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Influence of Hybrid Reactive Power Compensation on the Secondary Arc of Ultra-High-Voltage Transmission Lines (May 2018)

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ABSTRACT Hybrid reactive power compensation (HRPC) which consists of series compensation and a stepped-controlled shunt reactor will see use in China's future ultra-high-voltage (UHV) transmission system. As a result, some new characteristics of the secondary arc during a single-phase-to-ground fault on UHV transmission lines with HRPC may be raised. In this paper, the secondary arc characteristics during the single-phase auto-reclosure (SPAR) operation have been simulated with regard to the UHV AC system installed with HRPC. Based on the UHV system model with HRPC and its secondary arc model, the influence mechanism of HRPC on secondary arc current is theoretically derived with the simulated waveforms and the Fourier analysis. Besides, the relationship among the secondary arc current, the arcing time with different HRPC compensation degrees, neutral reactance, as well as the grounding fault locations have been investigated in detail. Finally, an improved time sequential control strategy of bypass breaker and SPAR has been put forward. The research presented in this paper will provide necessary theoretical basis and technical support for the future application of HRPC in UHV transmission lines.

INDEX TERMS Hybrid reactive power compensation, secondary arc, single-phase auto-reclosure, ultra-high-voltage.

I. INTRODUCTION

Ultra-high-voltage (UHV) power transmission technology has become an important choice to optimize the resources allocation and improve the efficiency of the energy utilization. A number of UHV AC transmission lines have been put into operation, which gradually builds up Chinese UHV AC synchronous networks [1]–[3]. However, the safe and stable operation of the UHV AC synchronous network will face new challenges. With the influence of system stability limit, the transmission capacity enhancement of some transmission lines cannot satisfy the demand of the increasing load [4], [5]. There is also a contradiction between the high compensation degree of the fixed shunt reactors for restricting power frequency overvoltage and the requirement of reactive power adjustment for rapid-changing transmitting active power [6]–[9]. The hybrid reactive power compensation (HRPC) including series compensation (SC) and stepped controlled shunt reactor (SCSR) will be widely applied in UHV AC power grids as it can balance the growth of transmission active power and the adjustment of reactive power effectively [10]–[12]. However, the application of the HRPC will complicate the reactive compensation of UHV systems. Consequently, it is necessary to study the influence of the HRPC on the UHV transmission lines.

The single-phase auto-reclosure (SPAR) is widely adopted in the UHV transmission lines as to improve system stability [13]. The success of SPAR depends on timely extinction of secondary arcs [14]. The UHV system has the characteristics of high voltage, long distance and bulk capacity, which will prolong the arcing time of the secondary arc. If the secondary arc cannot be extinguished in time, the circuit breaker may be closed before clearing an arc grounding fault and cause a failure of SPAR [15]. After the installation of HRPC on UHV transmission lines, there will be some new characteristics of secondary arc during a single-phase-to-ground fault, which is not a simple combination of the effects of SC and SCSR on the characteristics of the secondary arc. The effects of low frequency oscillation caused by SC and SCSR may reduce the number of zero crossings of secondary arc current [16]. As a result, the arcing time of secondary arcs will be prolonged and may lead to SPAR failure [14]. Thus, the conventional analysis of second arc during SPAR operation of UHV transmission lines cannot effectively guide the future engineering applications of HRPC [17].

In view of the above problems, the secondary arc characteristics for SPAR have been simulated and computed in this paper with regard to the UHV AC system installed with HRPC. We discovered the influence mechanism of HRPC on the secondary arc currents, the relationship between different factors, and an improved time sequential control strategy for bypass breaker and SPAR, which serves as a step-forward progress in the field of HRPC.

This work is organized as follows: In Section II, the UHV system with HRPC and its secondary arc model have been introduced. In Section III, the influence mechanisms of HRPC on secondary arc current has been theoretically derived with the simulated waveforms and Fourier analysis. In Section IV, the effects of HRPC compensation degree, neutral reactance as well as the grounding fault location on secondary arc have been evaluated. Finally, in section V, the time sequence of bypass breaker of HRPC and SPAR has been put forward [18]. These above researches will provide a necessary theoretical basis and technical support for the promotion of HRPC design, which has an important scientific significance for the future application of UHV HRPC technology.

II. THE UHV SYSTEM WITH HRPC AND ITS SECONDARY ARC MODEL

The 1000 kV UHV AC power system is taken as the research object in this paper. The arrangement of HRPC in UHV power system is shown in Fig.1. The SCs and the SCSRs are set at both terminals of the transmission line. Referring to Jin Southeast-Nanyang-Jingmen 1000 kV AC demonstration project of China, the main parameters of the UHV transmission line is shown in Table 1.

