Reclosing and Tapped Motor Load

Russell W. Patterson
George T. Pitts
Tennessee Valley Authority

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Abstract

This paper discusses the effect tapped motors have on transmission line reclosing and the effect reclosing has on tapped motor loads. An analysis is described to determine how long a delay is required before reclosing may safely and successfully occur. Actual captured events on the TVA power system will be used in the discussion.

Introduction

When supply voltage is removed from an induction machine, flux is trapped in its rotor. This flux decays with time and produces a residual voltage in the machine windings until its rotation ceases. Residual voltage can decay in a few cycles in small machines but may require up to five seconds in larger machines. The rate of decay for high-speed machines is less than that for slow-speed motors [1]. Higher inertia machines will tend to act as generators feeding the lower inertia machines on the bus such that the entire group decays together. Synchronous machines have the added complication of having their own field excitation to maintain good healthy internal voltage during the brief dead-time before high-speed reclosing occurs, putting them at increased risk over induction machines.

The problem that is encountered by these disconnected machines maintaining a residual voltage is that when reclosing occurs, the system voltage and machine residual voltage are typically out-of-phase. Reclosing with the utility can apply voltages above the motor design limits and result in high transient currents and torques. The motor(s) may not immediately fail but the resulting high shaft torque and torque on the coils can eventually result in "unexplained" failures of the machines. The phasor difference between the system voltage per Hertz and the motor residual voltage per Hertz should not exceed 1.33 per unit volts/Hertz at closing [2]. An historical "rule-of-thumb" for unsupervised reclosing on motor loads has been to delay until the motors residual voltage magnitude has dropped below 25% of rated. Many designers set 125% as a desirable limit of maximum momentary voltage applied to a motor [1, 14].

Additionally, the backfeeding motor loads can keep ionized fault paths intact during the dead time so a high-speed reclose has a low probability of success. The result is unnecessary wear and stress on all the interposing equipment (utility breakers, transformers, motors).

For purposes of this paper, high-speed reclosing is considered to be a blind reclose (not supervised by voltage conditions or synchronism check relays) that occurs within 30 cycles of initial circuit interruption. A common high-speed reclose setting on the TVA system is between 13 and 20 cycles from the time the contacts part (initially interruption the circuit current) until the contact recloses to reestablish the circuit. The faster time of 13 cycles is applied on oil circuit breakers having pneumatic mechanisms and the 20 cycles is applied on SF_6 breakers having spring mechanisms.

The topics covered in this paper may be applicable at the distribution level as well, on feeders that supply power to industries with heavy motor load or distributed generation and utilize high-speed or "instantaneous" unsupervised reclosing. Also, presently the IEEE Power System Relaying Committee's (http://www.pes-psrc.org) Rotating Machinery Subcommittee (J) has an active working group "J9 - Motor Bus Application and Issues Investigation Working Group", chaired by Jon Gardell, addressing issues related to transfer of generating plant auxiliary boards with motor load.

Actual Event

On August 24, 2006 after succesfully clearing a ground fault on the TVA Monsanto to Johnsonville Fossil Plant #1 161kV line, an unsuccessful high-speed reclose attempt occurred. Subsequent analysis of the event revealed that the high-speed reclose attempt was unsuccessful because of significant tapped motor load.

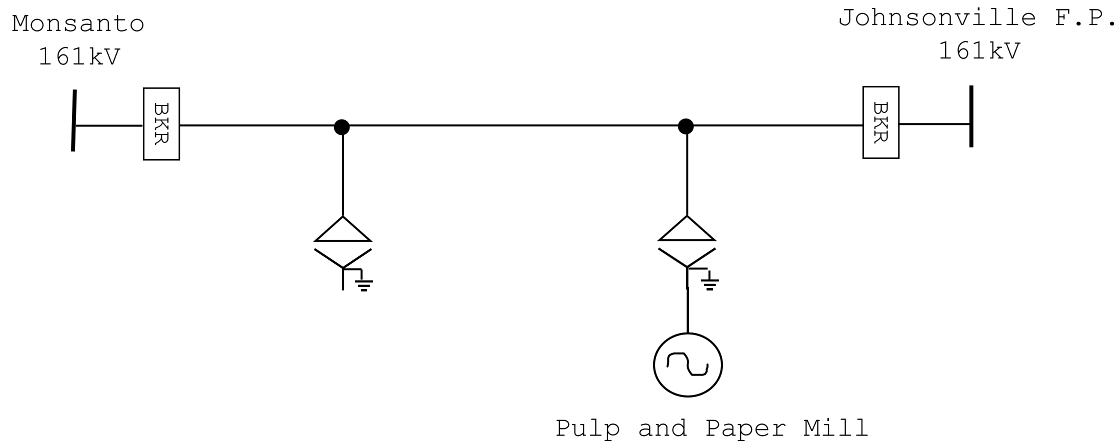

Figure 1. One-line of Monsanto-Johnsonville #1 161kV line.

