

A Novel Arc Suppression Coil

Abstract. The arc suppression coil (ASC) is one of the most important devices in distribution networks to obtain the optimal power supply quality. Though there exits many types of ASC, some problems have been still not solved. In order to develop an ASC with rapid and continuous tuning and limited harmonics, this paper proposes a novel type of ASC, which is based on a single phase matrix converter. Due to pulse width modulation (PWM) control, compensating currents can be adjusted in a wide range and the order of harmonics is so high to be filtered easily. Finally, by using PSCAD/EMTDC, simulations are given to illustrate the feasibility and validity of this novel ASC.

Keywords: Arc suppression coil, Resonant grounding, Compensated distribution network, Single-line-to-ground fault.

Introduction

An arc suppression coils (ASC) is an adjustable reactor connected between the neutral point and the ground, which was invented by Petersen in 1916 to suppress the fault current between the fault point and the ground (consequently it is also called Petersen coil). When a single-line-to-ground (SLG) fault occurs, by properly tuning the ASC, a lagging reactive current from the ASC and a leading current from the line-to-ground capacitance can be made almost exactly equal, so that the fault current is substantially zero. Under this condition the arc can not maintain itself, and is made self-extinguishing [1-3].

It is beneficial that the circuit will remain connected without tripping circuit breakers in the event of a SLG fault. This solution offers many advantages such as significant and economical improvements in safety and power supply quality. Therefore, the ASC is widely used in the 6-35kV distribution networks in China.

Until now many kinds of ASCs have been applied in the MV distribution network. For example, plunger core coils require a precise mechanical drive system, have a long response time and many noise [3-5]. Winding turned ASCs response more quickly and produce few harmonics, but can not continuously adjust the impedance [3, 6, 7]. Capacitor tuning ASCs use capacitors to cancel the inductive current generated from the reactor, but due to aging the capacitor value will become smaller as time goes on [8]. Magnetic controlled ASCs are more expensive [9-11]. Thyristor controlled ASCs overcome above drawbacks, but it is known that this kind of ASC generates low order harmonics. The unwanted low order harmonics are difficult to reduce [3, 12, 13].

In recent years some research scholars start to utilize the power electronic technology to design ASCs. [14] and [15] introduce an ASC based on transformer with controlled inverter load. The compensating current is generated by a DC/AC inverter. This voltage source pulse width modulation (PWM) inverter works as the secondary load of transformer, the reactance of the ASC can be regulated arbitrarily through controlling the inverter output current. However, one or more DC power is needed.

To overcome these drawbacks, this paper proposes a novel ASC, which is based on the single-phase matrix converter (SPMC) principle and the PWM technology.

The circuit topology and principles

As shown in Fig. 1, the novel ASC consists of a single phase matrix converter (SPMC), a reactor, a 3-winding step-down transformer and a low-pass filter. If a neutral point exits, the ASC can directly connect to it. If there is no wye point available for ASC connection to ground, an artificial neutral must be created on delta connection systems.

Fig.1. Simplified equivalent circuit diagram of a distribution network in the event of a SLG fault

The SPMC, which was first realized by Zuckerberger [16-18], is a forced commutated converter that uses an array of controlled bi-directional switches as the main power elements to create a variable output voltage system with unrestricted frequency. It does not have any dc-link circuit and does not need any large energy storage elements.

The SPMC consists of four bi-directional switches capable of blocking voltage and conducting current in both directions as shown in Fig. 1 [16]. Because the bi-directional switch is not available to date, it can be implemented by connection of two diodes and two IGBTs in anti-parallel (common emitter back to back) as shown in Fig. 1. The IGBT were used because of its high switching capabilities and high current carrying capacities desirable for high-power applications.

Owing to limitations of low rated voltage of IGBT, a 3-winding step-down transformer is needed. The low-pass filter, which is connected to the tertiary winding, is used to filter high order harmonics in compensating currents. For the sake of clarity, the 3-winding transformer and the low-pass filter are negligible in the following discussion.

Gating signals are generated by comparing a reference signal \( u_i \) with a triangular carrier wave \( u_c \) of frequency \( f_c \) as shown in Fig. 2, where the symbols \( U_{cm}, U_{cm} \) are the peak amplitude of the carrier and the reference signal, respectively.
where:

\[ \begin{align*}
\alpha_k &= (2k-1)\pi - M\pi \\
\beta_k &= (2k-1)\pi + M\pi
\end{align*} \]

Fig. 3 shows the \( k \) triangular carrier \( u_c \) crosses the reference signal \( u_r \) at points of \( \alpha_k \) and \( \beta_k \), which can be represented as shown in (3).

With the initial condition described in (5), the solution of (4) is given as (6).

(7) 
\[ I_o(\beta_k) = \frac{U_m}{|Z|} \sin(\beta_k - \phi) + e^{\frac{\pi}{\omega}(\alpha_k-\alpha_i)} \]

During the ON state, the working current \( i_o \), equals \( i_o \) as shown in (8).

