SIMPLIFIED FIVE LEVEL INVERTER AS SERIES ACTIVE POWER FILTER FOR MINIMIZING THD IN A NON-LINEAR SYSTEM

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ABSTRACT

A series hybrid Active Power Filter has been focused more in the area of power quality. The hybrid filter is implemented with three phase simplified asymmetrical five level inverter as active filter and LC filter connected in parallel with power lines acting as passive filter. The harmonics produced by the non linear loads are filtered out by the passive filters and the filtering property of it is improved by active filter. The multi level voltages are obtained from a simplified inverter, which operates at lower switching frequency intern reduces the switching losses compared to conventional cascaded five level inverter. The filter is developed to inject voltage in series and also for harmonic isolation. Current harmonics are eliminated by controlling the APF with the P-Q theory based control strategy developed for this simplified inverter. The system produces voltage of same amplitude but opposite to load harmonic voltage to nullify the harmonics injected into the system. For current harmonics, the system produces voltage proportional to the current and offers high impedance path to the current harmonics. The validity of the control scheme is verified by simulation study with help of MATLAB/SIMULINK and comparative analysis is carried out with help of simulated values to obtain the harmonic values within standard values.

Keywords: Active Filters, Harmonic Distortion, PQ theory, Multilevel Converters, Power Quality

1. INTRODUCTION

The increase in use of power electronic components in today’s energy conversion system lead to the increasing power quality problems particularly power system harmonics. The harmonics introduces many malfunctions in equipments, overvoltage, heating and these cause harmonic impedance which affect system power quality. These harmonic current sources seems to be well identified, such as in industrial, commercial and residential facilities are exposed to well known patterns of waveform distortion. Non linear loads have been characterized into two types of harmonic sources as current source type and voltage source type harmonic sources. Their corresponding operating condition, features, applications issues, and adaptive harmonic sources of filters have been presented [1].

Different non linear loads produce different harmonics but identifiable harmonic spectra. Various configurations of filters for elimination of harmonics produced by non linear load such as active and passive filters are discussed. These harmonics can be easily abated by use of filters such as passive filters which provides lower impedance to the tuned harmonic frequency than the source impedance to reduce harmonics flowing into the system. However it suffers from few disadvantages like parallel and series resonance and the effect of filtering characteristics get affected by supply impedance. They are also bulky, not suitable for variable loads and tuning frequency gets reduced with ageing, deterioration and temperature change.

This increasing austerity of harmonics in known as active power line conditioners. Several topologies of active filters are proposed [1],[2], and
they have been surveyed based upon the types of
non linear loads \[3\]. The active power line
conditioners are classified as shunt and series, the
use of these active filters for improvement of
quality of power and their distinction is made \[4\].
Mostly shunt active filters have been implemented
which compensates the harmonic current. Thus it
acts as controlled current source for harmonic
current produced due to non linear loads. However
shunt active filters are expensive due to its large
rating i.e. power capacity of filter increase with
increase in load current to be compensated.
The emerging series filters can act as an active
filter, this is capable of compensating voltage
producing as well as current producing harmonics.
So the series active filter is better suited for
harmonic voltage source such as diode rectifiers
with dc smoothing capacitors \[5\]. The series active
filter acts as sinusoidal current source in phase with
mains of voltage was developed \[6\]. This paper
deals the filter used as hybrid i.e. in conjunction
with passive filter.
The hybrid filter is used to mitigate source
current harmonics as well as to regulate load
voltage so as to compensate for abnormal utility
voltages. Active filters can be implemented with
Voltage Source Inverters \[7\] but it possesses some
disadvantages like high switching losses and high
harmonic noise.
The multilevel inverter finds its own advantages
\[8\] such as capability of producing cleaner voltage
with low current distortion, operates with low
switching frequency which drastically can reduce
switching losses, Elimination of transformer by
providing required voltage levels which results in
faster response, simple structure and reduces
voltage stress on power electronic devices.
For higher number of inverter levels there is the
more complicated problem of maintaining capacitor
voltage balance while retaining good filtering
performances. To obtain efficient performance, it is
important to obtain proper reference voltage
generation. Major development in control strategy
took place by \[9\] who introduces instantaneous
power theory and another important technique by
Synchronous Reference frame theory.
In this paper the simplified multilevel inverter
was used to implement the hybrid filter along with
LC filter. This inverter increases the number of
output voltage level by using minimum number of
power switches, driver circuits and dc voltage
sources. Similar method of active filter is
implemented \[6\] which uses nine level topology
with transformers and nine level inverter which
makes the control circuit complex to control eight
switches. The present technique overcomes
advantages by eliminating the use of transformer
and it uses only six switches. The THD
comparisons have made for with and without
hybrid filters
There are several other techniques like hysteresis
controller, digital deadbeat control, synchronous
detection method and a CRC theory, among all PQ
theory is used in this paper. This method extracts its
harmonic components of current but requires
synchronization with grid voltage, under non
sinusoidal supply voltage conditions.

