD is 12.64%.

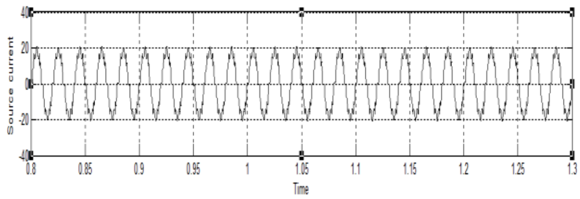
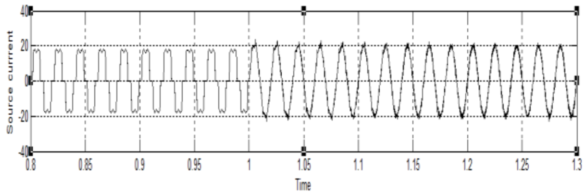
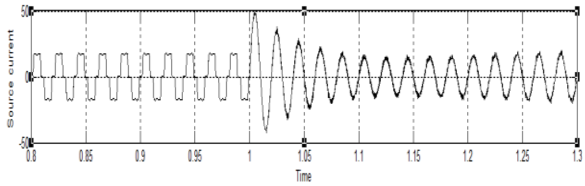


Figure 9 Source current when a series passive filter is connected alone

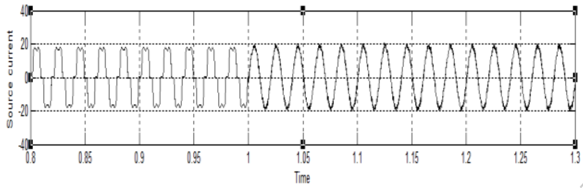
As evident from figures 8 and 9 the passive filters are not enough for harmonic mitigation, therefore active filters are used for further improvement. Three different control strategies are used to model the shunt active filter. The waveform of source current for these control strategies are shown in the figure 10.



(a)



(b)



(c)

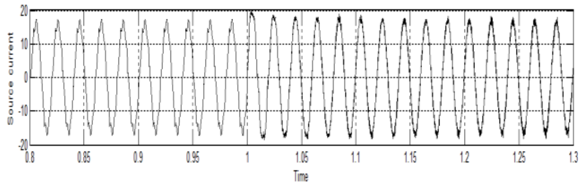
Figure 10 Source current waveform when a shunt active filter is connected at time t=1sec (a) p-q theory (b) Conventional method (c) d-q method

A table of comparison of these three strategies is shown in table-1. From the comparison it is found that when the source voltage did not have any harmonic, then p-q theory is giving best results but with the involvement of seventh harmonic component the d-q theory is giving good results.

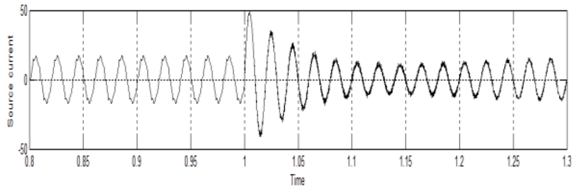
Table-1: COMPARISON OF THREE CONTROL STRATEGIES WHEN ONLY ACTIVE FILTER IS CONNECTED

Control strategy	THD% (Without Active filter)	THD%(With active filter only)	THD%(With active filter and 7th harmonic in source voltage)
p-q Method	25.49	4.32	5.12
Conventional Method	25.49	6.76	7.13
d-q Method	25.49	4.76	4.81

Then the modeling of hybrid1 configuration in which a shunt active filter is connected in parallel with shunt passive filter is done. The waveform of source current for the three different control strategies is shown in figure 11.



(a)



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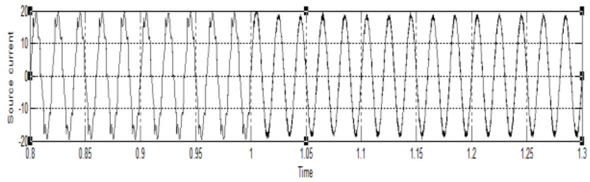


(c)

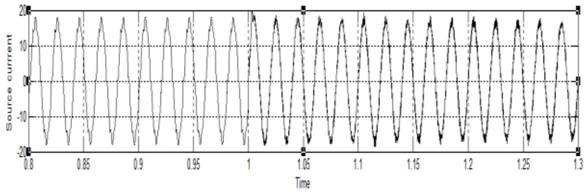
Figure 11 Source current waveform when Hybrid1 configuration is connected at time t=1sec (A) p-q theory (B) Conventional method (C) d-q method

A table of comparison is also shown in the table-2. From the result analysis it is found that p-q theory giving best results without involvement of harmonics in source voltage but d-q method giving best results with the involvement of seventh harmonic voltage components in the source.

