Protective coordination of main and backup overcurrent relays with different operating modes of active superconducting current controller

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Abstract: Active superconducting current controllers (ASCCs) are new generation of series compensators, which can also be categorised as fault current limiters because of their ability to decrease the fault current continuously. Although the performance of the ASCCs in different operating modes introduces a limiting impedance in series with the network, it can degrade the operation of the overcurrent relays (OCRs). In this paper the ASCC modelling and its control strategy for fault detection and converter operation is investigated. The simulation of a typical three-phase ASCC shows the effect of the ASCC on fault current limiting and confirms the operation of the control system. The impact of different modes of ASCC on the operation of the main and backup OCRs is studied through the simulation of a typical distribution system. Simulation results confirm that the protective coordination of different modes of the ASCC is achieved by modifying both the time dial and pickup current parameters of the OCRs.

Keywords: current controller, fault current limiters, main and backup protection, overcurrent relay, power distribution system, superconducting devices

INTRODUCTION

The recent growth of electrical energy demand and the rapid development of the power systems have increased short-circuit phenomena which can damage circuit breakers and other equipment. The application of fault current limiters (FCLs) can be regarded as an effective solution for this issue [1]. Several researches have introduced and evaluated different types of FCLs. For example, the resistive, magnetic-shield, high-temperature superconducting, saturated iron-core, and shunt superconducting FCL types have been presented and examined [2-5]. In general, these types
of FCLs have a low resistance against the line current under the normal state, but they suddenly represent a large resistance against the current when a fault occurs.

The active superconducting current controller (ASCC) as a new generation of series compensations is a combination of superconductor technology and power electronic devices [6]. This type of superconducting FCL can decrease the fault current continuously at different levels. In addition, it can also be implemented in the hybrid alternating-current-to-direct-current (AC-DC) power supply systems [7-8]. In spite of the aforementioned advantages, the ASCC may deteriorate the operation of employed over-current relays (OCRs). It stands to reason that reducing the fault current increases the trip time of the OCR and may deteriorate the transient stability of the network. The ASCC has been applied to reduce the fault current in the presence of a transformer rating of 100 megavolt-amperes to a level of normal current when a 45-megavolt-ampere transformer is used [9]. Although the protective coordination of the main relay has been considered [9], there seems to be no study of the protective coordination of both the main and backup OCRs. Thus, the main aim of this work is to analyse the protective coordination of the main and backup OCRs with adjustment of both the ASCC and OCR parameters to obtain a state of ASCC setting that can achieve simultaneously its most current-limiting capability and protective coordination.

NOTATIONS

\[ L_1, M_S \]: Self- and mutual-inductances of ASCC
\[ U_A, I_A \]: Superconducting transformer phase-A primary voltage and current in a transmission system
\[ U_a, I_a \]: Superconducting transformer phase-A secondary voltage and current in a transmission system.
\[ U_{SA} \]: Voltage source of phase A
\[ Z_L, Z_T \]: Line and load impedances
\[ I_{Af}^{with\ ASCC}, I_{Af}^{no\ ASCC} \]: Fault current with and without ASCC
\[ I_{Af,1}, I_{Af,2}, I_{Af,3} \]: Fault current in modes 1, 2 and 3
\[ Z_{ASCC-1}, Z_{ASCC-2}, Z_{ASCC-3} \]: Limiting impedance of ASCC in modes 1, 2 and 3
\[ K \]: Coefficient constant
\[ Z_{ASCC-F}, Z_{ASCC-N} \]: Limiting impedance of ASCC in fault and normal states
\[ Z_T^1, Z_T^2, Z_T^0 \]: Equivalent impedance of positive, negative and zero sequences
\[ Z_{ASCC-1}, Z_{ASCC-2}, Z_{ASCC-3} \]: ASCC impedance of positive, negative and zero sequences
\[ C_1, C_2 \]: Split DC link capacitors
\[ L_d, C_d \]: Filtering inductance and capacitor
\[ i_d, i_q, i_0 \]: Instantaneous system current in synchronous reference frame
\[ i_{d-ref}, i_{q-ref}, i_{0-ref} \]: Steady-state system current in synchronous reference frame
\[ \Delta i \]: Amplitude of error between the instantaneous and steady-state current
\[ A, B, P \]: Constants of a relay
\[ TD \]: Time Dial of OCR
\[ M \]: Multiple of current
\[ I_{input}, I_p \]: Fault current and pickup current of OCR
\[ \omega \]: Angular frequency of source voltage
\[ j \]: Index of imaginary numbers, which is equal to the square root of -1
CONFIGURATION AND MODELLING

Structure and Principle of ASCC

The ASCC structure for a typical three-phase circuit (Figure 1) consists of three superconducting transformers and one three-phase pulse-width-modulation (PWM) converter. In the normal state, the limiting impedance of the ASCC is adjusted to zero, but in the fault conditions it is increased through controlling the output current of the converter. Consequently, the fault current is limited to different levels [10-13].