An improved Mayer equation is adopted to represent the dynamic arc resistance model of secondary arc. The model is divided into two stages, including the short-circuit arc and secondary arc stage. The dynamic equation of the arc is expressed as (1) [19], [20].

$$\begin{cases} \mathrm{d}g_a/\mathrm{d}t = (G_\mathrm{a} - g_\mathrm{a})/T_a \\ G_\mathrm{a} = |i_a|/(E_a l_a t_r) \end{cases} \tag{1}$$

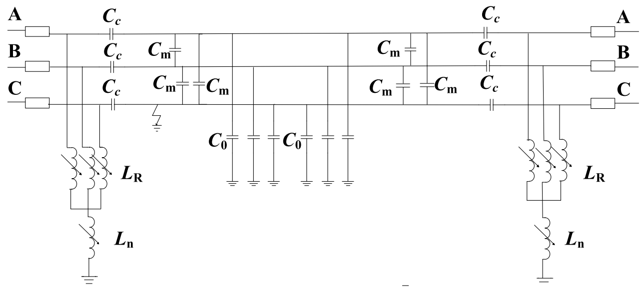

FIGURE 1. The arrangement of HRPC in UHV power system.

TABLE 1. Main parameters of 1000 kV transmission line.

Parameters		Unit	Value
system frequency		Hz	50
system power bus voltage		kV	1087
three - phase short - circuit capacity		GVA	50
line length		km	600
Line parameters (positive / zero sequence)	R	$\Omega\cdot km^{-1}$	0.007 83 0.196 37
	L	$mH\cdot km^{-1}$	0.834 08 2.673 66
	C	$\mu F\cdot km^{-1}$	0.013 79 0.008 46

where, g_a is the time-varying conductance of secondary arc; G_a is the steady conductance of secondary arc; g_a is the time varying arc conductance; T_a is the time constant; $|I_\mathrm{a}|$ is the absolute value of arc current; E_a is constant voltage parameter per unit length of secondary arc; l_a is the arc length.; t_r is the time from the initiation of secondary arc The subscription a could be p or s, which means short-circuit arc (p) or secondary arc (s).

The rate of rise of secondary arc voltage (given as $V_s l_s(t_r)/(0.15 I_s)$) is used to determine the time constant T_a, which is empirically obtained as

$$T_a = \frac{\beta I_a^{1.4}}{l_a t_r} \tag{2}$$

where I_a is the peak value of secondary arc current, the coefficient β is about 2.51×10^{-3} for low current arcs, which is empirically obtained by fitting (1) and (2) to match the experimental cyclograms of the low current arcs.

The main structure of HRPC is shown in Fig. 2. SC consists of a capacitor bank, a metal oxide arrester (MOA), a spark gap, a bypass breaker, and a damping device. In normal operation, only the capacitor bank is put into operation. MOA is the overvoltage main protection for capacitor bank. Spark gap is the overheat protection of MOA. The bypass breaker is a necessary device for system maintenance and scheduling, and it also provides the necessary conditions for the deionization of the spark gap. The damping device is used to limit the discharge current of the capacitor and prevent damage to the capacitor bank, spark gap, and bypass breaker during discharge. SCSR consists of a high impedance transformer, a set of series reactors, mechanical switches and thyristors. The high-impedance transformer contains the primary and

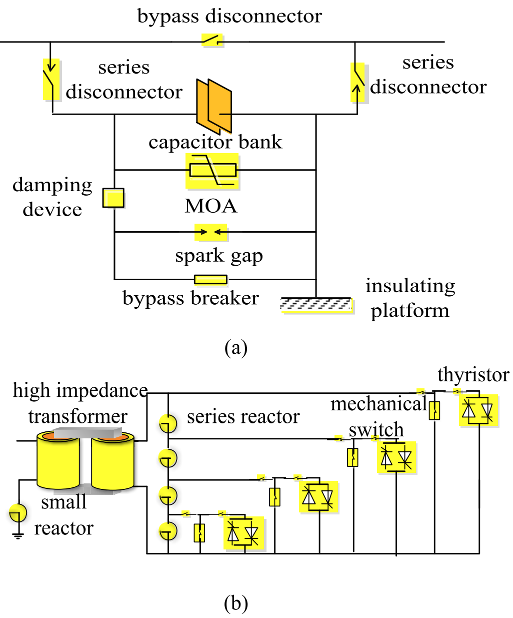

FIGURE 2. Structure of HRPC. (a) Series compensation. (b) Stepped controlled shunt reactor.