2. SYSTEM DESCRIPTION

2.1 System Configuration

The configuration of a hybrid filter connected
into a non linear system is shown in Fig.1. In this, a
three phase source is connected to a non linear load
which produces the voltage type harmonics. The
hybrid filter consists of shunt passive filter
connected to the load and series active filter in
series and parallel to the load.

![Figure 1: Hybrid Series Filter Configuration](image)

The three phase simplified five level inverter acts
as an active filter. A three single phase series
connected transformer is not only to inject voltage
into the system but also isolate the inverter from
source side and also match the current and voltage
of the inverter to the system specifications.

2.2 Operation Principle

The operating principle of series active filter is
different from shunt active filter. The series active
filter is considered as controlled voltage source
which generates compensation voltage for injection
into the system. The active filter consists of three
main circuits, namely control circuit for generation of compensation voltage, generation of gating pulse to the inverter and the inverter main circuit.

The first one produces reference voltage for the second part which produces gating pulses to the third part for compensation. Fig. 2 shows the single phase equivalent circuit of series active filter, where \( v_s \) is the source voltage with source impedance \( Z_s \) and current \( i_s \) is the source current. The voltage across load is denoted as \( V_l \); \( V_{af} \) denotes the compensated voltage by active filter. Current or Voltage signals contain fundamental as well as harmonic content which is denoted as: \( V_{af} \) and \( V_{sh} \) is fundamental and harmonic content of source voltage respectively, \( i_{af} \) and \( i_{sh} \) fundamental and harmonic content of source current respectively. Similarly, the load voltage is described as \( V_{lf} \) and \( V_{lh} \) for its fundamental and harmonic content. Reference voltage is generated by detecting source current harmonics \( i_{sh} \), and then form reference voltage which is \( k \) times proportional to source harmonic current (i.e. \( K \cdot i_{sh} \)). Thus the series active filter is represented as resistor which has the value of \( K \), the series active filter has value of zero for \( K \), while it is \( K \) ohms for harmonic components. The reference voltage to each phase is

\[
V_{af} = K \cdot i_{sh} + V_{sh} \quad (1)
\]

From Fig 2 the harmonic current content is directly derived as

\[
I_{sh} = \frac{V_{sh}}{Z_P + X} \quad (2)
\]

The series active filter offers high impedance path to the current harmonics and also acts as damping resistance, eliminating harmonic sinks problems which is an ingrained problem of shunt passive filter. [6]

The series active filter is mostly used as controlled voltage source which is operated with shunt passive filter to compensate voltage producing harmonics. The load current is made to circulate mainly through passive filter rather than power system. This technique is recommended for voltage unbalance and voltage sags from AC system and low power system. The filter is installed at PCC of the distribution line [10]. The active filter which injects current to a radial distribution system at PCC [11] which determines the spectra of harmonics and location of injection by suitable method.

3. MULTILEVEL INVERTER

3.1 Simplified Multilevel Inverter Topology

![Figure 3: Basic Switching Circuitry of Five level Inverter](image)

This topology used reduced number of switches than the conventional Cascaded H bridge inverter which is used drastically to reduce power circuit complexity with simple design. The basic circuitry of five level inverter with six switches is shown in Fig 3 [12]. The switching to the inverter is based on Phase Disposition PWM technique to produce five level output -2Vs to +2Vs. The strategy used two carriers and only one reference to produce the switching pulses.

The maximum positive voltage \( (V_{s1} + V_{s2}) = 2V_s \) is obtained when the switches \( S_{12}, S_{13} \) and \( S_{23} \) are ON. The maximum negative output voltage \( -(V_{s1} + V_{s2}) = -2V_s \) is obtained when the switches \( S_{11}, S_{13} \) and \( S_{22} \) are ON. The first levels of both positive and negative voltages are \( V_{s1} \) or \( V_{s2} \) and \( -V_{s1} \) or \( -V_{s2} \) are obtained when the switches \( S_{12}, S_{13} \), \( S_{21} \) and \( S_{23} \), \( S_{12} \) and \( S_{23} \) are ON. The zero voltage is obtained when all the switches from any one right or left leg are turned ON.

