Neutral Point Potential Balancing Algorithm for Autonomous Three-Level Shunt Active Power Filter


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Abstract- This paper presents a control method of the input DC voltages of three-level Neutral Point Clamped (NPC) autonomous shunt Active Power Filter (APF), which is applied to eliminate line current harmonics and compensate reactive power. In the first part, the authors present a topology of three-level NPC Voltage Source Inverter (VSI), and its space vector diagram. In the second part, as solution for instability problem of the input DC voltages of the APF, the authors propose a simplified Space Vector Pulse Width Modulation (SVPWM) with neutral point potential control. After that, the sliding mode regulator used to control the APF is developed. A theoretical analysis with a complete simulation of the system is presented to prove the excellent performance of the proposed technique.

Keywords- Active Power Filter; NPC Multilevel Inverter; Space Vector Pulse Width Modulation (SVPWM); Neutral Point Potential Control; Nonlinear Load

I. INTRODUCTION

Active power filters have proved to be an interesting and effective solution to compensate current harmonics and reactive power in power distribution systems [1], [2], [3]. Although many technical papers related with active power filter have been presented during the last decade, most of them dealt with their principles of operation, design of the control schemes, and the presentation of different techniques to calculate the reference signals required by the control scheme [4], [5], and do not address the limitation in medium voltage application due to semiconductor constraint. In order to achieve higher power level, hybrid topologies that combine active and passive compensation techniques have been proposed [3].

The structures of the filters knew an evolution, from two-level converters to multilevel converters [6]. Various topologies are developed such as flying capacitor multilevel converters, diode clamped multilevel converters, NPC multilevel converters, and H bridge multilevel converters.

The unbalance of the different DC voltage sources of the three-level (NPC) active power filters constitutes the major limitation for the use of these power converters.

Several methods are proposed to suppress the unbalance of neutral point potential, generally using redundant vectors. Some of these methods are based on adding a zero sequence or a dc-offset to output voltage [7], [8]. In [9], [10], power electronics circuitry is added to redistribute charges between capacitors. A method based on minimizing a quadratic parameter that depends on capacitor voltages is presented in [11]. This quadratic parameter is positively defined and reach zero when the two capacitors have the same voltage. Some other works use a converter-inverter cascade [12], and apply automatic control methods, such as fuzzy logic control [13] or sliding mode control [14] to this cascade. The drawback of these methods is either high costs and system complexity, or the use of open loop scheme. In this work we use a simple and closed loop method which makes a continuous measurement of output current and difference between capacitors voltages, and choose the redundant vector on the basis of these measurements.

In this paper, first part is dedicated to the presentation of the model of the three phases three-level NPC VSI with its space vector diagram. In the second part, the simplified SVPWM algorithm with the proposed neutral point potential control algorithm are presented. This APF is applied for the enhancement of voltage network power quality by compensation of harmonic currents produced by a nonlinear load (Fig. 1). At the end the simulation results of sliding mode controlled APF are presented.

II. MODELLING OF THREE-LEVEL NPC VOLTAGE SOURCE INVERTER

The three phases three-level NPC VSI is constituted by three legs and two DC voltage sources. Each leg has four bi-directional switches in series, and two diodes to get the zero voltage for \( V_{KM} \) (Fig. 2). Each switch is composed by a transistor and a diode in anti-parallel [15].

The switch connection function \( F_{KS} \) indicates the opened or closed state of the switch \( T_{KS} \):

\[
F_{KS} = \begin{cases} 
1 & \text{if } T_{KS} \text{ close} \\
0 & \text{if } T_{KS} \text{ open}
\end{cases}
\]
Fig. 1 Synoptic diagram of application of shunt APF on power supply fed nonlinear load

For a leg K of the three phases three-level NPC VSI, several complementary control laws are possible. The optimal control law of this inverter is:

\[
\begin{align*}
F_{K4} &= 1 - F_{K1} \\
F_{K3} &= 1 - F_{K2}
\end{align*}
\]  

(2)

Half leg connection function \( F_{km}^h \) is defined as:

\[
\begin{align*}
F_{km}^h &= F_{km}F_{K2} \\
F_{km}^h &= F_{K3}F_{K4}
\end{align*}
\]  

(3)

\( m =1 \): for the lower half leg;

\( m =0 \): for the upper half leg.

