Master Control Systems, Inc.
Engineering Bulletin

Date: 2001.06.11 Revised: 2005.09.20
To: Field Agents
Cc: W. F. Stelter, Engineering
From: J. S. Nasby
Re.: Fire Pump Motor Starting -- An Electrical Perspective on Centrifugal Pump Starting Methods.

Purpose: This is an attempt to reduce the theoretical and electrical formulae involving pump motor starting to practical every day terminology. One of the sources is the White Paper by Wm. F. Stelter on Reduced Voltage Motor Starting.

Energy: To help in this process, we will use energy as the main focus. A motor driven pump involves four useful energy conversions and one wasteful one. Electrical (current) to Magnetic Flux, Flux to rotary force (mechanical force), torque and rotation (mechanical work) to hydraulic pressure and flow (fluid work). All four of these also convert energy into (waste) heat since none of them is 100% efficient.

Running Motors: The motors used are "Squirrel Cage (Non-Salient Pole) Design "B", Starting Code "G" three phase induction motors. These are true energy converters only at or near running speed in their normal operating region. This is why if the voltage drops, the current increases by the same percentage so as to supply the same electrical power, namely that needed by the shaft load (plus inefficiencies). In the true motor region, motor current is *inversely* proportional to voltage. Assuming a unity Power Factor (phase angle near zero), the real (true) power is the product of volts times amps. P(watts) = V(volts) x I(amps). So: I = P / V ("I" is inversely proportional to "V"). This assumption is valid for motors running at or near their full rated load.

Motors Starting: On the other hand, in the starting or stalled regions, the motor is a simply a fixed impedance and acts like a "rotary solenoid" rather than a motor (energy convertor). It produces torque; but, not very efficiently as we well see. Since it is an impedance rather than an energy convertor, the current is *directly* proportional to the voltage applied, not inversely as in the running mode. The current increases in the same amount (percentage) as the voltage. So Ohms law applies. For impedance Z, E / I = Z or I = E / Z ("I" is directly proportional to "V").

Torques: The torque produced by a running motor is whatever is needed by the shaft load, although the speed does drop off a little. The motor draws more current, and thus more power, as needed to produce the torque needed to keep the shaft (rotor) turning at or near the rated speed. On the other hand, again, in the stall or starting mode, the motor torque is proportional to the square of the motor (winding) current. Since the motor acts as an impedance the motor starting torque is thus proportional to the square of the applied voltage, or more properly the percentage of starting torque is proportional to the square of the ratio of the applied winding voltage to the rated (running) winding voltage. It can be shown that the motor starting torque is actually proportional to the square of the current. Since the motor impedance is relatively fixed in the starting region, the torque also varies as the square of the motor voltage.

A-T-L Starting: Full Voltage Starting ("Across-the-Line" -or- "Direct-on-Line") simply connects the motor instantaneously to the power source ("Line" or "Mains"). The motors used will draw starting current (Locked Rotor Amps, LRA or Locked Rotor Current, LRC) of around 600% of the full load current (Full Load Amps, FLA or Full Load Current, FLC). Hence LRA = 6.0 x FLA. The current drops off as the motor accelerates, if it can, but remains close to LRA current until the motor reaches the Breakdown Torque speed of around 90% of rated running speed. The current than drops rapidly to that needed to drive the connected shaft load, usually at or below FLA (ignoring Service Factor). See Page 4 of M.C.S. bulletin #391, on the EC series controllers, which clearly illustrates the two regions of the motor current (-vs- RPM) curve and the two regions of the torque (-vs- RPM) curve. The locked rotor (zero RPM) torque is the motors rated locked rotor torque if the voltage is at the motor's rated voltage (460 Vac for a 460 Vac motor). This torque falls off as the square of the voltage drop.

T(stall torque) = K(torque constant) x V^2(volts).

Once the motor reached the break-down torque speed (about 90% of rated RPM) it changes to a true energy convertor and the current drops to that need to provide just the power need to drive the shaft load (plus inefficiencies).

Power Factor and Phase Angles: At stall or starting speeds, the motor power factor is around 30% to 40% (a phase angle of around 70 degrees) which is highly reactive (highly inductive). A motor running at speed at or near full load has a power factor near unity (around 80% or approx. 35 degrees). The power factor is the cosine of the phase angle difference between the voltage and the current. Specifically, P.F. = Cosine(*angle between voltage and current*) = Cos(Φ). Five of the seven starting methods described below do not affect the motor phase angle. Two of the seven add an external impedance to the motor during starting and do affect the starting Power Factor. This change in power factor affects the starting power (watts) to starting KVA (volts times amps) ratio. One (Primary Reactor) improves this ratio while the other (Primary Resistor) makes it worse from a real power (kilowatt) standpoint.

Efficiencies: A motor running at normal (rated) speed at or near full load is a very efficient energy convertor. The typical full load efficiency for motors of the type used for fire pumps is 95%. Efficiency drops slightly at lighter (smaller) loads. The efficiency drops enormously in the stall (breakdown) region of operation. This is why the currents are so high in this region. At stall (zero speed) the efficiency is zero since output power is torque times speed which is zero. However the motor is drawing well over normal full load electrical power. In fact at 600% of FLA, the stall (LRA) power (kilowatt) draw is:

P(KW) = E x I x cos(Φ) = 100% x 600% (.35) = 210% of full load power.

The Apparent Power (KVA) draw is:

KVA = A = E x I = 1.0 x 6.0 x = approx. 600% of Full Load KVA.

Reduced "Inrush" Starting: Starting means other than Across-the-Line (Direct-on-Line) reduce either the motor current (Reduced Current Starting) or its voltage (Reduced Voltage Starting). The latter also reduces the starting current which is the goal of reduced inrush starting. Some schemes change the intended (full running) motor windings, some impose an impedance in series with the motor and others change the voltage supplied to the motor during starting. The seven types used for fire pump starting will be discussed in turn. The discussion will center on the effectiveness of these seven starting types and the important parameters of: 1) Starting (Inrush) Current Reduction, 2) the resulting Starting Torque, 3) the Starting Power (versus Starting KVA), 4) the relative costs, and 5) other salient factors such as reliability and other important pros and cons of each starting method. All of these starting methods employ a starting (accelerate period) mode and a running (full voltage) mode. The accelerate time is manually set and remains constant from start to start regardless of the motor (pump) load, and is not allowed to exceed a period of 10 seconds per code (NFPA-20).

Reduced "Inrush" Starting Transition Transient Currents: Six of the seven reduced starting types are of the "Closed Transition" type. These six do not produce any harmful surge currents after the transition to full voltage occurs. The seventh type is the Open Transition Wye-Delta (Star-Delta) type. When applied on stiff (large) power sources, the transition transient current can exceed 2300% of FLA (23 times FLA) for a fraction of a line cycle. This can and does cause circuit breaker false tripping in certain cases. The problem is worse when a pump does manage accelerate to, or near, full speed since the maximum back EMF occurs at synchronous (full) speed. It is this back EMF that causes the large current spike unless its phase angle is controlled during this transition. The Closed Transition Wye-Delta starting method avoids this reverse voltage transition transient spike by adding two more steps to the starting sequence. This is why Closed Transition Wye-Delta starting cost more than Open Transition Wye-Delta starting.

Starting Duty Cycle: Most lightly load fire pumps can be started numerous times within a short period of time. Although not all motors or controllers are rated as such, dozens or scores of starts, at churn, are not unusual for most starting schemes with one notable exception. That one exception is Primary Resistor starting since the resistors get so hot. If the pump is loaded to any extent, the resistors get even hotter. The other three voltage reduction schemes - soft start, primary reactor, and autotransformer - don't develop much heat from each start. Two of the three motor re-configuration schemes - part winding and wye-delta open - don't drop any voltage (energy) inside of the controller and only motor heating limits the starting duty cycle. The third motor re-configuration method - and wye-delta closed transition - does use transition resistors; but, these produce very little heat per motor start since they are energized for only a fraction of a line cycle.

Part winding Starting: This starting technique is used on motors having two sets of motor windings intended to operate in parallel for running and that have been manufactured for this type of starting. This requires the motor stator winding method to be one which is suitable for part winding starting. Most dual voltage motors are not wound in this manner and are not suitable for this type of starting. Although the motor may be designed for running with the windings in either delta or wye, the motor windings must be of the parallel run type. This is the main draw-back to this scheme.

