Improving Grid-Connection Reliability and Safety of Synchronous Condensers With Start-Up Process Optimization

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ABSTRACT The new-type synchronous condenser uses the uncontrollable and irreversible freewheeling grid-connection mode during the start-up process, so that considerable rates of grid-connection failure could be observed in case of strict grid-connection criterions. Therefore, this paper proposes an optimized start-up process for the new-type synchronous condenser, with the effort to improving its grid-connection reliability and safety. This optimized process involves two new approaches, namely freewheeling speed ratio regulation and starting freewheel point setting, to adjust the covered range of the freewheeling speed over time, which indirectly expands the allowable initial phase angle difference and thus achieves an increased grid-connection success rate under strict grid-connection conditions. The effectiveness of the proposed optimized process incorporating the two new approaches is validated using statistical analysis in Matlab, as compared to the conventional freewheeling process without optimization. The results show that the successful grid-connection operations of the synchronous condensers can be guaranteed in strictest cases at the cost of a slight increase of the starting freewheeling point (from 105\% to around 107\%) with 99\% rated freewheeling speed ratio.

INDEX TERMS Synchronous condenser, grid-connection success rate, freewheeling speed ratio regulation, starting freewheel point setting.

I. INTRODUCTION

Thanks to the merit of longer transmission distance, larger capacity and lower power loss, high voltage direct current (HVDC) transmission system has become the most attractive way of electrical transmission in recent years [1]–[3]. However, the main operation risks such as commutation failure (CF) need to be carefully evaluated, since, for example, it is recorded that CF occurred more than 20 times in the East China Power Grid from January to September 2017 [4], [5]. During the recovery process of CF, as the DC power gradually increases, the reactive power demand of the inverter increases. Moreover, if the AC side voltage is not fully restored to the nominal value, a large amount of dynamic reactive power has to be absorbed from the AC system, leading to the so-called second drop of the commutating bus voltage [6].

In view of the demand of dynamic reactive power during fault recovery period, it is necessary to install reactive power compensation devices in the inverter station [7]. As the traditional reactive power compensation device with large capacity, the synchronous condenser can lower the HVDC system sensitivity to CF, effectively improving the fault recovery performance of the overall system and avoiding the second drop of the commutating bus voltage [8]. Compared with other power electronics based reactive power compensation equipment (e.g., SVC, STATCOM), the synchronous condenser has following advantages [9]–[15]:

1) During severe faults in stiff grids, such as three-phase line-to-ground faults, the synchronous condenser
brings the terminal voltage to the nominal value more quickly.

2) The synchronous condenser has stronger overload capacity that can remain outputting a large amount of reactive power during low voltage processes.

3) The lifetime of the synchronous condenser is longer.

Considering the urgent demand of voltage support after the CF and the requirement of fast reactive power regulation in the multi-fed HVDC transmission system, it is desirable to use the new-type synchronous condenser with smaller sub-transient reactance to address this issue. Though other start-up solutions are available [16], the new-type 300MVar synchronous condenser mainly adopts the static frequency converter (SFC) start-up mode [17]–[19] followed by a freewheeling grid-connection process, during which the SFC is disconnected and the condenser speed is self-decreasing [20]. Because this freewheeling speed is uncontrollable, the success of the grid connection operation depends on the “catching” of the speed when the frequency of the condenser terminal voltage approaches the grid frequency (i.e., the grid-connection window) [21].

In [22], the grid-connection success rate of the synchronous condenser during this freewheeling process is calculated on the basis of the allowable frequency difference and the phase angle difference at the grid-connection point. It concludes that the success rate is only 5.1% if the allowable frequency difference is set to 0.1 Hz whereas a 100% successful grid-connection operation will be achieved if the pre-set frequency difference reaches 0.5 Hz. In addition to these two factors, reference [23] indicates that the starting freewheel speed is another factor that affects the success rate. Furthermore, ignoring the terminal voltage that can be alternatively adjusted by the excitation system, it shows that the grid-connection process mainly faces the compromise between the success rate (reliability) and the surge current (safety). On one hand, if the frequency/phase angle starting freewheel speed differences set to a large value, the grid-connection success rate is high whereas a large grid-connection surge current is unavoidable (high reliability but low safety). On the other hand, if the frequency/phase angle starting freewheel speed differences are set to a small value, the grid-connection surge current is small while the grid-connection success rate is low (high safety but low reliability). As a result, it recommends that the frequency, phase angle, and starting freewheel speed differences are set to 1.05 times of the rated speed, 0.4–0.5 Hz, and 4.5–5.5°, respectively, in order to ensure the reliability of the grid-connection operation at the cost of a lower level surge current. Reference [24] points out that this surge current can be decreased via appropriately setting the grid-connection criterion, i.e., if the condenser frequency is larger than the grid frequency during the grid-connection window the condenser phase angle should lag behind the grid, and vice versa. Additionally, the reliability of the grid-connection operation can be improved by setting a small positive frequency combined with a large (maximum allowable) negative frequency. However, these approaches can only improve the reliability and safety to a limited extent.

Therefore, how to ensure the high success rate and the safety of grid-connection at the same time is the challenge that needs to be managed in the application of the new-type synchronous condenser. However, the analyses in [22]–[24] mainly focus on ensuring the success rate of the condenser through adjusting the grid-connection criterion, in which case a relatively large grid-connection criterion is usually used. That is, the above strategies cannot ensure a successful grid-connection if a strict grid-connection operation is required, for example with the frequency difference set to 0.1 Hz. To tackle this issue, the starting freewheel speed is selected as a new degree of freedom to adjust the initial phase angle difference between the condenser and the grid, with which the successful grid-connection operation can be ensured even with strict grid-connection criterions [25]. However, this method suffers from a high starting freewheel speed (inversely proportional to the grid-connection criterion) that may not be achievable with the SFC control.