![Figure 1. Structure of a three-phase ASCC](image)

In this paper, phase A shown in Figure 1 is studied for the sake of simplicity of modeling, and the other two phases can be analysed in the same way. The primary voltage of the superconducting transformer is expressed as follows [6, 11-13].

\[ U_A = j \omega L_{S1} I_A - j \omega M_S I_a \quad (1) \]

where \( L_{S1} \) is defined as:

\[ L_{S1} = L_2 + M_S \quad (2) \]

In the normal state, \( I_a \) should be adjusted as:

\[ I_a = \frac{L_{S1}}{M_S} I_A = \frac{L_{S1}}{M_S} \left( \frac{U_{S4}}{Z_1 + Z_2} \right) \quad (3) \]

When a fault occurs, the fault current without ASCC and with ASCC is defined as:

\[ I_{Af-noASCC} = \frac{U_{S4}}{Z_1} \quad (4) \]

\[ I_{Af-withASCC} = \frac{U_{S4} + j \omega M_S I_a}{Z_1 + j \omega L_{S1}} \quad (5) \]

In addition, the limiting impedance of ASCC (\( Z_{ASCC} \)) is defined as:

\[ Z_{ASCC} = \frac{U_A}{I_{Af}} = j \omega L_{S1} - j \omega M_S I_a \left( Z_1 + j \omega L_{S1} \right) \]

\[ \frac{1}{U_{S4} + j \omega M_S I_a} \quad (6) \]
Based on (5), three different modes are defined for the operation of ASCC [6-8]:

Mode 1: \( I_a \) is kept at the original setting, and

\[
I_{Af-1} = \frac{U_{SA} + j\omega L_{SI} I_A}{Z_1 + j\omega L_{SI}} \tag{7}
\]

\[
Z_{ASCC-1} = \frac{Z_2(j\omega L_{SI})}{Z_1 + Z_2 + j\omega L_{SI}} \tag{8}
\]

Mode 2: The amplitude of \( I_a \) is set at zero, and

\[
I_{Af-2} = \frac{U_{SA}}{Z_1 + j\omega L_{SI}} \tag{9}
\]

\[
Z_{ASCC-2} = j\omega L_{SI} \tag{10}
\]

Mode 3: \( I_a \) is adjusted so that the measured angle between \( u_{SA} \) and \( j\omega M_s I_a \) is equal to 180°, and this is obtained by setting \( j\omega M_s I_a = -K u_{SA} \). In this mode, the limiting impedance is defined as:

\[
I_{Af-3} = \frac{U_{SA} - j\omega M_s I_a}{Z_1 + j\omega L_{SI}} \tag{11}
\]

\[
Z_{ASCC-3} = \frac{K}{I - K} Z_1 + \frac{1}{I - K} j\omega L_{SI} \tag{12}
\]

In order to investigate the ASCC performance for asymmetric faults, it is assumed that a phase-A-to-ground fault occurs. The limiting impedance of phase A is therefore adjusted to the fault state impedance of modes 1, 2 and 3, and the limiting impedance for other phases is kept at its normal state. The voltage and current equations are thus expressed as:

\[
V^{abc} = Z^{abc} I^{abc} \tag{13}
\]

where

\[
Z^{abc} = \begin{bmatrix}
Z_{ASCC-F} & 0 & 0 \\
0 & Z_{ASCC-N} & 0 \\
0 & 0 & Z_{ASCC-N}
\end{bmatrix}.
\]

The zero-, positive- and negative-sequence components of phase A are obtained as:

\[
Z^{012} = \frac{1}{3} \begin{bmatrix}
1 & 1 & 1 \\
1 & a & a^2 \\
1 & a^2 & a
\end{bmatrix} Z^{abc} = \begin{bmatrix}
1 & 1 & 1 \\
0 & Z_{ASCC-N} & 0 \\
0 & 0 & Z_{ASCC-N}
\end{bmatrix} \begin{bmatrix}
1 & 1 & 1 \\
1 & a^2 & a \\
1 & a & a^2
\end{bmatrix} \tag{14}
\]

where \( a = 1 \angle 120^\circ \), \( a^2 = 1 \angle 240^\circ \).

