A Novel Soft Start Method of Super Large Capacity High Voltage Motor

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Abstract—The large current generated by starting directly of super large capacity and high voltage induction motor would have a huge impact on the grid as well as the motor itself. The variation of the power factor and electromagnetic torque during direct start of motors with different capacity and voltage levels are obtained. Aiming at the problem that the secondary impact of auto-transformer starter is too large and the cost of magnetic control starter is too high, the auto-transformer and magnetic control soft start method of super large capacity and high voltage motor is proposed and the basic working principle is analyzed. The calculation formula of cost for magnetic control soft starter and auto-transformer and magnetic control soft starter is deduced, and specific examples are analyzed and compared. It is concluded that the choice of auto-transformer with appropriate tapping ratio can greatly reduce the cost of auto-transformer and magnetic control soft starter compared with the other one. Finally, the simulation and experiment results show that the start method can effectively avoid secondary current impact and constrain the motor starting current to less than 2.5 times the rated current.

Index Terms—Auto-transformer buck, magnetic controllable reactor, super large capacity high voltage induction motor, soft start.

I. INTRODUCTION

With the development of economy, the number of super large capacity high voltage induction motors used in many industries has increased year by year. The start current can reach up to as high as 4-7 times of the motor’s rated current when high voltage motors start directly. For super large capacity motors (voltage above 6 kV, power above 10000 kW), the direct start current could reach 5000 Ampere or more [1]. Such large start current will cause a sudden decline of the grid voltage [2]. At the same time, such large start current will produce a great impact on the stator winding and rotor bar, causing the squirrel cage fracture and motor faults. In addition, since the motor torque is proportional to the square of the winding current, the large start current will cause rapidly wear of gear in the gear transmission equipment [3], [4]. Many soft start methods have been studied. The traditional soft starters including Y-Δ soft starters, liquid-state soft starters, solid-state soft starters, auto-transformer soft starters cannot continuously adjust the start voltage of the motor, which leads to a large inrush current during motor starting. They have the shortcomings of voltage sags, sudden torque mutation and secondary current impact [5], [6]. The high-voltage inverter has the best start performance, but they are very expensive [7]. The soft starter based on magnetic control reactor (MCR) has many advantages such as high reliability, flexible control, and so on. However, when the capacity of the motor is very large, the cost of start device using this method would be very high [8].

In order to resolve this issue, a novel auto-transformer and magnetic control (ATMC) soft start method of super large capacity and high voltage induction motor was proposed in this paper. The new structure of ATMC soft starter combines the two functions of the auto-transformer and MCR through ingenious electric and magnetic circuit design. The calculation method of the motor parameters is derived and the variation of the power factor and electromagnetic torque during direct start of motors with different capacity and voltage levels is obtained. The calculation formula of cost for magnetic control soft starter and ATMC soft starter is deduced, and specific examples are analyzed and compared. It is concluded that the choice of auto-transformer with appropriate tapping ratio can greatly reduce the cost of ATMC soft starter compared with the other one. Finally, the simulation and experimental results verify the feasibility and effectiveness of the proposed soft start method.

II. THE VARIATION OF POWER FACTOR AND TORQUE DURING DIRECT STARTING

The equivalent circuit of induction motors is shown in Fig. 1. Based on the equivalent circuit, the expressions of the phase impedance Z and electromagnetic torque $T_{em}$ under normal operating condition can be determined as shown in (1) and (2). The expression of start current, start electromagnetic torque and maximum electromagnetic torque is shown in (3). The power factor angle of the motor $\phi$ is equal to the impedance angle of Z. When the motor parameters are known, the impedance $Z$ can be calculated from (2) according to Fig. 1. Where: $U_1$ is the motor phase voltage, $I_a$ is the stator rated line current, $k_i$ is the start
current multiple, $T_N$ is the rated torque, $k_i$ is the start torque multiple, $k_M$ is the maximum torque multiple (also known as the overload capability), $r_1$ and $x_{1\delta}$ are the resistance and leakage reactance of the stator, $r_2'$ and $x_{2\delta}'$ are the resistance and leakage reactance of the rotor referred to the stator side, $r_m$ is the magnetizing resistance, $x_m$ is the magnetizing reactance.