This paper now proposes an optimization method through adjusting the freewheeling speed ratio and the starting freewheel point simultaneously to enhance the reliability and safety of the synchronous condenser grid-connection operation. This method is based on a comprehensive analysis of the influence of the initial phase angle difference on the final grid-connection success rate, with taking into account the primary power losses during the entire freewheeling process of the condenser. Furthermore, inspired by the knowledge that the condenser excitation current impacts on the acceleration of the freewheeling speed [26], the freewheeling speed ratio is used as another degree of freedom to lower the starting freewheel point on the basis of the derived grid-connection success area. In other words, the starting freewheel point and the freewheeling speed ratio are optimally adjusted at the same time to enhance the grid-connection success rate, even if under strict grid connection conditions. Experimental demonstration from Matlab as well as the calculated value in theorem validates the feasibility of the proposed optimization method and predicts the complete setting times and the starting freewheel point in different freewheeling speed ratio cases, with which the required computational burden during the setting process is significantly reduced.

II. THE PRINCIPLE OF THE SFC START-UP MODE OF THE SYNCHRONOUS CONDENSER

A. THE ELECTRICAL WIRING AND FEATURE OF THE SYNCHRONOUS CONDENSER WITH SFC START-UP MODE

At present, the new-type synchronous condenser mostly adopts the SFC start-up mode followed by a freewheeling grid-connection operation, with the system electrical wiring illustrated in Fig. 1. It mainly consists of a synchronous condenser, an SFC system that directly connects to the stator of the condenser, a start-up excitation system, a self-excitation system, and a synchronization device.
It should be noted that this electrical wiring is different from a conventional generator, since in the latter case the SFC is constantly connected to the stator side through a step-up transformer for the entire start-up process. Even if the synchronous point is missing in certain cases, the rotor could be reaccelerated immediately and the start-up procedure could be repeated, without system shutdown and restarting. On the contrary, the stator of the synchronous condenser is driven by a conventional SFC without using a transformer. Furthermore, the SFC rated output voltage is 2kV but the terminal voltage level of the synchronous condenser under rated excitation is 20kV. Therefore, in order to avoid damaging to the SFC, the SFC should be disconnected when the condenser starts to freewheel, after which the excitation system can be safely switched from the starting excitation system to the self-excitation system, and the condenser continues freewheeling with a slightly larger speed. In this freewheeling mode, once the synchronous point is missing for the reasons such as strict requirement of the phase angle difference, the synchronous condenser has to shut down and restart after long time of temperature resettling, which inevitably causes a certain waste of resources.

### B. THE ENTIRE START-UP PROCESS OF THE SYNCHRONOUS CONDENSER

The success of the synchronous condenser start-up requires precise cooperation among the SFC system, the start-up excitation system and the self-excitation system. The entire start-up process of a synchronous condenser from standing still until it connects to the grid is listed as follows:

1) The SFC system and the start-up excitation system are activated. With the rotor current controlled by the start-up excitation system in a closed-loop manner, the SFC system drags the rotor and accelerates its speed to 1.05 times rated speed [20].

2) Once the rotor speed reaches 1.05 times rated speed, the SFC is disconnected from the condenser, after which the rotor starts to freewheel due to the driving force, and then the self-excitation system is activated. The output current of the self-excitation system increases while that of the start-up excitation system decreases, enabling a smooth switch between the two excitation systems. The start-up excitation system will be shut down if the condenser terminal voltage is above 20% of the rated voltage.

3) The terminal voltage of the condenser is precisely controlled to the rated voltage by the self-excitation system, and then a synchronization device is used to detect the frequency difference, phase angle difference, and voltage difference between the synchronous condenser and the power grid in real time. Upon the measured difference is smaller than the pre-set criterion, the grid-connection command will be issued and hopefully the synchronous condenser can be safely connected into the grid.

As a result, ignoring the condenser terminal voltage amplitude which can be accurately controlled with respect to the grid voltage, it requires in-depth analysis regarding how the condenser frequency and phase angle are varied during the freewheeling grid-connection process.

### III. ANALYSIS OF THE FREEWHEELING GRID-CONNECTION PROCESS

#### A. POWER LOSS ANALYSIS

After the SFC is disconnected, the synchronous condenser starts to freewheel. During this process, the main power loss that affects the acceleration of the freewheeling speed consists of core loss $P_{Fe}$, the additional core loss under no-load conditions $P_{ad}$, the copper loss of the rotor $P_{Cu}$, and the mechanical loss $P_{mc}$ [27].

The additional loss of core under no-load conditions $P_{ad}$ comes from the movement of magnetic field along the surface of the core pole, while the mechanical loss $P_{mc}$ originates from the mechanical friction and ventilation system. During the freewheeling process, $P_{ad}$ and $P_{mc}$ are approximately the same as the normal condition, so the influence of these two parts on the acceleration of the freewheeling speed can be ignored.

In contrast, the core loss $P_{Fe}$ and the copper loss of rotor $P_{Cu}$ account for more than 70% of the total loss. The core loss includes the hysteresis loss $P_h$ and the eddy current loss $P_e$ as represented as follow:

$$\begin{align*}
P_h &= \sigma_h f B^a \\
P_e &= \sigma_e (f B)^2
\end{align*}$$

(1)

where $B$ is the amplitude of flux density, $f$ is the system frequency, $\sigma_h$ and $\sigma_e$ depends on the material property and the specification coefficient, and the value of $a$ generally varies from 1.6 to 2.2. The copper loss of rotor $P_{Cu}$ comes from the electrical loss caused by the rotor current in the rotor winding:

$$P_{Cu} = I_t^2 R_t$$

(2)

where $I_t$ is the excitation current and $R_t$ is the rotor winding resistance. During the freewheeling process, since the system frequency keeps decreasing and the excitation system is...
switched from the start-up excitation system to the main excitation system, the excitation current will increase. Therefore, these two parts are the dominant factors that determine the acceleration of the freewheeling speed.