As indicated in Table I, each leg of the inverter can have three possible switching states, P, O, or N. When the top two switches \( T_{i1} \) and \( T_{i2} \) are turned on, the switching state is P. When the medium switches \( T_{i2} \) and \( T_{i3} \) are turned on, the switching state is O. When the lower switches \( T_{i3} \) and \( T_{i4} \) are turned on, the switching state is N.

III. THREE-LEVEL INVERTER CONTROL

A. Space Vector Modulation for Two-Level Inverter

Fig. 4 shows structure of two-level inverter. Each one of the three phases of the inverter has two switches and two freewheeling diodes. Depending on the values of the switching signals, the two-level inverter has eight states, summarized in Table II, where it is also indicated the output voltage vector produced in each state. These output vectors are shown on the space vector diagram of Fig. 5. It also indicates an arbitrary reference vector \( V^* \), to be generated by the inverter.

\[
V^* = d_x v_x + d_y v_y + d_z v_z
\]  

(4)

Fig. 3 shows the space vector diagram for three-level inverter. Since three kinds of switching states exist in each leg, this converter has 27 switching states, as indicated in the diagram. The output voltage vector can take only 18 discrete positions in the diagram because some switches state are redundant and create the same space vector.

TABLE I STATES OF THREE-LEVEL INVERTER

<table>
<thead>
<tr>
<th>Switching Symbols</th>
<th>Switching States</th>
<th>Output Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>O</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>N</td>
<td>OFF</td>
<td>OFF</td>
</tr>
</tbody>
</table>

Fig. 3 Space vector diagram of a three-level inverter

The desired voltage vector, \( V^* \) (4), located in a given sector, can be generated by a linear combination of the two adjacent base vectors, \( v_x \) and \( v_y \), which are framing the sector, and one of the two zero vectors \( v_z \).

Fig. 4 Two-level inverter structure
TABLE II STATES OF TWO-LEVEL INVERTER

<table>
<thead>
<tr>
<th>State</th>
<th>( F_a )</th>
<th>( F_b )</th>
<th>( F_c )</th>
<th>Voltage vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( V_0 )</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>( V_1 )</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>( V_2 )</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>( V_3 )</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( V_4 )</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>( V_5 )</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>( V_6 )</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>( V_7 )</td>
</tr>
</tbody>
</table>

\( d_x, d_y \) and \( d_z \) denotes the so-called duty ratios of states X, Y and Z of the inverter within the switching interval, respectively.

The duty ratios \( d_x, d_y \) and \( d_z \) are calculated as \(^{[16],[17]}\):

\[
\begin{align*}
    d_x &= \frac{\sqrt{2} V_d}{V_d} \sin(60 - \theta) \\
    d_y &= \frac{\sqrt{2} V_d}{V_d} \sin(\theta) \\
    d_z &= 1 - d_x - d_y
\end{align*}
\]

\( d_x, d_y \) and \( d_z \) denote the so-called duty ratios of states X, Y and Z of the inverter within the switching interval, respectively.

\( s \) is calculated as

\[
\begin{align*}
    1 & \quad \text{if } -\pi/6 < \theta < \pi/6 \\
    2 & \quad \text{if } \pi/6 < \theta < \pi/2 \\
    3 & \quad \text{if } \pi/2 < \theta < 5\pi/6 \\
    4 & \quad \text{if } 5\pi/6 < \theta < 7\pi/6 \\
    5 & \quad \text{if } 7\pi/6 < \theta < 3\pi/2 \\
    6 & \quad \text{if } 3\pi/2 < \theta < 11\pi/6
\end{align*}
\]

**B. Simplified SVPWM For Three-Level Inverter**

In this work, we present a simple and fast method that divides the space vector diagram of three-level inverter into six small hexagons. Each hexagon is space vector diagram of two-level inverter, as shown in Fig. 6.