Fig. 1. Equivalent circuit of induction motors.

\[
\begin{align*}
T &= m_p U_1^2 r_1' s \\
I_a &= \sqrt{(r_1 + r_2')^2 + (x_{1\delta} + x_{2\delta}')^2} \\
I_a &= \frac{m_p U_1^2 r_1'}{2 \pi f_1 (r_1 + r_2')^2 + (x_{1\delta} + x_{2\delta}')^2} = k_a T_N \\
T_{\text{max}} &= \frac{m_p U_1^2}{4 \pi f_1 (r_1 + r_2')^2 + (x_{1\delta} + x_{2\delta}')^2} = k_m T_N \\
Z &= r_1 + jx_{1\delta} + \frac{(r_m + jx_m)(r_2' + jx_{2\delta}')}{r_m + jx_m + r_2' + jx_{2\delta}'} = |Z| \angle \phi
\end{align*}
\]

The parameters of $U_1, I_a, T_N, k_i, k_a$ and $k_M$ can be found through the motor's product catalog. The parameters such as $r_1$, $x_{1\delta}$, $r_2'$, and $x_{2\delta}'$ can be calculated by substituting these parameters into (2). According to the above method, the motor parameters of 7.5kW/0.38kV, 255kW/6kV, 1800kW/6kV and 19000kW/10kV can be calculated as shown in Table I.

| Performance | 7.5kW/0.38kV | 255kW/6kV | 1800kW/6kV | 19000kW/10kV |
|-------------|------------|----------|-----------|-------------|
| $r_1/\Omega$ | 0.782      | 1.83     | 0.74      | 0.124       |
| $x_{1\delta}/\Omega$ | 1.225      | 6.25     | 2.26      | 1.125       |
| $r_2'/\Omega$ | 0.943      | 3.71     | 0.76      | 0.123       |
| $x_{2\delta}'/\Omega$ | 1.225      | 6.25     | 2.26      | 1.125       |
| $r_m/\Omega$ | 3.2        | 45.5     | 8.75      | 33.74       |
| $x_m/\Omega$ | 25.08      | 131.02   | 70.03     | 270.04      |

A. The variation of the power factor

According to the parameters of the four motors in Table I, combined with (1), the curve of the power factor $\cos(\phi)$ changes with the increase of the motor speed $n$ is plotted in the direct start process, as shown in Fig. 2.

B. The variation of the electromagnetic torque

According to the parameters of the four motors in Table I, combined with (1), the curve of the per unit torque changes with the increase of the motor speed $n$ is plotted in the direct start process, as shown in Fig. 3.
From Fig. 3, the following conclusions can be drawn:

1) The start torque multiples of the four motors at zero speed are about 2.01, 1.55, 0.85 and 0.73, respectively. The larger the capacity, the higher the voltage level, the initial start torque is lower. Hence, large motors are more likely to encounter the problem of starting failure caused by too low start torque.

2) During the acceleration, the per unit torque of the four sample motors goes up and reaches the maximum value when the speed is between 900r/min-1300r/min. The larger the capacity and the higher the voltage level, the greater the maximum torque multiple, that is, the stronger the overload capacity, and the greater the speed when the maximum torque multiple is reached.

3) After reaching the maximum per unit torque, the per unit torque drops rapidly with the motor speed. But, the per unit torque of small motor drops much faster. Therefore, although the start torque multiple and maximum torque multiple of large motor are lower than these of small motor, it has a higher per unit torque when it is operated near a rated speed.

III. BASIC PRINCIPLE

Fig. 4 shows the topological diagram of auto-transformer and magnetic control soft starter. The starting procedure can be divided into the following three parts. At first, close the high voltage circuit breaker QF, and then close the contactor KM2, KM5, KM4, KM6. At this time, thyristor T of the magnetic control reactor (MCR) is turned off, the winding N1 of MCR and the additional winding N2 constitute an auto-transformer to reduce motor terminal voltage. After it, the motor is disconnected from the winding N2 and connected in series with MCR. Structure diagram of MCR is showed in Fig. 5. The core of MCR is composed of two parallel main core limb posts and AC bypass cores, the main core column has two coils, which have the number of turns of N1/2 respectively. The winding of each column has a tap with a delta ratio of \( \delta = N_2/N_1 \). There are thyristors T1 and T2 between them. The two main windings of different cores are interconnected, and the freewheeling diode D crosses the intersection ends. When MCR works, the control voltage of about 5% rated voltage is induced at both ends of the thyristor T1 and T2. In the positive and negative half cycle of the supply voltage, the thyristor T1 and T2 are switched on, and the DC control current is generated in the loop, so that the core magnetic valve is saturated, and the reactance value can be continuously adjusted. The output current of MCR depends on the conduction angle of the thyristors T1 and T2. The larger the conduction angle is, the stronger the control current is, the greater the magnetic resistance of the magnetic core valve is, and the smaller the reactor inductance is. Motor terminal voltage is gradually increasing, the voltage across the soft starter gradually decreases. At this time, the conduction angle of the control thyristor is increased and the equivalent reactance value is reduced to achieve constant current start. When the motor is approaching the rated speed, the motor is disconnected the soft starter.

