Power Controllability of a Three-Phase Converter With an Unbalanced AC Source Using Fuzzy Logic Controller

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Abstract: Three-phase dc–ac power converters suffer from power oscillation and over current problems in case there is the unbalanced ac source voltage which can be brought on by grid/generator faults. Existing solutions to deal with these issues are properly selecting and controlling the positive- and negative-sequence currents. In this paper, a new number of control strategies which make use of the zero sequence components are proposed to improve the ability control ability under this adverse condition. It's figured by introducing proper zero-sequence current controls and corresponding circuit configurations, the power converter can enable more flexible control targets, achieving better performances in the delivered power and the load current when struggling with the unbalanced ac voltage.

Keywords: DC-AC converter, FLC, Grid, Generator and Sequence Component.

I. INTRODUCTION

In many important applications for power electronics such as renewable energy generation, motor drives, over quality, and microgrid, etc., the three-phase dc–ac converters are critical components as the energy flow interface of dc and ac electrical systems [1], [2]. As shown in Fig. 1, a dc–ac voltage source converter with a corresponding filter is usually used to convert the energy involving the dc bus and the three-phase ac sources, that could be the energy grid, generation units, or the electric machines with respect to the applications and controls [3]–[5]. Since the power electronics are becoming so popular and becoming essential in the power conversion technology, the failures or turning off of the backbone dc–ac converters may end up in serious problems and cost. It is now a need in lots of applications that he power converters must certainly be reliable to withstand some faults or disturbances to be able to ensure certain accessibility to the power supply [6]–[13]. An example is visible the wind power application, where both the sum total installed capacity and individual capacity of the power conversion system are relatively high. The sudden disconnection.

The wind power converter should be connected or even keep generating power) under various grid voltage dips for several time according to the dip severity, and in certain uncritical conditions (e.g., 90% voltage dip), the power converter may require long-time operation [1], [2], [12], [13]. Once the ac source shown in Fig. 1 becomes distorted under faults or disturbances, the unbalanced ac voltages have already been demonstrated to be among the greatest challenges for the control of the dc–ac converter to be able to keep them normally operating and attached to the ac source [2], [14], [15]. Special control methods which could regulate both positive- and negative-sequence currents have already been introduced to deal with these problems [2], [16]–[21]. However, the resulting performances by these control methods be seemingly to be still not satisfactory: either distorted load currents or power oscillations will soon be presented, and thereby not merely the ac source but additionally the energy converter is likely to be further stressed accompanying with the costly design considerations.

Fig. 2. Phasor diagram definitions for the voltage dips in the ac source of Fig. 1. VA , VB , and VC means the voltage of three phases in the ac source. This paper targets to know and improve the energy control limits of an average three-phase dc–ac converter system under the unbalanced ac source. A new group of control strategies which utilizes the zero-sequence components are then proposed to improve the energy control ability under this adverse condition. Form grid integration, the proposed control methods have the potential to be applied under other applications like the motor/generator connections or microgrids, where in actuality the unbalanced ac voltage is probably be presented; therefore, the fundamental principle and feasibility are mainly focused.

II. LIMITS OF A TYPICAL THREE-WIRE CONVERTER SYSTEM

To be able to analyze the controllability and the performance of the power electronics converter under an adverse ac source, a severe
unbalanced ac voltage is first defined as an instance study in this paper. As shown in Fig. 2, the phasor diagram of the three phase distorted ac voltage are indicated, it is assumed that the type B fault happens with the significant voltage dip on phase A of the ac source. Also, there are numerous other kinds of voltage faults that have been defined as type A–F in [22]. Based on [2] and [19], any distorted three-phase voltage could be expressed by the amount of components in the positive sequence, negative sequence, and zero sequence. For simplicity of analysis, only the components with the fundamental frequency are thought in this paper, however, it can also be possible to increase the analysis to raised order harmonics. The distorted three-phase ac source voltage in Fig. 3 could be represented by

\[ V_S = V^+ + V^- + V^\cdot O \]

\[ = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \sin(\omega_0 + \phi^+) \\ \sin(\omega_0 - 120^\circ + \phi^+) \\ \sin(\omega_0 + 120^\circ + \phi^+) \end{bmatrix} \]

\[ + V^- \begin{bmatrix} \sin(\omega_0 + \phi^-) \\ \sin(\omega_0 + 120^\circ + \phi^-) \\ \sin(\omega_0 - 120^\circ + \phi^-) \end{bmatrix} + V^\cdot O \begin{bmatrix} \sin(\omega_0 + \phi^0) \\ \sin(\omega_0 - \phi^0) \\ \sin(\omega_0 + \phi^0) \end{bmatrix} \]  