To reach this simplification, two steps have to be done. Firstly, from the location of the given reference voltage, one hexagon has to be selected among the six small hexagons of the three-level space vector diagram. There exist some regions that are overlapped by two adjacent small hexagons. These regions will be divided in equality between the two hexagons as shown in Fig. 7. Each hexagon is identified by a number \( s \) defined in Equation (6).

**C. Neutral Point Potential Control Method**

In the space vector diagram of three-level inverter (Fig. 3), we can distinguish four types of vectors: large vectors, medium vectors, small vectors and zero vectors. The large vectors are the vectors that all of three legs are connected to either point P or N, except in the case of all the three being connected at the same point. There are six large vectors in the space vector diagram: PNN, PPN, NPN, NPP, NNP and PNP. The medium vectors are the ones that only one phase is connected to point O and other two phases are connected to P and N each other. There are six medium vectors: PON, OPN, NPO, NOP, ONP and PNO. The small vectors are those vectors that have two phases connected at the same point. There are twelve of them: PPO, OON, OPO, NON, OPP, NOO, OOP, NNO, POP, ONO and ONN. The zero vectors are the vectors that have all three phases connected at the same point. There are three zero vectors: PPP, OOO and NNN.
To show the effect of each type of vectors on the neutral point potential, we present the load connections of one example of each type in Fig. 9. It may be easily deduced from Fig. 9.a and Fig. 9.d that neither zero vectors nor large vectors inject current in the neutral point O. So they do not change the voltage of neutral point.

Fig. 9.b shows that medium vectors can inject current in the neutral point. Fig. 9.c1 and Fig. 9.c2 show two small vectors with two different switching combinations: POO and ONN. These two vectors product the same output voltage, but when the vector POO is applied, the current flows into the neutral point \( I_{d0} = -I_{d1} \), while with the vector ONN, the current flows out \( I_{d0} = I_{d1} \) (Fig. 2).

Table IV shows the current injected by the six small vectors. By using this table, one proposes the neutral point potential control algorithm of this converter as indicated by (8) (9) and (10).

Medium vectors also affect neutral point potential. However, as they are not redundant vectors, this influence will not be controlled, being therefore considered as perturbation for the dc-voltage stabilization [9], [19].

The neutral point potential control is based on the use of both two redundant vectors in each sector, in order to inject positive or negative current in neutral point, depending on the value of the two capacitors voltages and the load current (7).

\[
c \frac{dU_c}{dt} = I_{d0} - I_{d1}
\]

\[
c \frac{dU_c}{dt} = I_{d0} + I_{d2}
\]

\[
I_{d0} = -(I_{d1} + I_{d2})
\]

\[
I_{d1} = F11\cdot F12\cdot i_1 + F21\cdot F22\cdot i_2 + F31\cdot F32\cdot i_3
\]

\[
I_{d2} = F13\cdot F14\cdot i_1 + F23\cdot F24\cdot i_2 + F33\cdot F34\cdot i_3
\]

<table>
<thead>
<tr>
<th>hexagon</th>
<th>( V_{q}^{2x} )</th>
<th>( V_{q}^{2x} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( v_{q}^{+} )</td>
<td>( v_{q}^{+} )</td>
</tr>
<tr>
<td>2</td>
<td>( v_{q}^{+} )</td>
<td>( -\sqrt{3}/4 v_{q}^{+} )</td>
</tr>
<tr>
<td>3</td>
<td>( v_{q}^{+} )</td>
<td>( -\sqrt{3}/4 v_{q}^{+} )</td>
</tr>
<tr>
<td>4</td>
<td>( v_{q}^{+} )</td>
<td>( v_{q}^{+} )</td>
</tr>
<tr>
<td>5</td>
<td>( v_{q}^{+} )</td>
<td>( v_{q}^{+} )</td>
</tr>
<tr>
<td>6</td>
<td>( v_{q}^{+} )</td>
<td>( v_{q}^{+} )</td>
</tr>
</tbody>
</table>

Table V shows the current injected by the six small vectors. By using this table, one proposes the neutral point potential control algorithm of this converter as indicated by (8) (9) and (10).

