Coupled autotransformer and magnetic-control soft-start method for super-large-capacity high-voltage motors

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1 Introduction

With the ongoing development of the economy, the number of super-large-capacity high-voltage induction motors used in many industries has increased every year. When started directly, the starting current of these high-voltage motors can reach as high as four to seven times the motor’s rated current. For super-large-capacity motors (voltages >6 kV and power >10,000 kW), the direct starting current can reach ≥5000 A [1–6]. Such large starting currents are nearly equivalent to the impact of a three-phase short circuit on the power grid, which can easily cause power oscillations and destabilise the power grid, thus seriously affecting the normal operation of other power-grid equipment [7–11]. At the same time, such a large starting current will greatly impact the stator winding and rotor bar, causing squirrel-cage fracture and motor faults. In addition, this huge starting current will rapidly wear the gears in the transmission equipment [12–17].

Many soft-start methods have been studied. Traditional soft starters, including the Y-Δ, liquid-state, solid-state, and autotransformer soft starters cannot continuously adjust the starting voltage of the motor, which leads to a large inrush current when starting the motor. These methods have the shortcomings of voltage sags, sudden torque mutation and secondary current impact [18–20]. Resistive-type fault current limiter is simple, effective and has low cost, but will produce a large active power loss [21]. The high-voltage inverter has the best starting performance, but it is mainly used on occasions where speed regulation is required and is purely used for the soft start of super-large-capacity high-voltage motors, which is a huge waste of resources, and its cost performance is not high [22]. Superconducting fault current limiter can effectively reduce the starting current, but the cost is high [23–25]. The soft starter based on the magnetic control reactor (MCR) has many advantages, including high reliability, flexible control, and so on. However, during the starting process, the motor side current is the same as the system side current, so when the super-large-capacity high-voltage motor is started, the system short-circuit current must be higher to prevent too large a drop in the system voltage. Moreover, when the capacity of the motor is very large, the cost of the start device when using this method would be very high [26]. To resolve this issue, in this paper, we propose a novel coupled autotransformer and magnetic-control (CATMC) soft-start method for the super-large-capacity high-voltage induction motor. The structure of the new CATMC soft starter combines the functions of the autotransformer and MCR via an innovative electric and magnetic circuit design. Hence, the starting current is reduced in two ways and the structure is more compact and flexible. We analyse the performance of the current auto-decoupling step-down start method and conclude that this method can be used in the initial stage of starting to greatly reduce the current on the grid side. To meet the motor starting and grid voltage sag requirements, we determined the selection range for the tap ratio of the autotransformer. We also analyse the magnetic circuit structure and working principles of the CATMC soft starter. Using ANSYS Maxwell software, we establish a 3-D model of the CATMC soft starter. The simulation results verify that the starting current can be limited to 2.5 times the rated current, such that the voltage sag meets the national standard, the impact on the power grid is reduced, and there is a smooth start, stable performance and fast response speed.

2 Electrical parameters of induction motors

Fig. 1 shows the equivalent circuit of an induction motor.

In Fig. 1, $U_1$ is the motor phase voltage, $E_1$ is the induced electromotive force in the stator winding, $E_2$ is the converted rotor-winding electromotive force, $I_1$ is the stator current, $I_2$ is the converted rotor current, $I_0$ is the excitation current, $s$ is the slip ratio, $r_1$ and $x_4$ are the resistance and leakage reactance of the stator, respectively, $r_2$ and $x_2$ are the resistance and leakage reactance of the stator side of the rotor, $r_m$ is the magnetising resistance, and $x_m$ is the magnetising reactance.
Based on the equivalent circuit, the expressions of the phase impedance \( Z \) under normal operating conditions can be determined as shown in (1):

\[
Z = r + jx_m + \left( \frac{r_m + jx_m}{r_m + jx_m + (r_x/s) + jx_o} \right) = \left| Z \right| e^{j\phi}.
\]

The parameters \( U_1, I_1, T_{NC}, k_1, k_2, k_3 \) and \( k_4 \) can be obtained in the motor's product catalogue, and parameters such as \( r_1, x_{1b}, r_2, x_2 \) can be calculated by substituting these parameters into (1).