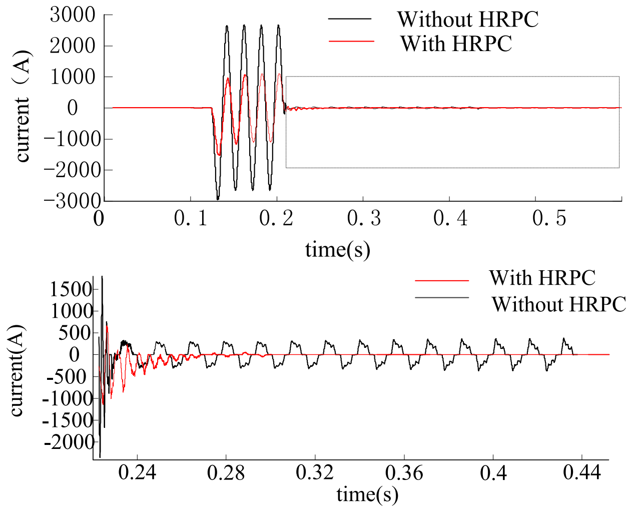

FIGURE 3. The single-phase-to-ground fault current waveform of UHV transmission line with hybrid reactive compensation before and after installation.

secondary windings, and the secondary side is connected with a series reactance. The number of series reactors is changed through thyristors and mechanical switches to adjust the capacity in stages. The thyristor completes the fast adjustment of the SCSR capacity, and the mechanical switch is used for bypassing the capacitor in the steady state operation to simplify the thyristor cooling system.

III. INFLUENCE MECHANISM OF HRPC ON SECONDARY ARC CURRENT

The resonance between the inductance and capacitance in different oscillation frequencies will occur on the UHV transmission lines installed with HRPC. In this circumstance, the secondary arc current will be affected and its oscillation may lead to the failure of single phase auto-recloses. In case that single phase to ground fault occurs at the midpoint of the transmission line, the secondary arcs of UHV power system before and after the installation of HRPC are simulated. The compensation degrees of the SCs and the SCSRs are set as 0.2, 0.44, respectively, which is selected from the parameters of fixed shunt reactor and SC installed in Jin Southeast-Nanyang-Jingmen 1000 kV AC demonstration project of China. Assuming that the secondary arc resistance is 10Ω, the circuit breakers at both ends of the transmission line clear the single-phase-to-ground fault successively at the time t_0 (0.1s).

According to the simulated waveforms of the secondary arc current at the fault point shown in Fig. 3, the short circuit arc extinguishes at the time t_2 (0.11s) after the circuit breaker tripped at the time t1 (0.1s), and the secondary arc appears at the same time in the situation that the HRPC is installed on the line. From the time t_2, the secondary arc undergoes a repeated process of igniting-extinguishing- reigniting, and the secondary arc extinguishes at the time t_3 (0.218s) eventually, where t_2 to t_3 is the arcing time of the secondary arc.

From the waveforms with installing HRPC in Fig.3, it is shown that the DC component of the secondary arc current is superimposed by the frequency component and the low frequency oscillation component which is rapidly attenuated in about two power frequency cycles. The waveform of the secondary arc current without compensation is characterized by the beat frequency, which is approximated to the superposition of several different frequency components. Considering that the SC is arranged at the side of the SCSR in the simulation model, the fault is assumed to occur in the midpoint of the transmission line. The capacitor residual charge causes the oscillation by discharging through the circuit consisted with SC capacitor, parallel shunt inductor and arc channel. The DC and low frequency components in the secondary arc current lead to the decrease of zero crossing times of the secondary arc current, which increases the difficulty of self-extinguish of secondary arc. To explore the influence of each frequency component on the secondary arc, it is necessary to do a Fourier analysis of secondary arc current before and after HRPC installation.

Each frequency component of secondary arc current is obtained by Fourier analysis which is shown in Table 2. When the HRPC is installed in the system, the amplitude of the power-frequency component of the secondary arc current drops from 250.8A to 18.6A, the amplitude of DC component is 67.9A and the low frequency component is 100.9A. After the initial extinction of the secondary arc, the secondary arc re-ignition may cause the failure of reclosure in case that the amplitude of the recovery voltage in the fault is higher than the dielectric recovery voltage.