<table>
<thead>
<tr>
<th>Positive Small vectors</th>
<th>( I_{d0} )</th>
<th>Negative Small vectors</th>
<th>( I_{d0} )</th>
<th>Medium Vectors</th>
<th>( I_{d0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONN</td>
<td>( i_1 )</td>
<td>POO</td>
<td>-( i_1 )</td>
<td>PON</td>
<td>( i_2 )</td>
</tr>
<tr>
<td>PPO</td>
<td>( i_3 )</td>
<td>OON</td>
<td>-( i_3 )</td>
<td>OPN</td>
<td>( i_4 )</td>
</tr>
<tr>
<td>NON</td>
<td>( i_2 )</td>
<td>OPO</td>
<td>-( i_2 )</td>
<td>NPO</td>
<td>( i_3 )</td>
</tr>
<tr>
<td>OPP</td>
<td>( i_1 )</td>
<td>NOO</td>
<td>-( i_1 )</td>
<td>NOP</td>
<td>( i_2 )</td>
</tr>
<tr>
<td>NNO</td>
<td>( i_3 )</td>
<td>OOP</td>
<td>-( i_3 )</td>
<td>ONP</td>
<td>( i_4 )</td>
</tr>
<tr>
<td>POP</td>
<td>( i_2 )</td>
<td>ONO</td>
<td>-( i_2 )</td>
<td>PON</td>
<td>( i_3 )</td>
</tr>
</tbody>
</table>

Table VI shows the current injected by all small and medium vectors. As we see, each small redundant vector can inject either positive or negative current. Those small vectors injecting positive phase currents into the neutral point will be called positive vectors (ONN, PPO, NON, OPP, NNO, POP), while those injecting opposite phase currents will be called negatives vectors (POO, OON, OPO, NOO, OOP, ONO).

Medium vectors also affect neutral point potential. However, as they are not redundant vectors, this influence will not be controlled, being therefore considered as perturbation for the dc-voltage stabilization [9],[19].

The neutral point potential control is based on the use of both two redundant vectors in each sector, in order to inject positive or negative current in neutral point, depending on the value of the two capacitors voltages and the load current (7).
IV. ACTIVE POWER FILTER CONTROL

A voltage source of 220V, 50Hz feeds a three phases nonlinear load illustrated in Fig. 1. This load produces distorted phases currents with THD of respectively 120%, 104 % and 76% which is above the tolerated THD limit standard. These currents with their spectral analysis are presented in Fig. 10.

For vector 1 and vector 4
\[
\begin{align*}
& \text{if } U_{i1} \geq U_{i2} \text{ and } i_{f} \geq 0 \Rightarrow \text{redundancy (b)} \\
& \text{if } U_{i1} \geq U_{i2} \text{ and } i_{f} \leq 0 \Rightarrow \text{redundancy (a)} \\
& \text{if } U_{i1} \leq U_{i2} \text{ and } i_{f} \geq 0 \Rightarrow \text{redundancy (a)} \\
& \text{if } U_{i1} \leq U_{i2} \text{ and } i_{f} \leq 0 \Rightarrow \text{redundancy (b)}
\end{align*}
\]

For vector 2 and vector 5
\[
\begin{align*}
& \text{if } U_{i1} \geq U_{i2} \text{ and } i_{f} \geq 0 \Rightarrow \text{redundancy (b)} \\
& \text{if } U_{i1} \geq U_{i2} \text{ and } i_{f} \leq 0 \Rightarrow \text{redundancy (a)} \\
& \text{if } U_{i1} \leq U_{i2} \text{ and } i_{f} \geq 0 \Rightarrow \text{redundancy (a)} \\
& \text{if } U_{i1} \leq U_{i2} \text{ and } i_{f} \leq 0 \Rightarrow \text{redundancy (b)}
\end{align*}
\]

