AC Drives and Soft Starter Application Guide

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Abstract: There are usually several choices for starting motors. Two of these, AC variable frequency drives (VFD's) and soft starters, seem to have similar characteristics. Terms and descriptions used in product literature are nearly the same. Even the list of possible applications is similar. However the technology and performance are significantly different. When these differences are understood, it becomes clear when and where to properly apply each of them.

I. Introduction

The objective of this paper is to provide the basic technical information to understand the differences. First covered are the operating principles of the VFD and soft starter. How motor performance is affected is the other key to selection of the proper starting method. Finally, guidelines will then be presented.

II. Variable Speed Drives

The VFD works on the principle that the AC line voltage is converted to a DC voltage. This DC voltage is then inverted back to a pulsed DC whose RMS value simulates an AC voltage. The output frequency of this AC voltage normally varies for 0 up to the AC input line frequency. On certain applications the frequency may actually go above the line frequency. Though high performance current regulated AC drives capable of operating in "torque mode" are available, the more prevalent volts per hertz drive is addressed here.

The most common VFD's manufactured today work using pulse width modulation to create the output sine wave. The conducting components used in drives are diodes, SCR's, transistors and IGBT"s. These inverters have three distinct and different sections to its power circuit as shown in the typical inverter block diagram figure 1 below.

The first section uses a diode or SCR full-wave bridge to convert the AC line voltage to DC. Filtering of this DC is done in the second section with a capacitor to supply the inverter bridge with a stable DC power source. A DC link choke is normally present on 10 horsepower and larger drives. The final section uses a transistor or IGBT bridge to deliver a pulse width modulated (PWM) DC voltage to the motor. The effective RMS voltage delivered to the motor is dependent on the fundamental output frequency that the inverter bridge is commanding. This is what lead to the term "volts per hertz drive".

The control or logic section of the inverter and user programmed settings determine the frequency output of the inverter. During acceleration, the frequency will vary according to a pre-determined algorithm such as linear ramp or s-curve, from minimum or 0 Hz up to commanded speed. The drive can also be programmed to skip over certain frequencies that may cause a mechanical resonance.

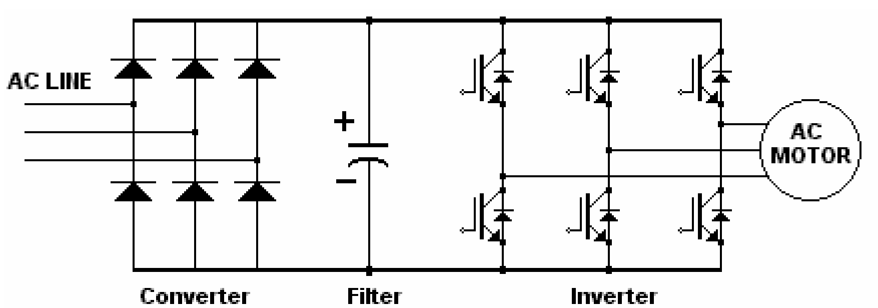


Figure 1 Typical Inverter Block Diagram

III. Soft Starters

The soft starter operates on a different premise. This principle is that by adjusting the voltage applied to the motor during starting, the current and torque characteristics can be limited and controlled.

For induction motors, the starting torque (LRT) is approximately proportional to the square of the starting current (LRA) drawn from the line. LRT $\propto I^2$. This starting current is proportional to the applied voltage (V). So the torque can also be considered to be approximately proportional to the applied voltage. LRT $\propto V^2$. By adjusting voltage during starting, the current drawn by the motor and the torque produced by the motor can be reduced and controlled.

By using six SCR's in a back to back configuration as shown in figure 2, the soft starter is able to regulate the voltage applied to the motor during starting from 0 volts up to line voltage. Unlike the VFD, line frequency is always applied to the motor. Only the voltage changes.

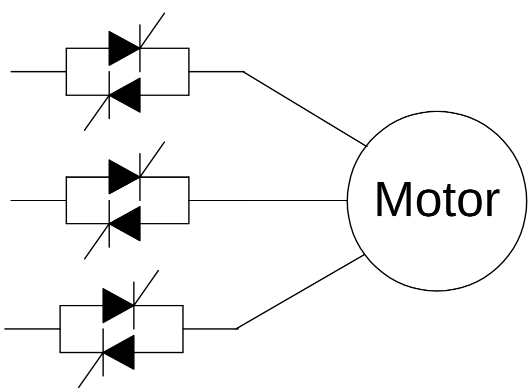


Figure 2.
Six Back to back SCR Configuration

Feedback from the motor to the logic circuit controlling the SCR firing is required to stabilize motor acceleration.

