POWER QUALITY IMPROVEMENT USING THREE-LEVEL NEURAL POINT CLAMPED UNIVERSAL CONDITIONER FOR ALL VOLTAGE DISTURBANCES COMPENSATION

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Key words: Unified power quality conditioner (UPQC), Three-level inverter, Voltage disturbance compensation, Synchronous reference frame strategies, Instantaneous reactive power strategies.

This paper proposes an efficient control scheme for unified power quality conditioner (UPQC) system based on three-level neutral point clamped (NPC) inverter capable to compensate all voltage disturbances. The proposed UPQC is designed by the integration of series and shunt active power filters (APFs) sharing a common dc bus capacitor. The dc voltage is maintained constant using proportional integral (PI) voltage controller. To get the reference signals for shunt and series APFs, synchronous reference frame (SRF) and instantaneous reactive power (PQ) strategies are adopted. These reference signals are derived from the control algorithm and injected in PWM controllers to generate the switching signals. The performance of proposed UPQC system is evaluated using MATLAB-Simulink software and SimPowerSystem Toolbox for all voltage disturbances compensation. The simulation results demonstrate that the proposed UPQC system can improve the power quality at the common connection point of the non-linear load.

1. INTRODUCTION

There has been a continuous rise of nonlinear loads over the years due to intensive use of power electronic control in industry. The utility supplying these nonlinear loads has to supply large vars. Moreover, the harmonics generated by the nonlinear loads pollute the utility. The basic requirements for compensation process involve precise control with fast dynamic response and on-line elimination of load harmonics. The traditional compensation methods using switched capacitor and thyristor controlled inductor [1] coupled with passive filters are increasingly replaced by active power filters (APFs) [2]. The two types of APFs are shunt and series. The shunt active power filter (APF) is usually connected across the loads to compensate all current-related problems such as the reactive power compensation, power factor improvement, current harmonic compensation, and load unbalance compensation, whereas the series APF is connected in a series with a line through series transformer [3]. It acts as controlled voltage source and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc. One of the best solutions to compensate both current and voltage related problems, simultaneously, is the use of unified power quality conditioner (UPQC) [4]. A UPQC can be installed to protect the sensitive load inside the plant as well as to restrict entry of any distortion from load side. This dual functionality makes the UPQC as one of the most suitable devices that could solve the problems of both consumers as well as of utility. UPQC thus can help to improve voltage profile and hence the overall health of power distribution system. The application of UPQC to compensate reactive power, current harmonics and voltage harmonics are some of the functions suggested [5, 6]. Recently more attention is being paid on mitigation of voltage sags, voltage swells and unbalance compensation by using UPQC.

This paper presents UPQC configuration based on three-level neutral point clamped (NPC) inverter using simple and efficient control scheme. The series AF is controlled to maintain voltage load to the reference level and to eliminate supply voltage sag/swell, harmonics and unbalance from the load terminal voltage. The shunt AF is controlled to mitigate the supply current harmonics. The dc bus voltage is maintained constant by the shunt active filter. The performances of the proposed UPQC system are verified through simulation for transient and steady-state conditions using Matlab-Simulink software and SimPowerSystem Toolbox.

2. UNIFIED POWER QUALITY CONDITIONER

Figure 1 shows the proposed UPQC connected to a power system feeding a nonlinear load. It consists of two three-level NPC inverters one for the shunt APF and the second for a series APF. The dc link of both active filters is connected to a common dc capacitor of 3000 μF. The series filter is connected between the supply and load terminals using three single phase transformers with turn’s ratios of 1:1. In addition to injecting the voltage, these transformers are used to filter the switching ripple of the series active filter. A small capacity rated C_s filter [7] is used with inductance L_s to eliminate the high switching ripple content in the series active filter injected voltage. The three-level inverters for both the active filters are designed with insulated gate bipolar transistors (IGBTs). The three leg shunt active filter is connected ahead of a series filter through a small capacity rated inductive filter. The control algorithm of UPQC is based on synchronous reference frame detection method for the shunt [8] and instantaneous reactive power theory for the series APFs [9].