For vector 3 and vector 6
\[
\begin{align*}
& \text{if } U_{i1} \geq U_{i2} \text{ and } i_{f} \geq 0 \Rightarrow \text{redundancy (b)} \\
& \text{if } U_{i1} \geq U_{i2} \text{ and } i_{f} \leq 0 \Rightarrow \text{redundancy (a)} \\
& \text{if } U_{i1} \leq U_{i2} \text{ and } i_{f} \geq 0 \Rightarrow \text{redundancy (a)} \\
& \text{if } U_{i1} \leq U_{i2} \text{ and } i_{f} \leq 0 \Rightarrow \text{redundancy (b)}
\end{align*}
\]

Active power filter is controlled using sliding mode regulator [20][21]. From the model of active filter associated to supply network (11) and by considering the error between harmonic current reference and the active filter current as sliding surface (12), and the smooth continuous function as attractive control function (13), one gets the control law (14).

\[
V_{\text{ref}K} - V_{K} = R_{f}i_{fK} + L_{f}\frac{di_{fK}}{dt}
\]

with : \( V_{K} = V_{SK} - R_{i}i_{SK} - L_{i}\frac{di_{SK}}{dt} \)

\[ K = 1,2 \text{ and } 3 \]

\[ S_{f} = i_{\text{ref}K} - i_{fK} \]

\[ U_{s} = k_{r}\frac{S_{f}}{S_{f} + \lambda} \]

\[ V_{\text{ref}K} = R_{f}i_{fK} + L_{f}\frac{di_{fK}}{dt} + V_{K} + k_{r}\frac{S_{f}}{S_{f} + \lambda} \]

The APF control strategy involves not only the production of currents whether to eliminate the undesired harmonics or to compensate reactive power, but also to recharge the capacitor values requested by \( (U_{c1}+U_{c2}) \) voltages in order to ensure suitable transit of powers to supply the three-level inverter.

The storage capacities absorb the power fluctuations caused by the compensation of the reactive power, the presence of harmonics, and the active power control. The average voltage \( U_{cm} \) across capacitor (15) through which the \( i_{cm} \) current (16) must be kept at a constant value. The regulation of this voltage is made by absorbing the fundamental active current in the reference current of APF [22]. To realize these objectives, a controller PI is added to regulate \( U_{cm} \). Voltage in this circuit; the voltage \( U_{cm} \) is calculated and compared with the reference value \( U_{\text{ref}}=400V \) (Fig.11). The output of PI controller is amplified and added to the \( p \), the output of high-pass filter. Therefore, active power allowed into the capacitor is been changed and the DC voltage is controlled.

\[ U_{cm} = (U_{i1}+U_{i2})/2 \]

\[ I_{cm} = (I_{d1} - I_{d2})/2 \]

Fig. 12 shows DC bus capacitor voltages before and after application of redundant vectors control. Before \( t = 4s \), these voltages diverge, but the average voltages \( U_{cm} \) remains constant. The application of SVPWM with neutral point potential control at \( t = 4s \) pushes these voltages toward the reference of 400V keeping them equal.

Fig. 13 a, b, c presents main source voltages and currents after harmonic currents compensation. Spectral analysis of each current is illustrated in Fig. 14 a, d, e, f. It is shown that source currents are almost sinusoidal with THD of respectively 2%, 1.9% and 2.3% and unity power factor.
Main source:
\[ V_{ph-ph} = 380V, f = 50Hz, R_s = 0.0001\Omega, L_s = 0.0001H. \]

Active power filter:
\[ U_{ref} = 400V, R_l = 0.001\Omega, L_l = 0.0005H, C = 0.08F, f_c = 5kHz. \]

Nonlinear load
\[ R_1 = 20\Omega, R_2 = 10\Omega, C_1 = 0.05F, C_2 = 0.05F. \]

REFERENCES