### 3 Topological structure analysis of CATMC soft starter

#### 3.1 Basic principle

Fig. 2 shows a topological diagram of the CATMC soft starter. The CATMC soft starter has a five-column core structure with a smaller volume, in which the main cores are cores I, II, and III. The topological diagram shows five windings, where cores I and II each comprise AC and DC excitation windings, and core III comprises an AC winding. The number of turns of the high-voltage-side AC winding is \( N_1 \), the number of turns of the DC excitation winding is \( N_2 \), and the number of turns of the low-voltage-side AC winding is \( N_3 \). The AC windings of cores I and II are connected in parallel and then in a series with the AC winding of core III. The two DC excitation windings are, respectively, connected in a series with cores I and II and then to the DC excitation power supply.

The soft-start process can be divided into two main stages. When starting, the DC excitation current is not applied to the high-voltage side, and the high-voltage-side winding \( N_1 \) and low-voltage-side winding \( N_2 \) are equivalent to the formation of an autotransformer, which realises an auto-decoupling step-down start. As the motor terminal voltage gradually rises, a DC excitation current is applied to the high-voltage side, and the core is saturated, so that the equivalent reactance of the high-voltage side is reduced, thereby maintaining constant current and achieving a constant-current start.

The structure of the proposed CATMC soft starter combines the functions of the autotransformer and MCR via an innovative electronic and magnetic circuit design. Hence, the starting current is reduced in two ways and the structure becomes more compact and flexible. The basic idea is to change the magnetic saturation by injecting DC excitation into the excitation winding through the rectifier, and then to change the equivalent permeability to smoothly change the reactance value and reactance capacity.

#### 3.2 Starting current analysis for auto-decoupling step-down start

For the convenience of research, we assume that the autotransformer is an ideal device and the excitation impedance is infinite. The induction motor has resistance–inductance load characteristics, so the resistance–inductance loads are equivalent. Fig. 3 shows an equivalent circuit model of an auto-decoupling step-down start.

In Fig. 3, \( U_1 \) is the voltage of the primary winding, and \( U_2 \) is the secondary winding voltage; \( N_1 \) and \( N_2 \) are the number of turns of the primary-side self-winding and the low-voltage-side common winding, respectively; \( I_1, I_2, \) and \( I_3 \) are currents passing through the high-voltage-side winding, the low-voltage-side common winding, and the load flowing through the motor, respectively; and \( X_1 \) and \( R_1 \) represent the reactance and resistance values of the equivalent resistance–induction load of the induction motor, respectively.

The tap ratio \( k_2 \) of the autotransformer can be determined as shown in (2)

\[
k_2 = \frac{U_2}{U_1} = \frac{N_2}{N_1 + N_3} = \frac{1}{K + \left( k_2 < 1 \right)}. \quad (2)
\]

Ignoring the leakage-related reactance voltage drop, the ratio of the primary and secondary side voltage is calculated as shown in (3):

\[
\frac{U_1}{U_2} = \frac{N_1 + N_3}{N_2} = K + 1. \quad (3)
\]

The balance relation of the magnetomotive potential under load is as shown in (4):

\[
N_1 I_1 - N_2 J_2 = N_4 I_a. \quad (4)
\]

Ignoring the excitation current, we can obtain the following:

\[
N_1 I_1 - N_2 J_2 = 0. \quad (5)
\]

Therefore, the current relationship can be obtained as shown in (6):

\[
I_i = \frac{N_2}{N_4} I_a = \frac{1}{K} I_a = \frac{k_2}{1 - k_2} I_2. \quad (6)
\]

For point a, using Kirchhoff's current law the current relationship can be obtained as shown in (7):

\[
I_i = I_a + I_2. \quad (7)
\]

If we bring (7) into (6), we obtain (8), as follows:

\[
I_i = I_a + I_2 = \frac{1}{k_2} I_a. \quad (8)
\]
as shown in Fig. 4. Fig. 5 shows the DC and AC flux flows in the second stage of the soft start.

To simplify the analysis, we assume that the BH curve of the core is a double broken-line model. When the core is saturated, the magnetic permeability of the core is \( \mu_s \), and when the core is not saturated, the magnetic permeability of the core is \( \mu_r \). The magnetic fluxes flowing through cores I, II, III, IV, and V are \( \phi_1 \), \( \phi_2 \), \( \phi_3 \), \( \phi_4 \), and \( \phi_5 \), respectively. The magnetic reluctances of cores I, II, III, IV, and V and the core yoke are \( r_{i1} \), \( r_{e2} \), \( r_{e3} \), \( r_{i4} \), and \( r_{p1} \) respectively.

Assuming that the current is in the positive half cycle, using the loop current method, we can obtain (9)

\[
\begin{align*}
\phi_1(2r_{p1} + r_{w1}) - N_1I_{ac1} - N_2I_{d} + H_{el}e_1 = 0 \\
2(\phi_1 - \phi_3)r_{p1} - 2N_3I_d - N_3(I_{ac2} - I_{ac1}) + H_{el}e_2 + H_{el}e_3 = 0 \\
2(\phi_1 - \phi_2)r_{p1} - N_2I_{ac1} + N_3I_{ac2} + N_3I_d - H_{el}e_2 + H_{el}e_4 = 0. \\
2(\phi_1 - \phi_4)r_{p1} - N_1I_{ac} - H_{el}e_5 = 0 \\
\phi_1 - \phi_3 = \phi_1 + \phi_3 + \phi_4.
\end{align*}
\]

In the above, \( H_{el} \), \( H_{el} \), and \( H_{el} \) are the magnetic field strengths of cores I, II, and III, respectively, and \( le \) is the equivalent magnetic circuit length of cores I, II, and III. \( I_{ac1} \) is the current flowing through the high-voltage-side winding, \( I_{ac2} \) is the current flowing through the low-voltage-side winding, and \( I_d \) is the DC bias current. Using (9), we can obtain the magnetic flux flowing through the five cores by (10) (see (10)). From (10), we can see that in the second stage of the soft start, when the DC excitation current is added, the DC flux mainly flows through cores I and II, which make cores I and II reach deep saturation.

To simplify the analysis, we assume cores I and II are equivalent to cores with only one AC winding and one DC excitation winding. Whether the AC current is in a positive or negative half cycle, the flux generated by the DC excitation current is consistent with that generated by the AC current. Therefore, in the second stage of the soft start, the equivalent core is always in a state of deep saturation. Fig. 6 shows the simplified equivalent magnetic circuit model.

Similarly, assuming that the current is in the positive half cycle, it can be obtained using the loop current method, as follows:

\[
\begin{align*}
\phi_1(2r_{p1} + r_{w1}) - N_1I_{ac1} - N_2I_{d} + H_{el}e_1 = 0 \\
2(\phi_1 - \phi_2)r_{p1} - 2N_3I_d - N_3(I_{ac2} - I_{ac1}) + H_{el}e_2 = 0 \\
\phi_1(2r_{p1} + r_{w1}) - N_1I_{ac} - H_{el}e_5 = 0 \\
\phi_1 - \phi_3 = \phi_1 + \phi_3.
\end{align*}
\]

where \( H'_{el1} \) is the simplified magnetic field strength of cores I and II, \( H'_{el2} \) is the magnetic field strength of core III, and \( le \) is the equivalent magnetic path length of the core. \( I'_{ac1} \) is the current flowing through the simplified high-voltage-side winding, \( I'_{ac2} \) is the current flowing through the high-voltage-side winding, and \( I'_d \) is the DC bias current. The flux passing through four cores are calculated as shown in (12).
From (12), we can see that in the second stage of the soft start, when the DC excitation current is applied, the DC magnetic flux mainly flows through the simplified high-voltage-side core, so that the core reaches deep saturation (see (12)). We can derive $\phi_1$ and $\phi_2$ for time $t$, respectively, as follows:

\[
\frac{d\phi_1}{dt} = -\frac{N_1}{2P_2} \cdot \frac{dI_{i1}}{dt} + N_1 \left( \frac{1}{2P_2} + \frac{1}{2P_1 + r_{es}} \right) \cdot \frac{dI_{a2}}{dt} \quad + \frac{I_1}{2P_2} \cdot \frac{dH_{e1}}{dt} - \frac{1}{2P_2 + 1} \cdot \frac{dH_{e3}}{dt}.
\]

(14)

In addition, the magnetic field strengths $H'_{e1}$ and $H_{e3}$ satisfy the following relationships:

\[
\frac{dH_{e1}}{dt} = \frac{r_{es}}{L_c} \cdot \frac{d\phi_1}{dt},
\]

\[
\frac{dH_{e3}}{dt} = \frac{r_{es}}{L_c} \cdot \frac{d\phi_2}{dt}.
\]

(15)

(16)

To simplify the analysis, let:

\[
a = \frac{1}{2P_2}, \quad b = \frac{1}{2P_1 + r_{es}}, \quad c = \frac{1}{2P_1 + r_{es}}.
\]

(17)

\[
X = \frac{\frac{d\phi_1}{dt}}{\frac{dI_{i1}}{dt}}, \quad Y = \frac{\frac{dI_{i1}}{dt}}{\frac{dI_{a2}}{dt}}, \quad P = \frac{\frac{dH_{e1}}{dt}}{\frac{dI_{a2}}{dt}}, \quad Q = \frac{\frac{dH_{e3}}{dt}}{\frac{dI_{a2}}{dt}}.
\]

(18)

By coupling (15)–(18), we can obtain the simplified single winding inductance $L_{a1}$ of the high-voltage-side core and the single-winding inductance $L_{a3}$ of core III, respectively:

\[
L_{a1} = \frac{N_1(a + b) - N_1N_2a(Q/Y) + N_2r_{es}a(P/Y)}{1 + r_{es}(a + b)}.
\]

(19)

\[
L_{a3} = \frac{N_3(a + c) - N_3N_2a(Y/Q) + N_2r_{es}a(X/Q)}{1 + r_{es}(a + c)}.
\]

(20)

Since the simplified high-voltage-side core is deeply saturated, the small cross-section at the junction of the high- and low-voltage sides is saturated, and core III is not saturated, $r'_{e1}$, $r'_{e2}$, $r'_{e3}$, $r'_{e4}$, and $r_{ps}$ are much smaller than $r'_{e1}$ and $r_{e2}$, and can be generally ignored. So, we can simplify (19) and (20) as follows:

\[
L_{a1} = \frac{N_1(a + b)}{1 + r_{es}(a + b)} \approx \frac{N_1}{r_{es} + 2P_1 + r_{es}}.
\]

(21)

\[
L_{a3} = \frac{N_3(a + c)}{1 + r_{es}(a + c)} \approx \frac{N_3}{r_{es} + 2P_1 + r_{es}}.
\]

(22)

Therefore, in the second stage of the soft start, when the DC excitation current is added, the impedances of the high- and low-voltage sides are, respectively:

\[
X_{\text{high second}} = \frac{aN_1}{r_{es} + 2P_1 + r_{es}},
\]

(23)

\[
X_{\text{low second}} = \frac{aN_3}{r_{es} + 2P_1 + r_{es}}.
\]

(24)

where $\omega$ is the angular frequency of the power supply. From (23) and (24), we can see that in the second stage of the soft start, when the DC excitation current is applied, the equivalent impedance of the high-voltage side mainly depends on the core reluctance $r'_{e1}$ once cores I and II are equivalent. Therefore, it is possible to adjust $r'_{e1}$ by changing the DC excitation current on the high-voltage side, thereby maintaining constant current and enabling the motor to start smoothly.

4 Calculation of CATMC soft starter parameters

4.1 Determination of tap ratio of auto-transformer

The direct start of super-large-capacity high-voltage motors can produce large currents similar to short-circuit currents, which can lead to voltage sags in the power grids. The depth of voltage sag $\Delta U$ is defined as the difference between the nominal voltage and the minimum voltage drop. The duration $\Delta t$ is defined as the time when the voltage is <10% of the voltage rating. Fig. 7 shows a diagram of voltage sag.

To meet the motor starting requirement and the voltage sag standard for power grids, it is necessary to determine the selection range of the tap ratio of the autotransformer.

Fig. 8a shows the equivalent circuit diagram when an autotransformer is used for a step-down start, and Fig. 8b shows that of the induction motor when starting directly under full voltage.