3.2 Modulation Strategy

In general, inverters are modulated by pulse width modulation or pulses are generated by comparison of a modulated signal with carrier. The index of modulation is represented in two indices signal.
Amplitude Modulation \( (m_a) = \frac{A_m}{(m-2)A_c} \) \( (3) \)

Frequency Modulation \( (m_f) = \frac{F_m}{F_c} \) \( (4) \)

The carrier signals are defined with same frequency \( F_c \) and amplitude \( A_c \). The index of modulation is shown in (6) and index of frequency is shown in (7) which is ratio of frequency of carrier with respect to the modulator. This is always greater than one.

**Table 1: Switching Sequence for Simplified five Level Inverter**

<table>
<thead>
<tr>
<th>Voltage levels</th>
<th>S11</th>
<th>S12</th>
<th>S13</th>
<th>S21</th>
<th>S22</th>
<th>S23</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{c1} )</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( V_{c2} )</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Zero</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( -V_{c1} )</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( -V_{c2} )</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1 lists the switching combination that generates the required five level output. The carrier and reference signal for pulse production is shown in Fig.4. The use of reduced number of switches naturally reduces switching losses and improves conversion efficiency.

**Figure 4: Comparison of Carrier and Reference signals**

### 3.3 Harmonic Elimination

Output voltage \( V(t) \) of MLI can be expressed in Fourier series as

\[
V(t) = \sum_{n=1}^{\infty} \left( A_n \sin(n \omega t) + B_n \cos(n \omega t) \right)
\]

Due to the quarter wave symmetry of output voltage the even harmonics are absent \( (B_n=0) \) and only odd harmonics are present [13]. The amplitude of \( n^{th} \) harmonic \( A_n \) is expressed only with first quadrant switching angle \( \alpha_1, \alpha_2, \ldots \) an

\[
A_n = \frac{f_{S11}}{2} \sum_{k=1}^{\infty} \cos(nk \alpha) \]

For any odd harmonics \( A_n \) can be expressed up to \( k^{th} \) term. Multilevel inverters are mainly employed in three-phase medium and high-voltage systems in which all the triplen harmonics are absent in output voltage because triplen harmonics can be automatically cancelled in line-line voltages for a balanced three phase system. The low order non triplen harmonics in the line-to-neutral voltages are to be eliminated.

### 4 CONTROL SCHEME

The reference voltage generator and controller circuit are mainly used in harmonic elimination PQ theory is employed for the purpose of generation of reference voltage. The controller for reference voltage generation is shown in Fig.5 which is based on PQ theory discussed in following section.

#### 4.1 Instantaneous power theory

The appropriate voltage is used as reference by use of generalized instantaneous power theory [9] also called as PQ theory. The PI controller is used to maintain constant DC voltage across the dc link capacitor. According to this theory, three phase sinusoidal source voltages and distorted line currents are considered for reference generation. Instantaneous quantities of voltages are \( V_a, V_b, V_c \) and the currents are \( i_a, i_b, i_c \) of a three phase system are considered. The a-b-c co-ordinates are to be transformed into a-β coordinates as orthogonal system by Clarke’s transformation as follows.
The three phase circuit can be defined as follows:

\[
P_{ac} = V_{a}i_{a} + V_{b}i_{b} + V_{c}i_{c}
\]

(9)

Instantaneous real power is passed through second order butterworth filter (50Hz Low Pass Filter) which eliminates higher order thereby permitting only fundamental component which is denoted by \( P_{ac,loss} \).

