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Term Paper

Soft Starters

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Table of Contents

Introduction

In industrial applications, almost everything uses a motor, in fact, motors may account for up to 80% of our country's energy usage. There are generally three different ways to start a motor: full-voltage, reduced voltage, and inverter. A full voltage, across-the-line, or direct on-line (DOL) start uses a contactor, which is a heavier duty three-phase relay. Reduced voltage starting can be accomplished via several different ways: auto-transformer, wye-delta, primary resistor/reactor, or with a solid state soft starter. Inverters are generally referred to as drives. This paper focuses on solid state soft starters (referred to as soft starter only from here on): what they are, why they are used, their construction, and applications.

What is a soft starter?

A soft starter is a solid state motor starter that is used to start or stop a motor by notching the voltage waveform, thereby, reducing the voltage to each phase of a motor and gradually increasing the voltage until the motor gets up to full voltage/speed all at a fixed frequency. The profile of the increase of voltage depends on the application. The voltage is reduced and controlled by 3 pairs of back-to-back silicon-controlled rectifiers (SCRs) (Fig. 1), which are a type of high speed thyristor. A soft starter takes the place of a contactor and can also take the place of an overload relay in a standard motor starting application. Fig. 1 demonstrates the configuration of a soft starter controlling a line or wye connected motor from a three-phase source.

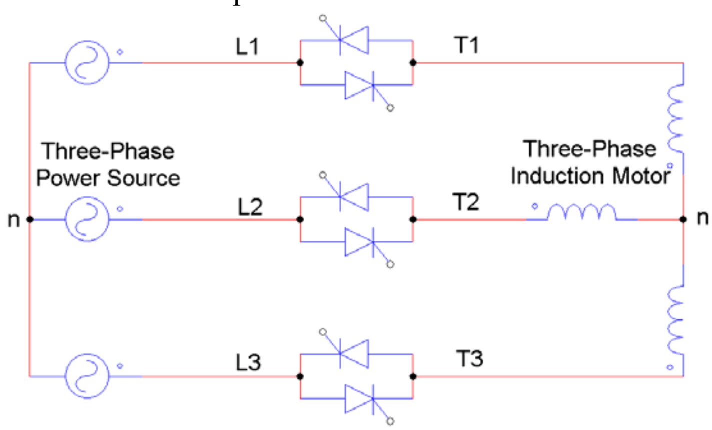

Figure 1: Standard Soft Starter Topology

Why use a soft starter?

In general, there are two reasons to use a soft starter: the power distribution network may not be able to handle the inrush current of the motor and/or the load cannot handle the high starting torque. As a rule of thumb, a motor utilizes around 600-800% of its full load current (FLA) to start. This current is referred to as inrush current or locked-rotor current. If a large motor is on a smaller power distribution network or on a generator system, this inrush current can cause the system voltage to dip or to "brown out." Brown outs can cause problems with whatever else is connected to the system, such as computers, lights, motors, and other loads. Another problem is that the system may not even be able to start the motor because it cannot source or supply enough current. Most industrial businesses run during the day can be fined or charged extra (Peak Demand charges) during this peak usage time for large transients caused by large horsepower (HP) motor start ups. These Peak Demand charges can add up very quickly, especially if the motor needs to be started multiple times during any given day. The inrush current can be controlled one of two ways with a soft starter: either with a current limit (discussed later) or reduced linearly with the reduced voltage, and follows this approximation:

$$I_{Reduced} \cong \left(\frac{V_{Reduced}}{V_{Rated}}\right) I_{Rated}$$

Applications such as conveyors may not be able to handle a sudden jolt of torque from an across-the-line start. Utilizing soft starters reduces the wear and tear on belts, conveyors, gears, chains, and gearboxes by reducing the torque from the motor. The torque decreases as a square of the reduced voltage, and follows this approximation:

$$\tau_{Reduced} \cong \left(\frac{V_{Reduced}}{V_{Rated}}\right)^2 \tau_{Rated}$$

Since soft starters are generally controlled and monitored by a microprocessor, a soft starter can add many features and protections fairly easily. It can offer a choice of the starting time, limited speed control, and energy savings. Power monitoring, such as three-phase current, three-phase voltage, power, power usage, power factor, and motor thermal capacity usage, can be implemented with current transformers, a voltage meter, and an internal clock. With the above implementations, protection, for the motor or the soft starter, from the items listed below (Table 1) can also be offered by stopping the firing of the SCRs, dropping out the bypass contactor (a contactor that carries the motor load after the motor is up-to-speed), and/or alerting a user via some form of communications with the microprocessor and another computer.