After interrupting transient single-phase-to-ground fault, the energy storage components in UHV power system like

TABLE 2. Oscillation frequency of secondary arc current by FFT.

Parameter	Frequency component /A	DC component /A	Low frequency component /A
Installed HRPC	18.6	67.9	100.9
No HRPC	250.8	0	0

inductors, capacitors of the transmission line and the HRPC can form the circuits with a variety of different oscillations, which can determine the oscillation frequency of the power system and affect the amplitude-frequency characteristics of the secondary arc current. For further analysis of the generation mechanism of low frequency components of secondary arc current, the method of Laplace transform can be used to build the equivalent impedance circuit after interrupting the faulty phase. In order to obtain the low frequency component and attenuation coefficient of the secondary arc current, an equivalent circuit after interrupting the faulty phase is proposed in Fig. 4 which considers two cases that the capacitors of the SC are bypassed or not. C_C is the equivalent capacitance of series compensation, L_R is the equivalent inductance of parallel compensation, L_m is the inductance that compensate for the phase-to-phase capacitance, C_m is the phase-to-phase capacitance, L_0 is the inductance compensate for the phase-to-ground capacitance, C_0 is the phase-to-ground capacitance, R_g is the arc resistance and R_1, L_1, C_1 are the line equivalent resistance, inductance and the capacitance respectively.

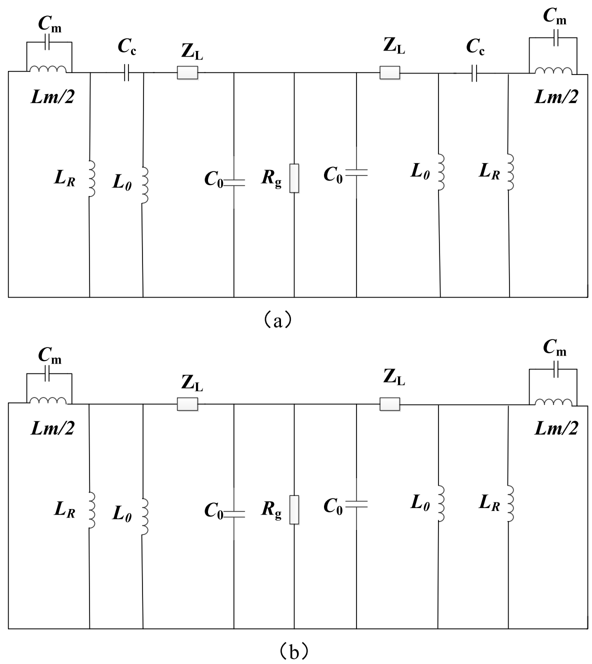

FIGURE 4. Equivalent calculation circuit of the single-phase-to-ground fault with HRPC. (a) Capacitor is not bypassed. (b) Capacitor is bypassed.

After applying Laplace transform, the equivalent impedance of the case that the capacitors of the SC are not bypassed is expressed as follows:

$$Z_g = \frac{a_6 s^6 + a_5 s^5 + a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}{b_7 s^7 + b_6 s^6 + b_5 s^5 + b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s} \quad (3)$$

where:

$$\begin{aligned}
a_6 &= C_1 C_m C_c L_0 L_1 L_m L_R;\\
a_5 &= C_1 C_m C_c L_0 L_M L_R R_1;\\
a_4 &= C_1 C_c L_0 L_1 L_m + 2C_1 C_c L_0 L_1 L_R + C_1 C_m L_0 L_m L_R\\
&\quad + C_1 C_m L_1 L_m L_R + C_1 C_c L_0 L_m L_R\\
&\quad + C_1 C_c L_1 L_m L_R + C_m C_c L_0 L_m L_R;\\
a_3 &= C_1 C_c L_0 L_m R_1 + 2C_1 C_c L_0 L_R R_1\\
&\quad + C_1 C_m L_m L_R R_1 + C_1 C_c L_m L_R R_1;\\
a_2 &= C_1 L_0 L_m + C_1 L_1 L_m + 2C_1 L_0 L_R + 2C_1 L_1 L_R\\
&\quad + C_c L_0 L_m + 2C_c L_0 L_R + C_m L_m L_R + C_c L_m L_R;\\
a_1 &= C_1 L_m R_1 + 2C_1 L_R R_1;\\
a_0 &= L_m + 2L_R;\\
b_7 &= C_0 C_1 C_m C_c L_0 L_1 L_m L_R;\\
b_6 &= C_0 C_1 C_m C_c L_0 L_m L_R R_1;\\
b_5 &= C_0 C_1 C_c L_0 L_1 L_m + 2C_0 C_1 C_c L_0 L_1 L_R\\
&\quad + C_0 C_1 C_m L_0 L_m L_R + C_0 C_1 C_m L_1 L_m L_R\\
&\quad + C_0 C_1 C_c L_0 L_m L_R + C_0 C_1 C_c L_1 L_m L_R\\
&\quad + C_0 C_m C_c L_0 L_m L_R + C_1 C_m C_c L_0 L_m L_R;\\
b_4 &= C_0 C_1 C_c L_0 L_m R_1 + 2C_0 C_1 C_c L_0 L_R R_1\\
&\quad + C_0 C_1 C_m L_m L_R R_1 + C_0 C_1 C_c L_m L_R R_1;\\
b_3 &= C_0 C_1 L_0 L_m + C_0 C_1 L_1 L_m + 2C_0 C_1 L_0 L_R\\
&\quad + 2C_0 C_1 L_1 L_R + C_0 C_c L_0 L_m + C_1 C_c L_0 L_m\\
&\quad + 2C_0 C_c L_0 L_R + 2C_1 C_c L_0 L_R + C_0 C_m L_m L_R\\
&\quad + C_1 C_m L_m L_R + C_0 C_c L_m L_R + C_1 C_c L_m L_R;\\
b_2 &= C_0 C_1 L_m R_1 + 2C_0 C_1 L_R R_1;\\
b_1 &= C_0 L_m + C_1 L_m + 2C_0 L_R + 2C_1 L_R;
\end{aligned}$$

From the expression, the free oscillation frequency can be determined by the high-order equation:

$$b_7 s^7 + b_6 s^6 + b_5 s^5 + b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s = 0 \quad (4)$$

The impedance expression for the case that the capacitors of the SC are bypassed can also be obtained by applying the similar principle. The low oscillation frequencies and corresponding attenuation coefficients of secondary arc current are shown in Table 3 for these two cases. In the case that the capacitor of SC is bypassed, it doesn't have the frequency of low frequency oscillation of secondary arc current. It will be propitious to the extinction of the secondary arc.

IV. MAIN INFLUENCE FACTORS OF THE SECONDARY ARC CHARACTERISTICS

A. EFFECT OF HRPC COMPENSATION DEGREE ON SECONDARY ARC CURRENT AND ARCING TIME

The effect of HRPC compensation degree on secondary arc current and arcing time is evaluated in this section by

TABLE 3. Oscillation frequency and decay factor of secondary arc current.

Condition	THE solution OF S	Low frequency component frequency/Hz
Capacitor is not bypassed	s1,s2=-3.28±j1876.54 s3,s4=-1.41±j471.84 s5,s6=-0.000309±j50.672	8.064
Capacitor bypass	s1,s2=-3.273±j1871.62 S3,s4=-1.42±j469.059	no

assuming that all the parameters except the compensation degree of SC in the UHV transmission line will keep constant. When a single-phase-to-ground fault occurs at the midpoint of the transmission line, the relationship curves of the secondary arc current amplitude and the arcing time with different compensation degrees of SC are shown in Fig. 5.

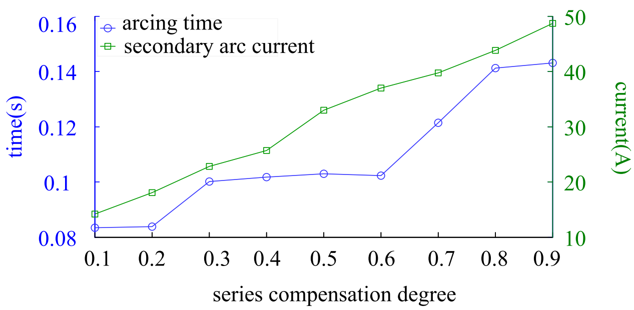

FIGURE 5. Relationship between secondary arc current and different compensation degrees of SC.

According to Fig 5, the arcing time of the secondary arc shows an increasing trend of ladder with the compensation degree from 0.1 to 0.9., the longest arc extinction time (0.142s) happens when the compensation degree is 0.9. And the amplitude of secondary arc current increases linearly with the compensation degree of SC, which means the increase of the SC compensation degree leads difficulty of the secondary arc extinguishment. Considering the variation of current amplitude and arcing time of secondary arc with different SC compensation degrees, the influence of secondary arc extinguishment on the single phase reclosure should be considered when the SC compensation degree is large and a reasonable closing time of the circuit breaker should be set to ensure the safety and reliable operation of the power system.