The short-circuit impedance $R_k + jX_k$ in the virtual box in Fig. 5 represents the induction motor at start-up. Based on the analyses in Section 3.2 and Fig. 8, we can obtain the following relationships:

\[
\frac{I_a}{I_{\text{un}}} = \frac{I_a}{I_{\text{un}}} = \frac{U_{\text{st}}}{U_t} = k_i.
\]

(25)

\[
\frac{T_a}{T_{\text{un}}} = \frac{U_{\text{st}}}{U_t} = k_i.
\]

(26)

According to the requirements for the motor starting parameters, the minimum starting current of the motor is $I_{\text{st.min}} = n_1I_N$, and the minimum starting torque is $T_{\text{st.min}} = n_2T_N$. Combining (25) and (26), we can obtain the following relationships:

\[
I_a = k_i I_{\text{un}} = k_i I_N \geq I_{\text{st.min}} = n_1 I_N.
\]

(27)

\[
T_a = k_i^2 T_{\text{un}} = k_i^2 k_i T_N \geq T_{\text{st.min}} = n_2 T_N.
\]

(28)

Solution:

\[
k_i \geq \frac{n_1}{k_1}.
\]

(29)

\[
k_i \geq \sqrt{\frac{n_1}{k_1}}.
\]

(30)

In the voltage sag standard for power grids, the maximum voltage sag is $\Delta U_{\text{max}} = n_1 U_c$, in which $U_c$ is the voltage standard unitary value of the public connection point (PCC). Fig. 9 shows an equivalent circuit diagram of the induction-motor power supply system, where $U_c$ is the power-side voltage, $Z_c$ is the equivalent system impedance, $Z_t$ is the equivalent impedance when the induction motor starts (equivalent to the short circuit impedance $Z_0$), $Z_1$ is the load impedance, and we let $Z_{\text{st}} = Z_4 + Z_5$. The short-circuit impedance of the autotransformer is expressed by $Z_{\text{AT}} = R_k + jX_k$.

From the analysis of the auto-decoupling starting current in Section 3.2, the voltage of the PCC node during the auto-decoupling starting of the motor is as follows (ignoring the current of other load $Z_0$):

\[
U_{\text{PCC at}} = k_i k_i I_N \left( R_k + k_i R_k \right) + (X_a + k_i X_k).
\]

(31)

By subtracting (31) from $U_c$ we have the following:

\[
\Delta U = U_c - k_i k_i I_N \left( R_k + k_i R_k \right) + (X_a + k_i X_k).
\]

(32)

Then, we substitute $\Delta U \leq \Delta U_{\text{max}} = n_1 U_c$ in (32), as follows: (see (33)). Therefore, the tap ratio $k_i$ of the auto-transformer can be determined by the inequality group (29), (30) and (33) in the auto-decoupling step-down start stage.
4.2 Determination of the capacity of MCR

After the auto-decoupling step-down start, the motor enters the starting stage of the series MCR. Fig. 10 shows a single-phase equivalent circuit diagram for the second stage.

\[
Z_{eq} = R_{sec} + jX_{sec}
\]

is the equivalent impedance of the motor at the beginning of the second stage. From Fig. 10, we can obtain the current flowing through the MCR at this time, as shown in (34)

\[
I_{sec} = \frac{U_2}{\sqrt{R_{sec}^2 + (X_{sec} + X_{L2})^2}} = \frac{U_2}{\sqrt{R_{sec}^2 + (X_{sec} + X_{L2})^2}}.
\]

By substituting \( U_2 = k_a U_1 \), we can calculate the reactance \( X_{L2} \), which must be connected in a series at the beginning of the second stage, as shown in (35)

\[
X_{L2} = \frac{R_{sec}^2 + (X_{sec} + X_{L2})^2}{k_a^2} - R_{sec} - X_{sec} - X_1.
\]

Equation (36) shows the voltage across the MCR at this time:

\[
U_{L2} = \frac{U_1 X_1 k_a}{\sqrt{R_{sec}^2 + (X_{sec} + X_{L2})^2}}.
\]

Fig. 11 shows a single-phase equivalent circuit diagram of the end of the motor start-up. When the motor speed reaches 95% of the rated speed, the slip ratio \( s = (n_2 - 0.95n_1)/n_1 \) is substituted into (1) to obtain the equivalent impedance \( Z_{end} \) of the motor at the end of the start stage. From Fig. 11, we can calculate the equivalent reactance value \( X_{L1} \) of the MCR at the end of the start stage, as shown in (37):

\[
X_{L1} = \sqrt{\frac{U_1^2}{k_a^2 U_1^2 X_{L2}}} - R_{end} - X_{end} - X_1.
\]

At this time, the voltage across the MCR is: \( U_{L1} = k_a U_1 X_{L1} \), where \( k_a \) is the starting current adjustment coefficient, which is generally 0.8–0.9, and \( k_{set} \) is the starting current requirement multiple.