Table 1: Possible protections that can be offered by a soft starter

SCR Open Gate	Phase Unbalance	Power Loss
Undervoltage	Overtemperature	Jam
Underload	Phase Reversal	Overload
Overvoltage	Stall	Excessive Starts/Hr
Line Loss	Ground Fault	Bypass Failure

Construction

Generally, a soft starter is constructed with three pairs of SCRs reverse parallel connected to allow the current to flow to or from the motor. Soft starters can be made by controlling just one or two phases, but this paper will focus on the most prevalent implementation, three-phase control. Each phase of a soft starter can be controlled with an SCR pair reverse parallel connected (Fig. 2), an SCR/diode pair reverse parallel connected (Fig. 3), or a triac (Fig. 4), depending on cost and/or quality. The most prevalent switch in industry is probably the SCR pair and will also be the focus of this paper. Soft starters are used almost exclusively for starting and stopping and not during the run time because of the heat loss through the SCRs from the voltage drop across them.

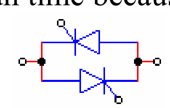

Figure 2: SCR Pair

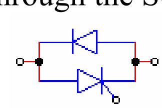

Figure 3: SCR/Diode Pair

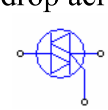

Figure 4: Triac

A standard assembly of a soft starter uses one SCR pair per phase and once the voltage gets to within approximately 1.1V of full voltage (depending on the voltage drop across the SCR) a bypass contactor (internal or external to the soft starter), running parallel to the SCR pairs, pulls in (Fig. 5). Once pulled in the SCRs stop firing. Typically, the bypass contactor is much smaller than compared to what is needed for a full voltage start as the contacts only need to be able to handle the full load current of the motor. Since the mechanical contacts cannot handle the inrush current, the SCRs must be sized correctly to handle the motor's locked-rotor current.

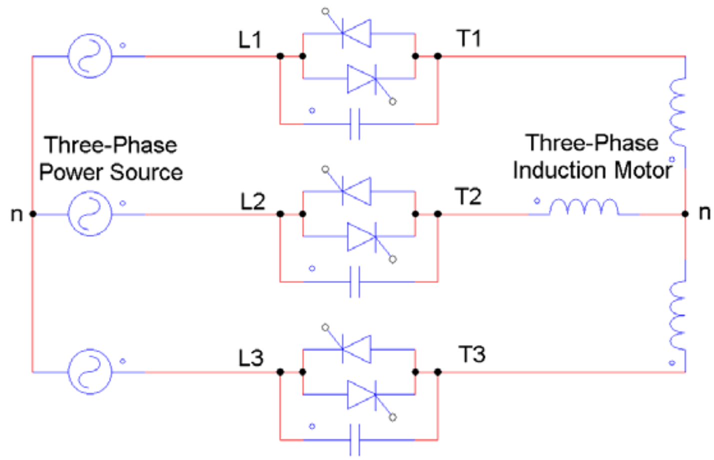

Figure 5: Standard Soft Starter Topology With Bypass

The transition from SCRs to bypass should also be near full speed to minimize the jump in current (Fig. 6). Fig. 7 shows a transition at slow speed; the transition has a jump in current near the locked-rotor or starting current, defeating the purpose of a soft starter.

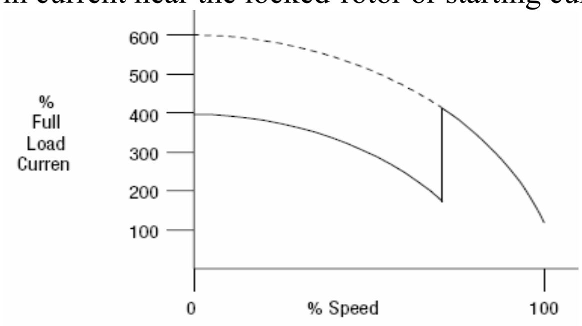

Figure 6: Near Full Speed Transition [7]

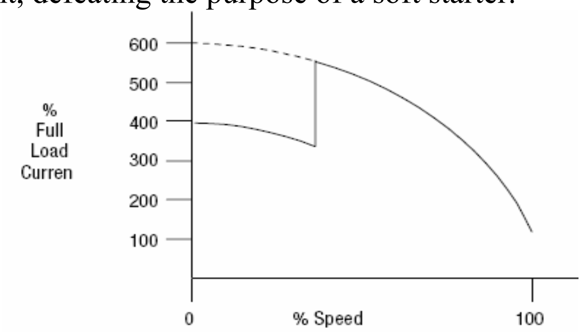

Figure 7: Low Speed Transition [7]

Control

A soft starter reduces the voltage by "notching" the applied sinusoidal waveform, simulations of which can be seen in Figures 8-13. A notch is a non-technical term for the zero voltage area in the middle waveform seen in Fig. 9. Fig. 9 also shows the forward firing SCR pulses in green and the reverse firing pulses in blue to notch the output voltage. Fig. 10-13 show a progression from a 90º firing angle to 30º. As the notch decreases in size, the V_{rms} increases along with I_{rms}. An initial voltage, determined by the user, is ramped up to full voltage by varying the firing angle depending on the preset profile of the soft starter. Soft starters can be controlled via open-loop or closed-loop control.

