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Design and test of a novel power electronic device for phase sequence exchange technology

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ABSTRACT

With the development of power electronic technology, many conceptual technologies have been applied in practice. Phase sequence exchange (PSE) is a recently developed emergency control technology that can reduce the power angle by 120°, thus preventing the system from losing synchronization. In this paper, a novel power electronic device for PSE is designed. This device consists of three sets of solid-state circuit breakers (SSCBs) for each phase of A, B, and C, namely three SSCBs per set for a total of nine SSCBs. Switching between the three sets of SSCBs can reduce the power angle by 120°. In this paper, the resistance-capacitance diode (RCD) circuit and metal-oxide varistor (MOV) circuit are designed, and the component selection standards are presented. The proposed device is tested via PSpice simulations and a 2.4 kV/50 A prototype. The experimental results show that PSE operation can be completed in 5.2 ms. The performance of the PSE device is verified using two standard systems.

1. Introduction

Power electronics have proven to be an important technology for the substantial improvement of power grid performance, and power electronic equipment has been extensively used in power systems [1–4]. With the improvement of the manufacturing technology of power electronic devices, many new technologies have been developed [5–9].

Phase sequence exchange (PSE) is a recently developed emergency control technology in which a PSE device is utilized to disconnect the primary-side phase of the communication line, causing a swift misalignment of the connection [10]. The three-phase A, B, C sequence then connects to the three-phase C, A, B sequence and reduces the power angle by 120°, thereby changing the power angle back to a smaller angle and preventing the system from falling out-of-step while maintaining the structural integrity of the power grid. In previous research [10], the mechanism of improving system stability via PSE was described, and the PSE technology was verified by using the one-machine infinite bus (OMIB) system as an example. In another previous work [11], the conditions under which the system can endure PSE were determined; a PSE control mode of split-phase switching control, which greatly reduces the impact of PSE, was also proposed. In yet another existing study [12], the installation position of a PSE device in a multi-machine system was proposed and its application was discussed.

The PSE device is an important component of PSE technology. If the disconnection of the PSE device is too slow, the optimal PSE power angle threshold may be missed. If the dislocation connection is too slow, the generator may obtain additional kinetic energy during the period between disconnection and reconnection with the system, which may result in failure to restore synchronization. Therefore, the key to PSE device design is to disconnect the line and misalign the connection as quickly as possible.

With the development of power electronic technology, the solid-state circuit breaker (SSCB) based on high-power electronic devices has become an important technical scheme for quickly breaking the current [13–17]. Not only do the characteristics of the SSCB meet the opening speed and control accuracy requirements of PSE, but the SSCB also has a short cooling time and can thus be used for continuous multiple-PSE operation. Therefore, according to the technical requirements of PSE, a new power electronic device based on the SSCB is designed in this paper, and insulated-gate bipolar transistors (IGBTs) are used as the opening element [18,19].

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The main contributions of this paper are as follows:

1. The structure of the PSE device and the topology of the SSCB are designed;
2. The working procedures of the SSCB are explained;
3. The component selection standards of the SSCB are proposed;
4. A 2.4 kV/50 A PSE device prototype is built, and the performance of PSE is presented.

The remainder of this paper is organized as follows. In Section 2, the structure of the PSE device and the topology of the SSCB are designed. Section 3 explains the working procedures of the SSCB. The component selection standards of the SSCB are given in Section 4. In Section 5, a 2.4 kV/50 A PSE device prototype is built and tested, and the PSE performance in two standard systems is verified.

2. Proposed PSE device

2.1. PSE device structure

For an OMIB system, the PSE device is installed at the outlet of the generator, as illustrated in Fig. 1.

The PSE device consists of three groups of nine SSCBs; SSCB1A, SSCB1B, and SSCB1C are the first group, etc. The structure is illustrated in Fig. 2.

The sequence connection mode can be changed by controlling the opening and closing of the three groups of SSCBs. To prevent a three-phase short circuit, when one group is turning on, the other two groups must be turned off. Normally, the first group of SSCBs is turned on, as represented by the red lines in Fig. 2, and the other two groups are turned off. When the PSE command is received, the first group of SSCBs is turned off, the second group of SSCBs is then turned on, resulting in the A-a, B-b, and C-c three-phase current connection, as represented by the green lines in Fig. 2. The PSE operation is completed and the power angle is reduced by 120° [10]. When multiple PSE operations are needed, the three groups of SSCBs are alternately switched.