If a single-phase fault occurs, the fault current of positive, negative and zero sequences will be equal, and they are calculated as:

\[
l^0_f = l^1_f = l^2_f = \frac{U_{SA}}{Z_1 + Z_2^1 + Z_2^2 + 3Z_f} \tag{15}
\]

In (15), \( Z_1^1 \), \( Z_1^2 \) and \( Z_1^0 \) are the equivalent impedance of positive, negative and zero sequences, which are defined as:
The fault current of positive, negative and zero sequences \( I_1^f, I_2^f \) and \( I_0^f \) for two-phase and two-phase-to-ground faults are obtained by (17) and (18) respectively:

\[
\begin{align*}
I_1^f &= -I_2^f = \frac{U_{SA}}{Z_f^1 + Z_f^2 + Z_f} \\
I_0^f &= 0
\end{align*}
\]

\[
\begin{align*}
I_1^f &= -I_2^f = \frac{U_{SA}Z_f^2(Z_f^0 + aZ_f)}{Z_f^1 + Z_f^2 + Z_f^0 + aZ_f} \\
I_0^f &= 0
\end{align*}
\]

Control Strategy for Fault Detection and Voltage Source Converter

The control strategy for fault detection is illustrated in Figure 2. For the sake of simplicity of the design, the currents are expressed in the synchronous reference frame. In order to detect the normal and fault conditions, instantaneous currents \( (i_d, i_q \text{ and } i_0) \) and steady-state currents \( (i_{d-ref}, i_{q-ref} \text{ and } i_{0-ref}) \) are compared. If \( \Delta i > \Delta i_{\text{threshold}} \), a fault occurs, and the ASCC provides the required compensating voltage to control the fault current level [1].

In addition, the control system diagram of a three-phase converter is shown in Figure 3. The reference current signals \( (i_{abc-ref}) \) are determined based on the operating state of the main circuit and the current-limiting mode of the ASCC. Consequently, the reference currents and voltages are calculated. Finally, the voltage reference signals of the converter can be obtained by \( dq0-abc \) transformation [11].

Distribution System

In a number of research work [14-17], the system used by the Korea Electric Power Corporation was chosen for investigation in the presence of superconducting fault current limiters since it contains both main and backup protections. So this system is selected here as the case study. The ASCC employed in this system is depicted in Figure 4. \( R_f-R_5 \) are OCRs that protect the related feeders of the distributed system, and \( R_6 \) is used not only as the main protection for the transformer, but also as the backup protection for \( R_f - R_5 \). In turn, \( R_f \) is employed as the backup protection for \( R_6 \). The parameters of the distribution system, along with the initial settings of the OCRs, are shown in Table 1 [16].
\[ \Delta i = \sqrt{(i_d - i_{d_{ref}})^2 + (i_q - i_{q_{ref}})^2 + (i_0 - i_{0_{ref}})^2} \]

**Figure 2.** Control strategy for fault detection

**Figure 3.** Control strategy for a three-phase pulse-width-modulation converter
**Figure 4.** Schematic configuration of the distribution system

<table>
<thead>
<tr>
<th>Configuration components</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>154 (KV), 1.75%</td>
</tr>
<tr>
<td>Transformer</td>
<td>154/22.9 (KV), 100 (MVA) , j 20(%)</td>
</tr>
</tbody>
</table>
| Distribution line        | $Z_0=8.68+j22.86$ (%) , (100MVA)  
                          | $Z_1=3.48+j7.44$ (%) , (100MVA) |
| Loads                    | Feeder1: 10 (MVA) , pf=0.95 Lag  
                          | Feeder2: 7(MVA) , pf=0.95 Lag  
                          | Feeder3: 9 (MVA) , pf=0.95 Lag  
                          | Feeder4: 8 (MVA) , pf=0.95 Lag  
                          | Feeder5: 8 (MVA) , pf=0.95 Lag |
| OCR                      | Load current: 1.13 (KA rms)  
                          | Full load current: 1.51 (KA rms)  
                          | Pick-up current of time delay operation: 2.1 (KA rms)  
                          | Level: 1 |
| Parameters of very-inverse-type OCR | $A=3.88$, $B=0.0963$, $P=2$, $TD=0.4$ |
| Superconducting FCL parameters | $L_{j1}=L_{j2}=5$ (mH), $M_j=4$ (mH) |

