# Research on Reactive Power Compensation Issues in Process of Motor Soft Start

[1,2]CHANG Yu-fang, *[2,1]HUANG Wen-cong, [2]YUAN You-xin, [1]WU Ming-hu, [1]WANG Su
*1 School of Electrical and Electronic Engineering, Hubei University of Technology, Wuhan, China, changyuf@sina.com*
*2 School of Automation, Wuhan University of Technology, Wuhan, China, whhwc@sina.com*

## *Abstract*

*In order to deal with the problems of large start current and low power factor that caused by three-phase asynchronous motors start, a new integrative method of soft start and dynamic reactive power compensation is proposed. In this paper, the rule of power factor vs. speed in a three phase asynchronous motor is investigated and the reason of such rule is analyzed. Aiming at the large start current problem, soft start method based on auto-transformer and magnetic control reactor (ATMCR) is invented. This method can further reduce start current from gird. Aiming at the low power factor problem, the method of thyristor switched capacitor (TSC) is used to dynamically compensate reactive power. Simulation and experimental results can prove that the integrative method can effectively deal with the problems of large start current and low power factor.*

**Keywords:** *Asynchronous Motor, Soft Start, Reactive Power Compensation, Power Factor*

## 1. Introduction

When large and super large capacity motors start directly tremendous impact current will produce and it can reach five to seven times of rated current. Such large start current has a strong impact on grid and can cause serious problems to motor such as heat, coil deformation, squirrel cage bar fracture, insulation damage and so on [1]. Therefore the process of motor start should be controlled. Traditional soft start methods are starting in series with reactance, starting with autotransformer, star-triangle changing start and so on. These methods can not continuously adjust starting voltage of the motor and still cause large impact current [2]. In recent years, some foreign scholars and large companies are committed to developing exclusive soft start controllers suitable for ordinary three-phase asynchronous motors start. Many scholars have done a lot of work in this regard. Some new soft starters have been invented continuously such as liquid-state soft starter of high voltage motors [3], solid-state soft starter (thyristor tandem in main circuit) [4][5], discrete frequency soft start device[6], soft starter based on magnetic control reactor (variable reactor) [7][8] and so on. These soft start devices achieve good results in restricting start current and have respective advantages. However function of these soft start devices is single. In these soft start devices, soft starter based on magnetic control reactor has most excellent start performance. Based on this soft starter, a new soft start starter is invented to further reduce start current. At the same time, we find that power factor of motor is low in start process. In order to improve power factor in start process, restrict start current and reduce grid voltage fluctuation, a new integrative method of soft start and dynamic reactive power compensation is proposed. Soft starter based on auto-transformer and magnetic control reactor (ATMCR) is invented to further reduce current absorbed from grid. Soft starter adds reactive power compensation device to improve power factor. This is important to stabilize grid voltage, improve power supply equipment utilization, reduce grid line losses, improve power quality, and improve system security and so on.

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* Corresponding author.
*Email address:* huangwencong@mail.hbut.edu.cn (Huang Wencong).

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## 2. Related Work

### 2.1. Soft starter based on magnetic control reactor

Magnetic control reactor (MCR) is also called variable reactor. Topological diagram of soft starter based on MCR is shown in Figure 1. Motor starts in series with primary winding of MCR, and the second winding of MCR is controlled by power electronics. The resistance of second winding can be changed through regulation trigger angles of power electronics, and the resistance of primary winding also be changed continuously. So voltage of motor can rise from zero to full-voltage. Soft start realizes.

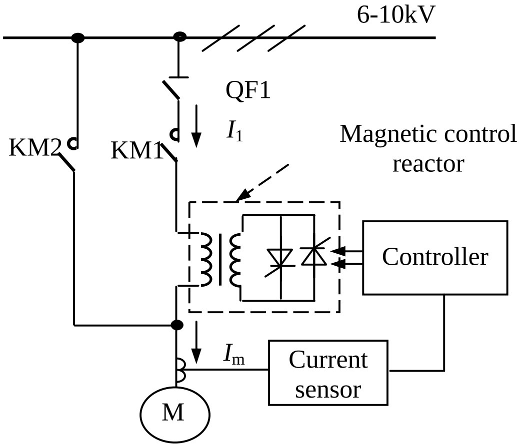


**Figure 1.** Topological diagram of MCR soft starter

From Figure 1 we can see, $I_m$ is equal $I_1$. $I_m$ is current of motor and $I_1$ is absorbed from grid. In order to further reduce $I_1$, we should change this structure.