2.2. SSCB module topology

Based on the IGBT, an SSCB that can quickly disconnect the AC current is proposed in this paper. The turning-off of the SSCB will cause a sudden change of the inductance voltage [20,21]; therefore, an RCD voltage-balancing circuit and metal-oxide varistor (MOV) circuit are designed. Taking phase A as an example, the structure is illustrated in Fig. 3.

The SSCB is divided into two parts: the main circuit and the auxiliary module. The main circuit is composed of four diode modules, one IGBT module, an RCD circuit, and an MOV snubber branch, which are connected to form a load current path. The auxiliary module consists of a measurement module, control and drive module, and cooling device, and is responsible for controlling the action of the circuit breaker and protecting the power electronic components [22].

When the SSCB is closed, the IGBT module is in the turning-on state; in Fig. 3, the positive half-cycle AC current path is represented by the blue line, and the negative half-cycle AC current path is represented by the red line. When the circuit breaker is turned off, the IGBT module is in the turning-off state, the current path is closed, and the MOV branch is in the high-resistance state without current flow.

The control and drive systems control IGBT devices to be turned on or off, and then control the SSCB to be turned on or off [23]. The measurement module includes a current transformer and measuring instrument, which can monitor the current of each IGBT branch in real-time and take over-current protection measures. The adopted cooling system is generally water cooling, as it has a low cost and good effect [24–26].

2.3. RCD circuit design

To solve the static and dynamic voltage-balancing problems of IGTBs in series, an RCD voltage-balancing circuit is proposed in this paper, the
structure of which is illustrated in Fig. 4(a). The voltage-balancing circuit is composed of the diode D, snubber capacitor C, thyristor Q, and resistors $R_1$ and $R_2$. When the number of IGBTs changes, they can be disassembled or installed flexibly [27–30].

The parallel circuit composed of C and D can dissipate the energy released by the inductor so as to limit the peak voltage generated by the IGBT at the moment at which the SSCB turns off, and the voltage of each IGBT in the dynamic process is balanced. In addition to the dynamic unbalanced voltage of IGBTs in series during turn-off, a static unbalanced voltage may also be caused by the differences in the operation characteristics after turning off; therefore, the static voltage-balancing resistances $R_1$ and $R_2$ are connected in parallel with the IGBT. Normally, the thyristor Q is in the off-state. The C-D circuit and static voltage-resistance circuit have different working times, and are therefore two relatively independent branches [31].

The MOV displays a high-impedance state when the voltage is lower than the breakdown voltage. When the voltage exceeds this value, the resistance drops sharply and the voltage is clamped to the rated value. Therefore, the breakdown voltage value of the MOV is set to the rated voltage of the IGBT to protect the IGBT. After the SSCB is opened, the current is transferred from the IGBT to the snubber capacitor C. When the voltage of snubber capacitor C reaches the MOV breakdown voltage, the MOV assumes a low-resistance state, and the fault current is transferred from C to the MOV. The energy released by the inductor passes through the MOV branch and is dissipated. In an actual circuit, there is an MOV submodule in parallel at each end of each IGBT, and the sub-modules form an MOV snubber branch in series [32–34].

The RCD voltage-balancing circuit can simultaneously solve the dynamic and static voltage-balancing problems. The dynamic and static voltage-balancing circuits are shown in Fig. 4(b) and (c), respectively.

Fig. 4(b) illustrates the dynamic voltage-balancing working circuit. During the turning-off process of the IGBT, the capacitor C is charged through the D-C circuit to limit the generation of the peak voltage and balance the dynamic voltage. The diode prevents the reverse discharge of the capacitor. The next time the IGBT is turned on, the thyristor Q is also briefly turned on, and the capacitor C is ready for the next snubber charge through the circuit discharge of $C \cdot Q \cdot R_2$.