**Modelling of OCR**

For the modelling purpose, the operational equations of OCR are obtained as follows [16]:

$$Time_{trip} = \left( \frac{A}{M^P - 1} + B \right) \times TD \quad (19)$$

$$M = \frac{I_{input}}{I_{pickup}} \quad (20)$$

where $A$, $B$ and $P$ are determined based on the type of relays. According to (20), $I_{input}$ is equal to the fault current and $I_{pickup}$ is one of the setting parameters of OCR. $TD$ is another setting parameter of OCR. By adjusting $TD$ and $I_{pickup}$ through analysis of the time-current curve, the protective coordination of ASCC with OCR is obtained for different current limiting modes. According to (7) - (11), the operational equations of OCR without ASCC and in the presence of ASCC are obtained as follows:
Equations (21) show that reducing the fault current increases the trip time of OCR so that ASSC with mode 3 provides the largest trip time of OCR (i.e. (Time\(_{trip}\)\(_{ASSC-3}\)) > (Time\(_{trip}\)\(_{ASSC-2}\)) > (Time\(_{trip}\)\(_{ASSC-1}\)). This increase in the relay operation may therefore deteriorate the transient stability. For this reason, the protective coordination between ASCC and OCR for the whole modes of ASCC is inevitable, and this is performed through the setting of OCR parameters.

**SIMULATIONS AND RESULTS**

In order to evaluate the effect of different modes of ASCC on current limiting, a simulation of the three-phase circuit shown in Figure 1 was performed. In addition, to study the protective coordination of the main and backup relays by considering all different modes of ASCC, a simulation of the distribution system depicted in Figure 4 was also carried out.

**Current Limiting Test**

To assess the performance of the three aforementioned modes of ASCC on current limiting, the model shown in Figure 1 with parameters as in Table 2 was simulated in MATLAB. In order to evaluate and compare the effects of different modes of ASCC on current limiting, the fault current waveforms with and without ASCC are compared (Figure 5), which shows that ASCC can reduce the fault current as expected. In addition, by adjusting the phase angle of output current of the converter to 90° (i.e. mode 3), the maximum effect of fault-current limiting is obtained.

### Table 2. Parameters of simulated system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>([U_{SA}, U_{dc}])</td>
<td>[220,600] (V)</td>
</tr>
<tr>
<td>(Z_1)</td>
<td>0.19 + 2.16 i (Ω)</td>
</tr>
<tr>
<td>(Z_2)</td>
<td>15 + 2 i (Ω)</td>
</tr>
<tr>
<td>(F)</td>
<td>50 (Hz)</td>
</tr>
<tr>
<td>(L_{S1}=L_{S2})</td>
<td>10 (mH)</td>
</tr>
<tr>
<td>([M_0, L_0])</td>
<td>[9, 6] (mH)</td>
</tr>
<tr>
<td>(C_1=C_2)</td>
<td>2000 (µF)</td>
</tr>
<tr>
<td>(C_f)</td>
<td>30 (µF)</td>
</tr>
</tbody>
</table>
By supposing the operation of ASCC in mode 3, the voltage and current reference signals of the converter under different conditions, viz. normal state, three-phase fault and single-phase fault, are shown in Figure 6. Figure 6a shows the reference currents of the normal state. The reference current of phase A can be obtained based on equation (3), and reference currents of the other phases (B and C) are the same as that of phase A due to symmetrical conditions \(I_{a-ref}=15.7 \angle 15.3^\circ, I_{b-ref}=15.7 \angle 135.3^\circ\) and \(I_{c-ref}=15.7 \angle 104.3^\circ\). In Figure 6b, the reference current of phase A is 15.7 \(\angle 90^\circ\) since the ASCC operates in mode 3. Consequently, due to a symmetrical fault, \(I_{b-ref}\) and \(I_{c-ref}\) are equal to 15.7 \(\angle 30^\circ\) and 15.7 \(\angle 150^\circ\) respectively. In Figure 6c, as a result of the operation of ASCC in mode 3, the current of phase A is 15.7 \(\angle 90^\circ\), and because of an unsymmetrical fault, \(I_{b-ref}=15.7 \angle 135.3^\circ\) and \(I_{c-ref}=15.7 \angle 104.3^\circ\) are obtained similar to the normal state. In addition, when the single-phase fault occurs, the AC components of DC link voltage of the converter \((U_{dc1} \text{ and } U_{dc2})\) are opposite to each other, and the total DC voltage is kept at the level of 600 V.