IV. Variable Speed Drive Operation.
The AC line voltage, figure 3, is rectified with a passive diode bridge. This means that the diode(s) conduct whenever the line voltage is greater than the voltage on the capacitor section. The resulting current waveform has two pulses during each half-cycle, one for each diode conduction window.

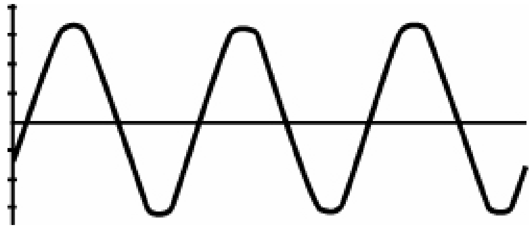


Figure 3 Line Voltage

The waveform, figure 4, shows some continuous current when the conduction transitions from one diode to the next. This is typical when a reactor is used in the DC link of the drive and some load is present.

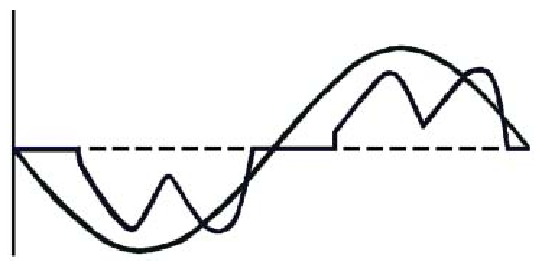


Figure 4. Line Voltage and Current Six-Pulse Full wave Diode Rectifier

Inverters use pulse width modulation to create the output waveforms. A triangle waveform is generated at the carrier frequency that the inverter IGBT's will switch at.

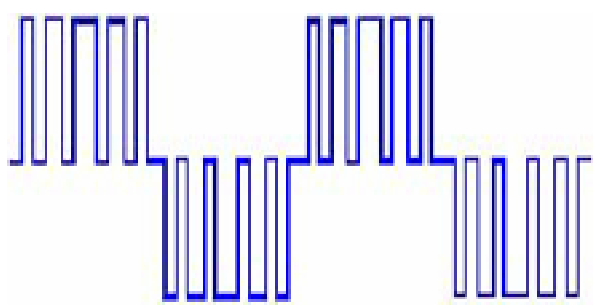


Figure 5

Inverter Output Voltage Wave Form
This waveform is compared with a sinusoidal waveform at the fundamental frequency that is to be delivered to the motor. The result is the voltage waveform shown in figure 5.

Figure 6 shows the resulting current waveform at the motor with a PWM signal applied.

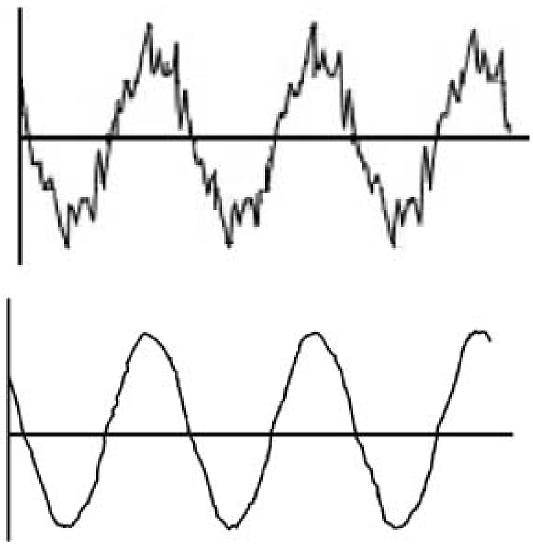


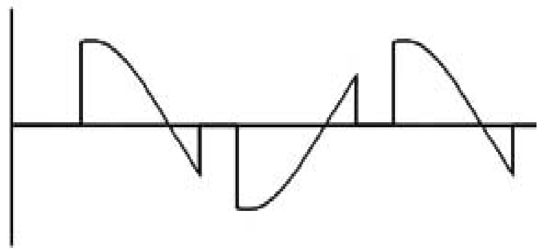
Figure 6
Inverter Output Current Wave Form
Bi-Polar (top) and IGBT