Fig. 4(c) illustrates the static voltage-balancing working circuit. The static voltage-balancing resistance is composed of $R_1$ and $R_2$, and the static voltage-balancing resistance of each voltage-balancing unit is equal. When the IGBT is turned on, the static voltage-balancing resistance has almost no current flow, and the static voltage-balancing resistance branch is equivalent to an open circuit. The turning-off of the IGBT can be equivalent to a large resistance. According to the principle of resistance voltage balance, because the static voltage balance resistance in parallel is small, the voltage at both ends of each IGBT is basically the same, and the voltage of series IGBT is balanced.

### 2.4 Operating procedures of the SSCB

The operating procedure of the SSCB is divided into three stages, namely the commutation stage, capacitor charging stage, and MOV snubber stage. The current flow direction of each working state is illustrated in Fig. 5.

As shown in Fig. 5(a), when the SSCB is turned on, the load current flows through the IGBT branch, and the voltage-balancing branch and snubber branch have no current flow.

When the SSCB receives the opening command, the IGBT turns off. The capacitance of the voltage-balancing circuit is in the charging state, and the load current is transferred from the IGBT branch to the RCD voltage-balancing branch. This stage ends when the load current is completely transferred to the RCD balancing circuit, and the working state of the SSCB is as illustrated in Fig. 5(b). The current continues to charge the capacitor, and the voltage of the capacitor increases continuously; this stage is the capacitor charging stage. When the capacitor voltage reaches the MOV breakdown voltage, the MOV resistance drops sharply, and the current quickly transfers from the RCD voltage-balancing circuit to the MOV snubber branch. When the load current is completely transferred to the MOV branch, the SSCB enters into the MOV snubber stage, and the current flow direction is as illustrated in Fig. 5(c). Eventually, the MOV branch current decays to zero, and the SSCB completes the opening process.

The closing process of the SSCB is relatively simple. The IGBT receives the command and turns on, and the closing process is completed. Due to the inductance in the circuit, it takes some time for the load current to return to normal. In addition, after the SSCB is turned on, the thyristor Q of the voltage-balancing circuit must be turned on for a short time, and the discharge circuit is turned on to discharge the capacitor in preparation for the opening.

The waveforms of the main collector-emitter voltage, internal branch current, and IGBT driving voltage in the opening and closing processes of the SSCB are presented in Fig. 6.

In Fig. 6, $V_{CE}$ is the collector-emitter voltage of the IGBT, $i_{IGBT}$ is the branch current of the IGBT, $i_{c}$ is the current of the voltage-balancing circuit, $i_{MOV}$ is the branch current of the MOV, and $V_{CE}$ is the gate-emitter voltage that controls the action of the IGBT.

As shown in Fig. 6, $t_1$-$t_2$ is the closing process. After the closing command is issued at $t_1$, $V_{CE}$ in Fig. 6(c) increases to drive the IGBT to turn on, so $V_{CE}$ in Fig. 6(a) decreases from the system-rated voltage $V_N$ to the saturation voltage $V_{CE}$ (SAT), the IGBT branch in Fig. 6(b) is re-energized, and the process of $i_{IGBT}$ recovering to the load current is represented by the a-b curve.

$t_2$-$t_3$ is the opening stage; the opening command is sent out at $t_3$, so $V_{CE}$ begins to decline. At $t_4$, $V_{CE}$ drops to the turning-off threshold to control the IGBT to begin to turn off, and the load current of the IGBT branch transfers to the voltage-balancing branch; therefore, $i_{IGBT}$ continues to decrease while $i_c$ continues to increase.

$t_5$-$t_6$ is the $i_{IGBT}$ and $i_{c}$ commutation stage, and their curves are respectively represented by c-d and e-f. As the IGBT gradually turns off, $V_{CE}$ increases. At $t_6$, the IGBT is completely turned off, and the current of the IGBT branch is transferred to the voltage-balancing branch.

$t_7$-$t_8$ is the capacitor charging stage. At this stage, $i_c$ has not yet been attenuated and is maintained at the load current, and charging the capacitor causes $V_{CE}$ to continue to increase. At $t_8$, $V_{CE}$ increases to the action voltage $U_{N,MOV}$ of the MOV, the MOV resistance decreases sharply, and the current quickly transfers from the capacitor branch to the MOV branch.

