Determination of soft starter firing angle performance to mitigate motor high inrush current using current limitation method

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Abstract. Inrush current in the simplest form can also be determined as current drawn by an induction motor during startup period. This starting current will shoot up about 5 to 7 times the rated current. However, this high current usually occur in the starting period only. To overcome this, several techniques can be implemented to reduce the high current. The configuration of soft starter just involving some power semiconductor device act as switches that control the current flow from power source to the motor. The switches is in form of thyristor and are connected back-to-back because the system conduct in AC system. The current output can be controlled by varying the firing angle. This changing of firing angle will be managed by a firing angle control circuit. This soft starter was connected between power source and motor. The thyristors that built in soft starter act like a gate to control the voltage applied to the motor. The firing angle for current limitation soft starter was changed to several angle and what can be concluded that the high current succeed to mitigate with increasing the firing angle. The current drawn for this type of starter is steadily constant. The lower current during starting took longer time for motor to reach its rated speed. This type of starter successfully reduces inrush current about 42 percent. Finally what can be concluded is that the soft starter was proven to mitigate inrush current. Type of soft starter that going to implement is depend on the application of motor. When the application need to control the torque is more suitable to use current limitation soft starter because the current is steadily control.

1. Introduction
Inrush current can easily be explained as the current drawn by electrical appliances which consist of mechanical parts. This starting current will shoot up about 5 to 7 times the rated current. However, this high current usually occurs in the starting period only. These temporary conditions might cause difficulties to both the power network and motor. [1]–[3] . Usually the inrush current caused by change in the flux linking with a coil where electro motive force is induced in the coil. Basically, when the...
current drawn is high means that the torque exerted also high. This starting current will severely disrupt the voltage in power supply until it quickly drops and disturb all other running devices that use the same power network. This loads coincidently become the major causes and the major victims of power quality problems. Due to their non-linearity, all these loads create disturbances in voltage waveform[4], [5]. This disturbance will bring harm to motor such as overheating[6]. Three phase induction motor has broad application in industry control and electrical drive. Assorted motor starters were created to overcome the problem. There are several types of motor which divided to conventional starters and electronic drives. Conventional starter are star-delta, autotransformer, and direct on line starter [7]. However the existing method still create current spike when the starter is being bypassed after the starting period. They also have disadvantages such as high installation cost, low efficiency and can be applied to certain type of motor only[8]–[10]. In order to overcome this improper method, the determination of soft starter firing angle can be performed to mitigate high inrush current. The angle that been determined will be controlled by firing control circuit. This control circuit operates by controlling the current flow through the circuit. Power electronic device are more reliable because it only consists several power semiconductor switches and controller[11], [12]. Nowadays, power electronic drives soft starter are broadly used in industry because it is capable in providing low inrush to prevent breakdown and finally minimize the maintenance cost.

2. Experimental method

2.1. Soft starter firing angle circuit system

Figure 1 demonstrates the block diagram of the determination of soft starter firing angle. The entire system contains inserting supply, managing the signal, and keeping track of the output. Initially the direct on line motor starting method will be implement and the fluctuation of output current will be noted. Then, the output will be compare to the soft starting method. The circuit is controlled by a firing control circuit. Then, thyristor firing control circuit get signal of firing angle from the firing angle control circuit.

![Soft starter firing angle block diagram](image)

Figure 1. Soft starter firing angle block diagram.

The firing angle was diversified to manipulate the voltage and current. To be able to alter the firing angle provided to circuit of the thyristor, the reference signal is determined to intersect the saw tooth voltage.

2.2. Calculation for Firing Angle

The most familiar type of SCR power control is phase control. Through this setup of operation, the SCR stayed in the open condition for a period of half cycle and then is triggered into short condition in the
half cycle which is decided by the control circuit. One SCR itself can only manage one half cycle of the waveform. When applying AC full wave, two SCR are needed in opposite direction. The period when the SCR is running known as the conduction angle. This signifies that the SCR operate by governing the voltage. The power source and load determine the circuit current. The power curve shows that when conduction angle of 30° supply only 3% of full power and 150° conduction angle supply 97% of full power. Therefore, it may become senseless in any situation to attain conduction angles more than 150° and smaller than 30°. Fundamentally when varying firing angle, the adjusting value only take place within the reference signal whilst the sawtooth remains to be the same. The reference signal have been adjusted that it is proportional with 360°. The time of conduction period is relies on firing angle.

$$\text{Triggering Time} = \frac{\text{Time for one period}}{360} \times \text{Firing Angle} \quad (1)$$

Right after deciding the triggering moment, next the conduction current could be researched with various firing angle. Notice that the thyristor current flow only can be controlled in form turn-on, therefore the current need to be zero again to turn off.

2.3. Direct-on-line Starting Method

A direct-on-line starter first was developed and conducted through PSCAD/EMTDC as shown in Figure 2. Motor parameters on W, S and TL were neglected. W at the motor represent speed input, S represent selection and TL represent torque input. The current then was recorded for further differentiation to the soft-starter current. This direct-on-line starting up technique typically will spike about 6 times the rated current.

![Figure 2. Direct-on-line Simulation.](image)

In addition, this configuration is the most famous type of starter due to its simplest connection which did not require any additional device. However, when the inrush current occur during startup, the fuse or circuit breaker will detect as fault then trip. This will create breakdown to the system. The current will increase from 5 to 7 times from the normal current. The normal rated current is 50A. Whilst, the line current for the motor could be determined by Equation 2:

$$I_L = \frac{S}{\sqrt{3} \times V_{LL}} \quad (2)$$

S is complex power and $V_{LL}$ is line to line voltage. With the $S = 100kV$ and $V_{LL} = 0.69kV$, the value of the line current can be calculated as 83.67A.

