

ELECTRONIC SOFT STARTERS FOR CONVEYORS

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INTRODUCTION

Much interest is being shown in electronic soft starters for conveyors and our operations have installed approximately 40 units, rated up to 250 kW on conveyors and crushers. This paper considers an overview of some issues relating to applying electronic soft starters to conveyors with medium tension profiles and drive powers of some 250 kW and below.

The topic is introduced by considering the unique demands that conveyors impose on the drive system, following which induction motor energy losses and torque basics are reviewed. An overview of advantages and disadvantages for variable speed drives and fluid couplings for conveyors is given.

The distribution of energy for a motor connected direct on line is examined both during starting and normal, full speed operation. It is shown that at normal operation the rotor heat losses are typically approximately ½% of its rated power, but are some 200 times larger (100% of the motor rated power) at the instant of start. Similarly, the stator losses during starting are 25 to 100 times those at rated conditions. The classic motor torque: speed curve is discussed in terms of starting a conveyor. An alternative electronic soft start control algorithm is proposed and finally some notes are given on motor selection.

CONVEYOR TORQUE REQUIREMENTS AT START

To ensure long belt life, at all times the torque applied to a conveyor drive should not change abruptly but should change slowly. At start, the applied torque should be gradually increased with time until the total length of the conveyor has started to move, when the torque should be reduced to a value sufficient to accelerate the belt to operating speed. Any deviations from this torque profile will introduce tension waves, which in turn may result in excessive stresses in the belt. These issues increase in importance with increasing motor power.

START ALTERNATIVES

The universal power source for conveyors is the electric induction motor. The methods used to start these machines are discussed below.

DIRECT ON LINE (“DOL”).

Because of the simplicity and low cost of this alternative, the majority of motors throughout industry and mining are started DOL. For example, four motors each rated 21 300 kW and 11 000 V, driving compressors at the Secunda petrochemical plant are started DOL. However the requirements of conveyors are such that common practice restricts DOL start to drives below some 5,5 kW.

FLUID COUPLINGS

Fluid couplings are well-proven to reduce the thermal load on a motor when starting a large inertia load and also to provide a smoother torque to a load than can be provided by a DOL start.

A fluid coupling provides a degree of separation of the motor and driven load during start. A fluid coupling applies a quadratic torque: speed load on the motor until the motor reaches full speed. A certain amount of control of the torque applied to the belt is possible by varying the oil fill in the coupling. In addition, variants of couplings are available that delay the flow of oil into the working chamber, to extend the start time further.

Once the motor is up to full speed, the coupling applies between 125% and 170% of the motor rated torque to the belt for acceleration, depending on the coupling selected, its oil fill

etc. Once the belt has reached full speed, the coupling has a “slip” of a few percent at normal load, increasing the system power losses correspondingly.

The principal advantages of fluid coupling starting for conveyors include:

- Reduced belt stresses compared with a DOL start;
- Reduced motor thermal stresses;
- Reasonable number of starts per hour may be achieved (this is made possible by reducing the motor thermal stresses, but at the cost of transferring the heat load to the fluid coupling);
- Typically, mine staff are familiar with fluid couplings and are competent to perform routine maintenance and repair work.

The main limitations of fluid couplings are that they are

- Maintenance intensive, particularly if incorrectly applied
- Decrease energy efficiency by 1 % to 3%

VARIABLE SPEED DRIVE (“VSD”)

A VSD allows very precise control of the torque and / or speed, allowing enhanced control of the belt starting. Thus the drive could apply torque to the drive pulley as a precise function of the tension and speed at other locations in the belt. Another advantage of VSD is that it allows the possibility of adjusting the belt speed to match the belt loading. This approach can reduce wear of the belt and of all moving parts as well as increase energy efficiency.

However, this power and flexibility is obtained at the expense of:

- A considerable capital premium
- Higher-level maintenance staff requirements,
- Large space requirements,
- Sensitivity to hostile environments,
- Sensitivity to supply disturbances,
- Harmonic distortion (particularly in weak networks).

ELECTRONIC SOFT START.

This is the subject of much of the remainder of this paper. To consider electronic soft starters it is useful to refresh our understanding of a few induction motor characteristics.

INDUCTION MOTOR PERFORMANCE DURING STARTING

Some of the induction motor issues affected by electronic soft starting are

- Rotor heating
- Stator heating
- Torque during start

These will be considered in turn¹.

The losses dissipated in the stator winding are given by:

$$\delta P_{\text{stator}} = i^2 r \quad (1)$$

During starting, the motor power factor is typically 1/5th and may be can be as low as 1/10th of its nominal value. A characteristic of an induction motor is that the percentage of nominal torque developed at stand still is equal to the percentage of nominal power drawn by the motor at stand still. Hence, to produce 100% torque at stand still, 5 per unit (“p.u.”) to 10 p.u. current will be drawn (because, as stated, the power factor at start is between 0,2 to 0,1). Squaring the current as per equation (1) above, determines that for rated torque during starting, **25 to 100 times** nominal heat is dissipated in the stator winding.

¹ More detail is given in Appendix A

The losses dissipated in the rotor are given by:

$$\delta P_{\text{rotor}} = s P_{\text{motor}} \quad (2)$$

Nominal slip is of the order of ½% (e.g. a machine with a nominal speed of 1493 rpm). Thus from equation (2) the nominal rotor losses are typically ½% of the motor nominal power. It follows that the motor is designed to dissipate of the order of ½% of the motor rated power continuously. At start when the motor speed is zero, the rotor slip is 1 per unit, or 100%. Applying equation (2) at start, the rotor losses are equal to the power drawn by the motor. Thus for rated torque during starting, approximately **200 times** nominal heat is dissipated in the rotor.

From the above, during starting both the stator and rotor are subjected to very considerable thermal stress. Hence motor manufacturers specify the maximum duration, in seconds, of a start and the maximum number of starts per hour that a motor may perform without being damaged. This data applies to full voltage on the motor terminals; for other voltages, the figures may be extended by the square of the reduced voltage. However, reducing the stator voltage slightly reduces the load inertia that a motor can start within its thermal limits.

During starting, reducing the terminal voltage reduces the torque generated by the square of the applied voltage.

$$T_{\text{start}} = k V^2 \quad (3)$$

During running at rated load, reducing the terminal voltage increases the motor losses (and hence motor temperature) and slightly reduces the motor speed. To avoid excessive temperatures – which reduce the motor life - it is therefore important to operate an induction that is delivering rated load, motor at close to its rated voltage.

SELECTION OF SOFT STARTER MOTOR TERMINAL VOLTAGE SETTING

Electronic soft starters typically control induction motor starting by applying a reduced voltage to the motor terminals and linearly increasing the voltage up to the 100% value. The conventional soft starter has two settings:

- The reduction in stator voltage and
- The time to “ramp” the voltage to full value.

However, the selection of the stator voltage is a compromise between two conflicting requirements. A low voltage is required to minimise the torque applied to the belt, particularly just as the motor reaches its full speed, and to prolong the start time. However, there is a very definite limit to the allowable reduction of the stator voltage or the motor will not develop sufficient torque to break the conveyor away.

Consider settings of 70% voltage at start, with a ramp time of 60 seconds, as shown below.

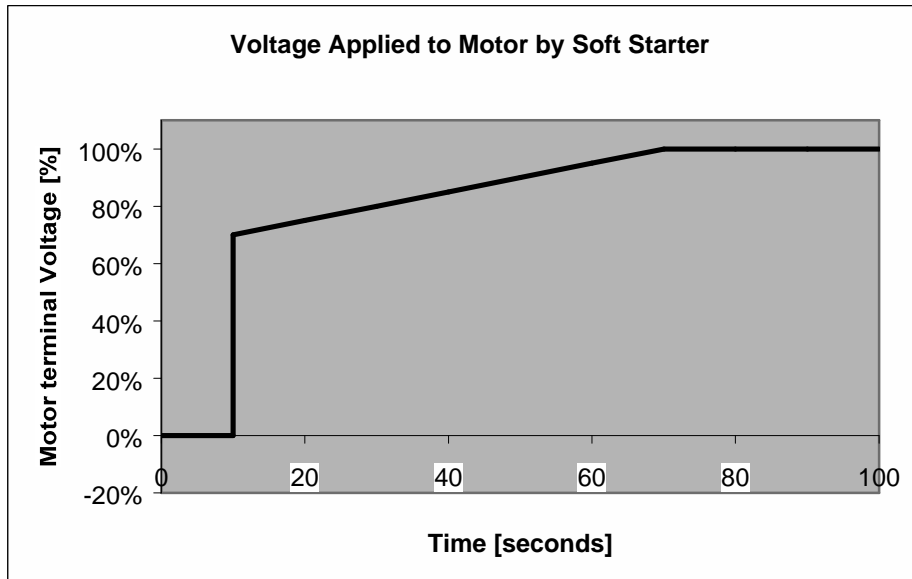


Figure 1: Voltage applied to motor terminals by conventional electronic soft starter

From equation (3), a 70% voltage applied to the motor terminals will result in the motor developing 50% ($0,7 \times 0,7 = 0,49$) of its rated locked rotor torque. Since locked rotor torque (at full voltage) is typically 140% to 240%, reducing the machine terminal voltage to 70% will result in the motor developing around 70% to 120% of its rated torque at switch - on.

The electronic soft starter increases the motor terminal voltage steadily, increasing the motor shaft torque. Simultaneously, the load will increase as more of the belt starts to move. However, due to skin effect in the rotor, an induction motor's torque typically falls steadily until at 75% speed the torque is around 10% to 20% less than the locked rotor torque (times the square of the terminal voltage).

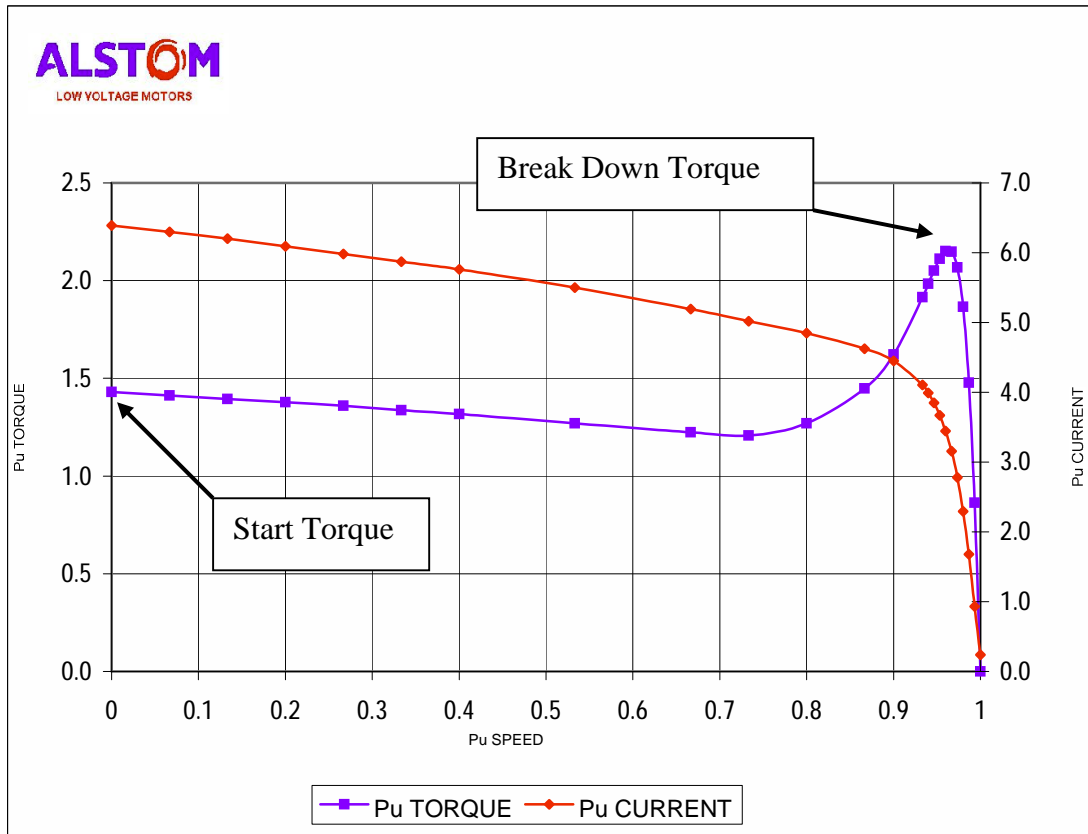


Figure 2: Motor Torque : Speed and Current : Speed curve for a 400 kW 4 pole induction motor.

Assuming that the soft starter settings cause the start to be complete at twenty seconds, then a 60 second ramp time will cause the motor terminal voltage to reach 80% of the motor's rated voltage when the motor reaches 95% speed. At this speed the motor torque abruptly increases to its Break Down Torque ("BDT") value of between 220% and 300%. With 80% terminal voltage, the motor will develop $0,8 \times 0,8 = 64\%$ of its full voltage BDT, or 140% to 190% of its rated torque. Hence this represents a limit case for the ramp time and voltage.

Even after the motor reaches full speed, until the expiry of the ramp time, the motor terminal voltage is considerably below its design value. This causes the motor to draw excessive current and increases the heat loading on the machine.

Thus, the selection of soft starter settings is a compromise of conflicting requirements, and the best trade off may not give satisfactory performance.

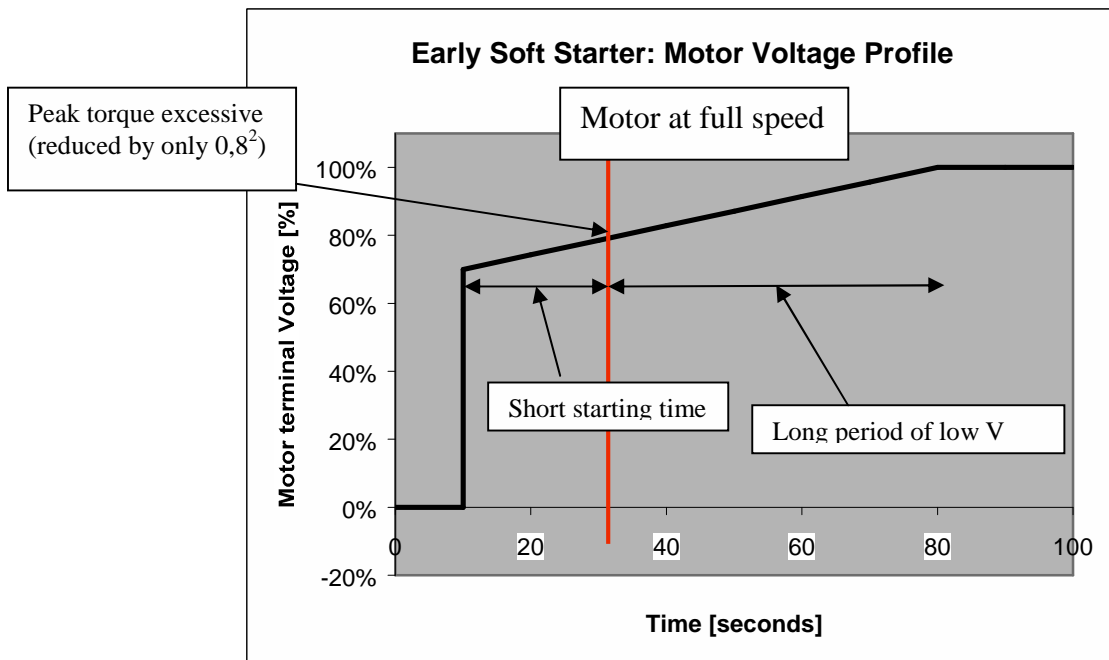


Figure 3: Motor terminal voltage versus time

As discussed, applying the above voltage profile to the motor terminals produces a torque time curve as shown below. Note the large peak torque just before maximum speed is achieved.

Figure 4: Motor torque versus time for a soft started drive

POTENTIAL STARTING PROBLEMS

The excess torque developed during starting, as discussed above, can be aggravated further by the following mechanism.

If the motor size is marginal for the belt load, the motor may crawl and its acceleration may be delayed until the soft starter delivers close to full voltage. Prolonged operation at low speed will cause the motor to be heated considerably, as per equation (2). In addition, the motor speed may remain low until its terminal voltage has been ramped up to close to its full value e.g. 90% or even more. When the motor does reach 85% to 90% speed, the motor torque abruptly increases to peak or “Break Down Torque” (“BDT”, also known as “break down torque”). BDT varies between 210% and 300%. Since the motor voltage is now high – say 90%, almost the full BDT will be applied to the belt. For example, if the terminal voltage is 90%, then $0,9 * 0,9 = 81\%$ of between 210% and 300%, or 170% to 240% torque will be applied to the belt. This may shorten the belt life and / or damage the belt structure.