When the high-speed reclose attempt occurred (approximately 20 cycles after the line breakers tripped) the motor load at the pulp and paper mill was still holding the line voltage up (roughly 60% of nominal at time of reclose). This kept the fault path ionized resulting in a reignition of the fault when the reclose occurred. It also resulted in an out-of-phase reclose between the mill motors and the TVA power system. A power quality monitor on the low-voltage bus (4,160V) of the mill captured the event (Figure 2). The data shown in Figure 2 is RMS voltage data recorded for each cycle (on 60Hz basis).

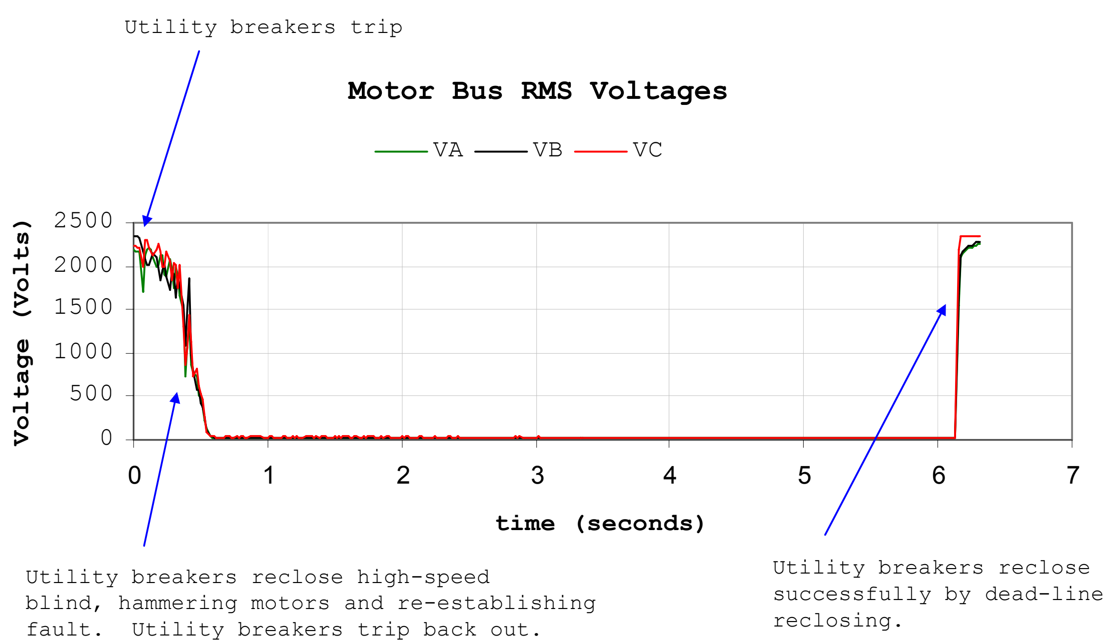

Figure 2. Power Quality data captured during unsuccessful high-speed reclose.

An earlier event analysis showed similar results for an event that occurred on August 6, 2005 and is fully described in reference 1. Figure 3 shows the motor bus voltages during that event and Figure 4 shows an estimation of power system voltage and islanded motor voltage during the period after separation, just prior to reclosing. The data shown in Figure 4 was captured at a rate of 128 samples/cycle.

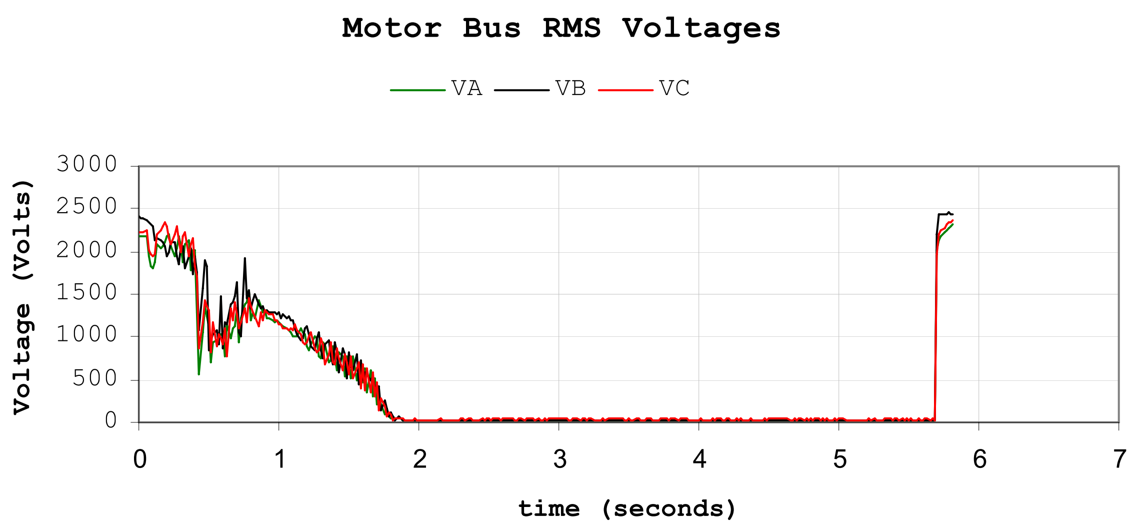

Figure 3. Power Quality data captured during August 6, 2005 event [3].

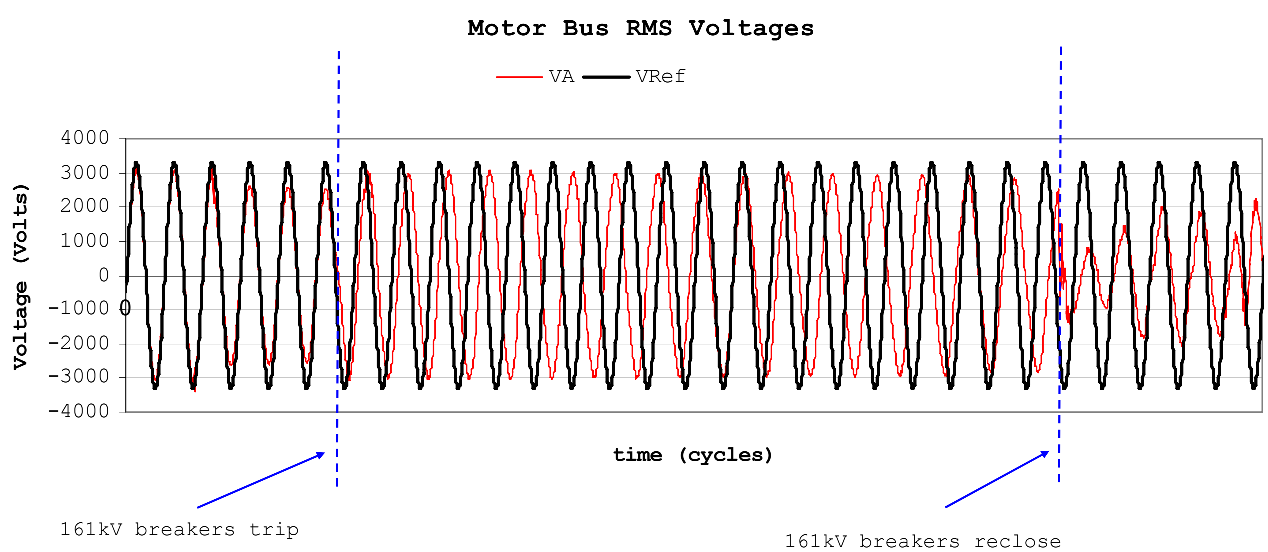

Figure 4. Oscillography of August 6, 2005 event with utility reference [3].

No successful high-speed reclose has been detected on this transmission line. Over a half-dozen unsuccessful attempts, similar to the above described events, have been recorded in the last several years.

Fault Arc Path

When lightning strikes a transmission line the field intensity stressing the insulation may exceed the ionization field intensity level (roughly 30kV/cm) and create an arc from the line to ground. A path now exists for current flow. The resulting discharge current flow from the lightning stroke is usually over within a few milliseconds but the ionized path has been established and a 60Hz "follow" current flows. This current must be detected and interrupted by de-energizing the line with circuit breakers. For the ionization path to dissipate, the voltage must be absent for a sufficient duration. The time during which the voltage is absent is commonly called "dead" time.

For transient faults to be successfully cleared, an adequate time for deionization must be afforded. Table 1 shows the minimum time required by voltage level and by probability of successfully reclosing and energizing the line according to reference 3.

Table 1. Minimum De-Ionization Time for Reclosing Breakers [4, page 491].

System Voltage	Cycles on 60-Cycle Basis	
(line-line kV)	95% probability	75% probability
23	4	
46	5	3.5
69	6	4
115	8.5	6
138	10	7.5
161	**13**	**10**
230	18	14

If sufficient motor load is still connected during the dead time the ionization path can/will be kept intact and a fault reignition will result when the utility breakers reclose. This occurs even though the fault is phase-ground and there is an interposing delta winding between the motor load and the fault, as in Figure 1. As can be seen in Figure 2, the tapped motor load holds up the voltage as it decays. At the time of the reclose the voltage is roughly 50% of nominal. Oscillographic data has been obtained in the past showing transmission line voltage being maintained by tapped motor load during reclosing dead time (John Boyle).

Effect on Motors

Unsupervised high-speed reclosing on islanded motors (induction or synchronous machines) before their "residual" voltage has subsided below 25% may subject the motors and other equipment to damage. Reference 2 indicates that the motor should not be subjected to a reclose when the phasor difference between the source volts/Hz and the motor residual volts/Hz exceeds 1.33 per unit volts/Hz. The available literature clearly indicates that reclosing on motor load should be delayed long enough for their residual voltage to decay to acceptable levels (or their contactors drop out) to prevent damage which may be immediate or cumulative. Alternatively, some means to ensure the two voltages are in-phase would be needed [2, 5]. Damage may include shifting of stator coils, loosening of rotor bars, distortion of coil ends, shaft damage etc. In some cases torsional resonance can be established with resulting torques as high as 20 times normal [2, 5, and 6].

When a motor is disconnected from its power supply it starts to slow down depending on its inertia and the characteristics of its connected load. For an open circuited induction (asynchronous) motor the voltage at its terminals will be a product of its speed, open circuit time constant, and its trapped rotor flux. For a synchronous machine with field forcing it may take much longer for its voltage to decay. If not open circuited, the motors will experience an electrical interaction with other motors bussed with them as well (an electrical to-and-fro of energy).

From the moment the motors are disconnected from the power system they begin to slip out-of-phase with the power system and their voltage magnitude begins to decay. The voltage impressed across them at reclose will be a function of this internal residual voltage and the power system voltage at time of reclosing. If the two voltages were equal in magnitude and 180° out-of-phase the resulting voltage difference would be 2.0 per unit.

Calculations of Out-Of-Phase Reclose

The simple circuit shown in Figure 5 can be used to calculate the initial currents that result from an out-of-phase reclose between the utility system and a single machine or equivalent group of machines. This is no different than typical circuits used for calculating fault currents. The voltage E_S and reactance X_S represent the utility system equivalent. The voltage E_M and reactance X_M represent the motor load equivalent. For purposes of this calculation the utility system voltage can be considered to be constant (60Hz) while the motor load will be slowing down and pulling out-of-phase during the time it is disconnected from the utility.

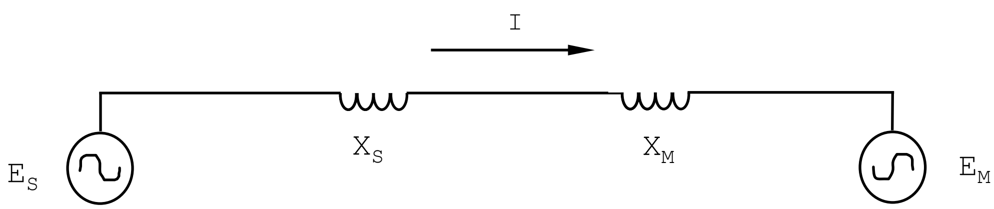

Figure 5. Simple System Equivalent for Current Calculation [6].

The current, I, that flows is simply the phasor difference between the two voltages divided by the series reactance between them.

$$\overline{I} = \frac{\overline{E}_S - \overline{E}_M}{\overline{X}_S + \overline{X}_M}$$

From this equation it is easy to see that no current will flow if no difference in magnitude and/or phase exists between the two systems. Also, the maximum current possible will occur when the two systems are exactly 180° out-of-phase and both voltages are at their highest magnitudes. It is possible for the system voltage to have risen upon breaker opening (e.g. to 1.05 per unit) and the open circuited motors may initially have as high as 1.45 per unit voltage [8] or higher (depending on the excitation method for synchronous machines). Note that under this condition the current experienced by some elements in the system can exceed those due to short circuits [7].

Figure 6 is oscillographic data of motor voltage decay on the customer bus described in Figure 1. It shows the natural decay of the motor system (mix of small and large induction and synchronous machines) without the influence of a high-speed reclose. It can be seen that, in this case, it takes the rotating system just over 1 second to decay to 25% voltage and just over 1.2 seconds to reach zero.

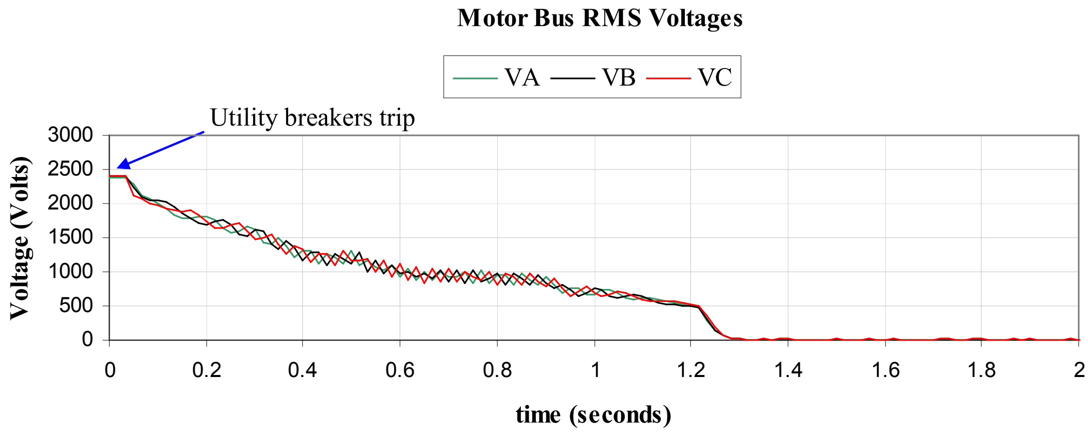

Figure 6. Power Quality data captured during disconnect of motor load.

Equipment Current Limits

TRANSFORMERS: IEEE Standards stipulate that power transformers are to be braced to withstand the maximum current experienced for a three-phase bolted fault on their secondary with full primary voltage applied, or 25 times nominal, whichever is less, for up to 2 seconds [6,9]. In other words, transformers must be built to withstand a per unit current of,

$$I = \frac{1.0}{X_T}$$

where X_T is the transformer reactance or a reactance of 4.0%, whichever results in higher fault current. Figure 7 shows a power transformer connected between the utility system and the motor load. The value of fault current, I, that flows when the two systems are reconnected is,

$$\overline{I} = \frac{\overline{E}_S - \overline{E}_M}{\overline{X}_S + \overline{X}_T + \overline{X}_M}$$

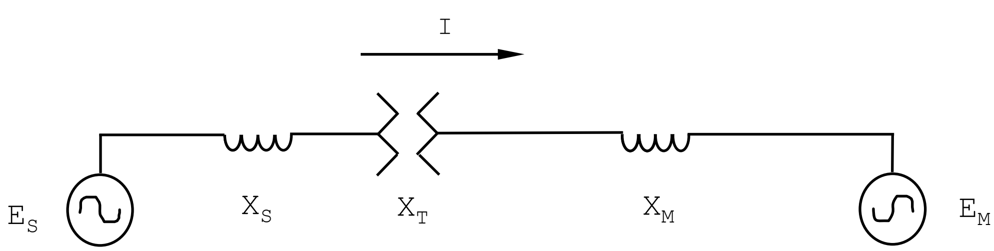

Figure 7. Transformer between out-of-phase systems.

which should not be allowed to exceed the transformer withstand current as discussed above. For example, the following system values will be assumed:

X_S = 3% on 100MVA base, 161kV
X_T = 4% on 30MVA base, 161kV
X_M = 15% on 7.5MVA base, 4.16kV

After converting to 100MVA, 161kV base:
E_S = 1.0, E_M = 0.9 @ -180°, X_S = 3%, X_T = 13.33%, and X_M = 200.0%.

$$I = \frac{1.9}{0.03 + 0.1333 + 2.0}$$

$$I = 0.88 \text{ p.u.}$$

So, for the conditions above the transformer experiences just under 1 per unit current flow when the two systems are initially tied back together. In contrast, the most current it would see for a bolted low-side three-phase fault would be 6.1 per unit.

$$I = \frac{1.0}{0.03 + 0.1333}$$

$$I = 6.1 \text{ p.u.}$$

It isn't very likely that the transformer will experience higher current when the two system are re-synchronized than it would for a bolted three-phase fault, but it should be considered and recognized that the likelihood increases with the size of the connected motor load and the phase angle between the two systems at time of reclosing. The above example is with a single 10,000HP motor. It is easy to see that increasing the size or number of motors drives the 2.0 value down in the denominator, increasing the current I.

ROTATING MACHINES: Reference 3 says that the maximum current that rotating machine windings are built to withstand is,

$$I = \frac{1.0}{X''}$$

where 1.0 is the machines rated voltage. For asynchronous (induction) machines X" is the locked rotor reactance. A reasonable estimate of the inductance of an induction motor is to assume the locked rotor (starting) current is six times the rated current. This is equivalent to using a 1/6 per unit impedance in the following equation [7].

$$L = \frac{Xpu(kV)^2}{\omega(MVA)}$$

For example, we could estimate the locked rotor inducance of a 3000kVA, 6.6kV motor as:

$$L = \frac{0.167(6.6)^2}{377(3)} = 6.43\text{mH}$$

For synchronous machines, X" is the direct axis subtransient reactance. Table 5 of C57.109-1993 gives estimates of subtransient reactance of three-phase synchronous machines.

Typically, the reactance of the largest machine in a plant will be much larger than the reactance of the utility thevenin equivalent and the interconnecting power transformer [8]. This means that the motor load is typically at higher risk than the utility equipment during out-of-phase reclosing. Using the numbers from above, the maximum current the equivalent motor load is designed for would be:

$$I = \frac{1.0}{0.15}$$

$$I = 6.7 \text{ p.u.}$$

Reference 3 indicates that reclosing on induction motors with residual voltage on the order of 0.9 to 1.0 per unit may produce peak electrical torque as high as 10 to 20 times normal. The paper explains that a simplified torque equation can be separated into two components, a unidirectional torque and a fundamental frequency oscillatory torque. The maximum value of the unidirectional torque occurs when the reclosing angle is 90 degrees. The maximum value of the oscillatory torque occurs when the reclosing angle is 180 degrees. The maximum values of these components are given by the following equations,

$$\text{Torque unidirectional} = \frac{E_S E_M}{X}$$

$$\text{Torque oscillatory} = \frac{(\Delta E)\, E_M}{X}$$

where ΔE is the magnitude of the phasor difference between E_S and E_M (see Figure 4), and X is the total equivalent reactance between the voltage sources.