The conventional instantaneous reactive power on the three phase circuit is

\[
Q = V_{a}^*i_{a} + V_{b}^*i_{b} + V_{c}^*i_{c}
\]

(10)

The power components P and Q are related to the same \( \alpha-\beta \) voltages and currents, they can be written as

\[
\begin{bmatrix}
P_a \\
Q_a \\
P_b \\
Q_b \\
P_c \\
Q_c
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2} & -\frac{1}{2} & 0 \\
\frac{1}{2} & \frac{1}{2} & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

(11)

The instantaneous real power is calculated from AC component of real power loss \( P_{ac,loss} \) and DC power loss which is denoted by \( P_{dc,loss} \). The DC power component is obtained by comparing dc link capacitor voltage of H bridge inverter and reference voltage. The PI controller determines the dynamic response and settling time of DC capacitor

\[
P_{dc} = [V_{dc,ref} - V_{dc}] kp + ki/s
\]

(12)

Instantaneous voltage on \( \alpha-\beta \) divided into real power loss and reactive power loss. The proposed controller computes only real power loss and reactive power loss is taken as zero

The reference voltage generation

\[
\begin{bmatrix}
V_{a0} \\
V_{b0} \\
V_{c0}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2} & -\frac{1}{2} & 0 \\
\frac{1}{2} & \frac{1}{2} & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
P_{dc} + P_{ac,loss} \\
0 \\
0
\end{bmatrix}
\]

(13)

Where

- \( P_{dc} \) is average component of instantaneous real power
- \( P_0 \) is zero sequence power
- \( P_{ac,loss} \) is power loss in the system.

The reference voltage generation for compensation in a-b-c coordinates can be obtained by inverse Clarke’s transformation

\[
\begin{bmatrix}
V_{a0} \\
V_{b0} \\
V_{c0}
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2} & -\frac{1}{2} & 0 \\
\frac{1}{2} & \frac{1}{2} & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
V_{a} \\
V_{b} \\
V_{c}
\end{bmatrix}
\]

(14)

\[
V_{c0} = -V_{o0}
\]

(15)

The instantaneous real and reactive power theory has several advantages such as it can be inherently applied to a three phase system which can be balanced or unbalanced, with or without harmonics in case of both current and voltage. The system with PQ controller has very good dynamic response. This includes only algebraic expressions which are relatively simple.

5 SIMULATION RESULTS

The proposed hybrid filter is implemented using MATLAB/SIMULINK for 2 kVA, 440V and 50Hz system using multilevel inverter as series active filter. From the above discussed equations the compensating voltage is obtained by taking the source current and voltage. Hybrid filter simulation model is tested for compensating voltage source producing harmonic load. Since the power supply is a voltage source, the series active filter tries to control the load voltage. But the load current depends on terminal voltages. The voltage that the series instantaneous active filter wishes to inject depends on the current of the load, and the current of the load depends on its voltage.

The non linear diode rectifier with R-C load acts as voltage producing harmonic load and the cascaded MLI as active filter in series at PCC for injection of anti harmonics. Elimination of harmonics in the system is done by computing load voltage and source current. The series active filter is more suitable for voltage harmonics non linear loads such as diode rectifiers with smoothing capacitors and SMPS. The harmonic spectra and THD for load voltage and source current are analyzed. It uses system with no filter, with passive filter and with hybrid filter are analyzed for the source current and load voltage of a three phase system in this section.

As per the PWM strategy, PWM signals for the six power switches are generated and shown in Fig.6. It is noted that one active switch from both the legs are operated at fundamental frequency
Figure 6: Simulated switching signals for the proposed inverter switches.

Figure 7: Simulated output phase voltage with filter, without filter and current waveforms of the proposed inverter. (single phase) and the memory switches are operated at the frequency of carrier signal. Hence the switching stresses for the switches are considerably reduced and the inverter efficiency is improved.

The magnitude of this output voltage from the inverter is varied by varying the input magnitude to the inverter. It is noticed that the voltage across the switches operating at high frequencies are equal to any one input voltage source $V_{s1}$ or $V_{s2}$. But the voltage across the switches operating at supply frequencies are equal to the addition of two input source voltages $V_{s1} + V_{s2}$. Hence the switching stresses for the switches are considerably reduced and the inverter efficiency is improved.

The output voltage obtained from the inverter is not a sinusoidal one. Hence suitable filter is designed and used as an output filter to improve the shape of the wave form. The output voltage with filter, without filter and the current through a linear load is shown in the Fig.7.

The compensated voltage is injected into the system with help of three single phase matching transformers. Fig.8 shows the source voltage and source current waveforms of the system when there is no compensation for the harmonics is made.

Figure 8: Simulated output for three phase Uncompensated System, (a) Source Voltage (b) Source Current

The harmonic spectra of the system with presence of harmonic contents are shown in Fig.9. These distorted components have to be compensated rather than isolating by use of filters.