$t_9$-$t_{10}$ is the $i_c$ and $i_{MOV}$ commutation stage, the current curves of which are represented by $g-h$ and $i-j$, respectively.

During $t_7$-$t_8$, the MOV clamps $V_{CE}$ at a fixed value and limits the energy stored in the inductance.

During $t_9$-$t_{10}$, the MOV branch continues to dissipate the system.

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![Fig. 4. Working procedures of the RCD circuit.](image-url)
energy, the current is finally reduced to 0, and the 
VCE tends to be stable. The tMOV attenuation curve is represented by j-k-l, and the 
SSCB completes the opening process.

3. SSCB design

In this section, according to the technical requirements of PSE and 
the working principle of the SSCB, the component selection standards 
are given.

3.1. Diode and IGBT selection

To improve the rated voltage of the SSCB, the diode module and 
IGBT module are connected in series and in parallel. According to the 
selection standards of power electronic components, the maximum 
voltaget of the diode and IGBT is 2–3 times the rated voltage, and the 
maximum current is 1.5–2 times the rated current [35,36].

The peak phase voltage of the SSCB is \( U_{\text{phin}} = \sqrt{2} U_N / \sqrt{3} = 0.816 U_N \), 
so the minimum rated voltage of the SSCB is

\[
U_{\text{min}} = 2U_{\text{phin}} = 1.632 U_N, \tag{1}
\]

and the maximum rated voltage of the SSCB is

\[
U_{\text{max}} = 3U_{\text{phin}} = 2.448 U_N. \tag{2}
\]

where \( U_{\text{min}} \) is the minimum rated voltage of the SSCB, \( U_{\text{max}} \) is the 
maximum rated voltage of the SSCB, \( U_{\text{phin}} \) is the peak phase voltage of the 
SSCB, and \( U_N \) is the line voltage where the PSE device is installed.

Therefore, the range of the rated voltage \( U_e \) of the SSCB is

\[
1.632 U_N < U_e < 2.448 U_N. \tag{3}
\]

The number of diodes in series \( n_1 \) is

\[
n_1 = \left\lceil \frac{U_e}{U_{\text{RRM}}} \right\rceil. \tag{4}
\]

Similarly, the number of IGTBs in series \( n_2 \) is

\[
n_2 = \left\lceil \frac{U_e}{V_{\text{CE}}(\text{sae})} \right\rceil. \tag{5}
\]

In (4) and (5), \( n_1 \) is the number of diodes in series, \( n_2 \) is the number of 
IGTBs in series, \( \lceil \cdot \rceil \) is the rounding-up operation symbol, \( V_{\text{RRM}} \) is the reverse 
repetitive peak voltage of the diode, and \( V_{\text{CE}}(\text{sae}) \) is the maximum voltage of the 
IGTB.

As shown in Fig. 3, each diode module only flows through half a cycle 
of current. The relationship between the average value of current 
flowing through the diode and the peak value of current flowing through 
the SSCB is as follows:

\[
2\pi I_{\text{di}} = \int_0^\frac{\pi}{2} (\sqrt{2} I_f \sin \omega t) \sin d\omega t = 2 I_m, \tag{6}
\]

where \( I_{\text{di}} \) is the average value of current flowing through the diode 
module, \( I_f \) is the effective value of current flowing through the SSCB, and 
\( I_m \) is the peak value of current flowing through the SSCB.

The minimum average value of the current flowing through the diode module is

\[
I_{\text{min}} = 1.5 \frac{1}{\pi} I_m = 0.477 I_m. \tag{7}
\]

The maximum average value of the current flowing through the diode module is
\[ I_{\text{dmax}} = \frac{1}{R} I_n = 0.637 I_n. \]  

(8)

Therefore, the range of the average current flowing through the diode module is

\[ 0.477 I_n < I_{\text{d}} < 0.637 I_n. \]  

(9)

Thus, the number of parallel branches \( n_1 \) of a single diode module is

\[ n_1 = \left\lceil \frac{I_{\text{d}}}{I_{\text{坎}}} \right\rceil. \]  

(10)

where \( I_{\text{坎}} \) is the average diode current.