(1)

Where \( V^+, V^-, \) and \( V^\cdot \) are the voltage amplitude in the positive, negative, and zero sequence, respectively. And \( \phi^+, \phi^-, \) and \( \phi^0 \) represent the initial phase angles in the positive sequence, negative sequence, and zero sequence, respectively.

![Figure 3: Typical three-phase three-wire 2L-voltage source converter.](image)

A typically used three-phase three-wire two-level voltage source dc-ac converter is chosen and basically designed, as shown in Fig. 3 and Table I, where in actuality the converter configuration and the parameters are indicated, respectively.

<table>
<thead>
<tr>
<th>DC bus voltage ( V_{dc} )</th>
<th>5.6 KV DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated primary side voltage ( V_p )</td>
<td>3.3 KV rms</td>
</tr>
<tr>
<td>Rated line-to-line grid voltage ( V_g )</td>
<td>20 KV rms</td>
</tr>
<tr>
<td>Rated load current ( I_{load} )</td>
<td>1.75 KA rms</td>
</tr>
<tr>
<td>Carrier frequency ( f_c )</td>
<td>750 Hz</td>
</tr>
<tr>
<td>Filter inductance ( L_f )</td>
<td>1.1 mH (0.25 p.u.)</td>
</tr>
</tbody>
</table>

Table 1: Converter parameters for the case study

It is noted that the three-phase ac source is represented here by three windings with a typical neutral point, which is often the windings of an electric machine or perhaps a transformer. Since there are only three wires and a standard neutral point in the windings of the ac source, the currents flowing in the three phases don’t contain zero-sequence components. As an outcome, the three-phase load current controlled by the converter could be written as

\[ I_C = I^+ + I^- \]  

(2)

With the voltage of the ac source in (1) and the current controlled by the converter in (2), the instantaneous real power \( p \) and the imaginary power \( q \) in \( \alpha \beta \) coordinate, in addition to the actual power \( p_0 \) in the zero coordinate could be calculated as

\[ \begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} p_{\alpha \cdot \alpha} + p_{\beta \cdot \beta} \\ p_{\alpha \cdot \beta} - p_{\beta \cdot \alpha} \end{bmatrix} \]

\[ = \begin{bmatrix} P + P_{c2} \cdot \cos(2\omega_{co} + P_{s2} \cdot \sin(2\omega_s) \\ O + Q_{c2} \cdot \cos(2\omega_{co} + Q_{s2} \cdot \sin(2\omega_s) \end{bmatrix} \]  

(3)

Then, the instantaneous three-phase real power \( p3\Phi \) and the imaginary power \( q3\Phi \) of the ac source/converter could be written

\[ \begin{bmatrix} p_{3\Phi} \\ q_{3\Phi} \end{bmatrix} = \begin{bmatrix} P + P_{O} \\ Q + Q_{O} \end{bmatrix} \]

\[ + \begin{bmatrix} P_{c2} \\ Q_{c2} \end{bmatrix} \cos(2\omega_{co}) + \begin{bmatrix} P_{s2} \\ Q_{s2} \end{bmatrix} \sin(2\omega_{so}) \]  

(4)

where \( P \) and \( Q \) are the average parts of the real and imaginary power, \( P_{c2} \), \( P_{s2} \) and \( Q_{c2}, Q_{s2} \) are the oscillation parts, which can be calculated as
$\overline{P} = \frac{3}{2}(v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^-)$

$P_{c2} = \frac{3}{2}(v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^-)$

$P_{s2} = \frac{3}{2}(v_q^- i_d^+ - v_d^- i_q^+ - v_q^- i_d^- + v_d^- i_q^-)$

$\overline{Q} = \frac{3}{2}(v_d^+ i_d^+ - v_d^- i_d^- + v_q^+ i_q^+ - v_q^- i_q^-)$