The SCSR compensates the distributed capacitor of the transmission line during normal operation. After the single-phase-to-ground fault occurs, the neutral reactance of SCSR changes the electrical characteristic of the secondary arc. Fig. 6 shows the relationship curves of the secondary arc current amplitude and the arcing time changed with different

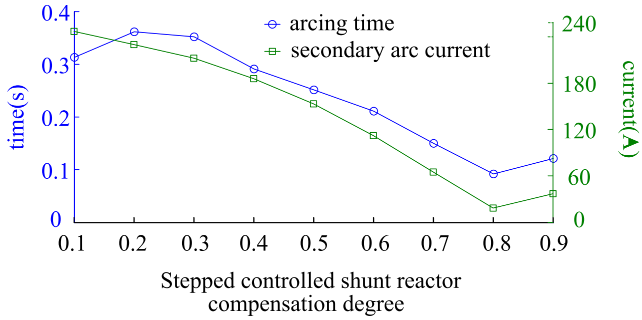

FIGURE 6. Relationship between secondary arc current and different compensation degrees of SCSR.

compensation degrees of SCSR when the neutral reactance remains unchanged.

According to the results in Fig. 6, the amplitude value of the secondary arc current changes in the range of 15A to 260A with the increase of the SCSR compensation degree. And the amplitude is the lowest when the compensation degree of SCSR is 80%. Compared with the secondary arc current that changes with the SC compensation degree, the variation range of the secondary arc current is larger than it when the compensation degree of SCSR changes. When the compensation degree of SCSR increases by 10%, the amplitude of the secondary arc current will decrease by about 30A, which is much higher than that of the same compensation degree of SC. The relationship curve between the arcing time and compensation degree of SCSR changes between 0.09s to 0.37s, which is much the same as the variation trend of the secondary arc current amplitude. The arcing time of the secondary arc increases with the increase of the compensation degree of SCSR, and the minimum value is approached when the compensation degree of SCSR is 80%. When the compensation degree of SCSR is 80%, a parallel resonance of the interphase inductance and capacitance between sound and fault phases occurs. This resonance helps to restrain secondary arc current amplitude and extinguish the secondary arc quickly. Thus, in order to effectively suppress the secondary arc current, the neutral reactance of the SCSR should be adjusted to the optimal compensation value with corresponding compensation degree of the SCSR. The optimized value of neutral reactor is concluded from the full compensation principle of interphase capacitance after transient fault, since the circuit is open if parallel resonance occurs.

B. EFFECT OF NEUTRAL REACTANCE ON SECONDARY ARC

At present, the neutral reactance installed at the neutral point of shunt reactor is widely used to shorten the arcing time of secondary arc. As the reactance value of SCSR varies according to the system state, the neutral reactance should be adjusted with the operating mode of SCSR. In practice, the neutral reactance usually is selected by the 1/3 of the shunt reactor as to avoid the series resonant overvoltage [21].

In order to investigate the influence of the neutral reactance on the secondary arc, the changing rule of arcing time, DC component amplitude and power frequency component amplitude of the secondary arc current with different neutral reactance from the 300mH to 1100mH are analyzed with constant compensation degree of HRPC, which are shown in Fig. 7.

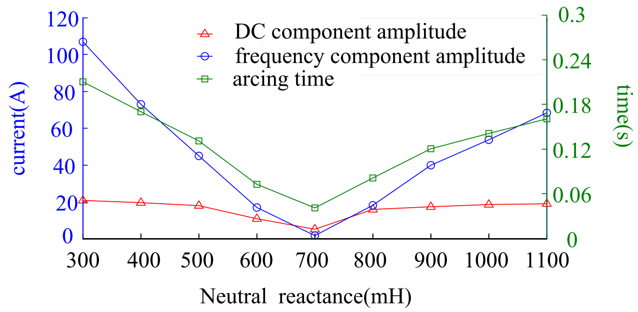

FIGURE 7. **Neutral reactance and DC component, power frequency component, arcing time relationship.**

The variation rules of arcing time, DC component amplitude and power frequency component amplitude of the secondary arc current with different neutral reactance are similar. The amplitude of arcing time, DC component and power frequency component of the secondary arc current approaches the smallest value when the neutral reactance is 700mH (about one third of SCSR inductance). Among them, the variation range in the amplitude of frequency component is larger than the DC component of secondary arc. In the vicinity of the optimum value of neutral reactance, the secondary arc current is only 1.7A, and the secondary arc will be successfully extinguished in 0.0407s. From Fig. 7, the greater the difference between the neutral reactance value and 700mH are, the larger the secondary arc oscillation and the arcing time of secondary arc are. In summary, choosing a reasonable neutral reactance with specific compensation degree of SCSR can achieve a good inhibition of the secondary arc.