### B. LAW OF THE FREEWHEELING SPEED

The torque equation of the synchronous condenser is described by [16]

\[ T_L = \frac{\sum P_x}{\Omega} = J\alpha_2 \]  

(3)

where \( T_L \) is the torque generated by loss during the freewheeling process, \( P_x \) denotes each loss, \( \Omega \) is the angular velocity of the synchronous condenser, \( J \) is the moment of inertia, and \( \alpha_2 \) is the angular acceleration.

Through manipulating (3), the differentiation of the frequency can be derived as below

\[ \frac{df}{dt} = \frac{\sum P_x}{4\pi^2\rho_2 f} \]  

(4)

From (1) it is evident that the hysteresis loss \( P_h \) and the eddy current loss \( P_e \) are proportional to the frequency and the square of frequency, respectively, but after substituting it to (4), the hysteresis loss \( P_h \) becomes independent of the acceleration of the freewheeling speed while the eddy current loss \( P_e \) still varies according to the frequency. Since during the freewheeling process, the frequency variation of the condenser is relatively small (typically smaller than 1.05 times the rated value), the influence of the eddy current loss \( P_e \) on the acceleration of the freewheeling speed can also be neglected.

It can be known from (2) that the copper loss of rotor \( P_{Cu} \) is proportional to the square of the excitation current. During the freewheeling process, the excitation system is switched from the start-up excitation system to the main excitation system whose current rises from 0.1 p.u. to 1.0 p.u. Therefore, the excitation current has a direct impact on the acceleration of the freewheeling speed.

### C. THE STAGES IN THE FREEWHEELING PROCESS

With the conventional freewheeling process where no optimization method is used, the entire freewheeling process can be divided into the following three stages: 1) the excitation system switching stage, 2) the freewheeling speed ratio regulation stage and 3) the grid connection stage. The speed curve of the synchronous condenser is depicted in Fig. 2, where the black curve shows the trend of the speed in the freewheeling process without using any optimization method. \( \omega_1 \) is the speed of the synchronous condenser when switching the excitation system, \( \omega_2 \) is the speed at the beginning of the preparation of grid-connection, and \( \omega_0 \) is the reference angular frequency that equals to the grid frequency.

**Stage I:** The interval 0 to \( t_1 \) is the excitation system switching stage during which the excitation system should be switched from the start-up excitation system to the main excitation system when the interval finishes. This process is same and standard in different start-up events, therefore, the amount of change \( \Delta\omega_1 \) of the speed during this period is a fixed value (the value of \( \Delta\omega_1 \) is \( \pi \) rad/s).

**Stage II:** The interval \( t_1 \) to \( t_2 \) is the speed regulating stage during which the acceleration of the freewheeling speed can be adjusted through controlling the excitation current, with the reason provided in Section III.A and B.

**Stage III:** The interval after \( t_2 \) is the stage of grid-connection. Since the terminal voltage of the synchronous condenser should be consistent with the voltage of the grid during this period, a certain time margin is required after the speed regulation stage completes adjusting the excitation current. Therefore, the amount of change \( \Delta\omega_2 \) is also a fixed value (the value of \( \Delta\omega_2 \) is \( \pi \) rad/s).

### IV. THE INFLUENCE OF PHASE ANGLE DIFFERENCE ON GRID-CONNECTON SUCCESS RATE

#### A. CONSTRAINTS OF FREQUENCY AND PHASE ANGLE DIFFERENCES

According to the conclusion in Section III that \( \Delta\omega_1 \) and \( \Delta\omega_2 \) are fixed values, the speed point \( \omega_2 \) can be selected as an example to show the effect of the phase angle difference on the grid-connection success rate.

The upper limit of the frequency and the phase angle differences are labeled as \( \Delta f^* \) and \( \Delta\varphi^* \), respectively, and the phase angle difference between the synchronous condenser and the grid is denoted as \( \Delta\varphi_B \) when the speed drops to \( \omega_2 \). Note that \( \Delta\varphi_B \) can be any value between 0° and 360° and is positive when the grid is ahead of the synchronous condenser.

The grid-connection criterion requires that the practical phase angle difference and frequency difference between the synchronous condenser and the grid should be smaller than the predesigned value:

\[
\begin{align*}
|\Delta f| & \leq |\Delta f^*| \\
|\Delta\varphi| & \leq |\Delta\varphi^*|
\end{align*}
\]  

(5)

Equation (5) provides a grid-connection window during the freewheeling process that is marked using the blue areas in Fig. 3. The red curve in Fig. 3 illustrates the real-time
variation of the phase angle difference between the synchronous condenser and the grid while the blue curve shows the real-time frequency difference variation. Figs. 3(a) and (b) respectively describe two distinct grid connection cases when the initial phase angle difference is different. Note both the two are successful grid-connection cases since the red curves both get inside the blue areas.

It is useful to express the frequency difference constraint as a function of the time \( t \), where \( t \) is the period from the speed point \( \omega_2 \) to the final grid connected point. Therefore, the constraint of the frequency difference in (5) can be rewritten as

\[
\left| \frac{\omega_2 - \Delta t \times a_1 - \omega_0}{2\pi} \right| \leq \Delta f^* \tag{6}
\]

where \( a_1 \) is the acceleration of the freewheeling speed under rated excitation.

Furthermore, the constraints of the phase angle difference for grid-connection can also be defined as a function of \( t \), but it should be discussed respectively as per the positive and negative frequency difference at the final grid connection point.

1) POSITIVE FREQUENCY DIFFERENCE
In this case, the speed variation is shown in Fig. 4, and then the phase angle difference constraint in (5) can be expressed as

\[
\text{mod} \left( \left| \Delta \phi_B - \Delta \phi \right| \right) \leq \Delta \phi^* \tag{7}
\]

where \( \Delta \phi \) is the variation of the phase angle difference during the period \( \Delta t \) [see the red shaded region in Fig.4], and the period of the mod function is \( 360^\circ \). \( \Delta \phi \) can be further expressed as

\[
\Delta \phi = \left[ \Delta \omega_2 + (\Delta \omega_2 - \Delta t \times a_1) \right] \times \Delta t \times 1/2 \times 360/2\pi \tag{8}
\]

Combining with the frequency difference constraint (6) and substituting (8) into (7) gives

\[
\left\{ \begin{array}{l}
\frac{\Delta \omega_2 - \Delta f^* \times 2\pi}{a_1} \leq \frac{\Delta \omega_2}{a_1} \\
-\Delta \phi^* \leq G(\Delta t) \leq \Delta \phi^*
\end{array} \right. \tag{9}
\]

where

\[
G(\Delta t) = \text{mod} \left( \frac{90}{\pi} \frac{d\omega}{dt} \Delta t^2 - \frac{180}{\pi} \Delta \omega_2 \Delta t + \Delta \phi_B \right)
\]

2) NEGATIVE FREQUENCY DIFFERENCE
In this case, the speed variation is shown in Fig. 5, and then the phase angle difference constraint in (5) can be expressed as

\[
\text{mod} \left( \left| \Delta \phi_B + \Delta \phi' + \Delta \phi'' \right| \right) \leq \Delta \phi^* \tag{10}
\]

where \( \Delta \phi' \) and \( \Delta \phi'' \) are the positive and negative phase angle difference variations during the period \( \Delta t \), respectively. (\( \Delta \phi' \) is the red shaded region of Fig. 4 while \( \Delta \phi'' \) is the black
Again, combining with the frequency difference constraint (6) and substituting (11) into (10) yields

$$
\begin{align}
\frac{\Delta \omega_2}{a_1} & \leq \Delta t \leq \frac{\Delta \omega_2 + \Delta f^* \times 2\pi}{a_1} \\
-\Delta \phi^* & \leq G(\Delta t) \leq \Delta \phi^* 
\end{align}
$$

Overall, the frequency and phase angle difference constraint can be eventually derived via combining (9) and (12) as

$$
\begin{align}
\frac{\Delta \omega_2 - \Delta f^* \times 2\pi}{a_1} & \leq \Delta t \leq \frac{\Delta \omega_2 + \Delta f^* \times 2\pi}{a_1} \\
-\Delta \phi^* & \leq G(\Delta t) \leq \Delta \phi^* 
\end{align}
$$

### B. THE INFLUENCE OF THE PHASE ANGLE DIFFERENCE ON THE GRID-CONNECTION SUCCESS RATE

As analyzed above, the grid-connection criterion expressed in (5) are now represented by the length of the period $\Delta t$ which should satisfy (13). If there is a solution to (13), it means that during the freewheeling process, there are possible grid-connection points that meet both the constraints of the required frequency difference and phase angle difference. Conversely, there is no possible grid-connection point that satisfies (5) if there is no solution to (13).

Rearranging (13) gives the following equivalent inequalities

$$
\begin{align}
-\Delta \phi^* + \text{mod} \left( \frac{90}{\pi} \times \frac{\Delta \omega_2^2}{a_1} \right) & \leq \Delta \phi_B \\
\Delta \phi_B & \leq -\Delta \phi^* + \text{mod} \left( \frac{90}{\pi} \times \frac{\Delta \omega_2^2}{a_1} \right) \\
\Delta \phi_A = \Delta \phi_B + \left( \omega_1 + \omega_2 \right) \times \frac{\omega_1 - \omega_2}{a_1} & \leq \frac{1}{2} \times \frac{360}{2\pi} 
\end{align}
$$

where $\Delta \phi_A$ is the phase angle difference between the synchronous condenser and the grid when the speed drops to $\omega_1$ as shown in Figs. 4 and 5. As a result, $\Delta \phi_A$ can be used as a vital index that determines if there are grid-connection points or not. Since the value of $\Delta \phi_A$ is a random value between 0° and 360°, the successful grid-connection area represented by (14) is shown by the red area in Fig. 6, in which the starting and ending points is given by

$$
\begin{align}
\phi_a & = -\Delta \phi^* + \text{mod} \left( \frac{90}{\pi} \times \frac{(\omega_1 - \omega_0)^2}{a_1} \right) \\
& \times \frac{\Delta f^* \times 2\pi^2}{a_1} + (\omega_1 + \omega_2) \times \frac{\omega_1 - \omega_2}{a_1} \leq \frac{1}{2} \times \frac{360}{2\pi} \\
\phi_B & = \Delta \phi^* + \text{mod} \left( \frac{90}{\pi} \times \frac{(\omega_1 - \omega_0)^2}{a_1} \right) \\
& + (\omega_1 + \omega_2) \times \frac{\omega_1 - \omega_2}{a_1} \leq \frac{1}{2} \times \frac{360}{2\pi} 
\end{align}
$$

Therefore, the overall grid-connection success rate can be obtained by calculating the proportion of the red area in a fundamental cycle, which gives

$$
P = \min \left( \frac{90}{\pi} \times \frac{(\Delta f^* \times 2\pi)^2}{a_1 \frac{d\omega}{dt}} + 2 \Delta \phi^* \right) \times 100\% \hspace{1cm} (16)
$$

Equation (16) shows that at a given freewheeling speed ratio the grid-connection success rate of the condenser solely depends on the criterion $\Delta f^*$ and $\Delta \phi^*$, if no other actions are taken. It is apparent that the success rate is low if the criterion is strict, so that additional measures should be employed to improve the reliability of the grid-connection operation, as detailed in the next section.