### 2.2. Soft starter base on auto-transformer and magnetic control reactor

Soft starter based on auto-transformer and magnetic control reactor (ATMCR) absorbs advantages of auto-transformer and magnetic control reactor. Circuit diagram of ATMCR soft starter for high-voltage motor is show in Figure 2.

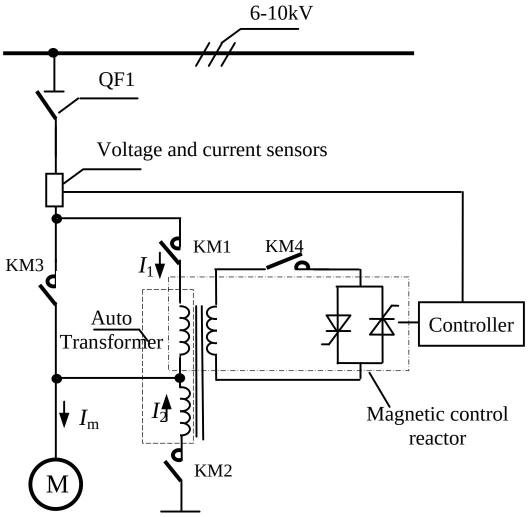


**Figure 2.** Circuit diagram of ATMCR soft

Soft starter based on ATMCR has double characteristics, one is reduction voltage of auto-transformer and the other is regulation voltage of magnetic control reactor. When it is used to start motor, the fist stage is reduction voltage of auto-transformer. After closing high voltage breaker, $KM_2$ and $KM_1$ are closed in turn. Motor starts under about 70% of power voltage; of course the voltage can be adjustable according start torque. In this stage, start method is reduction voltage. Then in second stage, open KM2 and close KM4, motor starts in series with the primary winding of magnetic control reactor. Controller regulates trigger angle of thyristors according start current. The resistance of the primary winding reduces gradually and the voltage also reduces continuously. So voltage of motor smoothly increases to power voltage and soft start complete. Then KM3 is closed and motor runs under full power voltage.

From Figure 1, it is known $I_m = I_1$. From Figure 2, $I_m = I_1 + I_2$. If $I_m$ is equal, so $I_1$ in Figure 2 is less than in Figure 1 obviously. So the method of using auto- transformer in initial start stage has obvious advantage that can reduce influence of the grid.

# 3. Reactive power compensation in soft start process

## 3.1 Variation rule of power factor in start process of three-phase asynchronous motor

The T-equivalent circuit of three-phase asynchronous motor [9] is shown in Figure 3.

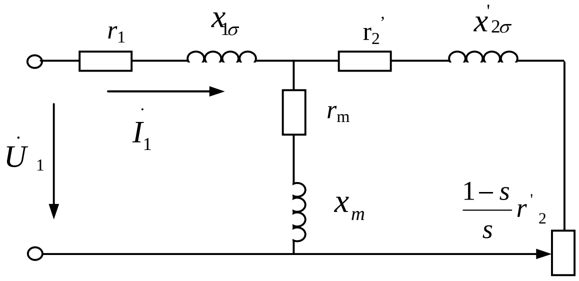


**Figure 3.** T-equivalent circuit of asynchronous motor

In the Figure 3:$\dot{U}_1$: effective value of infinite power grid phase voltage; $r_m$, $x_m$: excitation resistance and excitation reactance; $r_1$ , $x_{1\sigma}$:The stator resistance and leakage reactance of the stator; $r_2'$, $x_{2\sigma}'$:The conversion value of rotor resistance and leakage reactance of motor; s: slip ratio.