Part winding Starting - cont'd: The technique energizes only one of the two sets for starting. This drops the starting amps by about 35% down to about 65% of the normal 600% or about 390% of FLA rather than 600%. The amount (percentage) current reduction is approximate since the motor characteristics affect the amount of current reduction. This current reduction is less than 50% due to the rotor and stator magnetic interaction.The starting torque is around 48% of full voltage starting torque. For this starting type only, the starting torque is not proportional to the square of the motor current since the motor winding configuration is altered by leaving half of the windings un-energized. Moreover, even for motors specifically rated for part winding starting, a torque dip (cusp in the torque-speed curve) occurs at around half speed which prolongs the accelerate time. The scheme is economical since only one additional contactor is needed in the motor controller (starter). Also, it is important that any motor replacement or re-winding also be suitable and rated for Part Winding Starting.

Wye-Delta (Star-Delta) Starting Torque: This method also re-configures the motor windings for starting. It requires motors wound for delta running. For starting, the delta winding connections are broken and re-connected together to form a wye (star) configuration. Note that the star point needn't be grounded nor connected to any neutral and, if fact, never is in fire pump controllers. In this configuration each motor winding (coil) sees only 57% ($1/\sqrt{3}$) of the line voltage in the starting mode. This drops the line currents down to only 33% of full voltage starting or 200% of FLA rather than 600% of FLA. This is because the line current drops by the square of the 57% of the normal motor winding current since each line connects with only one winding rather than two. Technically, each coil impedance is 1.732 per unit at full voltage since the winding, or coil, (phase) current is 57% of the line current. When the coils are reconnected in star (wye), their voltage is 57% of their full voltage and their impedance is 1.732 per unit. Thus $I = E / Z = 0.57 / 1.732 = 0.33 = 33\%$. Unfortunately, since the current through the windings is down to 57% the torque reduction is the square of this 57% which yields only 33% of normal starting torque. As a result, a loaded pump will not accelerate in the allowed time, or ever for that matter. This results in the line current jumping up to the stall current for whatever speed the pump had gotten up to for as long as it takes the motor to finish accelerating the pump to full speed. This current is typically 500% to 600% depending on the setting of the accelerate timer, the pump load, the motor frame size, and also on the churn (shut-off, no flow) pump load.

Wye-Delta (Star-Delta) Open Transition Starting: As described above, open transition starting can and does cause large momentary transition current spikes (transients) which are large enough to cause false tripping of circuit breakers. Various methods are used to deal with this hazard. First, some power distribution systems are high enough in impedance to diminish the resulting transients. This is not usually the case in the U.S. To avoid the transient, some controllers have a very short accelerate time. This is done to prevent the motor from achieving full speed. This does prevent the back EMF transition transients; but instead creates full voltage LRA (starting) currents after the transition instead. Other controllers delay the transition to allow the motor magnetic field to decay to reduce the transition current. This works only if the delay is set for at least one second. However, this causes severe motor *deceleration* since a centrifugal pump is a very low inertia load, even at churn (shut-off) pump load. This method also results in full voltage LRA (starting) currents after the transition. In either case, reduced inrush starting is defeated and degrades to full voltage starting at the end of the accelerate period which is why it is sometimes referred to as "Delayed Across-The-Line" starting.

Wye-Delta (Star-Delta) Open Transition Starting Transition Transient: Finally, the one method that will reduce the likelihood of either a large transition transient or a large starting current after the transition is to use a full accelerate period (up to and including the maximum allowed ten seconds) *and* control the phase angle *and* do a rapid transition. This can be done with the use of a phase angle monitor (like the Master Leading Phase Monitor®). It is used to ensure a leading phase angle transition to avoid the aforementioned transition transient (spike) currents. This allows Master Control models ECO and MCO controllers to be set for full acceleration time. They also preserve the motor's speed by doing an instantaneous transition to full voltage.