### V. THE PROPOSED START-UP PROCESS OPTIMIZATION OF THE SYNCHRONOUS CONDENSER

#### A. THE INFLUENCE OF THE FREEWHEELING SPEED RATIO REGULATION ON THE GRID-CONNECTION SUCCESS RATE

As analyzed in Section II, the excitation current directly influences the acceleration of the freewheeling speed. Therefore, it is possible to improve the grid-connection success rate by indirectly regulating the freewheeling speed ratio through adjusting the excitation current. To be specific, the interval $t_1$ to $t_2$ as shown in Fig. 2 is the speed regulating stage in which...
the freewheeling speed ratio can be increased or decreased through controlling the excitation current. Therefore, the tolerant range of the phase angle difference is increased, thereby the grid-connection success rate of the synchronous condenser is increased.

FIGURE 7. Illustration of the optimization method by incorporating the freewheeling speed ratio regulation. The freewheeling speed curve before and after adopting this regulation method is shown in Fig. 7, where the black curve indicates the freewheeling speed acceleration is $a_1$ while the blue curve indicates the freewheeling speed acceleration changes to $a_2$ (Note $a_2$ is specified as the lowest freewheeling speed ratio that can be achieved within the allowable range of the excitation current adjustment).

As shown in Fig. 7, when the freewheeling speed acceleration is $a_1$, the speed decreases from $\omega_1$ along AB to $\omega_2$, and the phase angle difference generated is the area AFCB. After implementing the freewheeling speed ratio regulation method, the speed alternatively decreases along AE to $\omega_2$ and the phase angle difference generated updates to the area AFDE. As a result, the increased area ABCDE is the increased range of the phase angle difference from $\varphi_B$ to $\varphi_E$ that can be used to increase the grid-connection success rate. Since from (14) whether the grid-connection point exists or not is determined by the phase angle difference $\Delta \varphi_A$ (or $\Delta \varphi_B$) at the time of speed dropping to $\omega_1$ (or $\omega_2$ ), it is able to reduce the freewheeling speed ratio to a certain value so that the phase angle difference $\Delta \varphi_E$ satisfies (14) when $\Delta \varphi_B$ does not satisfy (14). This is the principle of improving the grid-connection success rate through the freewheeling speed ratio regulation method.

For simplification of calculation, the area ABCDE is divided into two areas ABE and BCDE, respectively

$$S_{ABE} = \frac{1}{2} a_2 (\omega_1 - \omega_2) \times (\omega_1 - \omega_2) \times \frac{360}{2\pi}$$

$$S_{BCDE} = \frac{1}{2} a_2 (\omega_1 - \omega_2) \times (\omega_2 - \omega_0) \times \frac{360}{2\pi}$$

(17)

The total area is their summation as

$$S_{ABCDE} = \frac{1}{2} (\omega_1 - \omega_2) \times \left( \frac{\omega_1 + \omega_2}{2} - \omega_0 \right) \times \frac{360}{2\pi}.$$ 

(18)

As mentioned above, $a_2$ is the lowest allowable freewheeling speed acceleration through adjusting the excitation current, so the adjustable range of the phase angle difference (defined as $S$) using the freewheeling speed ratio regulation method is calculated as

$$S \in \left[0, (\omega_1 - \omega_2) \times \left( \frac{\omega_1 + \omega_2}{2} - \omega_0 \right) \times \frac{360}{2\pi} \times \left( \frac{1}{a_2} - \frac{1}{a_1} \right) \right].$$

(19)

Compared with Fig. 6, the added grid-connection success area using the freewheeling speed ratio regulation method is marked with the blue areas in Fig. 8. In other words, if the phase angle difference $\Delta \varphi_A$ falls within the range of $[\varphi_B, \varphi_E]$, the freewheeling speed ratio regulation method can assure the synchronous condenser connected to the grid successfully, where

$$\varphi_E = \mod \left( \varphi_B + (\omega_1 - \omega_2) \times \left( \frac{\omega_1 + \omega_2}{2} - \omega_0 \right) \times \frac{360}{2\pi} \times \left( \frac{1}{a_2} - \frac{1}{a_1} \right) \right)$$

(20)

However, if the phase angle difference $\Delta \varphi_A$ falls beyond the above successful range, further actions are required to
assure the grid-connection success rate, as detailed in the following sub-section.

**B. THE INFLUENCE OF THE STARTING FREEWHEEL POINT SETTING ON THE GRID-CONNECTION SUCCESS RATE**

If the phase angle difference $\Delta \phi_A$ at point A is located in the grid-connection failure area [see the yellow area in Fig. 8], it is necessary to further increase the adjustable range of the phase angle difference by increasing the starting freewheel speed at point A.

The speed curve after adopting the starting freewheel point setting method is shown in Fig. 10. As compared with the previous freewheeling speed ratio regulation and starting freewheel point methods, the possibly adjustable area updates to $A'B'C'D'$ when the starting freewheel point increases, where the phase angle difference $\Delta \phi_B'$ at point B’ is

$$\Delta \phi_B' = \Delta \phi_A - (\omega'_1 + \omega_2) \times \frac{\omega'_1 - \omega_2}{a_1} \times \frac{1}{2} \times \frac{360}{2\pi} \quad (23)$$

Representing $\Delta \phi_B'$ with $\Delta \phi_B$ yields

$$\Delta \phi_B = \Delta \phi_B' + \frac{\omega_2^2 - \omega'_1^2}{a_1} \times \frac{1}{2} \times \frac{360}{2\pi} \quad (24)$$

The adjustable range of the phase angle difference corresponding to $A'B'C'D'$ is calculated as

$$S_{A'B'C'D'E'} = \left( \frac{\omega'_1 - \omega_2}{a_2} - \frac{\omega'_1 - \omega_2}{a_1} \right) \times \left( \frac{\omega'_1 + \omega_2}{2} - \omega_0 \right) \times \frac{90}{\pi} \quad (25)$$

Compared with Fig. 8, the improved grid-connection success area using the starting freewheel point setting method is marked with the green area in Fig. 11. Different from solely using the freewheeling speed ratio regulation method, the green area increases when the augmented freewheel point increases, and when the green area increases to a certain
range, interval \([ \varphi_\alpha, \varphi_\sigma ]\) is possible to cover the entire failure region, which means it can achieve 100% grid-connection success rate. The value of the boundary phase difference \(\varphi_\sigma\) is calculated as

\[
\varphi_\sigma = \text{mod} \left( \varphi_r + \left( \frac{\omega_1^2 - \omega_2^2}{2} - \omega_0 \omega_1^1 + \omega_0 \omega_1 \right) \times \frac{1}{a_2} \times \frac{360}{2\pi} \right)
\]

(26)

C. THE PROPOSED OPTIMIZATION METHOD COMBINING THE FREEWHEELING SPEED RATIO REGULATION AND THE STARTING FREEWHEEL POINT SETTING

Based on the above analysis, the following steps are designed to ensure that the synchronous condenser could be successfully connected to the grid under the freewheeling grid-connection mode.