The inverter output can be any frequency below or above the line frequency up to the limits of the inverter and/or the mechanical limits of the motor. Note that the drive is always operating within the motor slip rating

V. Operation of Soft Starters

Timing of when to turn on the SCR's is the key to controlling the voltage output of a soft starter. During the starting sequence the logic of the soft starter determines when to turn on the SCR's. It does not turn on the SCR's at the point that the voltage goes from negative to positive, but waits for some time after that. This is known as "phasing back" the SCR's. The point that the SCR's are turned on is set or programmed by what is called either initial torque, initial current or current limit setting.

The input voltage to the soft starter is the same as the VFD shown in figure 3. The result of phasing back the SCR's is a non-sinusoidal reduced voltage at the terminals of the motor which is shown in figures 7. Since the motor is inductive and the current lags the voltage, the SCR stays turned on and conduct until the current goes to zero. This is after the voltage has gone negative.



Voltage Output of Individual SCR
Figure 7 Soft Starter Voltage Wave Form

If compared to the full voltage waveform in figure 3, it can be seen that the peak voltage is the same as the full voltage wave. However the current does not increase to the same level as when full voltage is applied due to the inductive nature of motors.

When this voltage is applied to a motor, the output current looks like figure 8. As the frequency of the voltage is the same as the line frequency the frequency of the current is also the same. As the SCR's are phased on to full conduction, the gaps in current fill in until the wave form looks the same as applying the motor directly across the line.

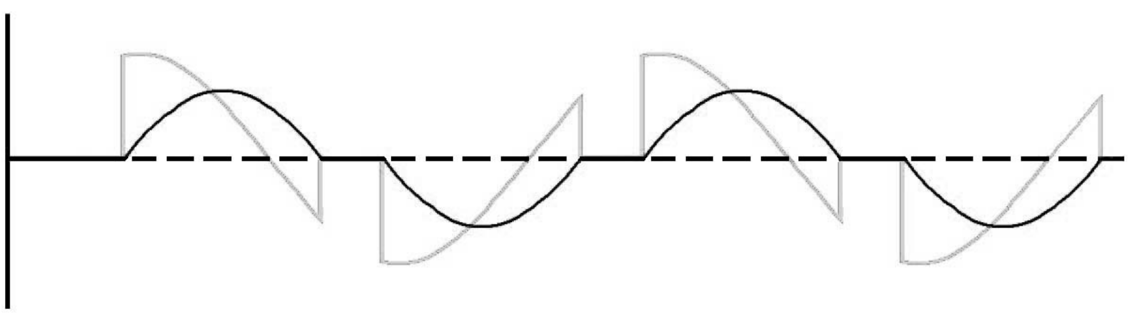


Figure 8 Soft Start Starting Current Wave

VI. Motor Characteristics Using VFD'd

During acceleration, the inverter applies different frequencies to the motor. It also changes the voltage but in direct proportion to the frequency. This is know as constant volts per hertz and provides constant torque while the motor accelerates.

A series of speed torque curves are shown in figure 9. These relate to speed torque curves at various frequencies. The "Constant Torque" line represents the full load or rated torque of the motor.

This "Constant Torque" line is actually the full load point on a locus of curves representing the speed torque curves of the motor from 0 to full speed. The inverter

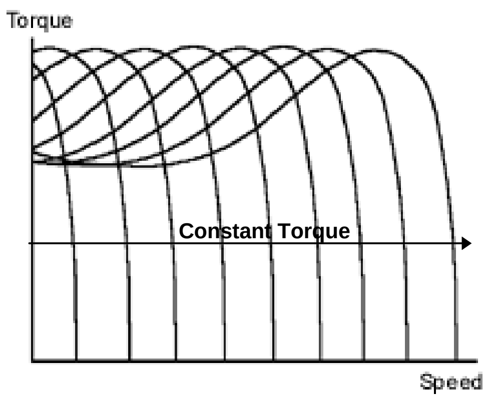


Figure 9 Inverter Speed Torque Curves

produces rated motor torque from 0 to rated speed. And it will produce full load torque while drawing much less than full load current from the power line during starting. This is due to the fact that the motor is effectively always running "at speed" for the applied frequency.

When full voltage starting, the slip of the motor at 0 speed is 100% and the motor is highly inductive. This results is the very high inrush current, 600 – 800%, and relatively low starting torque, 150-180% of full load torque, compared to the current draw. Almost all of the motor current here is reactive. Reactive current, by nature, does not produce torque.

When a motor runs "at speed" the slip is typically in the area of 1-3%. Under this condition the reactive current is much less and the motor produces rated torque at rated current. With a VFD the motor runs virtually "at speed" during acceleration. Since the voltage is reduced at low speeds, the input current can be 10% or less with more than 150% torque.

Since the motor always runs "at speed", or "within rated slip", the acceleration time is dependent on the ramp time setting. This assumes that the drive has been properly selected for the load.

VII. Motor Characteristics Using Soft Starters

Unlike the AC drive, the line current and motor current for a soft starter is always the same. During starting the current varies directly with the magnitude of the applied voltage. The motor torque varies as the square of either the applied voltage or current.

The most critical factor when evaluating a soft starter is the motor torque. Standard motors produce approximately 180% of the full load torque at starting. Therefore, a 25% reduction in voltage or current will result in the locked rotor torque equal to the full load torque $(180\%*(.75)^2 = 101\%)$. If the motor draws 600% of the full load current on starting then the current in this example will reduce the normal 600% starting current to 450% of the full load current.

Table 1 below gives more examples of the affects of reducing the voltage or current on a motor's locked rotor torque. This data is valid for soft start and series impedance starting. They do not apply to other types of reduced voltage starting such as autotransformer and wye-delta starting.

Table 1 Locked Rotor Torque Vs Locked Rotor Amps for Soft Starters

% Current or Voltage	% Full Load Current	% Full Load Torque
100	600	180
90	540	146
80	480	115
75	450	101
70	420	88
60	360	65
50	300	45

40	240	29

When applying soft starters, the same constraint as electro-mechanical reduced starters applies. That constraint is "will the motor be able to produce enough torque to get the load started with the current the soft starter is allowing to flow to the motor?"

Soft starters do have an advantage over conventional reduced voltage starting. They are able to adjust voltage, current and therefore torque over a wide range instead of single or a few fixed values. This can be seen in Figure 10. When voltage or current is held to a constant value, the speed-torque curve labeled "Current Limit" is produced. This curve would move up or down depending on the current limit setting. The upper boundary of this adjustment is the "Full Voltage" curve.

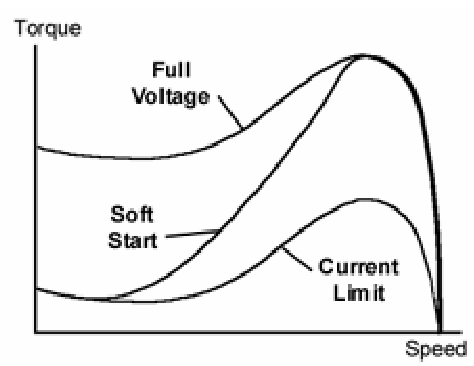


Figure 10 Soft Start Speed Torque Curves

The soft starter can also ramp the voltage from an adjustable initial value up to full voltage over an adjustable time frame. This is represented by the "Soft Start" curve. A stepless transition, which is designed to eliminate current/torque transients, is produced by this ramp.

The operating speed of the motor cannot be varied because the soft starter only adjusts the voltage to the motor and not the frequency. The frequency applied to the motor is always the line frequency. Because of this, the acceleration time is more dependent on the load than the ramp time.

VIII. Application Differences

With the knowledge of VFD and soft starter principles of operation and motor performance with each, application differences can be reviewed. With the list of applications being very similar, the general application parameters will be covered along with several application examples.

Motor speed is a parameter where a VFD has an advantage over soft starters. First, and most obvious, is where the speed of the motor needs to be varied from 0 to line frequency and sometimes higher than line frequency. The soft starter applies line voltage and frequency and therefore the operating speed is fixed.

The second speed related advantage that an inverter relates to processes that require a constant speed. If a fixed frequency is applied to a motor, the actual speed of that motor is not precisely regulated by the input frequency. The output speed is actually regulated by the load applied to the motor. So if a process requires very tight speed regulation, the frequency applied to the motor must be changed in relation to the load that is applied. With the use of feedback to the VFD this can be accomplished. Again the soft starter only applies line frequency so any speed regulation is not possible.

On applications where acceleration time needs to be consistent, an inverter should be used. This is due to the fact that acceleration time for a soft starter is more dependent on the load than the selected ramp time. If acceleration time is not an issue and controlling the torque or current is what is needed, then a soft starter is a good candidate for the application. (Note: some soft starters use feedback, such as tachometers. These units can provide timed acceleration with varying loads. It should be noted that current during feedback acceleration could reach the same level as starting at full voltage – 600 – 800% of full load).

With regard to stopping, a VFD will bring the motor to a rest in a specified time. This may be built into an inverter or may require a dynamic braking optional function for high inertia and overhauling type loads. The soft starter with a soft stop feature can only extend the stopping time. And just like acceleration, the stopping time is dependent on the load. If stopping time and stopping characteristics are not critical then a soft stop may fit the application.

Some specially designed soft starters can also provide braking. These are designed to reduce stopping time where coast to rest is very long. If the load is not a pure inertia and can vary the stopping time will also vary.

Where limiting current is the prime reason for not starting at full voltage, the first method to be considered today is usually soft starters. This is due to the cost differential between a soft starter and a VFD at the ampere ratings that current limiting becomes a factor. In most instances the soft starter is an appropriate choice.

There are applications where the additional cost of an inverter is appropriate. These cases are where the motor cannot provide sufficient torque to start the load with the ampere limitations imposed by the distribution system. Table 1 shows the motor torque provided at various levels of soft starter current limit. Unlike soft starters, drives can accelerate a motor to full speed at full load torque with line current that does not exceed the full load amps of the motor. Keep in mind that the power into the VFD is equal to the power out plus the losses. Therefore, for those loads that require higher torque than the soft starter can provide with the limits imposed by the distribution system, an inverter may be the required solution.

If starting torque is a concern when selecting a drive or starter, keep in mind the drastic difference in the amount of torque that can be developed for a given amount of line current. The drive has a much higher torque per amp ratio.

IX. Sample Applications

Provided here are four sample applications. Two will be for pumps and two will be for conveyors. These examples do not require variable speed or precise speed regulation, so a VFD or soft starter could be used.

Application 1) A pump is being started on full voltage. There is significant water hammer and the pipe bracing needs constant maintenance.

Answer: A soft starter will fit the application. It provides controlled torque during acceleration and has been shown to minimize and in many cases eliminate water hammer. There is no concern about current limitations as the application is now being started on full voltage.

Application 2) A new irrigation pump is being installed in a rural location. Because of this, the maximum current draw from the utility line without significant voltage drop has been calculated as 200% of the motor nameplate reading.

Answer: An inverter is preferred over a soft starter. In some instances soft starters can accelerate pumps with as little as 200% current. Application experience indicates that more often 250 – 300% current is required. The VFD can provide the torque required to accelerate the pump within the current limit restrictions of the distribution system.

Application 3) An overland conveyor requires 100% torque to accelerate when starting fully loaded. The maximum current draw from the utility is limited to 500% of the motor full load amps. The conveyor will normally be started unloaded, however, on occasion it may need to be started when it is loaded. Rate of acceleration is critical to prevent the conveyor belt from being damaged

Answer: Initially a soft starter seems to be the correct choice. The soft starter can provide 101% torque with 450% current (table 1). However the rate of acceleration, which equates to starting time is critical. The load also varies from unloaded to fully loaded. In this case a VFD would be the correct solution.

Application 4) A 20 horsepower motor drives an overhead plastic chain conveyor through a gearbox. It starts and stops frequently. Full voltage starting could be used but if the conveyor starts too quickly the product will swing and may be damaged or the chain may break.

Answer: A soft starter would fit the application. There is no time constraint and no limitation on current. Ramp start would typically be used to allow for minor load variations reflected back to the motor. If the gear reduction is high enough, a current limit start could provide a smoother start.

X. Conclusion

These examples were designed to show how slight application variations can change the type of motor starting that is required. Each application must be evaluated on its own merits. Neither soft starters nor VFD's are the perfect solution for all situations.