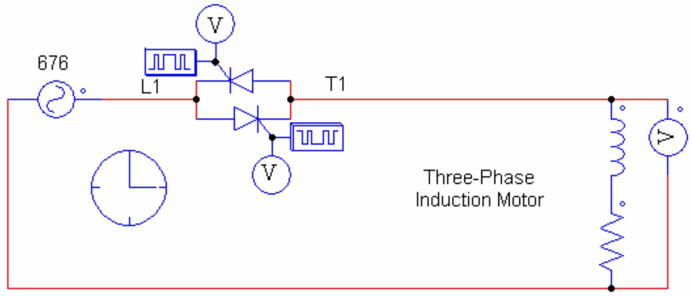

Figure 8: Single Phase Simulation

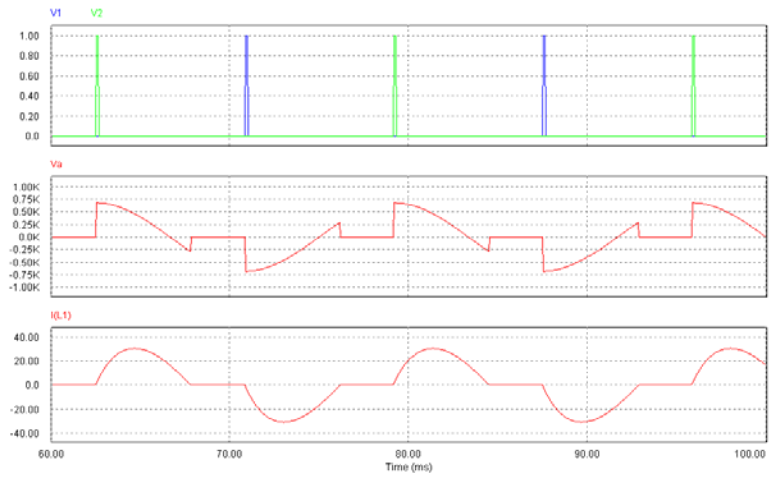

Figure 9: Single Phase Simulation (90º Firing Angles, Voltage, and Current)