Power factor angle $\varphi$ is phase difference of $U_1$ and $I_1$, and equal to impedance angle of a phase impedance Z. Impedance angle [10] can be calculated as formula (1).

$$Z = r_1 + jx_{1\sigma} + \frac{(r_m + jx_m)(\frac{r_2'}{s} + jx_{2\sigma}')}{r_m + jx_m + \frac{r_2'}{s} + jx_{2\sigma}'} = |Z|\angle\varphi \tag{1}$$

When motor is certain and working frequency is constant, synchronous speed of the motor $n_s$ is

$$n_s = \frac{60f}{p}. \tag{2}$$

$n_s$ is constant. Speed of motor is

$$n = n_s(1-s). \tag{3}$$

Relation of power factor angle ( $\varphi$ ) vs. speed (n) is derived from formula (1), (2) and (3) and shown in formula (4).

$$\varphi = f(n) \tag{4}$$

Power factor is

$$\lambda = \cos\varphi . \tag{5}$$

The curve of power factor vs. speed is shown in Figure 4.

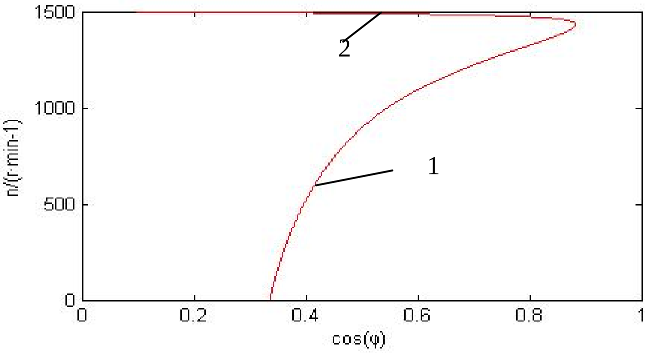


**Figure 4.** Curve of power factor vs. speed

Figure 4 shows power factor is low and changes rapidly in stat process. From start beginning, speed of motor changes from static state, power factor gradually increases following speed. When speed up to the rated speed, power factor reaches maximum value. It is shown as curve 1 in Figure 4. If motor is in light load, speed can rise further. At the same time, power factor decreases following speed up. It is shown as curve 2 in Figure 4. Power factor is about 0.35 at start beginning, and is low in whole start process. So reactive power is needed to compensate and power factor should be improved.

### 3.2 Plan of reactive power compensation in motor soft start process

Methods of reactive power compensation are concentrated compensation, grouping compensation and local compensation for asynchronous motor. Among these three methods, the third is the most thorough compensation method. Because reactive power compensation device is directly connected to the terminals of the asynchronous motor side or into the line, this compensation method is equivalent to move the reactive power to the side of asynchronous motor, most reactive power needed by motor is supplied by local reactive compensator, and reactive power flows only between motor and shunt capacitors. This method can eliminate reactive power flow and reduce load current and losses in the circuit. So the soft start method based on MCR shown in Figure 2 can be further improved. The topology structure of integration of soft start and dynamic reactive power compensation is shown in Figure 5.

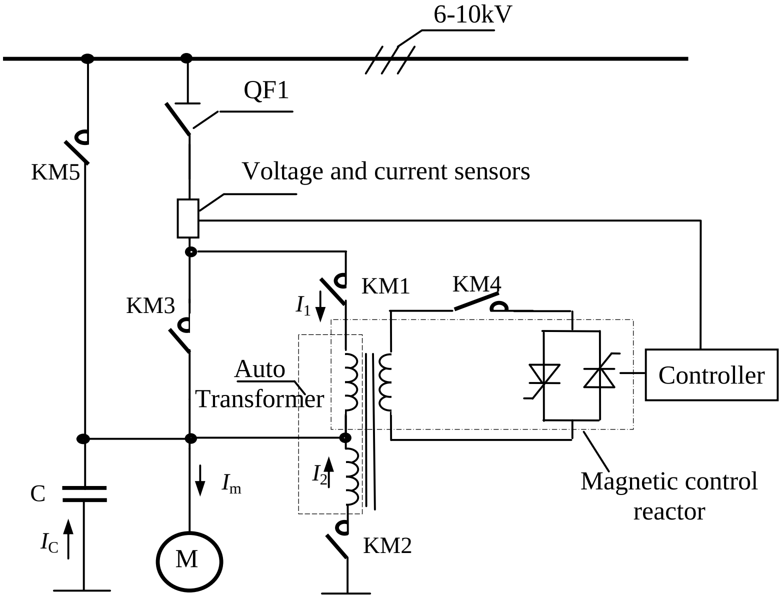


**Figure 5.** Structure of integration of soft start and dynamic reactive power

Figure 5 based on Figure 2 adds capacitor group C as local reactive power compensation device for asynchronous motor. Capacitor group C is parallel with motor and supplies reactive power to motor. Current relationship is expressed as formula (6).

$$I_m = I_1 + I_2 + I_c \tag{6}$$

Formula (6) shows that in the case of $I_m$ constant, adding $I_c$ can further reduce $I_1$ which absorbed from grid by motor and grid voltage drop also can further reduce.

### 3.3 Parameter calculation of the capacity of reactive power compensation

There are many methods to calculate the capacity of reactive power compensation. In this paper, the method of according measured active power and power factor to determine the capacity is chosen.

Energy balance tester is chosen to measure input power $P_1$ and power factor $\cos\varphi_1$ of three-phase asynchronous motor. If power factor is needed to enhance to $\cos\varphi_2$, capacity of reactive power compensation is calculated as formula (7).

$$Q = P_1(\tan\varphi_1 - \tan\varphi_2) \tag{7}$$

In formula (7), Q is capacity of reactive power compensation (kvar); $P_1$ is input power of motor (kW); $\varphi_1$ is power factor angle before reactive power compensation; $\varphi_2$ is power factor angle after reactive power compensation. It is the most accurate because this method uses the actual measurement values to calculate.

### 3.4 Optimal switching control strategy of reactive power compensation

Reactive power compensation uses the method of thyristor switched capacitor (TSC) in Figure 5. When the grid voltage and capacitor voltage have same polarity and amplitude, capacitors are put into operation. Switch naturally shut off when thyristor current cross zero. So the switching control strategy is same voltage on and zero current off. Because the time of soft start process is short and the moment of capacitor put into operation is difficult to accurately detected, in actual reactive power compensation process the optimal moment of capacitor put into operation is the peak of power voltage[11]. Capacitors are charged to the peak value of the power voltage and trigger phases of the thyristors are fixed in the same peak point of the power voltage. According to characteristics of the capacitor

$$i_c = C\frac{du_c}{dt} \tag{8}$$

From formula (8), we know the change rate of the capacitor voltage is zero when capacitor put into operation at the peak of the power voltage, so $i_c$ is also zero. After putting into operation, current of capacitor rises sinusoidally with the change rate of supply voltage. Therefore the method which capacitor put into operation at the peak of the power voltage will not produce impact current and current does not step.

Reactive power changes dynamically in soft start process, if capacitor’s capacity is fixed, capacity is too large to easily lead reactive power over compensation in soft start process in soft start process. On the contrary, capacity is too small to easily cause reactive power under compensation [12]. In order to improve the effect of reactive power compensation in the soft start process, the maximum value of capacity is determined according the calculation value shown in 3.3. Then the maximum capacitance value is cut into several groups. These capacitor groups are removed at different moment according to dynamical reactive power compensation capacity. Effect of reactive power compensation is be optimized.

There are two methods to cut capacitor into several groups, one is same capacity in every group, and the other is different capacity in every group [13]. The first method has many advantages such as simple structure, capacity easier to calculate, control more convenient and so on. However it has larger compensation differentials and easily cause over compensation and under compensation. In order to deal with this problem, the number of group should be added. At the same time, several problems emerge. For example the cost of reactive power compensation increases according the number of thyristor increasing; the volume of compensation device also increases and control becomes complicated and so on. The second method has smaller compensation differentials through many compound modes for capacitors. Effect of reactive power compensation is more accurate. The number of capacitor and thyristor in second method is less than in first method. So the second method is more excellent than the first method through comprehensive consideration of various factors.

## 4. Simulation results and analysis

Three-phase motor whose rated power is 11kW is chosen as an object of soft start and reactive power compensation. The model of soft start and reactive power compensation is established in Matlab and shown in Figure 6.