$Q_{c2} = \frac{3}{2}(v_q^- i_d^+ - v_d^- i_q^+ + v_q^- i_d^- + v_d^- i_q^-)$

$Q_{s2} = \frac{3}{2}(-v_d^- i_q^+ - v_q^- i_d^+ + v_q^- i_d^- + v_d^- i_q^-)$

$(5)$

$(6)$

$\overline{I}_O = \frac{3}{2}(v_d^0 i_d^0 + v_q^0 i_q^0)$

$I_{Oc2} = \frac{3}{2}(v_q^0 i_d^0 - v_d^0 i_q^0)$

$I_{Os2} = \frac{3}{2}(-v_d^0 i_q^0 - v_q^0 i_d^0)$

$(7)$

the place where a positive dq synchronous reference frame and a negative synchronous reference frame are applied, respectively, to the positive- and negative-sequence voltage/current. All the components on the corresponding positive-and negative-dq axis could be written as

$v_d^+ = V^+ \cos(\phi^+)$

$v_q^+ = V^+ \sin(\phi^+)$

$v_d^- = V^- \cos(\phi^-)$

$v_q^- = -V^- \sin(\phi^-)$

$i_d^+ = I_d^+ \cos(\delta^+)$

$i_q^+ = I_d^+ \sin(\delta^+)$

$i_d^- = I_d^- \cos(\delta^-)$

$i_q^- = -I_d^- \sin(\delta^-)$.

$(8)$

$(9)$

Then, (5) and (6) can be formulated as a matrix relation as

\[
\begin{bmatrix}
\overline{P} \\
\overline{Q} \\
P_{s2} \\
P_{c2}
\end{bmatrix} = \frac{3}{2}
\begin{bmatrix}
v_d^+ & v_q^+ & v_d^- & v_q^- \\
v_q^+ & v_d^+ & v_q^- & v_d^- \\
v_d^- & v_q^- & v_d^+ & v_q^+ \\
v_q^- & v_d^- & v_q^+ & v_d^+
\end{bmatrix}
\begin{bmatrix}
i_d^+ \\
i_q^+ \\
i_d^- \\
i_q^-
\end{bmatrix}
\]

$(9)$

It may be seen from (9) that when the ac source voltage is decided, then a converter has four controllable freedoms ($i_d^+, i_q^+, i_d^-$, and $i_q^-$) to regulate the current flowing in the ac source. That entails: four control targets/functions could be established. Normally, the three-phase average active and reactive powers delivered by the converter are two basic requirements for confirmed application, then, two control targets need to be first settled as

$\overline{P} 3\phi = \overline{P} = Pref$

$\overline{Q} 3\phi = \overline{Q} = Qref$

$(10)$

It is noted that different applications might have different requirements for the control of the average power, e.g., in the power production application, the active power reference Pref injected to the grid is usually set as positive, meanwhile the wide range of the reactive power Qref might be needed so as to greatly help to aid the grid voltage [12], [13]. When it comes to electric machine application, the Pref is defined as negative for the generator mode and positive for the motor mode, there might be no or simply several reactive power Qref requirements for magnetizing of the electric machine. During most power quality applications, e.g., STATCOM, Pref is generally set to be really small to supply the converter loss, and a massive amount Qref is generally required. Consequently, for the three-phase three-wire converter system, there are only two more current control freedoms left to achieve another two control targets besides (10). Both of these adding control targets may be used to help expand increase the performances of the converter under the unbalanced ac source, which were generally investigated in [2] and [16]–[18]. However, this paper focuses more on the evaluation of control limits and the control possibilities under the whole voltage dipping range. In these, two of the very most mentioned control methods accomplished by three-wire converter structure are investigated under the unbalanced ac source.

A. Elimination of the Negative-Sequence Current

In all of the grid integration applications, there are strict grid codes to regulate the behavior of the grid connected converters. The negativesequence current which always results in the unbalanced load current may be unacceptable from the purpose view of a TSO [13]. Therefore, extra two control targets which aim to eradicate the negative-sequence current could be added as

$i_d^- = 0$ and $i_q^- = 0$

$(11)$

Translating the control targets in (10) and (11), all the controllable current components can be calculated as

\[
\begin{align*}
i_d^+ & = \frac{2}{3} \cdot \frac{P_{ref}}{-v_d^+} \\
i_q^+ & = \frac{2}{3} \cdot \frac{Q_{ref}}{-v_d^+}
\end{align*}
\]