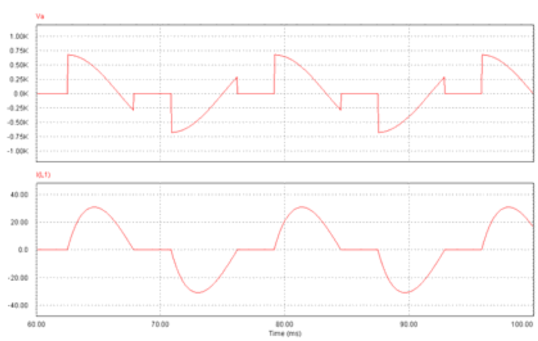

Figure 10: 90º ~ 341V_{rms}

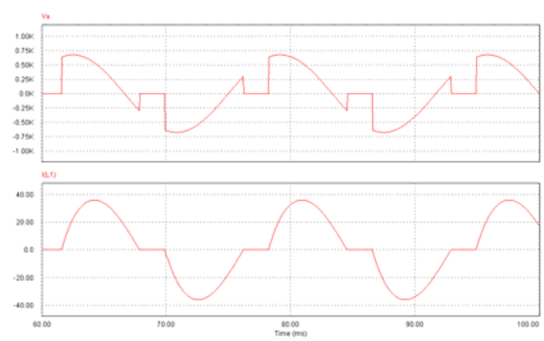

Figure 11: 70º ~ 405V_{rms}

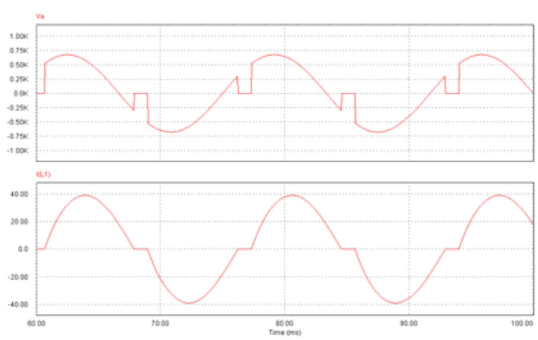

Figure 12: 50º ~ 452V_{rms}

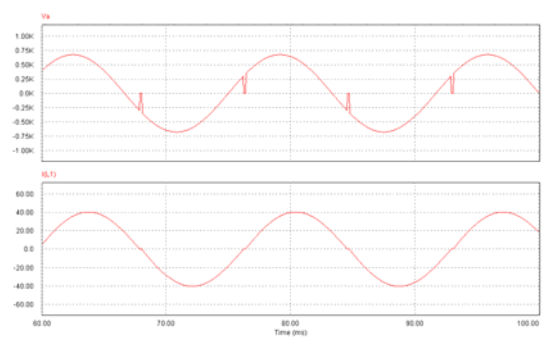

Figure 13: 30º ~ 469V_{rms}

Open-Loop and Closed-Loop

An example of open loop control is the voltage ramp (Fig. 14), the voltage ramps from an initial voltage to full voltage in a linear fashion without regards to the load. Pump start is another form of open-loop control. The pump starter's firing circuit ramps up the voltage with a profile that allows the speed/torque to ramp (Fig. 15) in a more efficient manner and helps protect against water hammering, a common problem in pump applications. Fig. 14-15 also show examples of soft stopping.

Applications such as current limit (Fig. 16) use feedback from the motor or the line current/voltage to change the firing angle of the SCRs as necessary, hence closed-loop.

All control schemes listed monitor back EMF of the motor as to not become unstable.

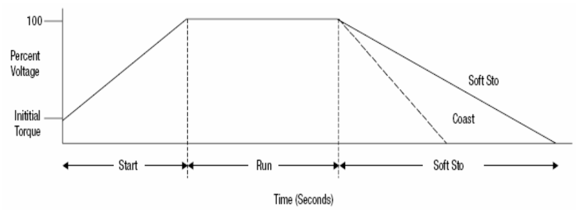

Figure 14: Voltage Ramp [7]

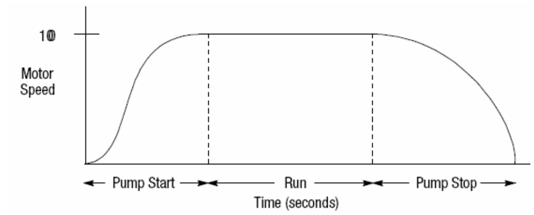

Figure 15: Pump Start [7]

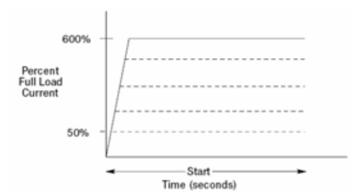

Figure 16: Current Limit [7]

Applications

Soft starters can be made for a reversing application by adding two extra SCR pairs that switch two phases. For example, line phase "b" is connected to load phase "c" and *vice versa*. L2 ("b") is connected to T3 ("c") and L3 ("c") is connected to T2 ("b") in Fig. 17. A delta configuration motor can also be controlled with a soft starter (Fig. 18), but it will see more current than a line connected motor. As a way to get around the larger current switching, a soft starter can be wired "inside the delta," as can be seen in Fig. 19. Wiring in this configuration will allow the soft starter to control a larger motor than even line connected by a √3 advantage. For instance, an "inside the delta" soft starter can switch a 277A load versus a line connected soft starter needs to be able to switch 480A to control the same rated motor load. A disadvantage of "inside the delta" is that it requires six leads coming from the motor which can be an added expense with larger HP motors.