Figure 7 depicts the current and voltage waveforms of the superconducting transformer in the presence of the ASCC. Interval \(t=0.2-0.23\) sec. is the time for detecting the fault for the operation of the converter, and the line current is reduced to 44.38 A since the ASCC operates in mode 1. Similarly, from \(t=0.23\) sec. to 0.4 sec., by setting the phase angle of compensating current \((I_a)\) to 90°, defined as mode 3, the fault current is reduced to 30.76 A. It is notable that when a fault occurs, the fault current is suddenly reduced to a suitable level when the ASCC with its original setting operates in mode 1. After fault detection, based on the converter’s control strategy, the ASCC operates in mode 3, causing the maximum effect on current limiting. In other words, the operating modes of the ASCC are selected based on the reference signals.
Figure 6. Reference current of normal state (a), three-phase fault (b) and single-phase fault (c), and dc link voltage of converter for single-phase fault (d)

Figure 7. Waveforms of superconducting transformer: (a) primary current ($I_A$); (b) primary voltage ($U_A$); (c) secondary current ($I_a$); (d) secondary voltage ($u_a$)

Operation of OCRs

In the first state, the operation of one relay ($R_6$) was investigated and its appropriate setting parameters for the protective coordination in the whole modes of ASCC were calculated. Then the protective coordination of the whole relays, illustrated in Figure 4, was evaluated. For different
operating modes of ASCC, the time-current curve of the OCR is shown in Figure 8. To meet the protective coordination in modes 1 and 2, the modification of $TD$ value from ‘0.5’ to ‘0.1’ is inevitable. The operation times of OCR in this case are reduced to 0.27 sec. and 0.3 sec. respectively. When the ASCC operates in mode 3 and $TD$ is equal to ‘0.1’, the operation time of OCR is 0.57 sec. and thus, in this mode adjusting the other setting parameter of OCR ($I_{\text{pickup}}$) is necessary. According to Figure 8d, when the $TD$ value of OCR changes from ‘0.5’ to ‘0.1’ and $I_{\text{pickup}}$ is also modified from ‘2.1’ to ‘1.9’, the protective coordination in three operation modes is performed. Based on equation (5), in mode 3, when the amplitude of output current of the converter is increased, the current limiting further decreases, and consequently the protective coordination cannot be achieved even by adjusting the OCR parameters to their minimum values.

![Figure 8](image-url)

**Figure 8.** Time-current curve of OCR operation for the protective coordination with ASCC operation: (a) original settings of OCR; (b) Coordination with modified $TD$; (c) Coordination by modifying both $TD$ and $I_p$ for mode 3; (d) Coordination by modifying both $TD$ and $I_p$ for modes 1-3

In the second state, to study the protective coordination of the whole OCRs, simulations consisting of 27 cases of coordination (nine protective states and three modes of ASCC) were considered. The values of rated current ($I_n$), short-circuit current ($I_{SC}$), current transformer ratio and tap setting of relays as the initial setting of OCRs are tabulated in Table 3. The instantaneous relays were set based on 50% of the short-circuit current at point $F$ (Figure 4). $R_7$ was also set based on 1.25 $I_{SC}$ when the fault occurred in location $R_6$. It should be noted that $R_6$ is the backup protection for $R_7$, $R_5$ is the backup for $R_7$.

Figure 9 shows the time-current curves of $R_1$-$R_3$ with different values of $TD$ when the ASCC operates in mode 1. The multiple currents of $R_1$-$R_3$ are shown in Table 4. Based on Figure 9, in order to meet the protective coordination of $R_1$ to $R_3$ for mode 1, the modification of $TD$ value from ‘0.5’ to ‘0.4’ (for $R_2$-$R_3$) and to ‘0.3’ (for $R_1$) is needed. Figure 10 shows time-current curves of the main and backup protection of $R_6$ and $R_7$ in mode 1 of ASCC. To perform the protective
coordination of \( R_6 \) and \( R_7 \) in mode 1, the modification of their \( TD \) values to ‘0.1’ and ‘0.5’ respectively is needed. Table 5 lists the modified values of setting parameters of \( R_6 \) and \( R_7 \) in the three operation modes of ASCC.