As the parameter \( I_{\text{坎}} \) of the IGBT refers to the current peak value, the rated current peak value range of the IGBT module is (Eq. (13))

\[ 1.5 I_n < I_{\text{d}} < 2 I_n, \]  

(11)

and the number of parallel branches \( n_4 \) of a single diode module is

\[ n_1 = \left\lceil \frac{I_{\text{坎}}}{I_{\text{坎}}} \right\rceil. \]  

(12)

where \( I_{\text{坎}} \) is the peak value of the rated current flowing through the IGBT module, and \( I_{\text{坎}} \) is the maximum collector current of the IGBT element.

### 3.2. RCD circuit design

The RCD circuit is shown in Fig. 4(b). During the IGBT turning-off process, the peak voltage is limited by the capacitor charging in the D-C circuit. After the IGBT is turned on, the thyristor Q is turned on to form a C-Q-R loop. The capacitor discharge is limited to be ready for the next turn-off. The stray inductance in the SSCB produces the peak voltage when the circuit breaker is turned off, and the voltage-balancing capacitor dissipates the energy released by the inductor to limit the spike voltage, thereby balancing the voltage in the dynamic process.

The energy released by the inductance is

\[ E_L = \frac{1}{2} L \Delta I^2. \]  

(13)

The energy dissipated by the capacitor is

\[ E_C = \frac{1}{2} C \Delta U^2. \]  

(14)

The energy dissipated by the capacitance should not be less than the energy released by the inductance, that is

\[ E_C \geq E_L. \]  

(15)

that is,

\[ C \geq \frac{L \Delta I^2}{\Delta U^2}. \]  

(16)

where \( E_L \) is the energy released by the inductor, \( E_C \) is the energy dissipated by the capacitor, \( L \) is the stray inductance in the SSCB, \( I \) is the current flowing through the inductor, \( C \) is the capacitance in the RCD circuit, and \( \Delta U \) is the overvoltage of the capacitance.

Thyristor Q turns on after the IGBT is turned on, and then turns off again after the capacitor is discharged. The discharge time constant \( \tau \) of the R-C circuit affects the preparation time of the reopening. The longer the reopening preparation time, the more unfavorable it is for multiple-PSE operation; therefore, when defining a time \( t_0 \), the discharge time constant should not be greater than \( t_0 \)

\[ \tau = R_C C \leq t_0, \]  

(17)

that is,

\[ R_C \leq \frac{t_0}{C}. \]  

(18)

where \( \tau \) is the discharge time constant of the C-Q-R circuit, \( t_0 \) is the reclosing preparation time of the SSCB, \( R_C \) is the resistance in the C-Q-R circuit, and \( C \) is the voltage-balancing capacitor.

The energy released by the capacitor in the C-Q-R circuit can only be dissipated through \( R_2 \), so the power parameter of \( R_2 \) should also meet the following requirements

\[ P \geq \frac{1}{2} C \Delta U^2 \cdot \frac{1}{\tau} = \frac{\Delta U^2}{2 R_2}, \]  

(19)

where \( P \) is the power parameter of \( R_2 \), \( \tau \) is the discharge time constant of the C-Q-R circuit, and \( \Delta U \) is the overvoltage of the capacitor.

Because of the differences in the production process and operating temperatures, the parameters of the IGBT will be inconsistent, which will result in the uneven voltage division of the series IGBT.

After turning off, the IGBT with uneven voltage division is equivalent to resistor \( R_{\text{IGBT}} \) having a different resistance value. To achieve static voltage balancing, the static voltage balancing resistors \( R_1 \) and \( R_2 \) are connected in parallel across the IGBT so that the equivalent resistance of the IGBT and \( R_1 + R_2 \) in parallel is basically equal, as shown in Fig. 4(c).