C. INFLUENCE OF SECONDARY ARC RESISTANCE ON THE CHARACTERISTICS OF SECONDARY ARC CURRENT

In addition to the compensation degree of HRPC and neutral reactance of SCSR, the value of arc resistance at the fault point also has a great impact on the secondary arc current. Table 4 shows the relationship between the secondary arc current and the secondary arc resistance with different compensation modes.

TABLE 4. **Relationship between secondary arc resistance and secondary arc current.**

Compensation method	Compensation degree	Arc resistance			
		100	200	300	400
No compensation	0	244.4A	222.2 A	196.8 A	172.9 A
Only SC	20%	310.9 A	279.8 A	246.4 A	215.7 A
Only SCSR	88%	147.4 A	85.55 A	10.5 A	9.85 A
HRPC	SC 20% SCSR 88%	110.2 A	49.9 A	18.1 A	12.2 A

As shown in Table 4, the secondary arc current is effectively suppressed after the installation of HRPC compared to the power system without any compensation. When the arc resistance value is 400Ω, the maximum value of secondary arc current can be limited to about 7% in the installed SCSR power system without compensation. The secondary arc current always decreases with the increase of arc resistance regardless of compensation mode. The suppressing effect to the secondary arc current is the best under the compensating mode only installed with SCSR. The attenuation of secondary arc current in the power system only with SCSR is the fastest with the arc resistance. When the SC is only installed in the transmission line, the equivalent impedance of the transmission line decreases and the secondary arc current amplitude becomes larger than it in the power system only installed with SCSR or installed with HRPC, which increase the difficulty in secondary arc extinguishment.

D. INFLUENCE OF GROUNDING FAULT LOCATION ON THE CHARACTERISTICS OF SECONDARY ARC

In practice, the fault location on the transmission line is uncertain. In order to obtain the characteristics of secondary arc at different fault positions, five positions are analyzed respectively, such as at the terminal, 1/8, 2/8, 3/8, and-middle point of the transmission line. The influence of fault location on secondary arc current and transient recovery voltage are shown in Table 5.

TABLE 5. **The influence of fault location on secondary arc current and transient recovery voltage.**

Fault location	Secondary current /A	Arcing time /s
terminal	32.77	0.10735
1/8	29.52	0.08168
2/8	23.51	0.09518
3/8	19.31	0.08574
middle point	18.09	0.08625

The results from Table 5 show that, if the distance from fault position to midpoint of the transmission line is smaller, secondary arc current will be smaller, which will drop from 32.77A to 18.09A.The relationship between the arcing time and different fault locations has a different change regulation with the secondary arc current. The variation range of the arcing time fluctuates with decreasing the distance from fault position to midpoint of the transmission line. The secondary arc current approach the minimum value at the midpoint of the transmission line, while the arcing time approach the minimum value at the 1/8 of the transmission line. This is because when single-phase-to-ground fault occurs at the terminal of the line, and the vertical induction electromotive force close to the electromagnetic induction component will reach the maximum value, while the midpoint of the line will reach the minimum value due to the electromotive force offset. Therefore, the most serious situation caused by secondary arc will occur if the fault locations of single-phase-to-ground fault are at both terminals of the line. In order to ensure the safe operation of power system, the terminals of the transmission line should be preferentially protected to reduce the occurrence of grounding faults.

V. TIME SEQUENCE OF THE SPAR SCHEME COORDINATED WITH HRPC

After single-phase-to-ground faults occurring on the UHV line, the circuit breakers start to interrupt the faults. In actual situation, the single-phase-to-ground fault is usually instantaneous and the circuit breakers will reclose automatically after interrupting the faults. If the secondary arc can't extinguish successfully or at the reclosing time, it will directly lead to the failure of the auto-reclosure. The bypass circuit breaker is an important device in the SC to control the input or withdrawal of a series capacitor bank. After fault occurring, the trigger gap without arc-extinguishing capability is easily broken with a long time discharge. Consequently, the timely and reliable action of the bypass breaker is critical to the safe operation of the series compensation. Considering that the existence of bypass circuit breaker changes the current flow path of the fault, it may affect the secondary arc. In the case of single-phase-to-ground faults, the influence of the tripping time of the bypass circuit breaker on the characteristics of the secondary arc should be studied.