Figure 9: Harmonic Spectra of Uncompensated System (a) Source Voltage (b) Source Current

When the active filter is offline it does not inject the compensating voltage into the system instead it shows anticipated waveforms. The shunt passive filters reduces the harmonic level to certain extent further reduction in harmonics will introduce resonance problems with increase in component value. The system with the use of passive filter can mitigate the harmonic to the level which is shown in Fig.10 and their harmonic content is shown in Fig.11.

THD= 5.24%

THD = 35.78%

Figure 10: Harmonic Spectra of Compensated System (a) Source Voltage (b) Source Current
However smaller harmonic distortion still remains at source current due to presence of distorted components in the system voltage. The use of passive filters will eliminate harmonic content in the source voltage from 5.24% to 3.29% and source current from 35.78% to 9.31%. The passive filters used in the system are shown in Table 2. The voltage that the series active filter injects depends on the current of the load, and the current of the load depends on its voltage. The use of active filter will eliminate the oscillating component of the real power.

### Table 2: List of Passive Filters

<table>
<thead>
<tr>
<th>Frequency</th>
<th>C(µF)</th>
<th>L(mH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250Hz</td>
<td>32.88</td>
<td>12.32</td>
</tr>
<tr>
<td>350Hz</td>
<td>32.88</td>
<td>6.29</td>
</tr>
</tbody>
</table>

The voltage source injects the voltage into eliminate the harmonics. The compensated voltage is to be injected into the system through series transformer is shown in Fig.12. Considerable amount of fundamental voltage appears across the terminals of the active filter, which is due to resistive loss at AC side of the filter transformers. By introducing hybrid filter the line current becomes sinusoidal than the expected outcome compared to the use of LC filter alone.

### 5.1 Simplified Multilevel Inverter as active filter

The simplified five level inverter as active filter injects the required amount of injection voltage into the system for harmonic elimination and the source becomes purely sinusoidal as shown in Fig.13. The line current THD is drastically improved by use of hybrid filters from 9.31% to 0.53% which is shown in Fig.14 and also the source voltage is reduced from 3.29% to 0.13% where almost all the harmonics goes to zero level.

The level of harmonics further reduces the source voltage harmonics and hence all harmonics go to zero with less harmonic content. Table 3 shows performance of THD of source current and source voltage of the system before compensation and series hybrid filter connected to it.

### Table 3

<table>
<thead>
<tr>
<th>THD of Source Current</th>
<th>THD of Source Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD=3.29%</td>
<td>THD=9.31%</td>
</tr>
<tr>
<td>0.05%</td>
<td>0.13%</td>
</tr>
</tbody>
</table>

Improvement of voltage source harmonic depends upon utility stiffness if is the system is...
Figure 13: Simulated output for Three phase system with Hybrid filter (SFLI) (a) Source voltage (b) Source Current

Figure 14: Harmonic spectra of System with Hybrid Filter(SFLI) (a)Source Voltage (b) Source Current

strong voltage is not affected by harmonic currents flowing from loads and action of APF cannot be seen clearly. Alternatively if the system is weak, line currents affect the source voltage and performance of APF can be understood clearly. From the above discussions, the FFT analysis of the hybrid filter indicates that the THD of source current is brought less than 5% as compliance of standards such as IEEE 516, IEC 61000-3.

Table 3: Source Voltage and Source Current Harmonic Content

<table>
<thead>
<tr>
<th>SL.No</th>
<th>Description</th>
<th>Type of Compensator</th>
<th>%THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Source Voltage</td>
<td>Without Filter</td>
<td>5.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With Passive Filter</td>
<td>3.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With Hybrid Filter(SFLI)</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>Source Current</td>
<td>Without Filter</td>
<td>35.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With Passive Filter</td>
<td>9.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With Hybrid Filter(SFLI)</td>
<td>0.49</td>
</tr>
</tbody>
</table>

6 CONCLUSION

Thus series active filter not acts as harmonic compensator rather as harmonic isolator. A hybrid series active power filter based on five level inverter, acting as high impedance path for voltage producing harmonic loads. It was developed with no active power consumption as good power line conditioning. The control strategy is to obtain almost sinusoidal voltages and currents. The effect nonlinear loads on the power quality of power delivered is analyzed and rectified. The controller used in this paper for compensation of harmonics. The proposed filter compensates harmonic voltage source generated by contaminating loads. The performance of the system is studied by comparing the harmonic profile with and without filter.

REFERENCES:


