Balancing Capacitors Voltages and Currents Control of a Hybrid Active Power Filter Comprising 3-Level NPC Inverter Based on PI-Predictive Control System

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Abstract— A model based predictive control system of a three-level four-wire NPC inverter operated in a hybrid active power filter (HAPF) is proposed in this paper. The inverter and two parallel passive filters (PPFs) tuned in 5th and 7th orders of harmonic currents form the HAPF. The PPFs are designed to compensate the source reactive currents, and to filter fifth and seventh orders of the source currents harmonic components for decreasing of the NPC inverter rated power. Also, this paper presents a regulation and balancing control system of the capacitors voltages of the three-level NPC inverter. The proposed control system is simulated by Matlab/Simulink software. The presented control system is assessed under balanced and imbalanced loads. In order to validate effectiveness of the proposed control system the simulation results are prepared.

Keywords— Hybrid active power system, NPC-inverter, predictive control, capacitor voltage balancing

I. INTRODUCTION

Nonlinear electrical loads, such as diode rectifiers, UPS, and adjustable speed drives inject harmonic currents into the electrical grids, and degrade the power quality. Low power quality may cause problems, such as additional losses in the transmission lines, equipment overheating and some undesirable effects. The permissible values of the harmonic currents and voltages are specified by the international standards (such as IEEE519, IEC61000-3-2, and EN50160). There are several solutions to improve the power quality. One of the simple methods is parallel passive filter (PPF). The PPFs are widely used for decreasing of the harmonic components because of their low cost and high efficiency, but they have some drawbacks, such as the effects of the source impedances on their characteristics, series and parallel resonance with the source and the loads, and over-voltage under no-load or light load conditions. [1, 2, 3]

Shunt active power filter (SAPF) is another solution method. Because the SAPFs output currents are adapted to the load currents, no over or under voltages, and no resonance are occurred. However, SAPF construction in high rated power with rapid response and low switching losses is so difficult [3].

Hybrid active power filter (HAPF) is an appropriate solution for harmonic currents compensation. The HAPF is formed by combination of the SAPF and the PPF. They have all of the advantages of PPF and SAPF. Not only they are cost effective and small size, but also their topologies are various. Due to low rated power of the HAPFs active parts, they can compensate high harmonic orders of the source currents, where the SAPFs cannot do it [3, 7].

In the recent years, multi-level inverters are widely used in HAPF. Not only multi-level inverters are applicable in high voltage, but also they are suitable for decrease of output current ripples, and reduce of electrical strain dv/dt on IGBTs [8-11]. Size of output passive filter of multi-level inverter is small in comparison with 2-level inverters. In [7-11], multi-level H-bridge inverter modules are used in a HAPF, but size of the proposed topology is large. Multi-Level H-bridge topology is widely used in power quality conditioners such as STATCOM because of low harmonic voltage [12-14]. [15] presents a topology of hybrid multi-level inverter that can be used in HAPF, but their control is more complex than conventional multi-level inverters such as neutral point clamped (NPC), flying capacitor (FC) and H-bridge inverters. NPC 3-level and five-level inverters are employed by [16] and [17] in HAPF, but they are based on space vector modulation, and switching functions are not used by them.

Many papers such as [18] and [19] use conventional PI controllers in their control systems. Some papers employ resonance and recursive PI controllers to selective harmonic compensation [20-24]. To improve controller systems, some papers use new controllers such as adaptive PI [25], predictive PI [26], Fuzzy logic, and neural controllers. Also the hysteresis controller is a simple method that can be combined with modern method such as Fuzzy logic [27-32].

In this paper, the inverter current control system is model based predictive method. DC-link voltages are controlled by a new proposed control system too. In order to reduce the inverter rated power, 5th and 7th parallel passive filters are employed. Not only the parallel passive filters (PPFs) absorb 5th and 7th orders of harmonic currents, but also they can
compensate the reactive power. Finally, this paper shows the simulation results of the proposed control system for balanced and imbalanced loads.

II. HAPF CONFIGURATION

Figure (1) shows a HAPF comprising a NPC three-level inverter (active part), and two parallel passive filters tuned in 5th and 7th orders of harmonic currents. The inverter is connected in parallel with the source and the loads through three inductors at the points of common coupling (PCC). The PCC voltages are shown by $V_{AFa,b,c}$ in figure (1). Some parameters of the circuit are listed in table 1.

Mathematical relations of the parallel passive filters can be written as equation (1), where $Q_{ave}$, $Q_3$, $Q_5$ and $R_e$ are the fundamental angular frequency, the average load reactive power, the reactive power of the 5th passive filter, the reactive power of the 7th passive filter, and the ratio of the reactive powers of the passive filters respectively. In this paper, the parameter $R_e$ is selected as 1.

$$Q_3 + Q_5 = Q_{ave}$$
$$Q_3 = \frac{3\omega_3^2}{L_{AF} \omega_3} - \frac{1}{(C_f \omega_3 - L_f \omega_3)}$$
$$Q_5 = \frac{3\omega_5^2}{L_{AF} \omega_3} - \frac{1}{(C_f \omega_3 - L_f \omega_3)}$$
$$R_e = \frac{Q_3}{Q_5}$$

Figure (3) shows the HAPF equivalent circuit in the harmonic domains. There are two parallel passive filters between the loads and the inverter, as shown in the figure:

$$i_{L(h)} = i_{S(h)} - i_{AF(h)}$$

If the inverter is controlled as a current source $i_{AF(h)} = K_i s_{(h)}$, the source harmonic currents can be obtained as:

$$\begin{align*}
  i_{AF(h)} + i_{AF(\bar{h})} = i_{S(h)} & \Rightarrow i_{S(h)} = i_{L(h)} - \frac{i_{AF(h)}}{1 + K_h} \\
  i_{AF(h)} = K_h s_{(h)} & \Rightarrow i_{S(h)} = i_{AF(h)} \frac{1}{1 + K_h}
\end{align*}$$

From equation (3), if parameter $K_h$ is sufficiently selected large value, the source harmonic components are decreased effectively.
Modulation

1. The PI controller for harmonic currents

The source currents harmonic components are obtained by subtracting of \( i_{sc(1)} \) from \( i_s \). By multiplying of the harmonic components with \( K_i \), the equation (3) is satisfied.

IV. CONTROL SYSTEM

The control system of the HAPF consists of three parts:
- PI controller for capacitors Voltages Regulation
- Predictive control system of inverter output currents
- PI controller for capacitors Voltages Balancing
- Modulation unit

A. PI controller for capacitors Voltages Regulation

The reference currents of the inverter are generated in this part. As shown in figure (5), summation of the signals \( V_{C1} \) and \( V_{C2} \) are prepared to subtract from \( V_{DC}^{ref} \). Then produced signal is entered into controller PI. The PI output is multiplied with PCC voltages to generate signals \( i_{Ca} \), \( i_{Cb} \), and \( i_{Cc} \). As seen in equation (6), these signals are used for generating reference currents as follows:

\[
\begin{align*}
\hat{i}_{A_{ref}} &= k_i (i_{w(a)} - R_{AF} V_{AF_a}) = k_i (i_{w(a)} - i_{Ca}) \\
\hat{i}_{B_{ref}} &= k_i (i_{w(b)} - R_{AF} V_{AF_b}) = k_i (i_{w(b)} - i_{Cb}) \\
\hat{i}_{C_{ref}} &= k_i (i_{w(c)} - R_{AF} V_{AF_c}) = k_i (i_{w(c)} - i_{Cc})
\end{align*}
\]

\[ (6) \]

After reference signals production, these signals are prepared for controller.

B. Predictive Control System of Inverter Output Currents

As seen in figure (1) in AC side of the inverter can be written as:

\[
\begin{bmatrix}
V_{AF_a}(t) \\
V_{AF_b}(t) \\
V_{AF_c}(t)
\end{bmatrix} =
\begin{bmatrix}
R_{AF} + L_{AF} \frac{d}{dt} & i_{AF_a}(t) & V_{PCC_a}(t) \\
& i_{AF_b}(t) & V_{PCC_b}(t) \\
& i_{AF_c}(t) & V_{PCC_c}(t)
\end{bmatrix}\]

\[ (7) \]