For values of residual motor voltage, E_M, below approximately 30% of the system voltage, E_S, the maximum torque is predominately unidirectional and occurs near the 90° out-of-phase point.

For values of residual motor voltage near 1.0 per unit, the largest torque occurs when reclosing near 120° out-of-phase. Reference 3 indicates that this maximum torque would be,

$$\text{Torque maximum} = \frac{2.6 \Delta E^2}{X}$$

For synchronous machines the issue of field forcing can dominate. If the d-c field excitation is maintained when a synchronous machine is tripped then its generated voltage can be quite high. A typical rated field produces internal EMF as high as 1.4 per unit for 0.8 power factor machines and 1.2 per unit for 1.0 power factor machines. The generated voltage at the machine terminals will decrease as the speed decreases, the rate of speed decrease being a function of the shaft inertial system (loads etc.) and the electrical load on the bus. It may take several seconds for a machine to stop.

Reference 3 says that high-speed reclosing (15-30 cycles) will result in high transient torques on the connected synchronous machine with field forcing present. It provides several analytically created charts for estimation of the torque shock experienced at time of reclosing for a synchronous machine. Closing angle, motor generated voltage, and system voltage are known quantities that are used together with machine data (reactances) to estimate the maximum torque to be expected.

CIRCUIT BREAKERS: The IEEE circuit breaker standard, IEEE C37.04-1999, describes an out-of-phase event as an abnormal circuit condition of loss or lack of synchronism between parts of an electrical system on either side of a circuit breaker and it is not considered necessary to include this as a standard rating for general purpose circuit breakers. An out-of-phase switching current rating applies to circuit breakers intended to be used for switching the connection between two parts of a three-phase system during out-of-phase conditions. For circuit breakers with an assigned out-of-phase switching current rating IEEE states the preferred rating shall be 25% of the rated symmetrical short circuit current, expressed in kA, at a phase separation angle up to 180 degrees, unless otherwise noted by the manufacturer [11]. Relaying engineers should also be aware that the interrupting time for out-of-phase switching is permitted to exceed the rated interrupting time by 1) 50% for five or more cycle circuit breakers and 2) one cycle for three or fewer cycle circuit breakers.

IEEE C37.013-1997 states that only generator circuit breakers having full interrupting capability (to clear short-circuit currents on either side of the circuit breaker) could have an assigned out-of-phase current switching rating. The rating is limited 50% of the symmetrical system-source short-circuit current at a 90 degree angle at maximum system voltage [11]. C37.013 states the majority of generator circuit breakers are expected to close but not to interrupt under full phase opposition conditions because the latter task could be solved more conveniently by the circuit breaker on the high-voltage side of the transformer.

These ratings are considered in the design and setting of out-of-step tripping schemes, but may have applicability to this issue of reclosing in some circumstances.

OPEN CIRCUIT TIME CONSTANT

Figure 8 shows the Steinmetz equivalent circuit of an induction motor where:

E_0 - residual voltage at terminals of opened motor
R_1 - stator resistance
R_2 - rotor resistance (on stator basis)
X_1 - stator reactance
X_2 - rotor reactance (on stator basis)
X_m - magnetizing reactance (on stator basis)

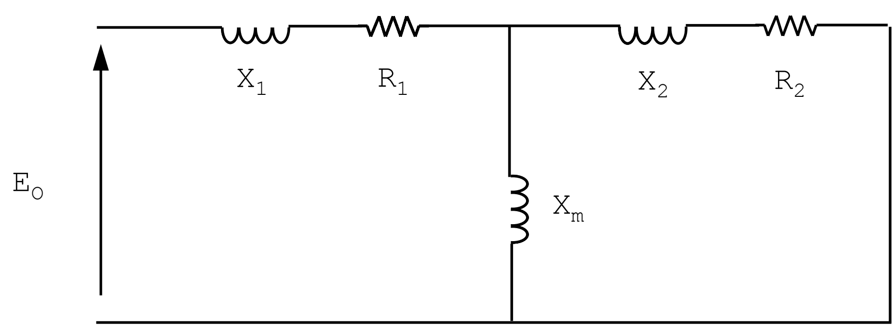

Figure 8. Steinmetz model of induction motor.

At the instant the motor is disconnected the supply current goes to zero. However, the current in the closed rotor loop will not immediately go to zero, it will change to match the motor flux present at that instant [12]. This flux is the “trapped” flux at the instant of disconnection. This flux decays with time and induces a voltage to sustain the slowly decaying rotor current. The following equations dictate the physics of the circuit in Figure 8 and are used to arrive at a formula for the open circuit time constant of the motor.