The abrupt torque at switch on followed by a torque peak close to full speed can result in excessive belt tension, as shown in the simulation below.

Figure 5: Belt tensions for a conventional soft started drive

OVER SIZED MOTOR

It is common practice to over size motors for soft start applications to increase the thermal capacity of the machine and to ensure adequate torque at starting. However, over sizing does not alter the **ratio** of torque at start to that at pull out. That is, a larger machine means

that a larger percentage torque is applied to the belt close to the end of the start, at motor pull out. A large machine also means that a jammed belt can be subjected to higher tensions.

IMPROVED SOFT STARTER

It is possible to improve the situation slightly with a different voltage versus time profile, although with a soft starter it is never possible to obtain the performance of a VSD.

On switch-on, the motor voltage should be quickly (+/- 5 seconds) ramped to an initial value of say 70%. During this short period the torque will increase in a quadratic manner from zero to 70% to 120% within say 5 seconds, allowing the belt to be tensioned without being subjected to large tension waves.

The voltage should then be held steady (or slightly ramped up a nominal 5% to 10% to overcome the typical “dip” in motor torque as the speed increases from zero to around 75% speed) for the duration of the start. This causes the motor to apply a fairly constant torque to the belt for most of the acceleration time.

Since the motor terminal voltage is held constant (or only increased slightly), BDT will be somewhat reduced compared with a traditional soft starter system. For example, if the soft starter maintains the motor terminal voltage at 70%, the BDT will be $0,7 \times 0,7 = 49\%$ of its full voltage value. Thus around 105% to 150% of the motor’s rated torque is applied to the belt at around 90% speed. Allowing say 50% motor over rating, the peak torque is thus 160% to 225% of rated belt tension. This may allow belt damage to be avoided.

Once the entire belt has been accelerated to operating speed, the motor terminal voltage is then ramped up to a value determined by the load.

Algorithms are available to optimise the stator voltage to maximise motor efficiency once the belt is running at full speed. During periods of light belt load, the motor terminal voltage is reduced to lower motor losses by around 1% to 2%.

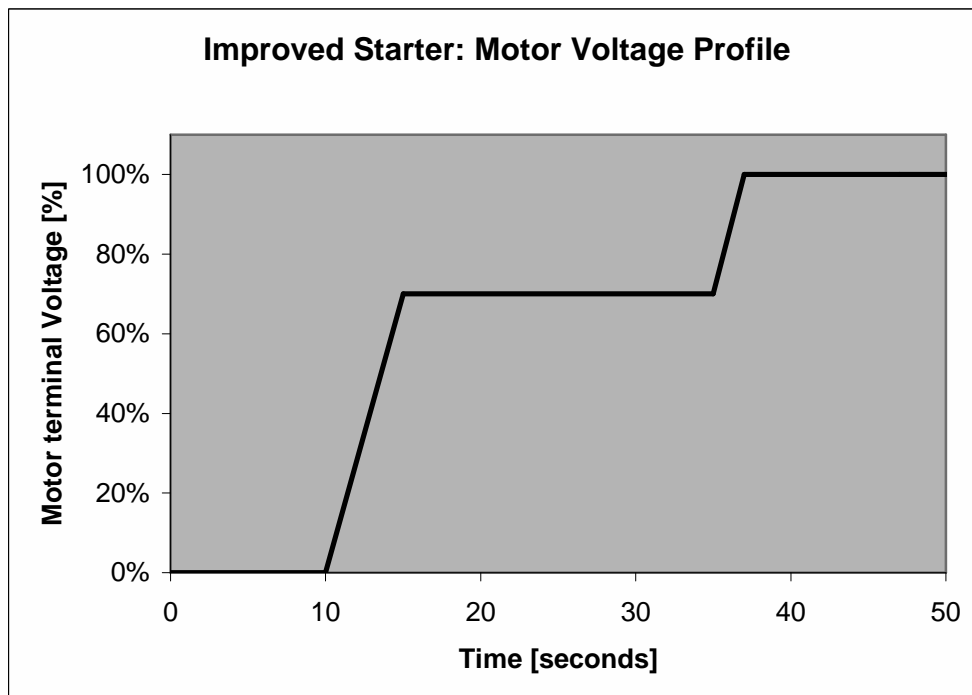
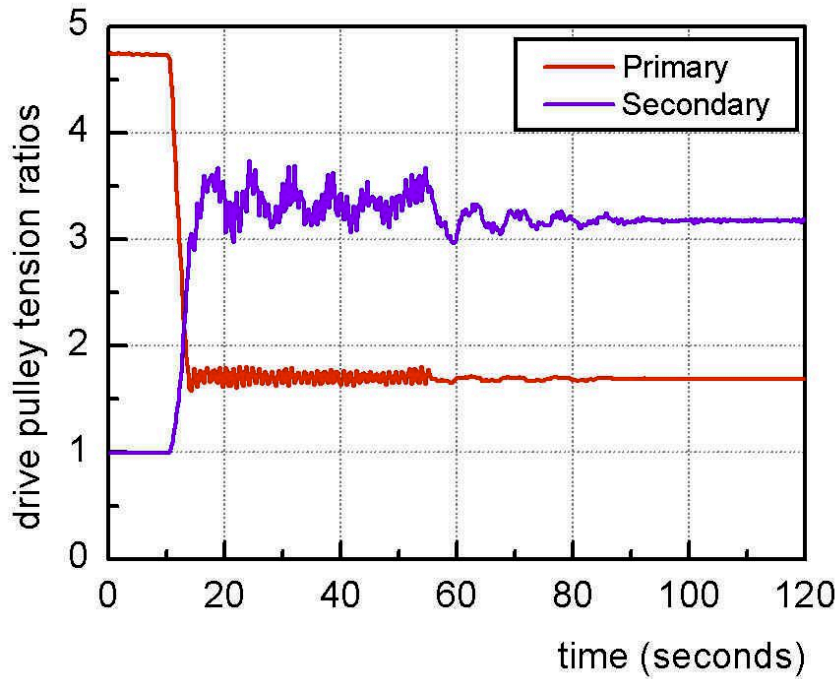
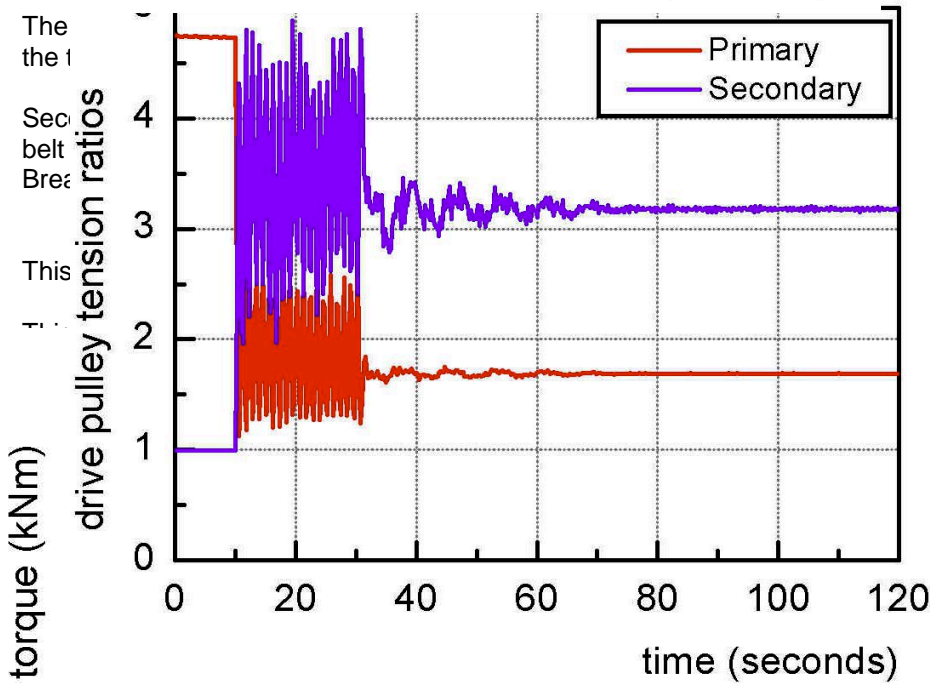


Figure 6: Improved electronic soft starter algorithm



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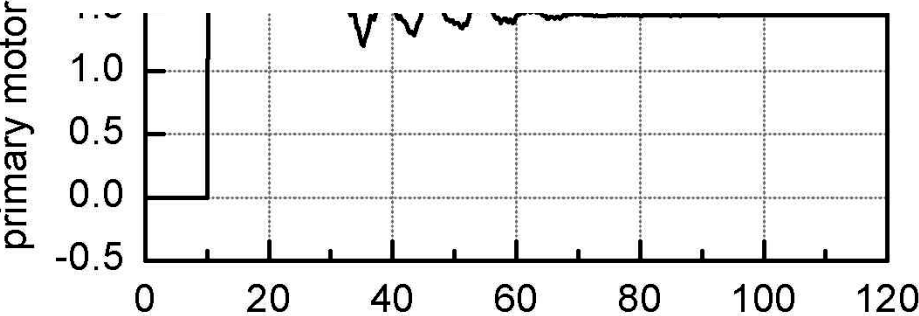
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² Note that if a conventional soft starter is employed, i.e. a unit that has a single voltage ramp, then the belt tension will be higher than as determined above and will be close to the motor full BDT.

MOTOR PROTECTION

It is recommended that the motor be protected with an electronic relay with at least the following functionality:

- “Electronic shear pin”, or “running stall”. This feature is disabled during a start but trips the motor if the belt is jammed while running, preventing an excessive tension being applied to the belt. It must trip the motor within 100 milliseconds of the motor torque exceeding a pre-set value of 50% to 150%. This protection feature is very desirable because the motor is typically oversized to allow it to start the belt without being damaged by over heating. And thus a jammed belt could be severely damaged.
- “Too long start time”
- Over temperature monitoring. Sophisticated start thermal models are now available, but it is recommended that a temperature sensor supplement this.
- Normal protection features of overload, earth leakage etc.

BELT INSPECTION

A soft starter is unfortunately not suitable to run the motor and belt at reduced speed, as the motor will overheat. Soft starters reduce the motor voltage, which can be used to slow a motor by increasing the motor’s slip. For this application consideration should be given to other solutions, such as an electronic VSD. This is explained in more detail in Appendix B.

STALLED MOTOR

As can be seen from figure 2, as the load torque applied to a motor increases, the motor slows down slightly and a motor torque increases the match the load requirement. If the motor is loaded beyond its peak torque, the motor torque collapses and the machine will stall. The motor current increases to typically 6 to 8 times its rated value as the motor slows down. The motor i^2r losses increase to 36 to 64 times their rated value and the motor must be tripped with a few seconds to prevent the motor from being burnt out.

SUMMARY

An improved soft start motor voltage versus time profile is presented to lower belt tension during starting.

Although not as versatile as a variable speed drive nor as easy to apply as a fluid coupling, an electronic soft starter does offer the advantage of higher efficiency than a fluid coupling and lower cost than a VSD.