The equation (7) can be described a space vector as follows:
\[ \bar{V}_F = R_{AF} \bar{i}_{AF} + L_{AF} \frac{d \bar{i}_{AF}}{dt} \bar{V}_{PCC} \]  

(8)

where

\[ \bar{V}_F = \frac{\sqrt{3}}{2}(V_{F_a} + aV_{F_b} + a^2 V_{F_c}) \]  

(9)

\[ \bar{i}_{AF} = \frac{\sqrt{3}}{2}(i_{AF_a} + ai_{AF_b} + a^2 i_{AF_c}) \]  

(10)

\[ \bar{V}_{PCC} = \frac{\sqrt{3}}{2}(V_{PCC_a} + aV_{PCC_b} + a^2 V_{PCC_c}) \]  

(11)

\[ a = e^{\frac{2\pi}{3}} \]  

(12)

For very small time interval, the equation (8) can be derived as:

\[ \bar{V}_F(t) = R_{AF} \bar{i}_{AF}(t) + L_{AF} \frac{\bar{i}_{AF}(t) - \bar{i}_{AF}(t-\Delta t)}{\Delta t} + \bar{V}_{PCC}(t) \]  

(13)

In experimental works, \( \Delta t \) is sampling time \( T_S \). Supposing that \( \bar{V}_F \), and \( \bar{V}_{PCC} \) are constant between sampling instants \( nT_S \), and \( (n-1)T_S \) - for \( n^{th} \) sample - the equation (13) can be expressed as:

\[ \bar{V}_F(nT_S) = R_{AF} \bar{i}_{AF}(nT_S) + L_{AF} \frac{\bar{i}_{AF}(nT_S) - \bar{i}_{AF}((n-1)T_S)}{T_S} + \bar{V}_{PCC}(nT_S) \]  

(14)

As seen in equation (15), the \( n^{th} \) samples of the inverter output voltages can be predicted by the \( n^{th} \) samples of the extracted reference currents, the \( (n-1)^{th} \) samples of the measured source currents and the \( n^{th} \) samples of the measured PCC voltages. Figure (6) shows implementation of the predictive controller based on equation (15). Papers [20-24] and [26] prepare the generated signals of the inverter output voltages for modulation part to control the inverter. But in this paper, these signals are sent to PI controller for capacitor voltage balancing, as seen in figure (7).

C. PI controller for capacitors Voltages Balancing

In order to good performance of NPC three-level inverter, the capacitors voltages must be effectively regulated. Not only the voltages regulation of DC link is necessary, but also balancing of them is important.

\[ \begin{bmatrix} V_{F_a}^* \\ V_{F_b}^* \\ V_{F_c}^* \end{bmatrix} = \begin{bmatrix} 1 & \kappa & 0 \\ 0 & 1 & \kappa \end{bmatrix} \begin{bmatrix} V_{F_a} \\ V_{F_b} \\ V_{F_c} \end{bmatrix} + \begin{bmatrix} 0 & 1 & \kappa \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_{F_a}^* \\ V_{F_b}^* \\ V_{F_c}^* \end{bmatrix} \]  

(16)

During harmonic compensation and source currents balancing, the capacitors voltages of C1 and C2 will be unequaled. In order to acceptable performance of the HAPF, the capacitor voltage should be equal. This paper employs PI2 controller for balancing capacitors voltages. Therefore, the signals produced by predictive control system are used as following equation for balancing of capacitors voltages:

Fig. 6. Predictive control system of the HAPF output currents

Fig. 7. Capacitors Voltages Balancing Method and Modulation Part
D. Modulation unit

The signals generated by capacitors voltages balancing unit are sent to modulation unit for producing of IGBTs gate signals. In modulation unit, the signals $V_{f_a}^*$, $V_{f_b}^*$ and $V_{f_c}^*$ are compared with two triangle waveforms to prepare PWM signals for IGBTs Drivers of the three-level NPC inverter. In this paper, the PWM signals are generated based on phase-shifted PWM method.