Kirchoff's voltage loop -> $$L_2\frac{di_2}{dt}+L_m\frac{di_2}{dt}+R_2 i_2 = 0$$

Solving for i_2 -> $$i_2 = Ae^{\frac{-R_2}{L_m+L_2}t}$$

where inductance is in henrys per phase and resistance in ohms on a stator basis, i_2 is the instantaneous rotor current (d-c), t is in seconds, and A is the initial rotor current at the moment of disconnection.

The open circuit time constant, T_0, of the decaying rotor current is

$$T_O = \frac{L_m + L_2}{R_2}$$

This is also the time constant of the decaying residual voltage induced in the opened stator winding, E_O. The equation for the decaying residual voltage can be written as,

$$E_O = Ee^{\frac{-t}{T_O}}$$

where E is the voltage at the motor terminals at instant of disconnection. It takes T_0 seconds for this residual voltage, E_O, to decay to 36.8% of the initial voltage E.

The model used in Figure 8 is acceptable as long as the frequency doesn't drop too low (roughly 30-40Hz range or below). If the frequency deviates too far from nominal the skin effect on rotor resistance and inductance must be taken into account (Eltom).

Example calculation of open-circuit time constant [12]: Below is the data for a 250-hp, 350-rpm, 440V, three-phase, 60Hz squirrel cage motor of typical design.

R_2 - 0.023 ohms
X_2 - 0.0637 ohms (L_2 = 0.169 mH)
X_m - 1.17 ohms (L_m = 3.104 mH)

For these values T_O = (0.169 mH + 3.104 mH)/0.023 = 0.142 seconds (8.54 cycles on 60Hz basis). This motor would take 8.54 cycles for its voltage to decay to 36.8% of rated value, assuming it was at rated voltage when disconnected. To reach 25% of rated voltage would require 11.8 cycles.

This approach, of course, doesn't include the effects of load inertia or of connected electrical load. It assumes the stator winding is opened. But, it can provide a basis for a good engineering estimate of how long is required to wait before reclosing. For instance, if the plant has one or two very large motors that make up the largest portion of its motor load, the conservative estimate based on open-circuit time constant should provide a good basis when deciding how long the reclosing dead time should be. The presence of heavy load on the motors and that of other smaller intertia motors (which will tend to be driven by these large motors upon disconnection) will tend to help speed up residual voltage decay.

Reference 8 notes that the larger the motor's horsepower, the longer the open-circuit time constant, T0, if other rating characteristics such as voltage and rpm are equal. Also, the higher a motor's rated speed, the longer its time constant with other rating factors being equal. So, because of their speed, 2-pole motors have longer open-circuit time constants than comparable motors with more poles. Motors in the 200 to 2000hp range typically have open-circuit time constants in the range of 0.25 to 2 seconds [13, 14].

Reference 8 also points out that designers have some degree of control over the open circuit time constant. The most effective means for controlling T_O (with least adverse affect on machine performance) is to control the magnetizing reactance. The magnetizing reactance is largely controlled by the air gap dimensions. An increase in air-gap will increase magnetizing current, decreasing X_m and subsequently T_O. This also has the adverse affect of reducing power factor.

Synchronous motors and generators have much larger time constants due to their independent field excitation, making them more vulnerable to damage from high-speed reclosing than comparable induction machines. Reference 14 indicates that typical open-circuit time constants for large salient-pole synchronous motors range from 1.5 to 10 seconds with an average value of about 4 seconds.

Page 188 of reference 4 shows charts of open circuit time constants for machines up to 150kVA and 1200RPM. Page 189 of reference 4 shows a very thorough table of typical constants for three-phase synchronous machines of various construction.

PRESENCE OF CAPACITORS: If a bank of capacitors is connected to the motor while disconnected from the supply system the time constant will be affected. The capacitors may be power factor correction capacitors, surge protection capacitors, or capacitors that supply excitation current to asynchronous generators like wind turbines.

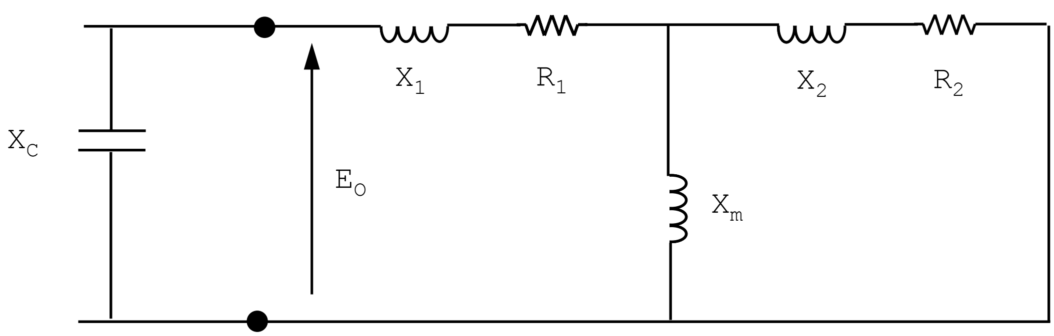

Figure 9. Capacitance located near terminals of motor.