1) **STEP1:** The measured phase angle difference satisfies (14), so that the condenser follows its predesigned grid connection command and no further action is required.

2) **STEP2:** The phase angle difference does not satisfy (14), whereas after using the freewheeling speed ratio regulation method, the phase angle difference falls into the grid-connection success area in Fig. 8.

3) **STEP3:** The condenser still cannot successfully connect to the grid, so the starting freewheel point is regulated until the phase angle difference falls into the grid-connection success area in Fig. 11.

It should be noted that it is able to achieve 100% grid-connection success rate by only using the starting freewheel point setting method theoretically. However, it is unrealistic to speed up the motor beyond its rated value too far, since for one hand, the internal thermal effects inside both the SFC and synchronous condenser accumulate faster, and for another hand, the high speed may affect the lifetime of the motor and SFC system. Therefore, it is not advisable to achieve a 100% successful grid-connection by only increasing the starting freewheel point while the freewheeling speed ratio regulation method is required to reduce the speed of the starting freewheel point appropriately.

The analysis in Sections III, IV.A, and IV.B are based on the assumption that the initial speed is \(\omega_1\). However, in practice, the SFC system should be cut off before the speed drops to \(\omega_1\) and the speed cannot be increased during this time. Therefore, it is necessary to adjust the starting freewheel point before the freewheeling process starts. Therefore, the complete grid-connection optimization method of the synchronous condenser is given as follows.

It is assumed the starting freewheel point is \(\omega_s\) \((105 \pi \text{ rad/s})\), the corresponding phase angle difference is \(\Delta \varphi_s\), and the acceleration of the freewheeling speed during the excitation switching stage is \(a_3\), observing from Fig. 2 yields

\[
\begin{align*}
\omega_1 &= \omega_s - \Delta \omega_1 \\
\omega_2 &= \omega_0 + \Delta \omega_2 \\
\Delta \varphi_A &= \Delta \varphi_s - \frac{\Delta \omega^2}{a_3} \times \frac{1}{2} \times \frac{360}{2\pi}
\end{align*}
\]

(27)

Furthermore, equation (14) can be transformed into (28), as shown at the bottom of the next page. Under the freewheeling speed ratio regulation method, the criterion determining if the grid-connection is successful or not is given in (29), as shown at the bottom of the next page. While under the starting freewheel point setting method, the criterion determining if the grid-connection is successful or not is equations of grid-connection success given in (30), as shown at the bottom of the 11th page, respectively. These steps are listed in the flow chart as shown in Fig. 12, following which the synchronous condenser can be connected to the grid successfully.

VI. STATISTICAL VERIFICATION

A. THE PARAMETERS OF SYNCHRONOUS CONDENSER START-UP SYSTEM

The engineering parameters of the new type 300 Mvar synchronous condenser are as follows. The rated terminal voltage is 20 kV. The rated speed is 100 \(\pi\) rad/s (equals to 3000 r/min), initially the speed is set at 1.05 times the rated speed when the SFC system cuts off, the speed at which the excitation system switching finishes is approximately 104 \(\pi\) rad/s, and under the rated excitation current, the acceleration rate of the freewheeling speed is selected according to the practical speed curve of a condenser as shown in Fig. 9, which

![FIGURE 11. The updated three possible successful grid-connection areas through the proposed combined optimization strategy.](image-url)
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FIGURE 12. The complete grid-connection flow chart.

is calculated as

$$\Delta \omega = \frac{(3153.06 - 3001.81) \text{r/s}}{(16 : 02 : 16 - 16 : 01 : 45) \text{s}} = 0.16 \pi \text{rad/s}^2 \quad (31)$$

B. THE STATISTICAL TEST OF THE GRID-CONNECTION SUCCESS RATE WITHOUT OPTIMIZATION METHOD

The constraint of the frequency difference is selected as 0.1Hz, 0.2 Hz, 0.3 Hz and 0.4 Hz, and the phase angle difference is selected as 1°, 3°, 5° and 10°, respectively. The above test is repeated 10000 times under random initial phase angles (i.e., from 0° to 360°), and the results of the grid-connection success rate is depicted in Fig. 13.

It can be concluded from Fig. 13 that the grid-connection success rate is dominantly affected by the constraint of the frequency difference, which is consistent with the conclusion in [23]. That is to say, the success rate of the grid-connection increases rapidly with the increases of the frequency difference constraint (e.g., a 0.2 Hz constraint has only around 25% success rate whereas a 0.4 Hz constraint increases the success rate to approximately 100%). This is the reason why the frequency difference is typically selected as the key parameter that guarantees the grid-connection reliability in conventional grid-connection processes. However, in the practical grid-connection process, if the constraint of the frequency difference is set to a higher value, it will cause large surge current, possible mechanical damage, and even the system protection and turn-off. Therefore, according to the safety requirement, the frequency difference should be set within a tolerant small value. Table 1 lists the matching results of the test from experiment and the calculated probability from theorem under the same condition assumed above, and it shows when the constraint of the frequency difference is set to 0.2Hz, the grid-connection success rate is as low as below 30%. Moreover, when the constraint of frequency difference is set as 0.1Hz, the grid-connection success rate is
difficult to exceed 10%. Therefore, it is necessary to improve the grid-connection success rate of the condenser using the proposed optimization methods.