In the soft start process, the controlled variable is the trigger angle of the thyristor. The detected output variables are the motor stator current and speed. The current of the motor is the ultimate control object, and the detected speed of the motor only plays an auxiliary role to determine the starting stage more accurately. The proportional–integral–derivative (PID) controller is widely used in process control and motion control due to its simple algorithm, robustness, and high reliability. In the design of the controller, to solve the performance degradation problem caused by static error, integral links are included. If there is a deviation in the direction of the system, it will increase with the continuous accumulation of the integral action, and result in the actuator reaching its position limit, which means that if the output of the controller continues to increase, the actuator can no longer increase. At this time, the control output exceeds the normal operating range and enters the saturation zone, that is, integral saturation. Once the reverse deviation occurs, the control output gradually withdraws from the saturated region. The longer it takes to enter the saturated region, the longer it takes to exit. During this period, the actuator stays at its position limit and will not immediately change with the deviation. As such, the system loses control, which not only degrades system performance, but also makes it unstable. Therefore, we use an anti-saturation integral PID algorithm to control the ATMC soft starter system, which solves the integral saturation problem caused by the limited control angle and enables the control system to have good dynamic performance.

The idea underlying the anti-saturation integral PID algorithm is that when calculating the control quantity \( u_k(k) \), the first step is to determine whether the control quantity used in the previous moment \( u_k(k-1) \) has exceeded the limit. If \( u_k(k-1) > u_{\text{max}} \), only a negative deviation will accumulate; if \( u_k(k-1) < u_{\text{min}} \), only a positive deviation will accumulate. This algorithm can prevent the control quantity from remaining very long in the saturated region. Figure 6 shows a block diagram of the control system.

In Fig. 6, \( i(t) \) is the given starting curve (constant current starting), \( i(t) \) is the output current of the soft starter, \( e(t) = i(t) - i(t) \) is the error, \( u_e(t) \) is the PID output voltage, and \( u_d(t) \) is the control voltage.

![Fig.4. Topological diagram of auto-transformer and magnetic control soft starter.](image-url)
Fig. 5. Structure diagram of MCR.

Fig. 6. Block diagram of anti-saturation integral PID algorithm system.

**IV. COST COMPARISON**

**A. Cost of Magnetic Control Soft Starter**

Fig. 7 shows the equivalent circuit of magnetic control soft start.

In Fig. 7, $X_L$ is the single phase equivalent reactance value of MCR; $U_1$ is the phase voltage; $U_{1}=U_{n}/\sqrt{3}$, $X_0=U_{n}^{2}/S_{\text{min}}$. $S_{\text{min}}$ is the minimum short circuit capacity of the system. If the start current is required to be reduced to $k_{\text{set}}$ times of the rated current $I_n$ of the motor, when the motor has just started, the initial reactance $X_{L0}$ can be calculated as shown in (4) from Fig. 7 (a).

$$X_{L0} = \frac{U_1}{k_{\text{set}}I_n} - R_k^2 - X_k - X_s$$  \hfill (4)

When the motor speed reaches 95% of the rated speed, the slip $s=(n_1-0.95n)/n_1$ is substituted into (3) to get the motor equivalent impedance $Z_{\text{end}}$ at the start of the motor. From Fig. 7 (b), the equivalent reactance value $X_{L1}$ of MCR at the end of the start can be calculated as shown in (5).

$$X_{L1} = \sqrt{\left(\frac{U_1}{k_{\text{set}}I_n}\right)^2 - R_{\text{end}}^2 - X_{\text{end}} - X_s}$$  \hfill (5)

The capacity range of MCR is shown in (6). The unit capacity cost of MCR is $x$, and the total cost of magnetic control soft starter is shown in (7).

$$Q_{\text{MCR}} = (K_{\text{set}}^2k_{\text{set}}^2I_n^2X_{L1} + k_{\text{set}}^2I_n^2X_{L0})$$  \hfill (6)

$$C_t = xk_{\text{set}}^2I_n^2 \sqrt{R_k^2 + (X_k + X_s)^2}$$  \hfill (7)

**B. Cost of ATMC Soft Starter**

Fig. 8 shows the equivalent circuit of ATMC soft starter.

Fig. 8. Equivalent circuit of ATMC soft starter.