After a grounding fault occurring, the bypass circuit breaker of SC receives the protection relay signal and then immediately closes. Now the bypass breaker and the main circuit breaker simultaneously disconnects (Strategy A), the bypass breaker disconnects after the secondary arc extinguishes (Strategy B) are proposed to make comparison. Using electromagnetic transient program to simulate the above two strategies, the results show that the arcing time of secondary arc in Strategy B is only 0.103s, which is 43.6% shorter than that of 0.148s in strategy A, and the corresponding amplitude of secondary arc current is also reduced from 21.18A to 16.87A. It is because the damping device in the SC of the case A is cut off when the bypass breaker is turned on, and cannot function to limit the current in the discharge circuit. As a result, the secondary arc current decay becomes slow.

Therefore, comparing the key parameters of the secondary arc under the two strategies, the amplitude of the secondary arc current is limited and the arcing time is shortened in the strategy B to provide the conditions for the rapid extinction of the secondary arc. Based on strategy B, the time sequence between the bypass breaker of HRPC and SPAR are shown in Table 6.

With regard to application of HRPC in UHV transmission line, interrupting the bypass breaker after the extinguishment of secondary arc will facilitate the success of SPAR. With the reference to the results in Fig. 5, it is suggested that the reference time t_6 of the time sequence should be increased appropriately when the SC degree is higher (more than 60%).

TABLE 6. Time sequence of the SPAR scheme coordinated with the HRPC.

time sequence	Interval with the previous time/s	Process description
t_0	/	Single-phase-to-ground fault occurs
t_1	0.002	The action voltage of MOV is achieved to bypass the SC capacitor
t_2	0.002	Spark gap triggers to bypass the SC capacitor and MOA
t_3	0.016	Relay protection acts, a signal is sent to close the SC bypass breaker and open the circuit breaker
t_4	0.024	The bypass breaker is closed
t_5	0.016	The circuit breaker opens
t_6	0.02	The circuit breaker parallel resistance is separated, the fault line is isolated from the system, and the secondary arc self-extinguish process begins
t_7	0.2	Secondary arc is extinguished, the discharging gap is deionization, the secondary arc extinguishes and a signal is sent to interrupt the bypass circuit breaker
t_8	0.045	The bypass breaker interrupts
t_9	0.015	The secondary arc deionization process ends
t_{10}	0.1	The switching signal is received by the circuit breaker, and the switching coil is electrified
t_{11}	0.2-0.25	The switching resistance is connected
t_{12}	0.02	The main connect of circuit breaker closed, the switching resistance is short-circuited, and the power supply returns to normal condition

The strategy of combining automatic reclosing and bypass circuit breaker of HRPC is beneficial for the rapid extinction of secondary arc, which will further shorten the setting time of SPAR and improve the transient stability of UHV power systems.

VI. CONCLUSIONS

In order to investigate the influence of HRPC on the secondary arc of UHV transmission lines, the simulation model of UHV transmission line with HRPC is established firstly. Combined bypass breaker of the SC with single-phase reclosure sequence can be achieved by suppressing the secondary arc to optimize the reclosing time, which improve the transient stability of the system. The installation of HRPC in UHV power grid facilitates the extinguishment of the secondary arc. After installing HRPC in UHV line, the following conclusions are obtained by combining theory with simulation:

1) The secondary arc characteristics are distinct from those without compensation. The frequency

component value, fault point transient recovery voltage and rising rate of the secondary arc are significantly decreased, and the arcing time is effectively shortened, but the low frequency component with fast attenuation appears, which might increase the difficulty of the arc extinguishment.
2) The secondary arc current value increases linearly with the increase of the series compensation, and shows the trend that first increase then linear decrease and increase again with the increase of the compensation degree of the SCSR. The lowest value appears near the optimal value of the neutral reactance. When the SCSR value is changed, the variation range of the secondary arc current is greater.
3) When the HRPC is installed at both ends of the UHV transmission line, the secondary arc current decreases with the increase of the arc resistance, and the attenuation speed of the arc resistance is the fastest in systems that only install the SCSR. The closer the ground fault location to the compensation device, the higher the value of the secondary arc current and the transient recovery voltage is.
4) The sequence of the automatic reclosing technology and HRPC bypass circuit breaker is put forward in this paper. It is suggested that the bypass circuit breaker should be tripped off after the secondary arc is extinguished, which will be more beneficial for the arc extinguishment. The simulation results verify the correctness of the strategy.

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