Since the introduction in 1981 [10], the three-level NPC voltage source inverter has attracted popular attentions. Apart from its application in high-capacity ac motor drive, other interesting applications of this topology include HVDC transmission, STATCOM, active power filters, PWM rectifier, as well as renewable energy interfacing applications. Although the three-level NPC topology provides significant advantages over the conventional two-level’s in high-power applications. In power quality applications, the three-level topology has been used in static var compensators (SVC’s), unified power flow controller (UPFC) [11] etc., due to its high speed and wide range of application.
reactive power. On the other hand, the application of NPC voltage source converters to UPQCs is being limited by the unbalance dc link voltages due to the inherent transient operating condition [6–12]. These structures are lot of advantages such as near sinusoidal current waveforms due to reduced unwanted harmonics in the voltage PWM waveforms, each power valve takes half the dc link voltage, thus the topology can handle twice the voltage respect to the two level topology for a given semiconductor and the first set of unwanted harmonics is at twice the switching frequency.

The expression of the reference current \( i_{a,\text{ref}} \) and \( i_{b,\text{ref}} \) are given by:

\[
\begin{align*}
i_{a,\text{ref}} &= \begin{bmatrix} \sin(\theta_{\text{ext}}) & -\cos(\theta_{\text{ext}}) \end{bmatrix}^{\top} i_{d} \frac{1}{i_q} \\
i_{b,\text{ref}} &= \begin{bmatrix} \cos(\theta_{\text{ext}}) & \sin(\theta_{\text{ext}}) \end{bmatrix}^{\top} i_{d} \frac{1}{i_q}
\end{align*}
\]  

(4)

\[
\begin{align*}
i_{a,\text{ref}} &= \frac{\sin(\theta_{\text{ext}})}{i_q} - \frac{\cos(\theta_{\text{ext}})}{i_q} i_{d} \\
i_{b,\text{ref}} &= \frac{\cos(\theta_{\text{ext}})}{i_q} + \frac{\sin(\theta_{\text{ext}})}{i_q} i_{d}
\end{align*}
\]  

(5)

The reference currents \( i_{\text{sc,ref}} \) in the (abc) frame are given by:

\[
\begin{align*}
i_{a,\text{ref}} &= \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \end{bmatrix} i_{\text{sc,ref}} \\
i_{b,\text{ref}} &= \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & 1 & -1 \end{bmatrix} i_{\text{sc,ref}}
\end{align*}
\]  

(6)

Finally, the compensation currents \( i_{\text{comp-a}}, i_{\text{comp-b}} \) and \( i_{\text{comp-c}} \) are given by:

\[
\begin{align*}
i_{\text{comp-a}} &= i_{a,\text{ref}} - i_{La} \\
i_{\text{comp-b}} &= i_{b,\text{ref}} - i_{Lb} \\
i_{\text{comp-c}} &= i_{c,\text{ref}} - i_{Lc}
\end{align*}
\]  

(7)

3.2. SERIES APFS

The control strategy used for extracting the series APF reference voltages is based on the PQ theory described in [9]. We assume that the three-phase voltage source in the grid is symmetric and distorted:

\[
\begin{align*}
V_{sa} &= \sum_{n=1}^{\infty} \sqrt{2} U_a \sin(n \omega t + \theta_1) \\
V_{sb} &= \sum_{n=1}^{\infty} \sqrt{2} U_b \sin(n \omega t + \frac{2\pi}{3} + \theta_2) \\
V_{sc} &= \sum_{n=1}^{\infty} \sqrt{2} U_c \sin(n \omega t + \frac{4\pi}{3} + \theta_3)
\end{align*}
\]  

(8)

When \( n = 1 \), it means three-phase fundamental voltage source:

\[
\begin{align*}
V_{sa} &= \sum_{n=1}^{\infty} \sqrt{2} U_1 \sin(n \omega t + \theta_1) \\
V_{sb} &= \sum_{n=1}^{\infty} \sqrt{2} U_1 \sin((n-2) \omega t + \frac{2\pi}{3} + \theta_1) \\
V_{sc} &= \sum_{n=1}^{\infty} \sqrt{2} U_1 \sin((n-4) \omega t + \frac{4\pi}{3} + \theta_1)
\end{align*}
\]  

(9)

Equation (8) is transformed into (\( \alpha-\beta \)) reference frame:

\[
\begin{align*}
V_{sa} &= C_{32} V_{sa} \\
V_{sb} &= C_{31} V_{sb} \\
V_{sc} &= C_{33} V_{sc}
\end{align*}
\]  