From Fig. 8 (a), when the motor has just started, the (8) can be calculated. In (8), $U_2=U_1N_2/(N_1+N_2)=U_1/(K+1)=k_aU_1$, $K=N_1/N_2$. The tap ratio $k_a$ can be calculated as shown in (9).

$$U_2 \sqrt{R_k^2 + (X_k + X_s)^2} = k_{\text{set}}I_n$$  \hfill (8)

$$k_a = \frac{k_{\text{set}}I_n \sqrt{R_k^2 + (X_k + X_s)^2}}{U_1}$$  \hfill (9)

Combined (8) and (9), the rated capacity of the auto-transformer is calculated as shown in (10).

$$S_{\text{in}} = U_1I_1 = k_{\text{set}}^2I_n^2 \sqrt{R_k^2 + (X_k + X_s)^2}$$  \hfill (10)

The unit capacity cost of the auto-transformer is $1/k$ ($k$ greater than 1) of MCR, and the cost of the auto-transformer is as follows:

$$C_t = \frac{xk_{\text{set}}^2I_n^2 \sqrt{R_k^2 + (X_k + X_s)^2}}{k}$$  \hfill (11)

Similarly, the capacity range of MCR can be obtained as follows:
\[ Q_{MCR2} \sim \left[ k_2^2 k_{set}^2 k_1^2 X_{12}^2 R_{a}^2 + \frac{k_2^2 U_{12}^2 (X_{a} + X_{12})^2}{k_1^2} \right] \] (12)

The total cost of ATMC soft starter is \( C_2 = C_T + C_{MCR2} \), as shown below:

\[ C_2 = C_T + \frac{Z_{a}^2 U_{a}^2 (X_{a} + X_{12})^2}{k_{set}^2} \] (13)

In (13), \( Z_{a}^2 = R_{a} + jX_{a} \) is the equivalent impedance of the motor at the start of magnetic control start.

C. Comparison of the Two Soft Starters

Take 12500kW/10kV motor for example, the parameters of the motor and system are: \( I_0 = 821A \), \( n_0 = 1487r/min \), \( k_1 = 3.91 \), \( k_{set} = 0.46 \), \( k_{set} = 1.76 \), \( S_{min} = 261MVA \). It is calculated that: \( r_0 = 7.6790\Omega \), \( x_m = 3.7636\Omega \), \( R_a = r_1 + r_2 = 0.7071\Omega \), \( X_a = x_{12} + x_{22} = 1.6536\Omega \), \( X_{a} = U_{a}^2 / S_{min} = 0.3831\Omega \).

By substituting the above parameters into (7), the functional relationship between the cost of magnetic control soft starter \( C_1 \) and the start current multiple \( k_{set} \) can be obtained: \( C_1 = f(k_{set}) \), and the relationship curve is drawn, as shown in Fig. 9.

From Fig. 9, it can be seen that as the start current multiple \( k_{set} \) increases, the overall change trend of \( C_1 \) becomes larger and then smaller. When \( k_{set} \) is not large, the equivalent reactance value of MCR that needs to be connected in series is large, but the increasing rate of the current flowing through MCR is greater, which makes \( C_1 \) increases with the increase of \( k_{set} \). When \( k_{set} \) increases to about 1.65, \( C_1 \) reaches the maximum, as shown in the section 1 of Fig. 9. The start current multiple \( k_{set} \) continues to increase. At this time, the equivalent reactance value of MCR needs to be connected in series becomes smaller, and it plays a leading role in the change of the capacity of magnetic control soft starter, so \( C_1 \) gradually decreases, as shown in the section 2 of Fig. 9.

When the speed is detected to be 1200r/min, it is set to switch from the auto-transformer buck start to the start stage of the series MCR. The \( Z_{a} = 1.3670 + j1.5227\Omega \) can be obtained and let \( k = 3 \). By substituting the above parameters into (13), the function relationship between \( C_2 \), the start current multiple \( k_{set} \) and the auto-transformer tap ratio \( k_a \) can be obtained: \( C_2 = f(k_{set}, k_a) \), the curve is drawn as shown in Fig. 10.

From Fig. 10, it can be seen that when \( k_{set} \) is constant, \( C_2 \) increases and then decreases with the increase of \( k_a \). This is because when \( k_a \) is not large, the terminal voltage of the motor is greatly reduced, the equivalent reactance value of MCR needs to be connected in series is small, and the total cost is reduced. When \( k_a \) reaches about 0.55, the cost is up to the maximum. As \( k_a \) continues to increase, the partial voltage of the secondary side of the auto-transformer obtained from the primary side becomes larger, the utilization of the auto-transformer increases, and the capacity and cost decrease. When \( k_a \) is constant, \( C_2 \) increases with the increase of \( k_{set} \). This is because, although the cost of the unit capacity MCR is approximately 3 times the cost of the auto-transformer, the start current has been greatly reduced by auto-transformer buck in the initial stage of start-up. The equivalent reactance value of MCR that needs to be connected in series is greatly reduced compared with the magnetic control soft starter. The change of \( C_T \) plays a leading role in total cost \( C_2 \). \( C_T \) is proportional to the square of \( k_{set} \), so \( C_2 \) increases with the increase of \( k_{set} \), and the rate of increase is also increasing.