$(12)$

\[
\begin{align*}
i_d^- & = 0 \\
i_q^- & = 0
\end{align*}
\]

$(13)$
When applying the current references in (12) and (13), the ac source voltage, load current, sequence current amplitude, and the instantaneous power delivered by the converter are shown in Fig. 5. The simulation is based on the parameters predefined in Fig. 4 and Table I. The ac source voltage is set with $V_A$.

\begin{align*}
    I_{Re}^0 &= \frac{v_{d}^{0} - v_{d}^{-} + v_{d}^{+}}{v_{Re}} \\
    I_{Im}^0 &= 0 \tag{14}
\end{align*}

While applying the current references in (13)–(14), the comparing source voltage, stack current, grouping current, and the immediate power conveyed by converter. It may be seen that by this control technique, the wavering of the dynamic power at twice of the fundamental recurrence could be discarded, and the heap current in the broken stage is lessened to zero. The present adequacy in the diverse groupings, and also the conveyed dynamic/receptive power link with the voltage on the plunging stage.

\begin{align*}
    Q_{c2} &= 0 \\
    Q_{s2} &= 0 \tag{15} \\
    P_{c2} &= 0 \\
    P_{s2} &= 0 \tag{16} \\
    Q_{c22} &= 0 \tag{17}
\end{align*}

**III. CONVERTER SYSTEM WITH THE ZERO-_SEQUENCE CURRENT PATH**

As may be concluded, in the conventional three-phase three-wire converter structure, four control freedoms for the load current appear to be insufficient to accomplish satisfactory performances under the unbalanced ac source. (No matter what combinations of control targets are employed, either significant power oscillation or overloaded/distorted current is going to be presented.) Therefore, more current control freedoms are expected to be able to increase the control performance beneath the unbalanced ac source conditions. Another series of the converter structure are shown as indicated because the four-wire system in Fig. 6(a) and the six-wire system in Fig. 6(b).

Compared to the three-wire converter structure, these kinds of converters introduce the zero-sequence current path [24]–[26], which can enable extra current control freedoms to accomplish better power control performances. It is noted that in the grid-connected application, the zero-sequence current isn’t injected in to the grid but trapped in the typically used d-Y transformer.
Fig. 5. Converter structure with the zero-sequence current path. (a) Four-wire system. (b) Six-wire system.

Fig. 6. Control structure for the converter system with the zero-sequence current.

A possible control structure is proposed by which an additional control loop is introduced allowing the controllability of the zero-sequence current. After introducing the regulated zero-sequence current, the three-phase current generated by the converter can be written as,

\[ I_C = I^+ + I^- + I^O \]  \hspace{1cm} (18)

![Diagram of zero sequence current control](image)

Fig. 7. Simulation of the converter control with no active power oscillation (three-phase three-wire converter, \( P_{ref} = 1 \) p.u., \( Q_{ref} = 0 \) p.u., \( P_{c2} = 0 \) p.u., \( P_c = 2 \) p.u., \( I_r = 0 \) p.u., \( I_r = 1 \) p.u., and \( f_0 \) means the amplitude of the current in the positive, negative, and zero sequences, respectively.

By operating the voltage of the ac source (1) and the current controlled by the power converter (20), the instantaneous generated real power \( p \), the imaginary power \( q \) in the \( a\beta \) coordinate, and the actual power \( p_0 \) in the zero coordinate can be calculated as

\[
\begin{bmatrix}
  p \\
  q \\
  p_0
\end{bmatrix} =
\begin{bmatrix}
  v_{\alpha} \cdot i_{\alpha} + v_{\beta} \cdot i_{\beta} \\
  v_{\alpha} \cdot i_{\alpha} - v_{\beta} \cdot i_{\beta} \\
  v_{O} \cdot i_{O}
\end{bmatrix}
\]

\[
\begin{bmatrix}
  \bar{P} + P_{c2} \cdot \cos(2\omega_{co} + P_{s2} \cdot \sin(2\omega_{si}) \\
  \bar{Q} + Q_{c2} \cdot \cos(2\omega_{co} + Q_{s2} \cdot \sin(2\omega_{si}) \\
  \bar{P}_0 + P_{0c2} \cdot \cos(2\omega_{co} + P_{0s2} \cdot \sin(2\omega_{si})
\end{bmatrix}
\]  \hspace{1cm} (19)