Among \( n \) series IGBTs, suppose that the \( k \)-th IGBT withstands the maximum voltage, the maximum voltage is \( U_{\text{max}} \), the \( j \)-th IGBT withstands the minimum voltage, and the minimum voltage is \( U_{\text{min}} \). The unbalance rate of voltage-balancing is defined as

\[ \lambda = \frac{U_{\text{max}} - U_{\text{min}}}{U_{\text{max}}}. \]  

(20)

that is,

\[ \lambda = \frac{U_{\text{max}} - U_{\text{min}}}{U_{\text{max}}} = \frac{R_{\text{IGBT}}}{(R_1 + R_2)}/(R_1 + R_2) \]  

\[ = \frac{(R_1 + R_2) R_{\text{IGBT}}}{R_1 R_2}. \]  

(21)

If the voltage imbalance rate is within 5% after adding \( R_1 \) and \( R_2 \), the range of static voltage-balancing resistance is as follows:

\[ R_1 + R_2 \leq \frac{R_{\text{IGBT}} R_{\text{IGBT}}}{20 R_{\text{IGBT}}} - \frac{2 R_{\text{IGBT}}}{10 R_{\text{IGBT}}} \]  

(22)

where \( R_1 \) and \( R_2 \) are the static voltage-balancing resistances, \( R_{\text{IGBT}} \) is the equivalent leakage resistance of the \( j \)-th IGBT, and \( R_{\text{IGBT}} \) is the equivalent leakage resistance of the \( k \)-th IGBT.

The leakage resistance can be calculated by the component parameters of the IGBT:

\[ R_{\text{IGBT}} = \frac{V_{\text{ce}}}{I_{\text{ce}}}. \]  

(23)

where \( V_{\text{ce}} \) is the collector-emitter blocking voltage, \( I_{\text{ce}} \) is the collector-emitter leakage current, and \( R_{\text{IGBT}} \) is the equivalent leakage resistance of the IGBT.

### 3.3. MOV selection

The MOV module is connected in parallel with the IGBT. When the voltage across the IGBT is below the threshold voltage, the MOV device acts as an infinite impedance and does not conduct any current. When the voltage exceeds the threshold, the MOV acts as a small impedance and allows the current to flow.

Assuming that the MOV operates when the voltage reaches 90% of the maximum withstand voltage of the IGBT, the MOV operating voltage \( U_{\text{MOV}} \) meets the following requirement:

\[ U_{\text{MOV}} = 0.9 V_{\text{ce}}. \]  

(24)
where $U_{NMOV}$ is the varistor voltage of the characteristic parameter of the MOV, and $V_{CR}$ is the maximum withstand voltage of the IGBT.

4. Simulation and test

4.1. SSCB performance test

According to the SSCB design proposed in this paper, a simulation was carried out on the PSpice platform. It required the SSCB to break at least a 10-kA current in a 10-kV voltage-level power system.

To meet the requirements of PSE technology, an RM1000DC-66F rectifier diode and CM1200HG-66H IGBT were respectively selected as the components of the diode module and IGBT module. The main parameters of the RM1000DC-66F rectifier diode were $I_{F(AV)}=1000\ A$ and $V_{RMM}=3300\ \text{V}$, and the main parameters of the CM1200HG-66H IGBT were $I_{C}=1200\ \text{A}$, $I_{CM}=2400\ \text{A}$, and $V_{CR}=3300\ \text{V}$, where $I_{C}$ is the rated current of the IGBT collector, $I_{CM}$ is the maximum collector current, $V_{CR}$ is the maximum withstand voltage of the IGBT, $V_{RMM}$ is the reverse repetitive peak voltage of the diode, and $I_{F(AV)}$ is the forward average current of the diode.

According to Eqs. (1)-(12), 9 IGBT parallel branches, 5 in series, and 7 diode parallel branches, 5 in series, can be obtained. According Eqs. (16), (18), and (19), the main parameters of the dynamic voltage-balancing circuit were determined to be as follows: $C=10\ \mu\text{F}$, $R_{2}=25\ \Omega$, and $P=220\ \text{kW}$. According to Eqs. (22) and (24), the static voltage-balancing resistance $R_{1}=1.6\ \text{k}\Omega$ and $U_{NMOV}=3135\ \text{V}$ were obtained. Finally, the rated voltage of the SSCB was 16.5 kV, the rated current was 10.8 kA, the maximum impulse current was 21.6 kA, and the rated capacity was 356 MVA.