A limitation of an electronic soft starter is that the selection of the stator voltage is a compromise between two conflicting requirements. On the one hand the motor voltage cannot be reduced too much or the motor will not develop sufficient torque to break away and accelerate the conveyor. On the other hand a low voltage is required to prolong the start time, to ensure that the belt is not subjected to excessive tensions. In addition, the voltage must be controlled just as the motor approaches full speed as in this region (pull out) the motor develops up to 300% of torque (at rated voltage)

Compared with a fluid coupling, this drive offers lower capital costs; lower maintenance costs and reduces network impact. At full load, some 2 – 3% energy savings are achieved by eliminating fluid coupling slip losses. At light load some 1-2% energy savings are achieved by optimising the motor voltage.

Limitations of this alternative conveyor starting strategy are significant thermal stresses in the motor during starting, restricted number of starts per hour and the danger of over stressing the conveyor if the system is incorrectly engineered or commissioned.

APPENDIX A: POWER DISSIPATION IN AN INDUCTION MOTOR DURING STARTING

Heat dissipation in the rotor

An induction motor may be thought of as a conventional air clutch. The stator magnetic field in the air gap may be likened to the clutch driving plate and the rotor is similar to the driven plate. In a clutch, the torque is preserved but speed is not. Thus we have:

$$T_{\text{stator}} = T_{\text{rotor}} \quad (1)$$

And

$$s = \frac{n_s - n_r}{n_s} \quad (2)$$

Which may be rearranged to express the rotor speed, n_r in terms of the slip and synchronous speed:

$$n_r = ((1-s) n_s) \quad (3)$$

Consider the well-known expression for mechanical power in a rotating system:

$$P = \omega T \quad (4)$$

This may be applied to the air gap of an induction motor by noting that the mmf in the air gap rotates at the motor's synchronous speed, n_s , and the speed of motors is measured in rpm whereas ω is in radians per second. Thus the air gap power is given by:

$$P_{\text{air gap}} = \frac{2\pi}{60} n_s T_{\text{air gap}} \quad (5)$$

Similarly, the motor shaft power is given by

$$P_{\text{rotor}} = \frac{2\pi}{60} n_r T_{\text{rotor}} \quad (6)$$

As stated above, torque is preserved across the air gap. Thus 100% of the air gap torque is developed in the motor shaft and $T_{\text{air gap}} = T_{\text{rotor}}$. Combining (3), (5) and (6) we have:

$$P_{\text{rotor}} = (1-s) P_{\text{air gap}} \quad (7)$$

$$= s P_{\text{air gap}} + P_{\text{air gap}} \quad (8)$$

By inspection:

$$P_{\text{rotor}} = \delta P_{\text{air gap}} + P_{\text{air gap}} \quad (9)$$

Thus the rotor loss is given by:

$$\delta P_{\text{rotor}} = s P_{\text{air gap}} \quad (11)$$

The power drawn by the motor from the electrical supply network results in stator winding i^2R and iron losses, with the balance of the power developed in the air gap.

$$P_{\text{motor}} = \delta P_{\text{stator}} + P_{\text{air gap}} \quad (12)$$

The losses are relatively small and may be neglected to a first approximation. Thus we have that

$$P_{\text{motor}} \approx P_{\text{air gap}} \quad (13)$$

Thus

$$\delta P_{\text{rotor}} = s P_{\text{motor}} \quad (14)$$

At rated conditions, the motor slip is approximately ½%: for example a 4 pole motor typically operates at 1 493 rpm at full load. By equation (14) above, ½% of the air gap power is dissipated in the rotor, as heat, when the motor is run at its rated condition. The motor is designed to accommodate this heat loading. Indeed, by International Standards the motor temperature rise is defined with respect to rated load.

However, when the motor is started, considerably more heat is dissipated in the rotor. When the motor is energised, the motor speed starts from zero and the slip is consequently 1 pu or 100%. Thus by equation (11) above all the air gap power is dissipated in the rotor, as heat, when the motor is first energised. That means that at switch on, heat is dissipated in the rotor at the rate of 200 times the rate at nominal load.

As the motor accelerates, the speed increases and the slip decreases. At 50% speed, the heat loading in the rotor is half the power drawn from the supply. However, that is still some 100 times the rate of heat dissipation at full load. At no load, the slip tends towards zero (as the motor speed tends towards synchronous speed) and the rotor losses tend to zero also.

If the motor terminal voltage is reduced, the power drawn by the motor reduces by the square of the motor voltage. This will reduce the rotor heat loading similarly. However, the resultant extension of the start time negates any thermal benefit for the motor (see the discussion under heat dissipation in the stator). The overall result is that reducing the motor voltage during starting increases the heat loading on a machine.

The additional heat dissipated in the rotor during start is very considerable. Although the common “squirrel cage” induction motor has no insulation in the rotor, the temperature is nevertheless limited by the need to avoid softening (by annealing) of the copper bars, thermal fatigue issues and secondary heating of the stator winding insulation and the bearings.

Heat Dissipation in the Stator

During starting the motor operates a power factor up to 10 times worse (lower) than in normal running. That is, the “torque per amp” of a motor is very poor during starting. This is serious because heat generation is proportional to the square of the current. Thus during starting the stator winding is subjected to severe thermal loading.

The life of the stator winding insulation is decreased exponentially at elevated temperatures, and the insulation is rapidly destroyed at a few tens of degrees C above the rated operating temperature.