Then, the instantaneous three-phase real power \( P_{3\Phi} \) and the imaginary power \( Q_{3\Phi} \) of the converter can be written as

\[
\begin{bmatrix}
  P_{3\Phi} \\
  Q_{3\Phi}
\end{bmatrix} =
\begin{bmatrix}
  P + P_{O} \\
  Q + Q_{O}
\end{bmatrix}
\]  \hspace{1cm} (20)

Then, the instantaneous three-phase real power \( P_{3\Phi} \) and the imaginary power \( Q_{3\Phi} \) of the converter can be written as

\[
\begin{bmatrix}
  P_{3\Phi} \\
  Q_{3\Phi}
\end{bmatrix} =
\begin{bmatrix}
  P + P_{O} \\
  Q + Q_{O}
\end{bmatrix}
\]  \hspace{1cm} (21)

It is noted that the voltage and the current in zero sequence only contribute to the real power \( P_{3\Phi} \) of the converter. Each part of (21) can be calculated as

\[
\bar{P} = \frac{3}{2}(v_d^+ \cdot i_d^+ + v_q^+ \cdot i_q^+ + v_d^- \cdot i_d^- + v_q^- \cdot i_q^-)
\]

\[
P_{c2} = \frac{3}{2}(v_d^+ \cdot i_d^+ + v_q^+ \cdot i_q^+ + v_d^- \cdot i_d^- + v_q^- \cdot i_q^-)
\]

\[
P_{s2} = \frac{3}{2}(v_q^- \cdot i_q^+ - v_q^+ \cdot i_q^- - v_d^- \cdot i_d^+ + v_d^+ \cdot i_d^-)
\]  \hspace{1cm} (22)

\[
\bar{Q} = \frac{3}{2}(v_d^+ \cdot i_d^+ - v_d^- \cdot i_d^- + v_q^+ \cdot i_q^+ - v_q^- \cdot i_q^-)
\]

\[
Q_{c2} = \frac{3}{2}(v_q^- \cdot i_q^- - v_d^- \cdot i_d^+ - v_q^+ \cdot i_d^- + v_q^\cdot i_q^+)
\]

\[
Q_{s2} = \frac{3}{2}(-v_d^- \cdot i_d^+ - v_q^- \cdot i_q^+ + v_d^+ \cdot i_d^- + v_q^\cdot i_q^-)
\]  \hspace{1cm} (23)

\[
\bar{P}_0 = \frac{3}{2}(v_{Re}^0 \cdot i_{Re}^0 + v_{Im}^0 \cdot i_{Im}^0)
\]

\[
P_{0c2} = \frac{3}{2}(v_{Im}^0 \cdot i_{Re}^0 - v_{Re}^0 \cdot i_{Im}^0)
\]

\[
P_{0s2} = \frac{3}{2}(-v_{Re}^0 \cdot i_{Re}^0 - v_{Im}^0 \cdot i_{Im}^0)
\]  \hspace{1cm} (24)

Then, the relationship of (22)–(24) can be formulated to a matrix equation as
When combing (23), (29), and (30),

\[
\begin{bmatrix}
\bar{P} + \bar{P}_O \\
\bar{P}_2 + \bar{P}_{0n2} \\
\bar{Q} + \bar{Q}_{0n2}
\end{bmatrix} = \frac{3}{2}
\begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^- \\
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix} \begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^- \\
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix} = \frac{3}{2}
\begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^- \\
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix} \begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^- \\
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix}
\]

(25)

It is noted that unlike the traditional approach in which the zero sequence components are normally minimized, the zero-sequence voltage and the current here look like single-phase AC components running at the same fundamental frequency.