(8) 
\[ i_o = \frac{U}{Z} \sin(\beta_k - \phi - \alpha_c) \]

If \( 2(k-1)\pi \leq \alpha_c \leq \beta_k \), the circuit is at OFF state. Similarly, with Kirchhoff’s Voltage Law applied, the output current \( i_o \), can be solved from (9).

(9) 
\[ 0 = i_o R + L \frac{di_o}{dt} \]

The initial value of \( i_o \) at \( \omega t = \beta_k \) is given in (7). Then the solution of (9) is got as (10).

(10) 
\[ i_o = I_o(\beta_k) e^{\frac{\pi}{\omega}(\alpha_k-\alpha_i)} \]

At the end of the OFF state, \( \omega t = \alpha_c, \). The output current \( i_o \), is given as (11).
\[ I_o(\alpha_{k+1}) \equiv I_o(\omega t)|_{\alpha=\alpha_k} = I_o(\beta_k) e^{\frac{\omega}{Z}(\alpha_k-\beta_k)} \]  

And this value is the initial value of the next ON state. During the OFF state, the working current \( i_o \) is zero as shown in (12).

\[ i_o = 0 \]

The two modes as described above are regularly repeated and the output current \( i_o \) is continuous, but the working current \( i_w \) is discontinuous. The waveforms of the output current \( i_w \) and the working current \( i_o \) during a switching period \([2k-1]\pi, 2k\pi]\) are respectively given from (13) and (14).

\[ i_o = \begin{cases} \frac{U_m}{Z} \sin(\omega t - \phi) + e^{\frac{\pi}{Z}(\alpha_k-\beta_k)} [I_o(\alpha_k) - I_o(\beta_k)], & \alpha_k \leq \omega t \leq \beta_k \\ 0, & \text{others} \end{cases} \]

(13)

\[ i_w = \begin{cases} \frac{U_m}{Z} \sin(\alpha_k - \phi), & \alpha_k \leq \omega t \leq \beta_k \\ 0, & \text{others} \end{cases} \]

(14)

**Harmonics analyses of the working current**

Let an input \( f_o(t) = F_o \sin \omega t \) be controlled by the PWM signals as shown in Fig. 2, the output \( f_o(t) \) can be expressed as (15).

\[ f_o(t) = \begin{cases} f_o(t), & \alpha_k \leq \omega t \leq \beta_k \\ 0, & \text{others} \end{cases} \]

(15)

According to the double Fourier series [19], the output \( f_o(t) \) can be described in a Fourier series as shown in (16) or (17).

\[ f_o(\omega t) = M F_m \sin \omega t + \sum_{n=1}^\infty (-1)^n \frac{F_m}{n\pi} \sin(n \omega t) \]

(16)

\[ f_o(\omega t) = F_m \sin \omega t \cdot g(\omega t) \]

(17)

where:

\[ g(\omega t) = M + \sum_{n=1}^\infty (-1)^n \frac{2 \sin(n \omega t)}{n\pi} \cos(n \omega t) \]

(18)

Thus, the output voltage \( u_o \) can be put in form of (19).

\[ u_o = MU_m \sin \omega t + \sum_{n=1}^\infty (-1)^n \frac{U_m}{n\pi} \sin(n \omega t) \]

(19)

Obviously, the fundamental component of the output voltage \( u_o \) is

\[ u_{o1} = MU_m \sin \omega t \]

The output current \( i_o \) can be yielded as (21).

\[ i_o = \frac{MU_m \sin(\omega t - \chi)}{|Z|} + \sum_{n=1}^\infty (-1)^n \frac{U_m \sin n M \pi}{n\pi} \sin(\omega t \pm n \omega t - \chi) \]

\[ \sum_{n=1}^\infty (-1)^n \frac{U_m \sin n M \pi}{n\pi} \sin(\omega t \pm n \omega t - \chi) \frac{Z_n}{Z_1} \]

(21)

where: \( Z = R + j\omega L \) and \( \chi = \arctan(oL/R) \) are the harmonic impedance and its phase angle. For a special example, if \( n = 1 \), \( \chi = \arctan(oL/R) = \phi \).

Similarly, the working current \( i_w \) can be derived from \( i_w = i_o g(\omega t) \), then

\[ i_w = \sum_{n=1}^\infty (-1)^n \frac{2 \sin n M \pi}{n\pi} \cos(n \omega t) \]

(22)

Thus, the fundamental component of \( i_w \) is

\[ i_{w1} = \frac{M U_m \sin(\omega t - \chi)}{|Z|} \]

(23)

It is obviously seen from (21) and (22) that the fundamental component of the output current \( i_w \) is linearly proportional to the modulation factor \( M \), but that of the working current \( i_o \) is not. The value of fundamental working current \( i_w \) can be controlled in a wide range by adjusting the modulation factor \( M \), which can be simply obtained by comparing a triangular wave with a reference signal. However, the working current \( i_o \) is not continual. When it is zero, the neutral point will become floating. Additionally, the ASC can only compensate the fundamental component of the fault current. So we can utilize filters to reduce harmonics and obtain the continual fundamental component.