Conclusion

In conclusion, starting causes tremendous heat to be generated in the stator and rotor of an induction motor. Manufacturers typically specify the maximum duration, in seconds, of a start and the maximum number of starts per hour that a motor may perform without being damaged. This data applies to full voltage on the motor terminals; for other voltages, the figures may be extended by the square of the reduced voltage. However, reducing the stator voltage slightly reduces the load that a motor can start.

Effect of variation of supply voltage

During starting, reducing the terminal voltage reduces the torque by the square of the voltage. (This also has other effects, as discussed in the above paragraphs on heat dissipation in the rotor and stator.)

During running, reducing the terminal voltage increases the motor losses (and motor temperature) and slightly reduces the motor speed. To avoid over temperature, it is important to operate an induction motor at close to its rated voltage.

APPENDIX B: POWER DISSIPATION IN AN INDUCTION MOTOR WHEN OPERATED AT REDUCED SPEED E.G. FOR INSPECTION

Soft Starters

As discussed before, the motor is designed to dissipate, without producing excessive temperatures, the heat losses that are developed at rated conditions. Since rated slip is typically ½%, from equation (2) in the main text the motor is capable of dissipating

$$\begin{aligned}\delta P_{\text{rotor}} &= s P_{\text{motor}} \\ &= \frac{1}{2} \% P_{\text{motor}}\end{aligned}\quad (1)$$

From equation (1) above, the rotor losses at 20% speed (which is 80% slip) will be given by
The losses dissipated in the rotor are given by:

$$\begin{aligned}\delta P_{\text{rotor}} &= s P_{\text{motor}} \\ &= 80\% P_{\text{motor}}\end{aligned}\quad (2)$$

The product of speed and torque gives motor power. For 20% speed and assuming that at belt inspection the torque is 15% of normal running torque, we have

$$\begin{aligned}P_{\text{motor}} &= \omega T \\ &= 0,2 \times 0,15 \times P_{\text{nominal}} \\ &= 3\% P_{\text{nominal}}\end{aligned}\quad (3)$$

That is, although the motor is designed to dissipate ½% of its rated power, if a soft starter is applied to operate the motor at 20% speed and a mere 15% of rated torque, the motor will be subjected to heat loading of some 3% of rated power, or 600% of its capability. Obviously the machine will rapidly burn out.

Electronic Variable Speed Drives

It should be noted that the above reasoning does not apply to electronic VSD drives, which are easier to operate at reduced speed, for example for belt inspection. In a VSD, the frequency of the power applied to the motor is varied in (approximate) proportion to the desired speed and the slip is maintained at or below the rated value. Thus a motor operated by a VSD has heat losses that are typically less than or equal to the design losses.

Caution is needed when applying VSDs to conveyors, which are “constant torque loads”. That is, a conveyor loads a motor shaft with torque in proportion to the belt loading, and the belt speed has little influence on the torque. The motor stator will draw current in (approximate) proportion to the load torque, that is the stator current will not decrease as the belt speed decreases (provided that the belt load is unaltered.) Thus the motor losses remain at full rated value.

However, the effectiveness of the shaft mounted fans on the motor decreases as the square of the speed. At 20% speed, the shaft mounted cooling fans will develop a mere 4% of the air pressure that will be developed at rated speed. The situation is not as bad as it seems, as heat will still be dissipated by natural conduction, convection and radiation. At 20% speed a motor can typically dissipate some 30% of its rated losses. This cooling

- Is adequate to cool a motor that is driving a fan or a pump (where the torque falls as the square of the speed),
- May be adequate to operate an empty belt, for example at inspection speed.
- But is inadequate to cool a VSD - driven motor moving a laden belt at reduced speed.

APPENDIX C: EXAMPLE OF MOTOR AND SOFT STARTER SELECTION

Consider a conveyor with the following drive requirements:

Absorbed power	85 kW (at the motor shaft, taking transmission losses into account)
Start time	15 seconds
Starts per hour	6

As a starting point, consider a motor rated one size greater than the conveyor full load. The catalogue data of a 110 kW / 4 pole motor is listed below.

<u>Performance data:</u>	<u>MOTOR</u>
Rated output Power:	110 kW
Rated speed:	1485 RPM
Full load torque, T _n :	709 Nm
Locked rotor torque, T _l /T _m :	2.3
Breakdown torque, T _b /T _n :	2.5
Allowable locked rotor time (hot / hot):	21 / 38 seconds

From the relation:

$$P = 2 \pi n T / 60$$

The full load absorbed power of 85 kW requires 547 Nm at the motor speed of 1 485 rpm. Assuming that at start the conveyor requires 110% of nominal absorbed torque plus an additional 10% margin, the soft starter and motor must deliver $1,1 \times 1,1 \times 547 \text{ Nm} = 662 \text{ Nm}$. Since the 110 kW machine selected has a locked rotor torque of 230% of rated torque of 709 Nm, at start the terminal voltage could be reduced to:

$$\begin{aligned} V_{\text{motor}} &= \sqrt{(662 / (2,3 \times 709))} \\ &= 64\% \end{aligned}$$

If the motor voltage is maintained at this voltage, the peak torque (at break down) will be limited to:

$$\begin{aligned} T_{\text{BDT}} &= 0,64^2 \times (2,5 \times 709) \\ &= 726 \text{ Nm} \end{aligned}$$

That is, the maximum torque delivered by the 110 kW motor during soft-start will be 726 Nm / 547 Nm = 133% of the nominal load torque. This is a satisfactory figure.

Note that a conventional single-ramp soft starter would typically apply very close to full rated voltage to the motor by the time the machine reaches around 90% speed / when the motor develops pull out torque. Thus for the case of a single ramp soft starter, the machine would develop:

$$\begin{aligned} T_{\text{BDT}} &= (2,5 \times 709) \\ &= 1 773 \text{ Nm} \end{aligned}$$

That is, the maximum torque delivered by the 110 kW motor during a single-ramp soft-start will be 1 773 Nm / 545 Nm = 324% of the nominal load torque. This could well cause excessive belt torques. Thus the advantage of a dual ramp soft start can readily be seen.