C32

(10)

Three-phase positive fundamental current template is constructed:

\[
\begin{align*}
i_{a} &= \frac{\sin(\omega t)}{\sqrt{3}} \\
i_{b} &= \frac{\sin(\omega t - \frac{2\pi}{3})}{\sqrt{3}} \\
i_{c} &= \frac{\sin(\omega t + \frac{2\pi}{3})}{\sqrt{3}}
\end{align*}
\]  

(11)
Equation (11) is transformed to (α–β) reference frame:

\[
\begin{bmatrix}
    i_{sa} \\
    i_{qb}
\end{bmatrix} = C_{32} \begin{bmatrix}
    i_{sb} \\
    i_{qc}
\end{bmatrix} = \begin{bmatrix}
    \sin(\omega t) \\
    -\cos(\omega t)
\end{bmatrix}.
\] (12)

According to the instantaneous reactive power theory, then:

\[
\begin{bmatrix}
    p \\
    q
\end{bmatrix} = \begin{bmatrix}
    u_{sa} \\
    u_{qb}
\end{bmatrix} \begin{bmatrix}
    i_{sb} \\
    i_{qc}
\end{bmatrix},
\] (13)

where dc and ac components are included:

\[
\begin{bmatrix}
    p \\
    q
\end{bmatrix} = \begin{bmatrix}
    p + p \\
    q + q
\end{bmatrix},
\] (14)

\(p\) and \(q\) are passed through low pass filter and dc component \(p\) and \(q\) are got:

\[
\begin{bmatrix}
    p \\
    q
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
    U_1 \cos(\theta_1) \\
    U_1 \sin(\theta_1)
\end{bmatrix}.
\] (15)

According to (13), transformation is made:

\[
\begin{bmatrix}
    p \\
    q
\end{bmatrix} = \begin{bmatrix}
    v_{sa} \\
    v_{qb}
\end{bmatrix} \begin{bmatrix}
    i_{sb} \\
    i_{qc}
\end{bmatrix} = \begin{bmatrix}
    v_{sa} - i_{sb} \\
    v_{qb} - i_{qc}
\end{bmatrix},
\] (16)

As for dc components of \(p\) and \(q\):

\[
\begin{bmatrix}
    p \\
    q
\end{bmatrix} = \begin{bmatrix}
    v_{sa}^{f} \\
    v_{qb}^{f}
\end{bmatrix} \begin{bmatrix}
    i_{sb} \\
    i_{qc}
\end{bmatrix} = \begin{bmatrix}
    i_{sa} \\
    i_{qb}
\end{bmatrix},
\] (17)

The fundamental voltages \(v_{sa}^{f}\) and \(v_{qb}^{f}\) in (α–β) reference frame are:

\[
\begin{bmatrix}
    v_{sa}^{f} \\
    v_{qb}^{f}
\end{bmatrix} = \begin{bmatrix}
    i_{sa} \\
    i_{qb}
\end{bmatrix} = \begin{bmatrix}
    p \\
    q
\end{bmatrix},
\] (18)

The three-phase fundamental voltages in (abc) reference frame are given by:

\[
\begin{bmatrix}
    V_{sa}^{f} \\
    V_{sb}^{f} \\
    V_{sc}^{f}
\end{bmatrix} = C_{32} \begin{bmatrix}
    V_{sa}^{f} \\
    V_{sb}^{f} \\
    V_{sc}^{f}
\end{bmatrix} = \sqrt{2}U_1 \begin{bmatrix}
    \sin(\omega t + \theta_1) \\
    \sin(\omega t + \theta_1 + \pi/3) \\
    \sin(\omega t + \theta_1 - \pi/3)
\end{bmatrix},
\] (19)

\[
C_{32} = \sqrt{3/2} \begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix},
\] (20)

\[
C_{33} = \sqrt{3/2} \begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & \sqrt{3}/2
\end{bmatrix}^T,
\] (21)

where \(C_{32}\) is the coordinate’s transformation matrix from three-phase system to two-phase system and \(C_{33}\) is the inverse coordinate’s transformation matrix from two-phase system to three-phase system.