V. SIMULATION RESULTS

The HAPF shown in figure (1) has been simulated in Matlab/Simulink to verify good performance of the proposed control system. The three-phase source is modeled by balanced sinusoidal three-phase 400V with source inductance 0.1mH and source resistance 0.1Ω. Other assumptions are as:
- A 10kVA 3-phase R-L load with power factor 0.5-lag is considered as linear load, and a 10kVA 3-phase uncontrolled rectifier is considered as non-linear load.
- Reference of DC-link capacitors voltages is selected as 500V.

A. Case 1: Non-linear balanced loads

Figure (8) shows the load currents, where the load impedances are balance. Under balancing condition, total harmonic distortions (THDs) of the load are equal to 17%. In addition to, the load power factor is around 86% lag.

The source currents are shown in figure (9), when the HAPF is connected with the proposed control system. As seen, the source currents waveforms are sinusoidal form, because of compensation. The source currents THDs are decreased from 17% to 4.1%. Also the power factor of the source is improved to 98.6% lag. Therefore the predictive control system can effectively improve the power factor and THDs of the source.

DC link voltage regulation and balancing of the capacitors voltages are shown in figure (10). As seen in the figure, the capacitors voltages are around 500V. The regulation system that is shown in figure (5) can fix the capacitors voltages around 500V. The capacitors voltages change among 497V to 503V. The capacitors voltages balancing unit can balance and
equal capacitors voltages rather together, under balanced load condition.

B. Case 2: Non-linear unbalanced loads

For building of unbalanced load, the inductor of phase "c" is shorted to the ground. Figure (11) shows the load currents under unbalanced condition. As shown in the figure, the current peak values of "a", "b", and "c" phases are 34.98A, 35A, and 44A respectively. Also, the load currents THDs of "a", "b", and "c" phases are 16.7%, 16.7%, and 13.3% respectively. Under this condition, the load power factor are 0.86 lag, 0.86 lag and 0.78 lead for "a", "b", and "c" respectively.

According to standard of IEC-61800-3 (published in 1996), the current unbalance percent is defined as current negative component of the 3-phase currents divided by the positive component of the 3-phase currents [28].

\[
CUP = \frac{I_1 - I_+}{I_+} \times 100\tag{17}
\]

where, CUP, I_1, and I_+ are current unbalance percent, negative component, and positive component of the 3-phase currents respectively. Permissible value of the current unbalance percent is less than 2%, as specified by the standard.

Under unbalanced load, the load CUP is 9%. This value is very larger than value specified by the IEC standard.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig11.png}
\caption{The unbalanced load current waveforms}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig12.png}
\caption{The unbalanced load current waveforms}
\end{figure}

Under unbalanced load, the source currents are shown in figure (12), when the HAPF works with the proposed control system. As seen, not only the proposed control can change the source currents waveforms to sinusoidal form, but also it can decrease the CUP of the source currents from 9% to 1%. Also the source currents THDs are decreased from 16.7%, 16.7%, and 13.3% to 4.3%, 4.5% and 4.85% for phases of "a", "b" and "c" respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig13.png}
\caption{The DC-link voltages with unbalanced loads during compensation}
\end{figure}

The power factor of the source is improved up to 96% under unbalanced condition. DC link voltages are shown in figure (10). As seen in the figure, the capacitors voltages are around 500V. Under unbalanced condition, the control system can regulate the capacitors voltages $V_{C1}$ and $V_{C2}$ among 500V
to 515V and 487V to 503V respectively. The capacitors voltages balancing unit can balance the voltages with relation deference around 2.5%, under balanced load condition as following equation:

\[ RD \% = \frac{V_{\text{C ave}}}{} - V_{\text{C ave}} \times 100 \]  (18)

VI. CONCLUSION

In this paper, a control system of a three-level NPC inverter employed in hybrid active power filter based on predictive control method is presented. The control system is designed to compensate harmonic currents and to regulate and balance DC link capacitors voltages. The proposed control system of the HAPF is simulated by Matlab/simulink under two conditions: balanced and unbalanced loads. The simulation results show, that presented control system can compensate harmonic components of the source currents and can reduce THD less than values specified by international standards. Also the source currents are balanced, when the HAPF works, under unbalanced condition. In addition to, the simulation results show, that the control system can effectively regulate and balance DC link capacitors voltages under balanced and unbalanced loads conditions with small relation deference.

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