An SSCB with a rated voltage of 16.5 kV and a rated capacity of 356 MVA was built on the PSpice platform, and it was installed in a 10-kV AC power grid for short-circuit current breaking tests. The simulated waveforms of the breaker current are presented in Fig. 7.

As can be seen from Fig. 7(a), the system short circuit occurred at 3.3 ms, and the short-circuit current then surged along the current curve a-b to 18.8 kA. The turning-off command was issued at 5 ms, and the SSCB acted after a delay of 0.3 ms. The short-circuit current then dropped to 0, and the SSCB turned off. This process corresponds to the current curve b-c-d in Fig. 7(a). The turning-off process took 1.4 ms. There was a conduction loss of 121 V in the SSCB before turning off, as indicated by point e in Fig. 7(a). The turning-off process produced a peak voltage of 16 kV which finally reduced to zero, corresponding to the voltage curve e-f-g in Fig. 7(a).

As can be seen from Fig. 7(b), the turning-on command was issued at 5 ms, and the SSCB acted at 5.3 ms. The current restored to 19.1 kA at 5.8 ms, and the SSCB turned on. The voltage dropped from 8.1 kV to 118 V at 5.43 ms (conduction loss of the SSCB). This process corresponds to the curves a-b and c-d in Fig. 7(b), and took a total of 0.8 ms.

In summary, the SSCB was found to have a turning-off time of 1.4 ms and a turning-on time of 0.8 ms. To prevent a phase-to-phase short circuit, a 3-ms time delay was added between the process of turning-off and turning-on, so the total time was 5.2 ms.

During the turning-off process, the impulse voltage was controlled to be within twice the rated voltage, and the on-state voltage loss rate of the SSCB was 1.21%; this was still within the acceptable range, because not every generator outlet is equipped with a PSE device.

Compared with mechanical circuit breakers, the opening speed of the SSCB designed in this paper is greatly improved, and overvoltage is effectively limited.

4.2. PSE device prototype test

To validate the proposed power electronic device, a simplified small-power prototype was designed and constructed. The SSCB structure is presented in Fig. 3, and photographs of the drive circuit and SSCB prototype are displayed in Fig. 8. The rated voltage and current of the prototype were 2.4 kV and 50 A, respectively. According to the component selection standards presented in Section 4, the component parameters of the prototype are listed in Table 1.

A photograph of the PSE device prototype is displayed in Fig. 9.

The PSE device prototype depicted in Fig. 9 was tested at 15 A/50 Hz three-phase AC. First, the first set of SSCBs was turned off, a 3-ms delay was added after the first group of SSCBs was turned off to avoid phase-to-phase short circuit, and the third group of SSCBs was then turned on. The current waveform is presented in Fig. 10.

Taking phase A as an example, the current before PSE is a-b, and the current after PSE is c-d. If PSE is not carried out, a-b and e-f constitute a complete sine wave, but the current after PSE in phase B is e-f, i.e., the PSE prototype changed the original phase B current into the phase A current. Therefore, the PSE prototype was demonstrated to successfully exchange the 15 A AC phase sequence.

4.3. PSE device performance test

The performance of the PSE device was tested by an OMIB system and IEEE-118 bus system, and the OMIB test system is illustrated in Fig. 11.

The other parameters were the same as those reported in a previous study [10]. The structure of the PSE device was as shown in Fig. 2; nine identical SSCBs were divided into three groups and connected. As illustrated in Fig. 9, the PSE device was installed at the outlet of the generator.

When $t=1\ s$, a three-phase, short-circuit fault occurred at the beginning of the line, and the fault line was cut off at $t=1.5\ s$. Because the fault was cleared too late, the system lost synchronization. According to PSE technology, to prevent the system from entering an out-of-step condition, it is necessary to carry out PSE operation by using the PSE device when the power angle of the generator reaches $172^\circ$.

The power angle curve and $\delta-\Delta\delta$ trajectory of the system with and without PSE are presented in Fig. 10.