Wye-Delta (Star-Delta) Closed Transition Starting: The Closed Transition Wye-Delta starting method avoids the reverse voltage transition transient spike by adding a third and forth step to the starting sequence which occur at the end of the accelerate time. They are used to connect the motor windings to the full line voltage through resistors for a fraction of a line cycle. This is done in order to pull the motor's magnetic phase angle to approximately that of the line voltage. This avoids the transition transient even if the motor does achieve full speed since the motor and line voltage phase angles are nearly the same. This prevents any large difference between the motor back EMF and the line voltage.

Primary Resistor Starting: This method inserts an external impedance in series with the motor during motor starting. It is independent of the motor winding configuration. E.G., it works with any motor. Typically, the resistors are sized to provide a 35% reduction in voltage. Thus, the starting current is around 65% of LRA or 390% of FLA and provides around 42% torque (0.65 squared). There are several disadvantages to this starting method. The main draw-back is the heat produced by the resistors and the energy consumed from the power source to produce that heat. Although this scheme does reduce the starting current and, the starting KVA, it increase the starting power requirements. This is because the phase angle is reduced (power factor comes closer to unity) due to the unity power factor of the resistors. This makes the starting power (KW) worse than Full Voltage (A-T-L) starting and is rarely suitable for starting on emergency generators. Another problem is the damage that results if the accelerate time is delayed for any reason. The resistors become red hot in a matter of a few seconds. Another problem is repeated starts which will cause damage in short order. Another problem is the venting needed to dissipate this heat which makes the controller vulnerable to spraying water.

Soft Start (SCR) Starting: This type of starter employs Silicon Controlled Rectifiers (SCRs) to modulate the voltage applied to the motor. This is done by modulating the SCR firing angle, in each half line cycle, to produce an approximate linear voltage ramp to the motor. This reduces water surging on start-up and reduces water hammer due to check valve closing on shut down. It does also reduce the starting current during part of the accelerate period. At the end of the accelerate period, the motor will draw between 250% and 400% of FLA or more if the pump is heavily loaded. The torque starts low but increased to full starting torque at the end of the period. Since the voltage, torque, RPM and load horsepower are all changing during the accelerate period, no single set of torque or current reduction percentages is applicable. This starting method is usually better when applied for one or both of the hydraulic reasons given. This is the second most expensive starting means costing nearly the same amount as Autotransformer starting. In fire pumps, the soft starter is by-passed by the main contactor after the accelerate time. Master Control Systems also employs a start contactor to isolate the soft starter to protect the solid state components (SCRs) from line voltage transients when not in use.

Autotransformer Starting: This type of starting provides the best combination of electrical characteristics; but is the most expensive starting means. It provides efficient torque to starting current ratio. On the normal 65% tap, the starting current is reduced by 54% down to 46% of LRA or 276% of FLA while providing 42% of locked rotor torque (0.65 squared). It is a closed transition three step starting scheme which employs three contactors plus the autotransformer. The closed transition is accomplished by opening the wye point of the autotransformer which puts the main transformer windings in series with the motor windings after the accelerate period. This puts the autotransformer in the primary reactor mode for a fraction of a line cycle. After that time, the main contactor shorts out the autotransformer winding to apply full voltage to the motor. The starting power factor is not changed and so remains the same as the motor itself during starting or around 30% to 40%. As a result, both the starting KVA and the starting KW are also 46% of the A-T-L values. Note that an ideal autotransformer would reduce the current, KVA and KW down to 42%. The difference is due to losses and relatively high magnetizing (no load) currents in the autotransformer, itself.

Primary Reactor Starting: This is the best starting means when cost is factored in. It reduces the current the same amount as primary resistor (65% on the 65% taps); but drops the starting power factor rather than raising it. As a result, the starting KVA for both is also 65% of the A-T-L case. However, the primary reactor case drops the starting power (Kw) down to 48% as opposed to an increase of 31% for the primary resistor case. E.G. Primary reactor starting power (Kw) is 48% compared to 131% for primary resistor. This is why primary resistor is often worse for generator sizing than Across-the-Line (Full Voltage) starting. The reduction in power factor occurs due to the very low power factor of the reactor, typically around 3%. This makes it around 95% efficient. This is also the reason that it can reduce the voltage to the motor with very little heat developed in the reactor. It is very highly inductive an so, the voltage drop across the reactor is at a high phase angle of around 84 degrees making the voltage across the reactor nearly 90 degrees out of phase with the current thru it. In the electrical sense, the current flow thru the reactor is almost pure imaginary (near zero Power Factor) and as a result, very little real power (kilowatt power) is dissipated in the reactor. It thus, serves as an efficient energy storage and voltage dropping means.