V. Simulation Results and Analysis

According to the conclusion of the cost calculation, the total cost of the auto-transformer and magnetic control soft starter is reduced as much as possible by selecting the appropriate tap ratio of the auto-transformer. Motor parameter setting is give as follows: rated power is 18MW, rated voltage is 10kV, rated speed is 821A, rated current is 1487A.

When the tap ratio of auto-transformer \( k_a \) is equal to 0.8, the comparison diagram for \( C_1 \), \( C_2 \) and \( C_1-C_2 \) versus start current multiple \( k_{set} \) is shown in Fig. 11. When \( k_{set} = 1.25 \), \( C_1 \) minus \( C_2 \) reaches the maximum which is \( 0.91 \times 10^6 \), \( C_1 \) is 32% higher than \( C_2 \). Therefore, we can get the conclusion: the choice of auto-transformer with appropriate tap ratio can greatly reduce the cost of ATMC soft starter compared with the cost of magnetic control soft starter under the same starting requirement.
current is 1.039kA, rated speed is 1485r/min. The simulation results for three start methods, namely direct start, auto-transformer soft start and auto-transformer and magnetic control soft start, are shown in Fig. 12.

![Simulation results of stator current](image)

Fig. 12 (a) shows that when the motor starts directly, the stator current reaches as high as more than 5000 A. It is about 5 times of the rated current. Such large start current will be harmful to the grid and the motor. The starting current can be reduced to about 2.5 times of the rated current when using ATMC soft start method. Fig. 12 (a) and (b) show that there is obvious secondary current and torque impact during auto-transformer soft starting. Fig. 12 (c) shows that start time of ATMC soft starter is about 15s which is 5s less than auto-transformer soft starter.

**VI. EXPERIMENTAL RESULT AND ANALYSIS**

The auto-transformer and magnetic control soft starter of super large capacity and high voltage induction motor has been designed successfully. The prototype of the experimental device is shown in Fig. 13.

![Experimental device](image)

The 18MW/10kV motor is selected as the experimental object, whose rated current is 1039A. The start current is set to 2.5 times the rated current (2598A). According to the conclusion drawn from the cost calculation, the proper auto-transformer tap ratio is selected to minimize the total cost of the soft starter. The experimental results of stator current for three start methods are shown in Fig. 14.

![Experimental results of stator current](image)

From Fig. 14, we know that the start time with ATMC soft starter is 16s, which is less than with auto-transformer soft starter. Moreover, when the motor starts directly, the maximum stator current reaches as high as more than 5000 A. The maximum stator current with ATMC soft starter is only 2210 A. The start process is very stable, and the start current is basically constant, which are very close to the simulation result. The start current can be restricted within 2.1 times of the rated current, which is very favorable to reduce harm to the power grid and the motor. Fig. 14 show that there is obvious secondary current impact during auto-transformer soft starting, which could do great harm to the grid and the motor.

**VII. CONCLUSION**

This paper proposed a novel auto-transformer and magnetic control (ATMC) soft start method of super large capacity high voltage induction motor. The basic principle of the proposed method is explained. The cost for magnetic control soft starter and ATMC soft starter is compared. Simulation and experimental results verify the effectiveness of the proposed soft start method. The conclusions are as follows:

1) The calculation method of motor parameters is derived, and the variation of the power factor and electromagnetic...
torque during direct start of motors with different capacity and voltage levels are obtained and compared. It is concluded that the larger the capacity, the higher the voltage level, the motor is more likely to encounter low power factor and low start torque problems.

2) The calculation formula of cost for magnetic control soft starter and auto-transformer and magnetic control soft starter is deduced, and specific examples are analyzed and compared. It is concluded that the choice of auto-transformer with appropriate tapping ratio can greatly reduce the cost of auto-transformer and magnetic control soft starter compared with the other one.

3) The simulation and experimental results show that the ATMC soft start method can effectively avoid secondary current impact and constrain the motor starting current to less than 2.5 times the rated current. Hence, the ATMC soft-start method provides a promising alternative for the popularization and real application of the soft-start motor.

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