If capacitors (such as power factor correction capacitors) remain in parallel with the motor load during the time of disconnection from the power system they will help maintain residual winding magnetism by storing energy during half of each voltage cycle, and returning it to the winding during the other half [6]. Capacitors that are large enough will cause the residual voltage to rise when initially opened. Losses will still reduce the energy but the time of decay will be extended, in some cases greatly. For example, the open circuit time-constant of a typical 400-hp, 460V, 6-pole motor without capacitors present is 0.35 seconds (21 cycles). With a terminal capacitance of 110kVAR the open circuit time-constant goes to 5.8 seconds - an increase of more than 15 times [6].

Also, switching an excessive amount of capacitance near a motor may well expose the motor to large overvoltages.

Options

The simplest solution for the utility is to disable the high-speed reclose and rely on dead-line reclosing. If studies support this option (to ensure no stability problems or transient voltage issues) then it is simple and no cost. On highly interconnected transmission systems the loss of one line is unlikely to cause the two parts of the system to lose synchronism. In this case delayed reclosing is acceptable.

Another option that is commonly used is direct transfer-trip from one utility terminal to trip the tapped motor load. This would allow high-speed reclosing to remain, restoring the transmission tie quickly. Delayed voltage check reclosing could be used at the tapped station with appropriate delay to restore service to the plant.

Summary

- Reclosing must be delayed to allow the fault arc ionization path to dissipate.

- High-speed transmission line reclosing before tapped motor load can be disconnected or its voltage allowed to decay (plus delay to allow the fault arc ionization path to dissipate) should be avoided to prevent damage/undue wear to utility breakers and transformers.

- To limit transient motor currents and torques to acceptable values motor residual voltage should be allowed to decay below 25% before reclosing the line. This may take as long as 5 seconds for some large motor loads. An alternative is to use direct transfer trip.

- The phasor differences between the source voltage/Hertz and the motor bus voltage/Hertz should not exceed 1.33 per unit volts/Hertz at instant of closing.

- The largest torque perturbations for the motors may occur at reclosing angles between 90° and 120°.

- Good oscillographic capture devices (digital fault recorders or power quality monitors etc.) are essential to proper monitoring and analysis of power system operation. Thorough event analysis is essential.

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Biographical Sketch

Russell W. Patterson is Manager of System Protection & Analysis for the Tennessee Valley Authority (TVA, www.tva.gov) in Chattanooga, Tennessee. Prior to this he was manager of TVA's Advanced Power Applications group responsible for the maintenance and expansion of the state estimators used by TVA. As Manager of System Protection & Analysis he is responsible for the setting of all protective relays in the TVA transmission system and at Hydro, Fossil and Nuclear generating plants. He is responsible for ensuring that TVA's protective relays maximize the reliability and security of the transmission system. This includes setting and ensuring the proper application and development of protection philosophy for the TVA. Prior to this role Russell was a Project Specialist in System Protection & Analysis and was TVA's Power Quality Manager responsible for field and customer support on PQ related issues and disturbances. Russell is an active member of the IEEE Power System Relaying Committee (PSRC) and a prior member of the Protection & Controls Subcommittee of the Southeastern Electric Reliability Council (SERC). Mr. Patterson earned the B.S.E.E. from the Mississippi State University in 1991. Russell is a registered professional engineer in the state of Tennessee and is a Senior Member of IEEE. Russell's website is http://webpages.charter.net/rwpatterson357/ and he can be e-mailed at rwpatterson@tva.gov.

George T. Pitts is a Senior System Protection & Analysis Engineer for the Tennessee Valley Authority (TVA, www.tva.gov) in Chattanooga, Tennessee. He is responsible for the setting of protective relays, supporting maintenance & testing, performing fault studies, and modeling of the Mississippi region of TVA's transmission system. He is a TVA representative to the Protection & Controls sub-committee for the SERC Reliability Corporation. Prior to this he was a process control engineer for the Mead Corporation located at a pulp & paper mill in Stevenson, Alabama and responsible for control of power boilers, pulp mills and paper machines. Prior to this role he was the maintenance electrical & instrument engineer for Mead and was responsible for high voltage to control systems design, construction, and startup of a new pulp & paper plant along with Mead corporate engineers, BE&K construction, and Rust Engineering. Previously, he was with IDS Technical Services, Houston, Texas, where he served as a lead engineer/project manager of E & I aspects of pipeline engineering for customer Exxon. Before that, he was a project engineer in system-wide engineering at Texas Eastern Pipeline in Houston, Texas. Mr. Pitts earned the B.S.E.E. from the Mississippi State University in 1993. He is a member of IEEE. He can be e-mailed at gtpitts@tva.gov.