The dominant harmonics of the current are near the switching frequency and its multiplies \((o \pm n \omega_o)\). Compared with thyristor controlled ASCs, due to the high switching frequency, these high order harmonics contents are more easily filtered. Therefore, only a low-pass filter can reduce the harmonics in the working current and maintain the continuity of compensating currents. This is one of advantages.

**Simulations**

This section consists of two parts: one is to verify the relationship between the working current of the ASC and the modulation factor \( M \) of the SPMC; the other is to validate the compensated effect of the ASC in a distribution network. The well-known PSCAD/EMTDC program was used to analyze how this ASC work [23].

Part 1: a voltage source with 5.774kV takes the place of the neutral voltage (In fact, the neutral voltage is nearly 5.774kV when a SLG fault occurs in a 10kV distribution network). Parameters in this simulation are listed in Table 1. By changing the modulation factor \( M \), we can get different working currents as shown in Table 2, where the second column lists the fundamental component of working currents without the low-pass filter, while results shown in
the third column describes the effect of the low-pass filter. Obviously, due to the low-pass filter, the working current becomes smaller.

Table 1. The simulation parameters in Part 1

<table>
<thead>
<tr>
<th></th>
<th>Reactor</th>
<th>Step-down transformer</th>
<th>Low-pass filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>L=7.352 mH</td>
<td>6/1/2/0.5 kV</td>
<td>C_f=144 μF, L_f=0.085 mH</td>
</tr>
</tbody>
</table>

Table 2. Working currents

<table>
<thead>
<tr>
<th>Modulation factor</th>
<th>No low-pass filter [A]</th>
<th>Low-pass filter [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>0.2</td>
<td>4.0</td>
<td>2.6</td>
</tr>
<tr>
<td>0.3</td>
<td>9.0</td>
<td>7.1</td>
</tr>
<tr>
<td>0.4</td>
<td>16.1</td>
<td>13.4</td>
</tr>
<tr>
<td>0.5</td>
<td>25.1</td>
<td>20.9</td>
</tr>
<tr>
<td>0.6</td>
<td>36.2</td>
<td>29.4</td>
</tr>
<tr>
<td>0.7</td>
<td>49.2</td>
<td>38.6</td>
</tr>
<tr>
<td>0.8</td>
<td>64.1</td>
<td>48.1</td>
</tr>
<tr>
<td>0.9</td>
<td>81.0</td>
<td>57.8</td>
</tr>
</tbody>
</table>

Fig. 4 shows a 2-cycle wave of the working current in case of no low-pass filter and the modulation factor M=0.7. It is evident that the working current is not continuous and contains many harmonics. As result of a low-pass filter, the working current becomes smooth (Fig. 5).

Fig. 5 The working current (with a low-pass filter)

Part 2: according to Fig. 1, a simple radial distribution network is constructed. This distribution network consists of 4 feeders. The power supply voltage is 10kV neglected the source impedance, which simulates an infinite power system. The length of each feeder is 2km, 6km, 12km and 13km respectively, whose parameters are as follows [24]: the positive sequence resistance R_1=0.075Ω/km, the positive sequence inductance L_1=0.254mH/km and the positive sequence capacitance C_1=0.316μF/km; the zero sequence resistance R_0=0.102Ω/km, the zero sequence inductance L_0=0.892mH/km and the zero sequence capacitance C_0=0.210μF/km.

A typical SLG fault was examined at the middle of the 13-km-long feeder. This simulation network has a total length of 33km, with the total capacitance current of 37.8A. According to Table 2, we should set the modulation factor M=0.7 so as to make the ASC work at a full-compensation state.

Fig. 6 and Fig. 7 show simulation results. When the SLG fault occurred at 0.103s, a transient over-current happened as shown in Fig. 6. Because of compensation of this novel ASC, the current-to-ground at the fault location drops from the maximum peak (165.1A) to 5.736A, to 3.239A, which are a small residual value (RMS<5A) as shown in Fig. 6. Therefore, the fault current can be limited to lower than 5A, so that the arc can not reignite. Due the fault resistance equals nearly zero, the neutral voltage increased to the phase voltage as shown in Fig. 7. When the fault disappeared at 0.410s, the neutral voltage decreases relatively slowly and it was not 866V (15% of the phase voltage 5.774kV) until t=1.145s (Fig. 7). That is to say, the recovery voltage in the fault phase is likewise slow. This characteristic is very beneficial for the suppression of the arc reignition.

Conclusions

This paper presents a novel ASC, which is based on SPMC and PWM technology. Compared with other ASC such as winding turned ASC and the thyristor controlled ASC, this ASC not only can be continually tuned, but also generates much high order harmonic contents, which are easy to filter. If the value of the ASC is correctly tuned the current of a possible earth fault can be reduced to a suitable range. Simulations illustrate feasibility and validity.

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