Lastly the motor's thermal performance during starting should be considered. The motor data sheet states that the maximum permissible stall time is 21 seconds from the cold condition and 38 seconds from hot (i.e. operating temperature). At reduced voltage, this time may be increased by the square of the voltage (to maintain the rated $i^2 R t$ thermal loading on the motor). Thus the allowable start time is given by:

$$\begin{aligned} t_{\text{max start}} &= 21 \text{ secs} / 0,64^2 \text{ (from hot) and } 38 \text{ secs} / 0,64^2 \text{ (from cold)} \\ &= 52 \text{ secs (from hot) and } 93 \text{ secs (from cold)} \end{aligned}$$

Since the belt start time is 15 seconds, this machine can perform 52 seconds per hour / 15 seconds = 3 starts per hour from hot and 6 starts per hour from cold. That is, the motor

selected cannot deliver the specified number of starts per hour from the operating condition. Thus the calculations should be repeated with a larger motor.

Consider now a 132 kW motor:

<u>Performance data:</u>	<u>MOTOR</u>
Rated output Power:	132 KW
Rated speed:	1485 RPM
Full load torque, T _n :	854 Nm
Locked rotor torque, T _l /T _m :	2.2
Breakdown torque, T _b /T _n :	2.6
Allowable time of locked rotor Hot/Cold:	31 / 56 seconds

At start the terminal voltage could be reduced to:

$$\begin{aligned}
 V_{\text{motor}} &= \sqrt{(662 / (2,2 \times 854))} \\
 &= 59\%
 \end{aligned}$$

If the motor voltage is maintained at this voltage, the peak torque (at break down) will be limited to:

$$\begin{aligned}
 T_{\text{BDT}} &= 0,59^2 \times (2,6 \times 854) \\
 &= 782 \text{ Nm}
 \end{aligned}$$

That is, the maximum torque delivered by the 132 kW motor during soft-start will be 782 Nm / 547 Nm = 144% of the belt's absorbed load torque. This is a satisfactory figure.

Note that a conventional single-ramp soft starter would typically apply very close to full rated voltage to the motor by the time the machine reaches around 90% speed / when the motor develops pull out torque. Thus for the case of a single ramp soft starter, the machine would develop:

$$\begin{aligned}
 T_{\text{BDT}} &= (2,6 \times 854) \\
 &= 2\,306 \text{ Nm}
 \end{aligned}$$

That is, the maximum torque delivered by the 132 kW motor during a single-ramp soft-start will be 2 220 Nm / 547 Nm = 405% of the belt's absorbed load torque. As is to be expected, selecting a larger motor increases the break down or pull out torque (as a percentage of the belt absorbed power) and could well cause excessive belt torques. Thus the advantage of a dual-ramp soft start can readily be seen. The need for the drive to be tripped instantaneously in the event of a belt jam is also apparent.

Lastly the motor's thermal performance during starting should be considered. The motor data sheet states that the maximum permissible stall time from the cold condition is 31 seconds per hour from hot (i.e. operating temperature) and 56 seconds from cold. At reduced voltage, this time may be increased by the square of the voltage. Thus the allowable start time is given by:

$$\begin{aligned}
 t_{\text{max start}} &= 31 \text{ secs per hour} / 0,59^2 \quad \text{and} \quad 56 \text{ secs per hour} / 0,59^2 \\
 &= 89 \text{ secs per hour (hot)} \quad \text{and} \quad 160 \text{ secs (cold)}
 \end{aligned}$$

Since the belt start time is 15 seconds, this machine can perform 92 seconds per hour / 15 seconds = 6 starts per hour from hot and 160 / 15 = 11 starts per hour from cold.

Thus a 132 kW motor, with a nominal power one size larger than the initial selection, is required to deliver the required starting performance.

If the motor is de-rated, it is always advisable to check with the soft starter vendor whether the soft starter rating should be increased as well. It should be noted that selecting a larger

machine does not always deliver a significant increase in thermal rating. For example, a particular manufacturer may offer machines in the same frame size for two (or more) nominal powers. If the motor is oversized, the selection of the protection relay to trip the motor in the event of a belt jam becomes increasingly important.

ABOUT THE AUTHOR

Peter Warner graduated from the University of the Witwatersrand in 1975 with a B.Sc. in electrical engineering and obtained an M.Sc. in 1986 also in electrical engineering from the University of the Witwatersrand. He has worked in the manufacture of LV and MV motors, sales and commissioning of machines up to 27 MW. He is currently employed as a Principal Electrical Engineer with Anglo American plc.

Symbols

i	Current	[Amps]
k	Constant	[-]
n	Speed	[rpm]
P	Power	[kW]
R	Resistance	[Ohms]
t	Time	[seconds]
T	Torque	[Nm]
s	slip	[-]
V	Voltage	[Volts]

Subscripts

δ	Change in a variable, or loss
BDT	Break Down Torque or peak or stall torque
air gap	Pertaining to the air gap between the electric motor stator and rotor
belt absorbed	Belt rated absorbed quantity
belt start	Condition when the belt is stationary
in	Input, or stator
locked rotor	Condition when the rotor is stationary
max start	Rated maximum allowable start condition
motor	Pertaining to the electric motor, typically the stator
nominal	Rated
out	Output or rotor
r	Rotor
s	Stator

Superscripts

'	Quantity is referred to the belt nominal torque requirement
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