2.4. Simulation of Current Limitation Soft Starter
Figure 3 shows how the motor and power source was interrupted by antiparallel thyristor in the middle which use breaker symbol. This thyristor was connected to each three phase. The placement of soft starter can be subjective and can be located anywhere in between.

![Figure 3. Soft Starter Simulation Circuit.](image)

The breaker shown in Figure 3 then was zoomed in and look like in the Figure 4. There are two set of breakers was connected in the circuit. The thyristor breaker was closed short at starting and the main breaker was open because the soft starter operation took place. When the motor has reaches its rated speed, the source was straightly supplied to the motor. Hence the thyristor breaker open the circuit and main breaker directly supply the source.

![Figure 4. Breaker Simulation Circuit.](image)

Breaker shown in Figure 4 along with the thyristor firing angle circuit is the additional part which is different from the direct-on-line starting. The parameter of power supply and motor used in both simulation is the same. The firing angle then was varied to several increment so that it is suitable with desired torque which is depends on the load and application itself.

### 2.5. Firing Circuit for Current Limitation Soft Starter

Firing control circuit is the main heart of whole operation in order to perform firing angle in the middle between the source and motor. Figure 5 shows how the circuit was implemented and using a certain
device to generate the pulses for the thyristor. The devices used are phase locked loop, interpolated firing pulse and summing junction.

**Figure 5.** Control Circuit of Soft Starter Firing Circuit.

Firstly, the fundamental product required is sawtooth signal and reference voltage. The intersection between this two will generate the pulse. The sawtooth was generated by phase locked loop. The parameter of the sawtooth then was adjusted so that the peak is 360 as shown in Figure 6, which is easier to calculate the reference voltage when varying the firing angle. The frequency of this device also need to be alike with line frequency because it will be more tally and neat. The sawtooth signal then is going to be connect with the input of interpolated firing pulse to ensure the device can function, which its purpose is to compare and contrast both the sawtooth signal and reference signal and then finally generates pulses.

**Figure 6.** Generated Sawtooth.

The thyristor can only function in one half of the cycle only, so in this situation there are two SCRs which connected in parallel back-to-back in order to perform both cycle conduction period. To perform
this operation, summing junction device was used as mathematical constant which will total up from first reference signal. The constant which is to be use is 180 due to the 180° delay from the primary triggering angle. Out of this parameter, the pulse will efficiently be produced.

3. Results and Discussion

3.1. Direct-on-Line Motor Starting

Direct-on-line may be the most straightforward form configuration of all the starters. It entails quite simple devices to apply this particular starter. However, the inrush current occurrence in the mean starting period annoyed the motor. The current rise can be as high as 0.6 kA such shown in Figure 7.

![Figure 7. Highest Magnitude of Inrush Current.](image)

Besides of the high magnitude in inrush current, the time taken for the motor to reach rated speed also being affected. The high current shown in Figure 8 delay for a very long time until 1.75s can harm the motor from several aspect. The motor winding will likely be harm by continuous excessive current caused by power loss in heating form.

![Figure 8. Time Taken for DOL Starter to Reach Rated Speed.](image)
3.2. Current Limitation Soft Starter

Thyristor works by controlling the voltage by the gate signal. Should there be pulse existing, the voltage begin to supply and current is going to be lagging caused by inductive load as demonstrated in Figure 9.

![Figure 9. Triggering Time and Pulse for Thyristor.](image)

In conclusion, what can be relate from Table 1 is that the main function of this type of soft starter is set limit to protect the motor from breakdown. The increasing of firing angle also means that the conduction angle is decreasing. The main idea to decrease the conduction angle is to decrease the voltage applied to the motor. When the average voltage applied is decreasing, the current to the motor also decreasing. Despite the goodness of current reduction, the time taken by the motor to reach its rated speed escalating as the current minimize due to the torque. The connection amongst torque and current is the fact that torque of motor deviates the square of the current.

| Firing Angle | Current Limit (kA) |
|--------------|-------------------|
| 40           | 0.45              |
| 50           | 0.445             |
| 60           | 0.44              |
| 70           | 0.435             |
| 80           | 0.42              |
| 90           | 0.4               |
| 100          | 0.36              |
| 110          | 0.31              |
From the fluctuation of every firing angle that being change, what the Figure 10 try to show is that when the current is being limit or reduce, the motor torque also reduce that affecting the time for the motor to reach its rated speed. This type of starter is very much suitable when the amount of current need to be limit and the time taken for the motor to reach the rated speed or the torque needed is not an issue. The current level is selected by the user to provide a suitable balance between load on the electrical system, starting torque, and acceleration time.

| Firing Angle (°) | Current (kA) |
|------------------|--------------|
| 120              | 0.26         |
| 130              | 0.19         |
| 140              | 0.12         |

**Figure 10.** Graph of Current against Time.

4. Conclusion
An induction motor is well known for drawing high current during startup. The maximum spike up of the current can goes from 5 to 7 times higher than the rated current. This high current could take up to 30 to 40 cycles or higher until the current normalize again. It can be conclude that the firing angle set on 100° is the best because the inrush current can be limit to 0.36kA only and the time frame taken up to arrive at rated speed may be the fastest which is 1.1s. This type of starter is very good in reducing the current depends on application. When a certain motor which demands for large amount of torque, then the setting for current limit must be increase in order to fulfill the demand. It also very reliable to implement because the tripping of circuit breaker can be avoid when there is no transient current rise occur on the system.

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