### C. The Statistical Test of the Grid-Connection Success Rate with the Freewheeling Speed Ratio Regulation

In this part, the freewheeling speed ratio regulation is solely used to demonstrate its effectiveness in increasing the grid-connection success rate. The same grid-connection condition as used in sub-section A is retained here while the freewheeling speed ratio is regulated to 99%, 98%, 97% and 96% of rated value, respectively. These four cases show how the reduction of the freewheeling speed ratio impacts on the grid-connection success rate, with the comparative results depicted in Fig. 14.

Comparing Fig. 14 with Fig. 13 reveals that reduction of the freewheeling speed ratio can effectively increase the grid-connection success rate. For example, when the freewheeling speed ratio is reduced to 99% of the rating, the success rate is increased from around 25% to near 50% when the frequency difference is fixed at 0.2 Hz. Furthermore, if the speed ratio is reduced to 97% of the rating, the success rate is approximately approaching 100% with the frequency difference set to 0.2 Hz. Finally, when the freewheeling speed ratio drops to 96% of rating, the success rate of grid-connection would reach 100% under any frequency/phase angle difference requirements. This is because when freewheeling speed ratio is small enough, the blue and red area in Fig. 8 would cover the entire circular region, so that 100% successful grid-connection operation can be achieved under strict grid-connection conditions. Table 2-5 lists the four speed reduction cases with matching test result from experiment and calculated probability in theorem with respect to the conclusion from Fig. 14.

### TABLE 1. The grid-connection success rate under two test cases without using the optimization method.

| Frequency Difference/Hz | Phase Angle Difference/° | Success Rate |
|-------------------------|--------------------------|--------------|
|                         |                          | Test | Probability |
| 0.1                     | 1                        | 6.47% | 6.8%          |
|                         | 3                        | 7.84% | 7.91%         |
|                         | 5                        | 8.81% | 9.02%         |
|                         | 10                       | 11.58% | 11.8%        |
| 0.2                     | 1                        | 24.93% | 25.55%       |
|                         | 3                        | 26.64% | 26.67%       |
|                         | 5                        | 27.53% | 27.78%       |
|                         | 10                       | 29.93% | 30.55%       |
| 0.3                     | 1                        | 55.26% | 56.8%        |
|                         | 3                        | 57.16% | 57.92%       |
|                         | 5                        | 58.13% | 59.02%       |
|                         | 10                       | 60.76% | 61.8%        |
| 0.4                     | 1                        | 98.17% | 98.16%       |
|                         | 3                        | 99.14% | 99.55%       |
|                         | 5                        | 100%   | 100%         |
|                         | 10                       | 100%   | 100%         |

### TABLE 2. The grid-connection success rate under two test cases when freewheeling speed ratio drops to 99% of rating.

| Frequency Difference/Hz | Phase Angle Difference/° | Success Rate |
|-------------------------|--------------------------|--------------|
|                         |                          | Test | Probability |
| 0.1                     | 1                        | 29.23% | 29.13%       |
|                         | 3                        | 31.16% | 30.96%       |
|                         | 5                        | 32.27% | 32.41%       |
|                         | 10                       | 34.64% | 34.30%       |
| 0.2                     | 1                        | 47.70% | 48.65%       |
|                         | 3                        | 48.61% | 49.32%       |
|                         | 5                        | 50.56% | 50.73%       |
|                         | 10                       | 52.12% | 52.05%       |
| 0.3                     | 1                        | 78.83% | 78.43%       |
|                         | 3                        | 79.97% | 79.65%       |
|                         | 5                        | 81.02% | 80.52%       |
|                         | 10                       | 83.40% | 81.65%       |
| 0.4                     | 1                        | 100%   | 100%         |

### Table 2

| Frequency Difference/Hz | Phase Angle Difference/° | Success Rate |
|-------------------------|--------------------------|--------------|
|                         |                          | Test | Probability |
| 0.1                     | 1                        | 29.23% | 29.13%       |
|                         | 3                        | 31.16% | 30.96%       |
|                         | 5                        | 32.27% | 32.41%       |
|                         | 10                       | 34.64% | 34.30%       |
| 0.2                     | 1                        | 47.70% | 48.65%       |
|                         | 3                        | 48.61% | 49.32%       |
|                         | 5                        | 50.56% | 50.73%       |
|                         | 10                       | 52.12% | 52.05%       |
| 0.3                     | 1                        | 78.83% | 78.43%       |
|                         | 3                        | 79.97% | 79.65%       |
|                         | 5                        | 81.02% | 80.52%       |
|                         | 10                       | 83.40% | 81.65%       |
| 0.4                     | 1                        | 100%   | 100%         |

However, the influence of the excitation current regulation on the freewheeling speed ratio is limited in practice, so the lowest freewheeling speed ratio that can be achieved may
not meet the 100% successful grid connection conditions as analyzed above. Therefore, the starting freewheel point setting method is necessary to be used to combine with the freewheeling speed ratio regulation to further improve the grid-connection success rate to 100%.

D. THE STATISTICAL TEST OF THE GRID-CONNECTION SUCCESS RATE WITH THE STARTING FREEWHEEL POINT SETTING

For cases where the adjustable range of the freewheeling speed ratio is limited, the starting freewheel point setting method should be used to increase the success rate of grid-connection to 100%, following the procedure as outlined in Fig. 12. This experiment is performed under the same grid-connection condition as in sub-sections VI.B and VI.C, and the three achievable cases where the freewheeling speed ratio is regulated to 99%, 98% and 97% of the rating is considered, respectively. The setting times of the freewheel point and the final starting freewheel point required for each case are presented in Table 4.