As presented in Fig. 12(a), the PSE device caused the power angle to instantaneously decrease by $120^\circ$, and the system then oscillated into a stable state after about 2 s. As shown in Fig. 12(b), the system stabilized at a new stable equilibrium point after several oscillations. In summary,
The PSE device prevented the system from entering an out-of-step condition. After the fault is cleared, the period of the first swing is usually hundreds of milliseconds or even seconds; in contrast, the PSE device designed in this paper was found to have a turning-off time of 1.4 ms and a turning-on time of 0.8 ms. The sampling interval of this simulation was 1/60 s, and the time of PSE was even less than one sampling period. In other words, the time delay for PSE operation is negligible, and the generator will not gain additional kinetic energy during this period. Additionally, due to the robustness of PSE technology, even if PSE is not operated at the optimal power angle threshold, it can still restrain the system from entering an out-of-step condition.

The fault line was cut off at \( t = 1.5 \) s, and the PSE device acted at \( t = 1.72 \) s; the impulse voltage waveform is presented in Fig. 13.

It can be seen from Fig. 13 that the impulse voltage of PSE was within the design range. Therefore, the PSE device designed in this paper can be applied to PSE technology.

In the IEEE-118 bus system, there were 19 generator nodes and 186 lines, the total power generation output was 437.4 MW, and the total load in the system was 424.2 MW. A three-phase ground short-circuit fault occurred between bus 23 and bus 25. After 0.7 s, the fault was cleared and the system was out-of-step.

Using the control method proposed in previous research [12], the generators requiring PSE were 10, 12, 25, 26, and 31, and the power angle thresholds are reported in Table 2. The power angle curves with and without PSE are presented in Fig. 14, from which it can be seen that PSE restrained the out-of-step system.

It is evident that the control method proposed in this paper can restore synchronous operation.

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**Table 1**

Component parameters of the prototype.

| Component | Mouser number          | Parameter value |
|-----------|------------------------|-----------------|
| IBGT      | 726-IGW25T120          | 1200 V, 50 A    |
| Diode     | 747-DH20-18A           | 20 A, 1800 V    |
| MOV       | 603-RSF200UB-73-300R   | 2 W, 300 Ohm 5% |
| Varistor  | 576-V625LA40AP         | 210 pF          |

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**Fig. 8.** Photographs of the drive circuit and SSCB prototype.

**Fig. 9.** Photograph of the PSE device prototype.

**Fig. 10.** PSE current waveform.
5. Conclusion and future work

In this paper, a novel power electronic device that can be used for PSE was designed. It consists of three sets of SSCBs for each phase of A, B, and C, namely a total of 9 SSCBs. Each SSCB is composed of one set of IGBTs and four sets of diodes. The PSE can be operated by switching the three sets of SSCBs. The RCD circuit and MOV circuit were designed, and the component selection standards were presented. A 10-kV SSCB simulation was carried out in PSPICE, and a 2.4 kV/50 A PSE device prototype was built. The breaking test results show that the SSCB had a turning-off time of 1.4 ms and a turning-on time of 0.8 ms. During the turning-off process, the impulse voltage was controlled within twice the rated voltage, and the conduction loss rate of the SSCB was 1.21%, which was still within the acceptable range. The power electronic device proposed in this paper can realize PSE and restore the system to stability.

The performance of the PSE device was verified using two standard systems. The time delay for PSE operation was negligible, and the generator did not gain additional kinetic energy during this period. Additionally, PSE technology has certain robustness; even if PSE is not in the optimal power angle threshold, it can still restrain the system from entering an out-of-step condition.

PSE is a recently developed emergency control technology with many theoretical and practical issues that remain to be solved. Due to the limitation of experimental conditions during the COVID-19 epidemic period, only a 15-A current phase sequence exchange test was carried out. Additionally, the 1.21% on-state loss can be further reduced, and
the stability of power electronic devices incorporated into the system cannot be ignored. In the future, this research team will consider using hybrid circuit breakers to replace solid-state circuit breakers, and will build a stability control system based on PSE technology to eventually implement the application of PSE technology.

CRediT authorship contribution statement

Yifan Li: Conceptualization, Methodology, Formal analysis, Writing - original draft. Shaofeng Huang: Funding acquisition, Project administration, Resources. Hui Li: Writing - review & editing, Visualization. Yiling Huang: Investigation. Xinrong Xiao: Validation. Yangjingyi Luo: Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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