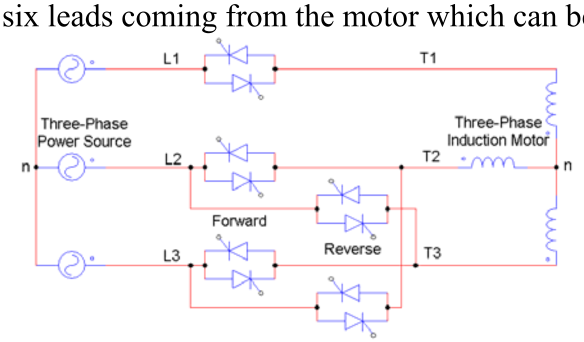

Figure 17: Reversing Soft Starter Topology

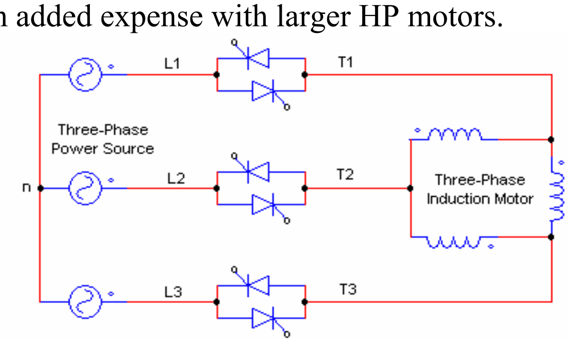

Figure 18: Delta Soft Starter Topology

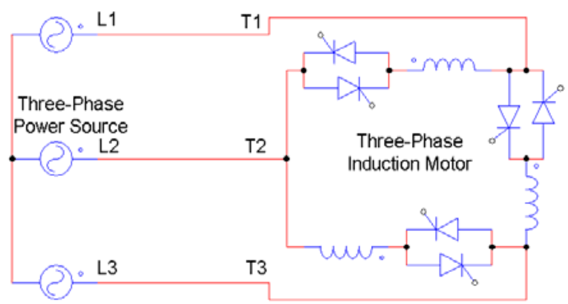

Figure 19: "Inside the Delta" Topology

Above are some physical variations of soft starter applications. In contrast, kick starting and low speed ramps are some other applications that can be implemented via different programming of SCR firing angles. See Appendix Fig. 33-34 for kickstart and low-speed starting profiles.

High Inertia Load Characteristics

Below are some calculated simulations of different applications of soft starters with high inertia loads. Table 2 holds the properties the motor simulated. Fig. 20-21 shows a general full voltage start for comparison with a motor that has a locked-rotor current LRA that is 600% of the FLA and a locked-rotor torque LRT or starting torque that is 180% of the full load torque. See Appendix Fig. 35 for an explanation of the %Current & % Torque vs. Speed curves.

Table 2: Simulated Motor

Motor Information		Load Information	
Motor Type	NEMA B	Load Type	High Inertia
Rated HP	200	Load Inertia	36000
Rated Speed	1750	Load Speed	605
Frequency	60	%Load Factor	80%
# of Poles	4	Motor Inertia	100
LRA %	600%	%Inefficiency	30%
LRT%	180%		

Motors must be sized appropriately to have enough torque with respect to its load or the motor will not be able to start, irregardless of starter type.

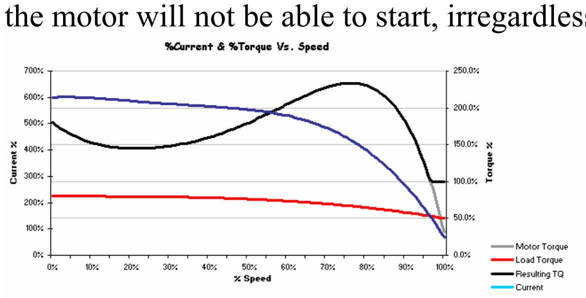

Figure 20: Full Voltage Starting [8]

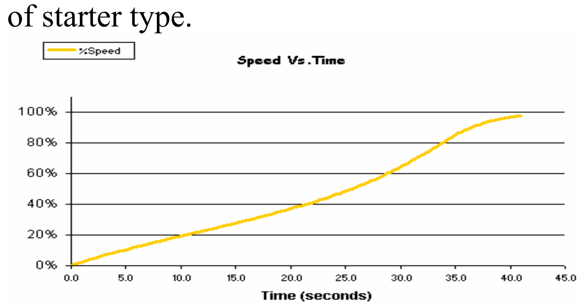

Figure 21: Full Voltage Starting [8]

As you can see in Fig. 22, the starting current is reduced from 600% to roughly 400% and the initial starting torque is set to 50%. The initial torque for this motor application cannot be any less than the load torque, or a stall condition may occur (discussed later).

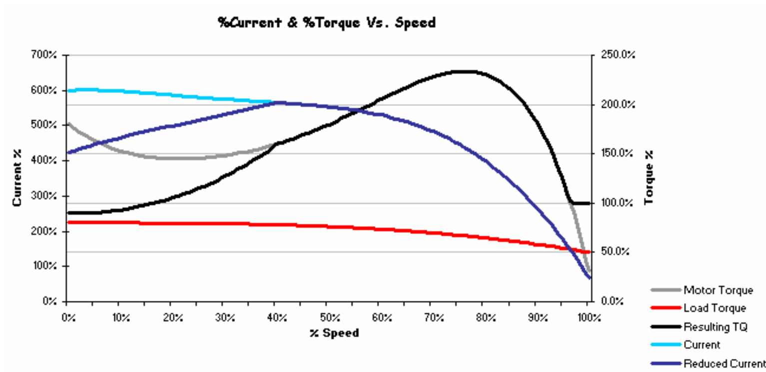

Figure 22: Soft Start Motor Starting Characteristics [8]

In a current limit start (Fig. 23), the current is limited to a specified value, in this instance 450% of the FLA. The lowest level to which the current can be limited depends on the motor torque. Again, caution needs to taken in setting the current limit to make sure the motor torque does not dip below the load torque to avoid stall conditions.