Therefore, we can obtain the capacity range of the MCR, as shown in (38):

\[
Q_{MCR} = k_a U_1 X_{L2} \left[ k_a \right]^2 = \frac{R_{sec}^2 + (X_{sec} + X_{L2})^2}{X_{L2}}.
\]

5 Simulation results

To validate the principle and performance of the CATMC soft starter, we established an 18 MW/10 kV model using ANSYS Maxwell software based on the above proposed structure. To simulate the material characteristics of steel cores, we used an actual non-linear model. Based on the capacity of the soft starter
and using the method for calculating the parameters of the induction motor described in Section 1, Table 1 shows the calculated model parameters.

The starting procedure can be divided into two parts. In the first stage, the DC excitation current is not applied to the high-voltage side. Neither the high-or low-voltage-side cores are saturated. The high- and low-voltage-side windings are equivalent to an autotransformer, and provide ∼80% of the rated voltage for the motor, which reduces the motor terminal voltage. In the second stage, as the motor terminal voltage gradually increases, which increases the DC excitation current of the high-voltage side, the magnetic circuit analysis in Section 3.3 reveals that the direction of AC flux is the same in the left and right core columns on the high-voltage side, but the direction of the DC flux is opposite. The AC flux and DC flux overlap each other, which makes the magnetic valves in the two core columns continuously alternate between saturated and unsaturated states. As such, the equivalent reactance value is decreased to achieve a constant-current start. At the same time, there are small cross sections with widths of $l_2$ between the high- and low-voltage-side windings. When DC excitation is added to the high-voltage side, as revealed by the magnetic circuit analysis in Section 3.3, the deep saturation of the small cross section leads to greater magnetoresistance, which is equivalent to separating the high- and low-voltage sides. As such, the second stage is equivalent to starting with a soft start by a series reactor.

When $t = 0.05$ s, the AC flux reaches a positive peak and the left-core-column magnetic valve on the high-voltage side is deeply saturated, whereas the right-core-column magnetic valve is unsaturated. When $t = 0.015$ s, the AC flux reaches a negative peak, the right-core-column magnetic valve at the high-voltage side is unsaturated.
standard and reduce the impact on the power grid. However, in the bypass autotransformer, when the motor is under full voltage, due to the large gap between the motor terminal and system voltages, there will be great secondary impacts from the current, torque, and bus voltage, which also cause great harm to the motor and power grid.

In contrast, by starting the motor using the CATMC soft starter and choosing the appropriate autotransformer tap ratio, not only can the starting current be further reduced to <2.5 times the rated current, but the voltage sag requirement of the IEEE standard can also be met, thereby reducing the impact on the grid. The whole starting process becomes smooth, with no secondary impact, so the start performance is stable and has a fast response.

6 Conclusion

In this paper, we proposed a novel CATMC soft-start method for the super-large-capacity high-voltage induction motor and explained the basic principle of the proposed method. The simulation results verify the effectiveness of the proposed soft-start method. Our conclusions are as follows:

i. To meet the motor starting and grid-voltage-sag requirements, we determined the selection range of the tap ratio of the autotransformer.

ii. The structure of the new CATMC soft starter combines the functions of the autotransformer and MCR through an innovative electric and magnetic circuit design. Hence, the start current is reduced in two ways and the structure is more compact and flexible.

iii. We compared the simulation results of the three start methods and verified that the CATMC soft-start method has better start performance with respect to the starting current and secondary impact. Hence, the CATMC soft-start method provides a promising alternative for the popularisation and real application of the soft-start motor.

7 Acknowledgments

This work was supported in part by the National Key Research and Development Program of China under Grant no. 2017YFB0902904, in part by the Natural Science Foundation of Hubei Province under Grant no. 2016CFB448, in part by the Shenzhen City Science and Technology Innovation Plan under Grant no. JCYJ20170306170937861 and in part by Wuhan City Science and Technology Program under Grant no. 2016070204020165.

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