The difference between the injected current (voltage) and the reference current (voltage) determine the modulation wave of the reference current (voltage). These signals are compared with two carrying triangular identical waves shifted one from other by a half period of chopping and generate switching pulses [13, 14].

The control of inverter is summarized in the two following stages:

- Determination of the intermediate signals \(V_{i1}\) and \(V_{i2}\):
  - If error \(E_c \geq 1\), then \(V_{i1} = 1\)
  - If error \(E_c < 1\), then \(V_{i1} = 0\)
  - If error \(E_c \geq 2\), then \(V_{i2} = 0\)
  - If error \(E_c < 2\), then \(V_{i2} = 1\),

where \(V_{i1}\) and \(V_{i2}\) are intermediate voltage. \(E_c\) is the difference between injected and reference currents.

- Determination of control signals of the switches \(T_i\) and \(V_{i2}\) \((i = 1, 2, 3, f = 1, 2, 3, 4)\):
  - If \((V_{i1} + V_{i2}) = 1\), then \(T_i = 1, T_2 = 1, T_3 = 0, T_4 = 0\)
  - If \((V_{i1} + V_{i2}) = 0\), then \(T_i = 0, T_2 = 1, T_3 = 1, T_4 = 0\)
  - If \((V_{i1} + V_{i2}) = -1\), then \(T_i = 0, T_2 = 0, T_3 = 1, T_4 = 1\).

4. SIMULATION RESULTS AND DISCUSSION

Figure 2 shows the block diagram of the proposed UPQC, the simulation is performed using MATLAB-Simulink software and SimPowerSystem Toolbox. The UPQC parameters are: \(V_S = 220\) V, frequency \(f_S = 50\) Hz, resistor \(R_5 = 0.1\) m\(\Omega\), inductance \(L_5 = 0.0002\) m\(\Omega\), resistor \(R_6 = 48.6\) \(\Omega\), inductance \(L_1 = 40\) mH, \(C_u = 3000\) \(\mu\)F, resistor \(R_7 = 0.27\) m\(\Omega\), \(L_s = 0.8\) mH.

![Fig. 2 – Unified power quality conditioner based on three-level NPC inverter.](image-url)
To evaluate the performance of the proposed UPQC during transient and steady conditions, different voltage disturbances are introduced between $t_1 = 0.05$ s and $t_5 = 0.3$ s with sudden change in the load current between 0.25 s and 0.35 s. The simulation results are shown in Fig. 3.
The proposed UPQC system has been validated through simulation using MATLAB-Simulink software and SimPowerSystem toolbox. Through visualization Fig. 3, we are able to conclude that the operation of the proposed UPQC is successful. Before the application of shunt APF, the source current is equal to non-linear load current; it is highly distorted and rich in harmonic with poor power factor. After compensation, the current becomes sinusoidal and the load voltage is instantly improved for separate or simultaneously voltage disturbances such as sags, swells, unbalances and harmonics. When the sudden load current disturbance is introduced between 0.25 s and 0.35 s, the UPQC controller acts immediately without any delay. The dc voltage is maintained at the reference value \( U_{dc-ref} = 800 \text{ V} \) using PI controller. It is observed in Fig. 3d that the dc voltage reaches its reference \( U_{dc-ref} = 800 \text{ V} \) with moderate peak voltage approximately equal to 5 V when a step change in load current is introduced between \( t_3 = 0.25 \text{ s} \) and \( t_4 = 0.35 \text{ s} \). The effectiveness of the proposed UPQC has been demonstrated in maintaining the load voltages balanced and sinusoidal; moreover the proposed system does not show any significant effect of disturbance type present in the utility voltages on its compensation capability.

5. CONCLUSIONS

To enhance the power quality and improve the voltage delivered to sensitive loads, a new UPQC configuration using three-level NPC inverter has been proposed in this paper. The control strategy adopted is based on the instantaneous power method for the series AF and synchronous reference frame detection method for the shunt AF. The developed model is validating through simulation using Matlab-Simulink software and SimPowerSystem toolbox. The control algorithm has been observed to be satisfactory for various power quality improvements like voltage harmonics mitigation, voltage sag, swell and unbalance compensation. The UPQC controller acts immediately without any delay in the operation with fast dynamic response. The result of this study may be useful for potential applications of UPQC under wide practical situations.

Received on February 1, 2015

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