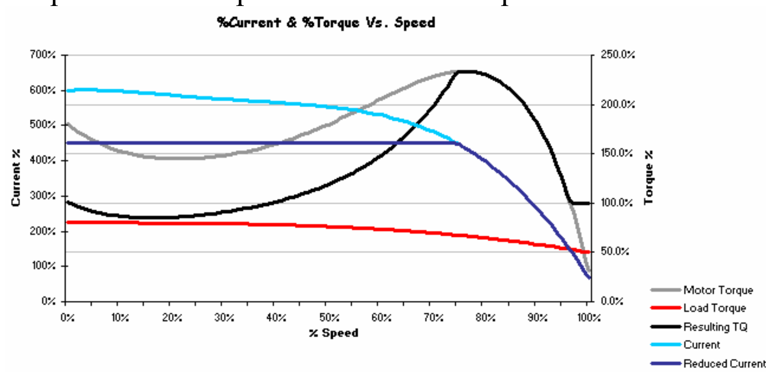

Figure 23: Current Limit Motor Starting Characteristics [8]

High Inertia Load Speed Characteristics

Fig. 24-25 are for comparison to an across-the-line start.

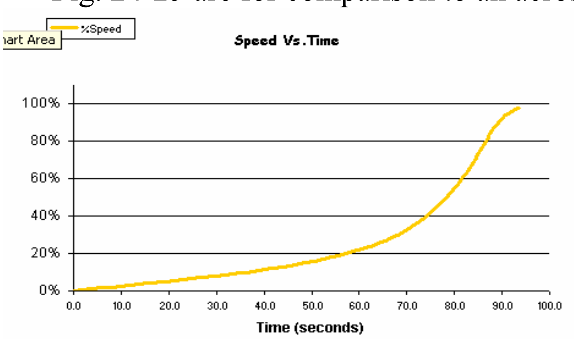

Figure 24: Soft Start [8]

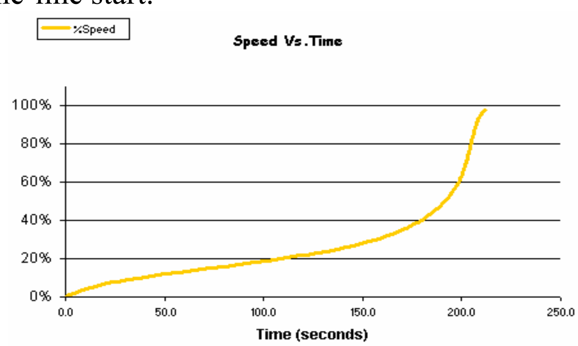

Figure 25: Current Limit Start [8]

High Inertia Stall Conditions

A stall occurs when the motor torque cannot overtake the load torque and the motor cannot rotate. When this happens, the motor will draw more current than the FLA to try to turn the load, again, defeating the purpose of the soft starter. Motor stalls are possible if the motor torque dips below the load torque; for a high inertia load, the starting load torque is quite high and stays relatively high. Fig. 26-27 show possible stall conditions (highlighted by arrows) for a soft start or a current limit start. Fig. 26-27 and 32 may be slightly misleading because once the motor stalls the speed will not increase.

Soft Starter Settings	
Starting Type	Soft Start
Initial Torque %	40%

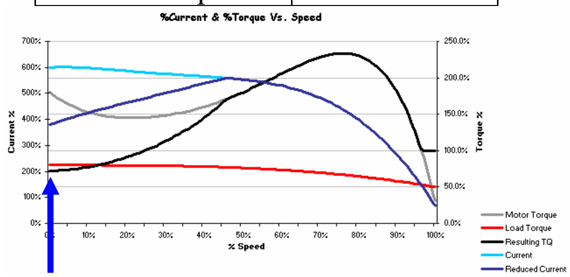

Figure 26: Soft Start Stall [8]

Soft Starter Settings	
Starting Type	Current Limit
Initial Current%	300%

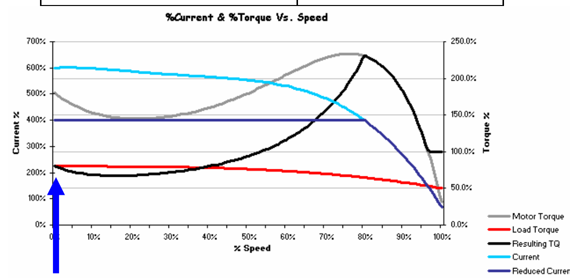

Figure 27: Current Limit Stall [8]

Pump Application Load Characteristics

The pump application simulation uses the same motor characteristics as the previous high inertia application but is connected to a pump. A pump load starts with almost no load torque and it increases with speed. The red line in Fig. 28 shows the load torque.