Thus, the zero-sequence voltage/current can be represented by vectors in a synchronous reference frame in the zero sequences

\[
V_O = v_O^R e^{j \theta} + v_O^I e^{-j \theta}
\]

(26)

\[
I_O = i_O^R e^{j \theta} + i_O^I e^{-j \theta}
\]

where the real part and imaginary part can be represented as follows:

\[
v_O^R = v_O^R \cos(\theta) \\
v_O^I = v_O^I \sin(\theta) \\
i_O^R = i_O^R \cos(\theta) \\
i_O^I = i_O^I \sin(\theta)
\]

(27)

It can be seen from (3.8) that if the three-phase ac source voltage is decided, then the converter has six controllable freedoms to regulate the current flowing in the ac source. That means: six control targets/functions can be established by the converter having the zero-sequence current path. Similarly, the three-phase average active and reactive power delivered by the converter are two basic requirements for a given application, then, two control functions need to be first settled as

\[
\begin{align*}
\bar{P}_{3\theta} & = \bar{P} + \bar{P}_O = \bar{P}_{ref} \\
\bar{Q}_{3\theta} & = \bar{Q} = \bar{Q}_{ref}
\end{align*}
\]

(28)

So, for the converter system with the zero-sequence current path, there are four control freedoms left to achieve two more control targets than the traditional three-wire system, this also means extended controllability and better performance under the unbalanced ac source.

As a result of more current control freedoms, the power converter with the zero-sequence current path can not merely eliminate the oscillation in the active power, but additionally cancel the oscillation in the reactive power at exactly the same time. This control targets can be written as,

\[
\begin{align*}
P_{3\phi2} & = P_{c2} + P_{oc2} = 0 \\
P_{3\phi2} & = P_{s2} + P_{os2} = 0 \\
Q_{c2} & = 0 \\
Q_{s2} & = 0
\end{align*}
\]

(29)

The power oscillation caused by the zero-sequence current $P_{oc2}$ and $P_{os2}$ are used to compensate the power oscillation caused by the positive- and negative-sequence currents $P_{c2}$ and $P_{s2}$. When combing (23), (29), and (30), each of the current components controlled by converter can be calculated as,

\[
\begin{bmatrix}
\bar{P}_{ref} \\
\bar{Q}_{ref}
\end{bmatrix} = \frac{3}{2}
\begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix} \begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix} = \frac{3}{2}
\begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix} \begin{bmatrix}
\bar{v}^+ \\
\bar{v}^- \\
\bar{q}^+ \\
\bar{q}^-
\end{bmatrix}
\]

(31)

In order to ease the analytical solution, assuming that the d-axis or the real axis in the synchronous reference frame is related with the voltage vectors in each of the sequence (positive, negative, and zero), then all of the controllable current components with the zero-sequence current path can be solved by,

\[
\begin{align*}
i_d & = \frac{2}{3} \cdot \bar{Q}_{ref} \\
i_q & = \frac{2}{3} \cdot \bar{P}_{ref} - \bar{P}_d \
\end{align*}
\]

(3.15)
Another promising control strategy for the converter using the zero-sequence current path is to eliminate the active power oscillation, and meanwhile cancel the negative-sequence current.

\[
\begin{align*}
i_{cl}^- &= \frac{v_{cl}^-}{v_{cl}^+} \cdot i_{cl}^+ \\
i_{q}^- &= -\frac{v_{cl}^-}{v_{cl}^+} \cdot i_{q}^+
\end{align*}
\]  
(32)

\[
\begin{align*}
i_{Re}^0 &= \frac{2}{3} \frac{P_{ref} - P}{v_{Re}^0} \\
i_{Im}^0 &= \frac{v_{cl}^+ \cdot i_{q}^- - v_{cl}^- \cdot i_{q}^+}{v_{Re}^0}
\end{align*}
\]  
(33)

Fig 9: Simulation of converter control with no active power oscillation and no negative sequence (three-phase converter with the zero-sequence current path, \( P_{ref} = 1 \) p.u., \( Q_{ref} = 0 \) p.u., \( P_s = 0 \) p.u., \( P_c = 0 \) p.u., \( id^- = 0 \) p.u., \( iq^- = 0 \) p.u., \( VA = 0 \) p.u. \( I^+, I^-, \) and \( I^0 \) means the amplitude of the current in the positive, negative, and zero sequences, respectively

**IV SIMULATION RESULTS**

The three-phase dc–ac converters are critical components as the power flow interface of dc and ac electrical system. A dc–ac voltage source converter with a corresponding filter is typically used to convert the energy between the dc bus and the three-phase ac sources as shown in figure 11. When the ac source becomes distorted under faults or disturbances, the unbalanced ac voltages have been proven to be one of the greatest challenges for the control of the dc–ac converter to keep them normally operating and connected to the ac source. The power converter with zero sequence current path can not only eliminate the oscillation in the active power, but also cancel the oscillation in the reactive power at the time.