**Table 3.** Values of OCR parameters

<table>
<thead>
<tr>
<th>Circuit breaker</th>
<th>( I_n ) (A)</th>
<th>( I_m ) (A)</th>
<th>Current transformer ratio</th>
<th>Tap setting of relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>252.11</td>
<td>12560</td>
<td>700/5</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>176.48</td>
<td>12560</td>
<td>700/5</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>226.9</td>
<td>12560</td>
<td>700/5</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>201.69</td>
<td>12560</td>
<td>700/5</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>201.69</td>
<td>12560</td>
<td>700/5</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>1058.87</td>
<td>12560</td>
<td>1100/5</td>
<td>8</td>
</tr>
<tr>
<td>7</td>
<td>157.46</td>
<td>21240</td>
<td>1100/5</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 9.** Time-current curves of \( R_1-R_5 \) in the case that \( TD \) is adjusted to meet the coordination in mode 1

According to Tables 4 and 5, if the modifications of \( TD \) value from ‘0.5’ to ‘0.3’ for \( R_1 \) and \( R_3 \) and from ‘0.5’ to ‘0.4’ for \( R_2, R_4 \) and \( R_5 \) are carried out, the protective coordination in mode 2 is achieved. In addition, the coordination of \( R_6 \) and \( R_7 \) in mode 2 is similar to that in mode 1. Similarly, when the ASCC operates in mode 3, the modification of \( TD \) value from ‘0.5’ to ‘0.3’ for \( R_1-R_5 \) is needed. By the same token, for the coordination of \( R_6 \) in mode 3, both setting parameters (\( TD \) and tap setting) need to be modified. Again, based on Table 5, the modifications of \( TD \) from ‘0.7’ to ‘0.1’ and also of the tap setting of relay from ‘7’ to ‘6’ are required for \( R_6 \). Finally, with the modification of \( TD \) from ‘1.7’ to ‘0.4’, the coordination of \( R_7 \) is done in mode 3.
Table 4. Setting parameters of $R_1$-$R_5$ in different modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Without correction</th>
<th>With correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Multiple of current</td>
<td>Trip time (sec.)</td>
</tr>
<tr>
<td>Mode1</td>
<td>$R_1$: 5.57 7.83 6.71 7.83 7.83</td>
<td>$R_2$: 0.27 0.22 0.24 0.22 0.22</td>
</tr>
<tr>
<td>Mode2</td>
<td>$R_1$: 5.43 7.67 5.57 7.67 7.67</td>
<td>$R_2$: 0.27 0.23 0.27 0.23 0.23</td>
</tr>
<tr>
<td>Mode3</td>
<td>$R_1$: 4.71 7.57 5.57 6.5 6.5</td>
<td>$R_2$: 0.31 0.24 0.27 0.24 0.24</td>
</tr>
</tbody>
</table>

Figure 10. Time-current curves of $R_6$ and $R_7$ to meet the coordination of main and backup protection in mode 1

Table 5. Setting parameters of $R_6$ and $R_7$ in different modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Tap setting of relay</th>
<th>$TD$</th>
<th>Multiple of current as backup protection</th>
<th>Trip time as backup protection (sec.)</th>
<th>Multiple of current as main protection</th>
<th>Trip time as main protection (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>$R_6$: 7 0.1</td>
<td>1.55</td>
<td>0.59</td>
<td>2.61</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_7$: 1 0.5</td>
<td>3.2</td>
<td>0.53</td>
<td>2</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td>$R_6$: 7 0.1</td>
<td>1.5</td>
<td>0.58</td>
<td>2.25</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_7$: 1 0.5</td>
<td>3.04</td>
<td>0.54</td>
<td>4</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Mode 3</td>
<td>$R_6$: 5 0.4</td>
<td>1.48</td>
<td>0.58</td>
<td>2.5</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$R_7$: 6 0.4</td>
<td>2.6</td>
<td>0.54</td>
<td>4</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>
CONCLUSION

When an ASCC was tested through simulations in a typical three-phase circuit to evaluate its effect on fault current limiting, simulation results confirmed the appropriate performance of different operation modes and control strategy of the ASCC. In other words, this study shows that by adjusting the ASCC in different operating modes, the setting parameters of OCRs are modified to obtain the protective coordination. Also, simulation results confirmed that for mode 3, when the amplitude of output current of the converter is increased, the current limiting further decreases. Although ASCC is more effective for current limiting in this case than the other cases, the protective coordination may deteriorate because of an excessive reduction in current even when the OCR parameters are adjusted to their minimum values. Therefore, this limitation should be considered in an ASCC setting.

REFERENCES


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