Motor Information		Load Information	
Motor Type	NEMA B	Load Type	Pump
Rated HP	200	Load Inertia	36000
Rated Speed	1750	Load Speed	605
Frequency	60	%Load Factor	80%
# of Poles	4	Motor Inertia	100
LRA %	600%	%Inefficiency	30%
LRT%	180%		

The closer the motor torque can get to the pumps torque with out dipping below it, the more potential for energy savings. With almost no starting load torque a soft start can be set much lower than in a high inertia load. Fig. 28 is set to 2% of locked-rotor torque.

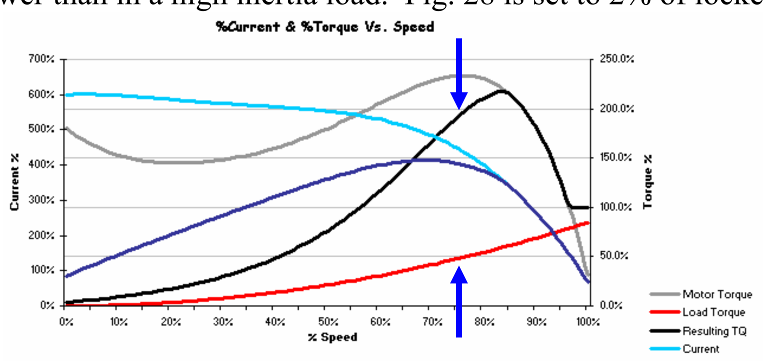

Figure 28: Pump Soft Start [8]

Using a current limit start with this application, the motor torque is kept closer to the load torque (highlighted by arrows) than with the soft start above (highlighted by arrows), allowing even more energy savings. Fig. 29 is set to 225% of the locked-rotor torque.

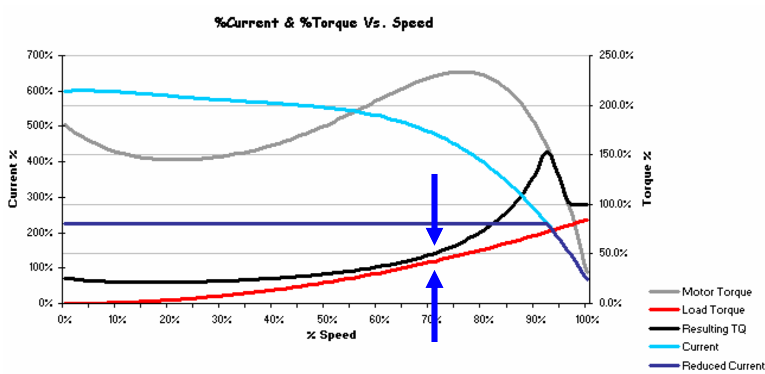

Figure 29: Pump Current Limit [8]

Pump Application Speed Characteristics

Fig. 30-31 are speed vs. time curves for comparison to the across-the-line start.

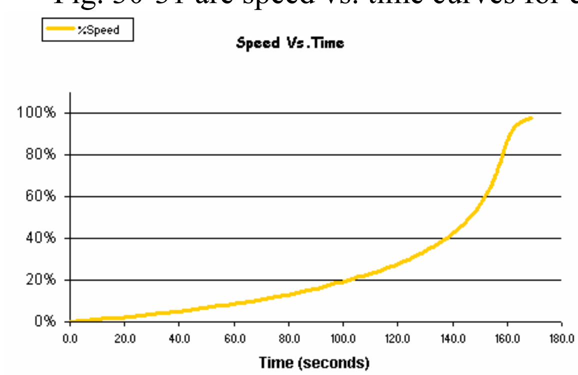

Figure 30: Soft Start [8]

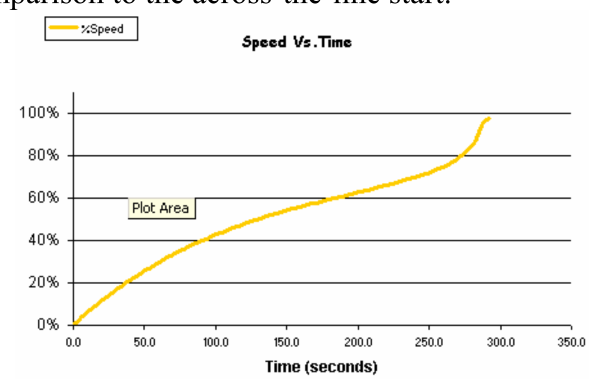

Figure 31: Current Limit [8]

Pump Application Stall Conditions

With a pump application there is almost no starting torque, and the soft start option almost cannot fault. However, the current limit has an inherent dip in its starting profile, and again, caution must be taken to avoid stall conditions. Fig. 32 has a current limit set to 200% of the FLA and the motor starts to stall at around 50% of its full speed (highlighted by arrow).