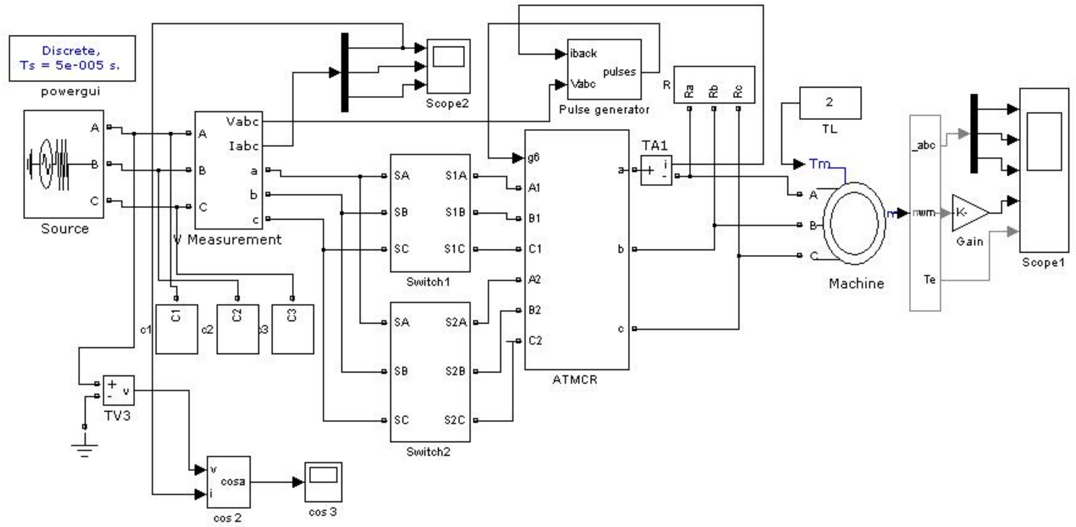


**Figure 6.** Simulation model of integration of soft start and reactive power compensation

Values of C1, C2, and C3 are calculated according formula (7) in Figure 6. Power factor is 0.65 before compensation and it enhances to 0.95 after compensation. Capacity of reactive power is 9.23 kvar, so capacitor whose rated voltage is 0.4kV and rated power is 10 kvar is chosen as local reactive compensator.

Capacity of capacitor which is three phase star connection is

$$Q = 3\times 2\pi f U^{2} C\times 10^{-3} \tag{9}$$

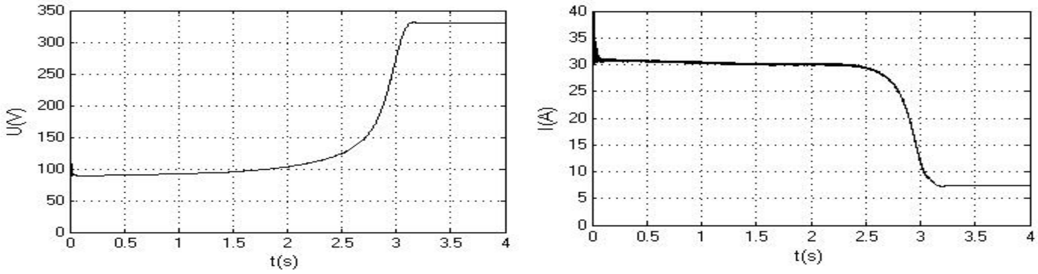
In formula (9), Q is capacity of capacitor (kvar); C is capacitance of single-phase capacitor （ $\mu F$ ）; *f* is frequency of power and is equal 50Hz.

From formula (9), capacitance C is calculated as following.

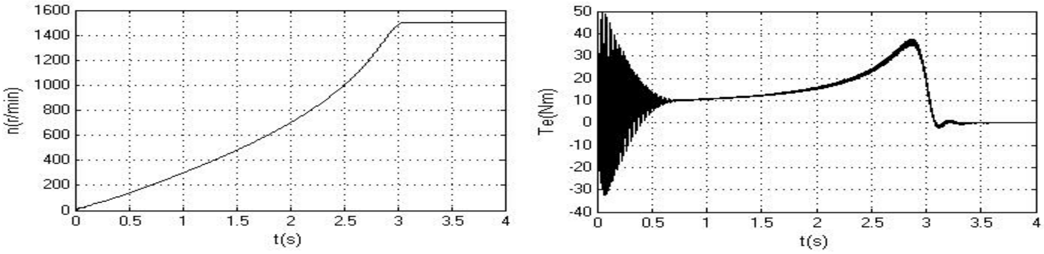
$$C=\frac{Q_C}{3\times 2\pi f U^{2}\times 10^{-3}}=\frac{10}{3\times 2\times 3.14\times 50\times 0.38^{2}\times 10^{-3}}=73.5uF\approx 8\times 10^{-5}F$$

So the capacitance of capacitor is $8\times 10^{-5}F$ . The simulation results are shown in Figure 7.