Summary of Starting Type Parameters.

Full Voltage (Across-the-Line) -- Not normally suitable for use on generator sets unless they are already oversized since the size of the generator will need to be increased to handle the Locked Rotor KW power draw and the Locked Rotor KVA (current) draw.

Part Winding -- May be suitable for use on generator sets when a part winding motor is available for the particular job and if the Half Speed Torque Cusp (dip) is above the pump's full flow torque curve.

Primary Resistor -- Never suitable for use on generator sets since the KW load increases to values even higher than full voltage (Across-the-Line) starting.

Wye Delta (Open or Closed Transition) -- Not suitable for use on normal size generator sets due to the low accelerating (33%) torque. As a result, if the pump is loaded, there will be a large accelerate (transition surge) current which will often require a larger generator set. This is because the low starting torques will not get the motor up to speed if it the pump is loaded, and often won't even if the pump is unloaded (at shut-off), particularly high-speed (3600 RPM) pumps.

<u>Soft Start</u> -- This starting means varies the voltage, and thus, the torque, current, KVA and KW load throughout the starting (accelerate) period. As a result, these values can only be calculated based on knowledge of the particular motor used and the horsepower curve of the pump used.

<u>Autotransformer</u> -- The best reduction in starting current while providing enough motor torque (42%) to fully accelerate the pump during the accelerate period.

<u>Primary Reactor</u> -- Suitable for use on generator sets since it reduces the starting KW load down to the same level as Autotransformer Starting, but at lower cost, while providing the same starting torque (42%) to fully accelerate the pump during the accelerate period.

<u>*The Bottom Line*</u>: If current reduction is the primary concern, Autotransformer (at 46% of LRA and 42% torque) is the best method; albeit, the most expensive one. If starting power (gen set KW and horsepower) is the primary concern, than Autotransformer or Primary Reactor starting are both suitable. Primary Reactor is less expensive than Autotransformer and can be used with <u>any</u> motor. Part Winding may be suitable if the above conditions (special motor and low pump torque curve) are all met.

Wye-Delta reduces the current to 33%, but, only at the expense of <u>very low (33%) starting torque</u>. Although the <u>initial</u> starting current is low, the current after the transition will be very high. Accelerating current <u>after</u> the transition will often be around 500% of FLA (near locked rotor currents). If open transition starting is used without lead-lag transition control, the transition current spike can rise to as high as 17 times FLA (1700%) which is often enough to trip circuit breakers when starting on the normal source.

Full Voltage (Across-the-Line) starting will require a larger gen set and Primary Resistor starting will require an even larger one since it is the least efficient (worse) starting method.

Soft Start starting parameters can't be calculated without knowing the specific parameters of the pump and motor to be used on the job. Since it costs the same as Autotransformer starting, it is usually better to use either Primary Reactor (or Autotransformer) unless there is a <u>hydraulic</u> need for the soft start and/or the soft stop capabilities.

<u>*Credits*</u>:

-- Wm. F. Stelter; "Reduced Voltage Controller Comparison" - Mathematical proofs, developments and details are from this paper.

-- Hough O. Nash; "An Analytical Look at Standby Diesel Engine/Generator Loading" - IEEE 81CH1674-1.

-- Master Control Systems, Inc. SK-0895 Wye-delta Transition Transients.

-- Robert J. Wooddall; "Why Wye-Delta Starters Cause Breakers to Trip - the Reason that Closed Transition Units are Preferable" - Electrical Apparatus/Nov. 1973

-- R. L. Nailen, P.E.; "Avoiding Switching Transient Damage in Motor Circuits" - Consulting-Specifying Engineer / March, 1987.

-- Robert A. Barr; "Applying Generators Sets to Motor Loads" - Kohler Co., Generator Division.