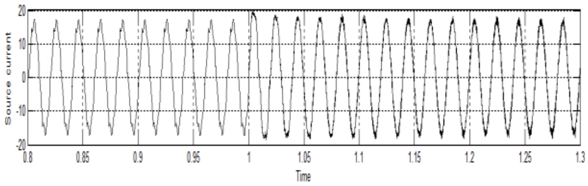
Table2: COMPARISON OF THE CONTROL STRATEGIES WHEN HYBRID ACTIVE FILTER-1 IS CONNECTED

Control strategy	THD% (Without Hybrid Filter)	THD% (With Hybrid Filter)	THD% (With hybrid filter and 7th harmonic in source voltage)
p-q Method	25.49	2.43	4.12
Conventional Method	25.49	2.92	4.82
d-q Method	25.49	3.13	3.30

Then a comparative analysis of three hybrid configurations is carried out. The respective source current waveforms for all the configuration is shown in figure 12.



(a)



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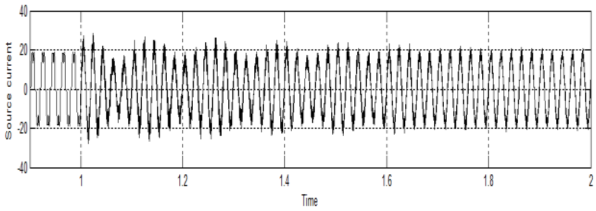
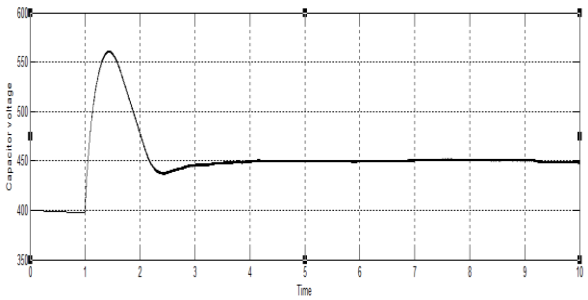


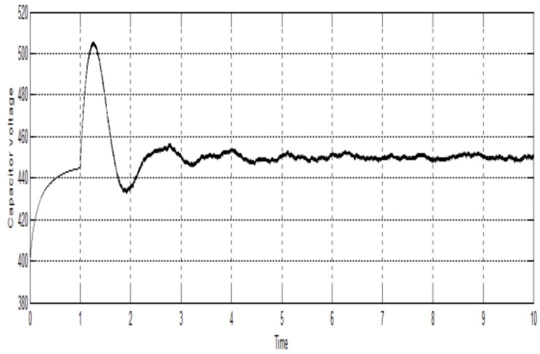
(c)

Figure 12 Source current waveform when connected (at time t=1sec) with (a) Hybrid-1 configuration (b) Hybrid-2 configuration (b) Hybrid-3 configuration

The dc link capacitor waveform comparison is also shown in figure 13. The hybrid-1 and hybrid-2 configuration has DC capacitor voltage as 450 volts but hybrid-3 configuration has the DC capacitor voltage as 18 volts.



(a)



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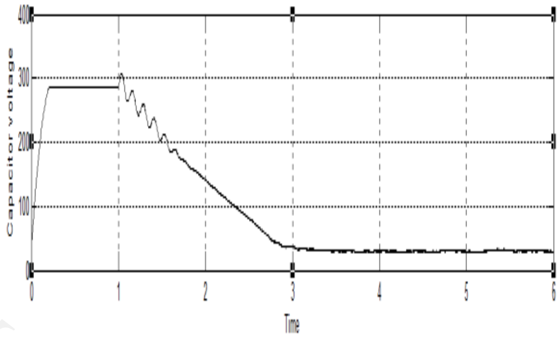

(c)

Figure 13 Capacitor voltage waveform when connected with (a) Hybrid1 (b) Hybrid2 (c) Hybrid3

Now a comparative analysis by making the table is done among the three configurations of hybrid active filter. The comparison is done on the parameters like THD percentage, the value of DC link capacitor, the rating of active filter, the cost and the performance capability. From the whole analysis it is found out that the hybrid3 configuration is best among all three hybrid filter configuration we have analyzed. The prime reason for this is very low value of DC link voltage which is kept at 18 volts.

Table3: COMPARITIVE ANALYSIS OF THREE HYBRID FILTER CONFIGURATION

Type of Hybrid configuration	THD%	DC capacitor voltage (in volts)	Rating of active filter	Cost	Performance (Based on the rating and cost of active filter)
Hybrid configuration1	2.43	450	Decreases with respect to active filter alone	Less than hybrid2 but higher than hybrid3	Very good
Hybrid configuration2	2.51	450	Maximum among three hybrid configuration	Maximum among three hybrid configuration	Good
Hybrid configuration3	3.02	18	Lowest among the three hybrid configuration	Lowest among three hybrid configuration	Best

V. CONCLUSION

Various simulations and the comparison among the control strategies and the various hybrid filter configurations are explained. From the comparative analysis of these three control strategies it was found that the p-q theory is preferable when there is no harmonic component in the supply but as soon as the harmonic currents are injected in supply the supply gets polluted. Under such conditions, the d-q method gives the best results. Performance of the three hybrid filter configurations is also analyzed. From their study it was observed that the Hybrid-3 configuration in which the active filter is connected in series with the passive filter is superior choice among the three because of its very low DC capacitor voltage and lowest rating of active filter in it. Hence it is more economical to use Hybrid3 configuration.

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