### TABLE 3. The grid-connection success rate under two test cases when freewheeling speed ratio drops to 98% of rating.

| Frequency Difference/Hz | Phase Angle Difference/° | Success Rate |
|-------------------------|--------------------------|--------------|
|                         | Test                     | Probability  |
| 0.1                     | 1                        | 52.74%       | 52.61%       |
|                         | 3                        | 53.64%       | 53.72%       |
|                         | 5                        | 55.62%       | 54.83%       |
|                         | 10                       | 58.57%       | 58.61%       |
| 0.2                     | 1                        | 71.79%       | 75.24%       |
|                         | 3                        | 72.25%       | 73.07%       |
|                         | 5                        | 73.77%       | 73.86%       |
|                         | 10                       | 76.73%       | 77.39%       |
| 0.3                     | 1                        | 100%         | 100%         |

### TABLE 4. The grid-connection success rate under two test cases when freewheeling speed ratio drops to 97% of rating.

| Frequency Difference/Hz | Phase Angle Difference/° | Success Rate |
|-------------------------|--------------------------|--------------|
|                         | Test                     | Probability  |
| 0.1                     | 1                        | 76.52%       | 76.68%       |
|                         | 3                        | 78.56%       | 78.35%       |
|                         | 5                        | 79.82%       | 79.73%       |
|                         | 10                       | 82.69%       | 83.21%       |
| 0.2                     | 1                        | 95.86%       | 94.96%       |
|                         | 3                        | 96.80%       | 96.35%       |
|                         | 5                        | 98.10%       | 98.52%       |
|                         | 10                       | 100%         | 100%         |

### TABLE 5. The grid-connection success rate under two test cases when freewheeling speed ratio drops to 96% of rating.

| Frequency Difference/Hz | Phase Angle Difference/° | Success Rate |
|-------------------------|--------------------------|--------------|
|                         | Test                     | Probability  |
| 0.1                     | 1                        | 100%         | 100%         |

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TABLE 6. The final starting freewheel point using the proposed combined method when the freewheeling speed ratio drops to 99% of the rating.

| Frequency Difference/Hz | Phase Angle Difference/° | Statistics |   |   |
|-------------------------|--------------------------|------------|---|---|
|                         |                           | Average Setting Times | Final Starting Freewheel Point/ rad/s |   |   |
| 0.1                     | 1                        | 39.29       | 107.16 |   |   |
|                         | 3                        | 37.65       | 107.12 |   |   |
|                         | 5                        | 36.44       | 107.1  |   |   |
|                         | 10                       | 34.18       | 107.04 |   |   |
| 0.2                     | 1                        | 21.38       | 106.67 |   |   |
|                         | 3                        | 20.02       | 106.64 |   |   |
|                         | 5                        | 19.50       | 106.63 |   |   |
|                         | 10                       | 17.70       | 106.57 |   |   |
| 0.3                     | 1                        | 3.75        | 105.81 |   |   |
|                         | 3                        | 3.34        | 105.75 |   |   |
|                         | 5                        | 2.96        | 105.71 |   |   |
|                         | 10                       | 2.27        | 105.64 |   |   |

TABLE 7. The final starting freewheel point using the proposed combined method when the freewheeling speed ratio drops to 98% of the rating.

| Frequency Difference/Hz | Phase Angle Difference/° | Statistics |   |   |
|-------------------------|--------------------------|------------|---|---|
|                         |                           | Average Setting Times | Final Starting Freewheel Point/ rad/s |   |   |
| 0.1                     | 1                        | 1.4         | 105.3  |   |   |
|                         | 3                        | 1.29        | 105.3  |   |   |
|                         | 5                        | 1.18        | 105.3  |   |   |
|                         | 10                       | 0.87        | 105.25 |   |   |
| 0.2                     | 1                        | 0.08        | 105.08 |   |   |
|                         | 3                        | 0.05        | 105.07 |   |   |
|                         | 5                        | 0.02        | 105.05 |   |   |

TABLE 8. The final starting freewheel point using the proposed combined method when the freewheeling speed ratio drops to 97% of the rating.

| Frequency Difference/Hz | Phase Angle Difference/° | Statistics |   |   |
|-------------------------|--------------------------|------------|---|---|
|                         |                           | Average Setting Times | Final Starting Freewheel Point/ rad/s |   |   |

100% success rate grid-connection, after adopting the starting freewheel point setting method is provided in Tables 6, 7, and 8, respectively. These results show that setting the starting freewheel point in any cases is able to increase the grid-connection success rate to 100%, but the final set value (i.e., the starting freewheel speed) depends on how strict the grid-connection criterion is. In the strictest case when the frequency difference is as low as 0.1 Hz and the phase angle difference is set to 0°, the highest starting freewheel point required to reach is only 107.16π rad/s (about 1.07 times the rated speed) when coordinated with the freewheeling speed ratio regulation method with 99% of rating. This is an acceptable value that can be achieved with a conventional SFC device.

VII. CONCLUSION

Since the new-type synchronous condenser uses the freewheeling grid-connection mode, its grid-connection success rate is generally low while ensuring the grid-connection reliability and safety.

The calculation of the success rate of the freewheeling grid-connection mode is provided, based on which the influence of the frequency difference and phase angle difference on the success rate of grid-connection is derived. From these, this paper has proposed an optimized start-up process, with the freewheeling speed ratio and the starting freewheel speed point incorporated as another two degrees of freedom to ensure the 100% grid-connection success rate under strict grid-connection criterions.

With the starting freewheel speed point slightly increased and the freewheeling speed ratio slight decreased, the reliable and safe grid-connection operation of the new-type synchronous condenser can be ensured. The statistical verification proves that the proposed method ensures the success of grid-connection operation even if the pre-set frequency difference criterion is set as low as 0.1 Hz, with the starting freewheel speed increased to 107.16 rad/s and the acceleration reduced to 99% of the rating.

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