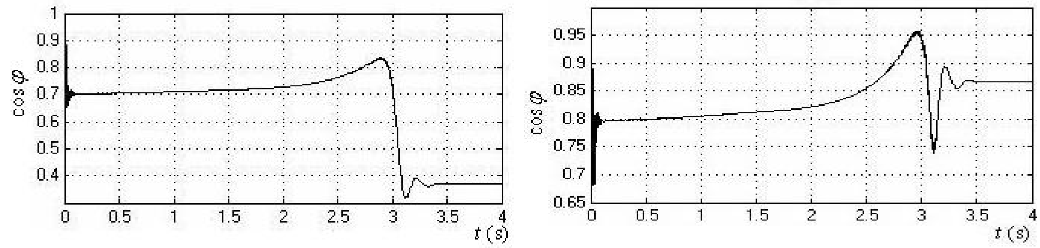
Figure 7 (a) shows terminal voltage of motor rises gradually to gird voltage in soft start process. Figure 7 (b) shows start current is restricted about 30A and it is about 1.4 times of rated current. Figure 7 (c) shows soft start completes about 3.3s and speed reaches to rated speed. Figure 7 (d) shows torque changes in soft start process. Figure 7 (e) is power factor curve before reactive power compensation and Figure 7 (f) is power factor curve after reactive power compensation. Compare Figure 7 (f) with Figure 7 (e), we find power factor improves obviously. Figure 7 (e) shows power factor improves from 0.7 to 0.82 in the period of 0-3s. After compensation, power factor improves from 0.7 to 0.95. In motor running period, Figure 7 (e) shows power factor is about 0.38, and 0.87 in Figure 7 (f).



（a）Terminal voltage of motor in soft start （b）Start current



（c）Speed （d）Torque



（e）Power factor before compensation （f）Power factor after compensation

**Figure 7.** Simulation results

## 5. Experimental results and analysis

This method which integrates soft start and reactive power compensation as a whole is applied in soft start for super large capacity and high voltage motor. Motor’s rated voltage is 10kV and rated power is 14000kW. Through calculation, reactive compensation capacity is 16Mvar. Experimental results are shown in table 1.

**Table 1.** Experimental results

| Item | Before using integration device | After using integration device |
|---|---|---|
| Start current from grid | 2420A | 1457A |
| Start current of motor | 2420A | 2400A |
| Voltage drop of grid | 20% | 9% |
| Start time | 42s | 46s |
| Power factor in soft start process | 0.35 | 0.8 |

Experimental results from table 1 shows that start current from grid is equal to start current of motor before using integration device of soft start and reactive power compensation, they are 2420A. After using compensation device, start current from grid reduces from 2420A to 1457A. Effects of restricting current and reducing impact on grid are obvious. Power factor in soft start process improves from 0.35 to 0.8, and improvement rate is about 128.6%. Voltage drop of grid decreases from 20% to 9%, decreasing amplitude is 55%. Experimental results show that effects of integrated design approach of soft start and reactive power compensation are excellent.

## 6. Conclusions and future works

In this paper, the rule of power factor vs. speed in a three-phase asynchronous motor is investigated and the reason of such rule is analyzed. In order to restricting start current and improving power factor, a new integrative method of soft start and dynamic reactive power compensation is proposed. Soft starter based on auto-transformer and magnetic control reactor (ATMCR) is invented to restrict start current. Reactive power compensation in integration device is used to improve power factor. All simulation results and experimental results show this integrated design can restrict start current under two times of rated current and start current from grid is obviously less than motor start current. This integrated method also can improve power factor and decrease voltage drop of grid obviously. Effects of restricting current and improving power factor are outstanding.

The future jobs are showed as following: 1) Research on other control strategy to further improve start performance; 2) Effect of harmonic waves to start performance.

## 7. Acknowledgement

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