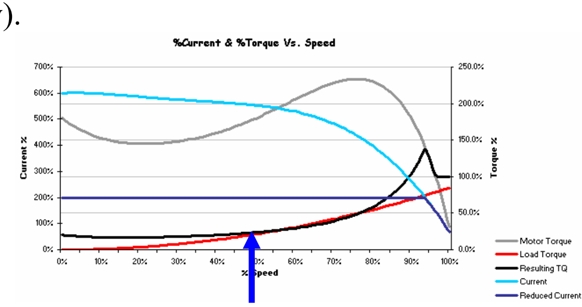

Figure 32: Pump Stall [8]

Conclusion

A soft starter is a versatile starter that can take many forms and be used to start many different applications. Along with protecting applications such as belt conveyors and saw mills, it can help save a great deal of energy by reducing the starting current and starting torque and help stop numerous conditions that are damaging to motors.

Appendix

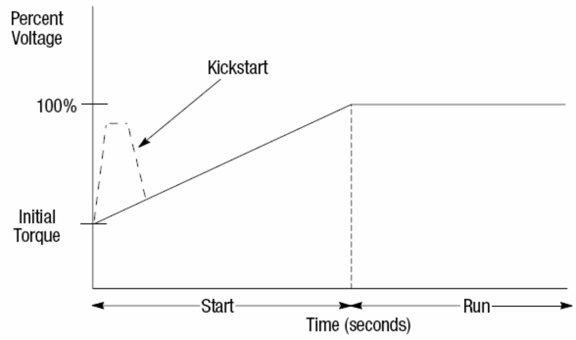

Figure 33: Kickstart Profile [7]

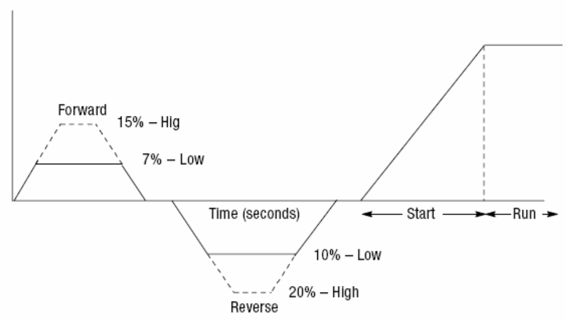

Figure 34: Low Speed and Low Speed Revering Profile [7]

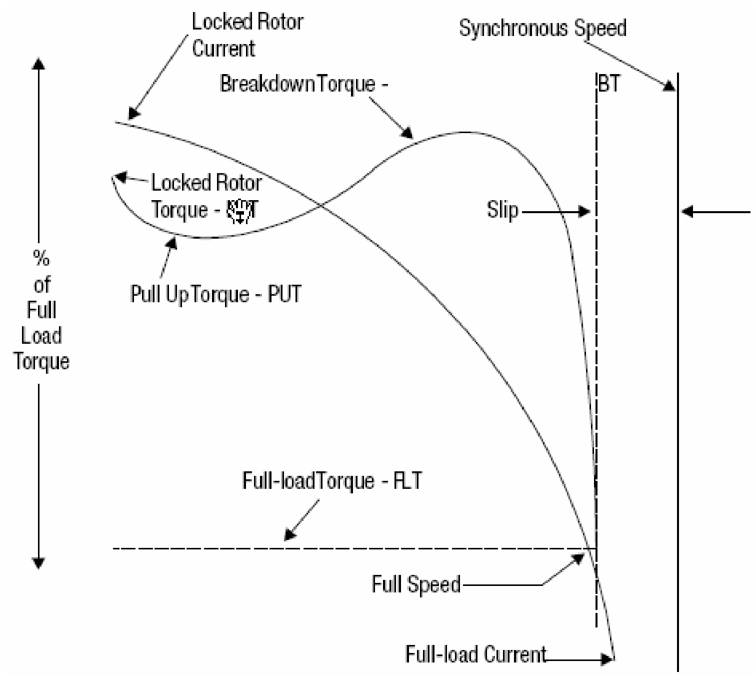

Figure 35: Speed/Current vs. Torque Curve Explanation [7]

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