**Figure 10:** Simulink model of DC to AC power converter

**Figure 11:** Simulation model of converter control with no active and reactive power oscillation with PI

**Figure 12:** Simulation model of converter control with no active and reactive power oscillation with FUZZY controller.
Fig. 13. Simulation of the converter with no negative-sequence current control (three-phase three-wire converter. $P_{ref} = 1$ p.u., $Q_{ref} = 0$ p.u., $I_d^- = 0$ p.u., $I_q^- = 0$ p.u., $V_A = 0$ p.u., $I_+$, $I_-$, and $I_0$ means the amplitude of the current in the positive, negative, and zero sequences, respectively).

Fig. 14. Simulation of the converter control with no active power oscillation (three-phase three-wire converter. $P_{ref} = 1$ p.u., $Q_{ref} = 0$ p.u., $P_{s2} = 0$ p.u., $P_c = 0$ p.u., $V_A = 0$ p.u., $I_+$, $I_-$, and $I_0$ means the amplitude of the current in the positive, negative, and zero sequences, respectively.

Fig. 15. Simulation of converter control with no active and reactive power oscillation (three-phase converter with the zero-sequence path. $P_{ref} = 1$ p.u., $Q_{ref} = 0$ p.u., $P_{s2} = 0$ p.u., $P_c = 0$ p.u., $Q_{s2} = 0$ p.u., $Q_{c2} = 0$ p.u., $V_A = 0$ p.u.).

Fig. 16. Simulation of converter control with no active power oscillation and no negative sequence (three-phase converter with the zero-sequence current path, $P_{ref} = 1$ p.u., $Q_{ref} = 0$ p.u., $P_{s2} = 0$ p.u., $P_c = 0$ p.u., $I_d^- = 0$ p.u., $I_q^- = 0$ p.u., $V_A = 0$ p.u., $I_+$, $I_-$, and $I_0$ means the amplitude of the current in the positive, negative, and zero sequences, respectively.

Control A: no active and reactive power oscillations.
Control B: no active power oscillation and no negative sequence current.

At last, the converter stresses for the active/reactive power oscillations and the current amplitude in the faulty/normal phases are compared in table 2, where different control strategies and converter structures are indicated respectively. It can be seen that by introducing the converter structures with zero sequence current path and corresponding controls, the power oscillations under unbalanced AC source are significantly reduced, meanwhile the current amplitude in the normal phases are not further stressed, and the current stress in the faulty phases are significantly relieved by using FUZZY Logic controller.

<table>
<thead>
<tr>
<th>Converter stress</th>
<th>PI Controller</th>
<th>FUZZY Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Converter A</td>
<td>Converter B</td>
</tr>
<tr>
<td>Active power oscillation</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Reactive power oscillation</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Current in faulty phase</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Current in normal phase</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>THD(Total harmonic distortion)%</td>
<td>8.02</td>
<td>4.22</td>
</tr>
</tbody>
</table>

Table 2: Converter Stress Comparison By PI and FUZZY Control Strategies (Values Are Represented In p.u., \( P_{ref} = 1 \) p.u., \( Q_{ref} = 0 \) p.u., and \( V_{dc} = 0 \) p.u.)

V CONCLUSION AND FUTURE SCOPE

In this thesis mainly focused on improvement of power control limits of a typical three-phase dc-ac converter system under the unbalanced ac source using fuzzy logic controller. A new series of control strategies which utilizes the zero-sequence components are then proposed to enhance the power control ability under this adverse condition. The three-phase converter structure having six current control freedoms. The extra two control freedoms coming from the zero-sequence current can be utilized to extend the controllability of the converter and improve the control performance under the unbalanced ac source. By using fuzzy logic control strategies, it is possible to totally cancel the oscillation in both the active and the reactive power, or reduced the oscillation amplitude in the reactive power. Meanwhile, the current amplitude of the faulty phase is significantly relieved without further increasing the current amplitude in the normal phases.

This project work can be extended further by Controls scheme for photo voltaic three-phase converters to minimize peak currents during unbalanced grid-voltage sags. By using the unbalanced voltage sources, the reduction of complexity and total cost of the converter can be achieved.

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