Thermal Protection of Undocumented AC Motors

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THERMAL PROTECTION OF UNDOCUMENTED AC MOTORS

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Abstract—This paper proposes a two-step procedure to estimate key motor parameters for ac motors with missing manufacturer's motor specifications. Often users do not possess the motor specifications needed to provide optimal motor performance and protection. The manufacturer may never have supplied motor information, or the documentation may have been lost. This method provides motor users with a way to estimate the lost or missing information.

Index Terms—thermal protection, motor protection, ac motors.

I. INTRODUCTION

Digital motor protection relays offer the user numerous advantages:

- Precise protection
- Accurate metering
- Detailed starting and event reports
- Historical data concerning the power system
- Historical data concerning the protected equipment
- Communications to an external computer

To achieve these advantages, the relays require key motor data to customize them for the specific power system and motor application. Unfortunately, in the real industrial world, motor manufacturer's data are not always available.

This paper proposes a way to overcome this lack of data by initially setting the relay using conservative settings based on practical field experience and then refining them using motor historical data collected by the digital motor relay.

II. MOTOR NAMEPLATE INFORMATION

For the safe operation of any ac motor, a certain amount of information is necessary. The National Electric Code requires specific information be included on a motor nameplate. This information includes the manufacturer, rated voltage, full-load current, frequency, phase, rpm, temperature rise or insulation class and ambient temperature, duty rating, rated horsepower, and locked-rotor design letter. Additional information typically includes service factor, enclosure type, connection diagrams, frame size, and other information specific to the motor.

However, nameplates do not display all the information needed to set a digital motor protection relay. Commissioning a motor without this data is not a "by the numbers" protection setting scenario. Even without a complete set of data, which is only available from the motor specifications, the following procedure can provide adequate protection for most ac motors.

Two assumptions are included in the basic premise of this paper. First, the authors are assuming that the motor is sized properly for the specific application. Second, they assume the starter and cable(s) are sized to carry the needed current as well as safely start the motor without excessive voltage drop.

III. IMPORTANT MOTOR PARAMETERS (RATED VOLTAGE)

The motor voltage rating has a direct impact on the proper protection of a motor. When starting, reduced bus voltage causes reduced starting torque, potentially resulting in a stalled rotor. When running, reduced bus voltage causes an increase in motor current, potentially resulting in an overload.

Set the voltage to the rated system voltage, and set the undervoltage trip to 80 percent of rated voltage. This setting will allow the motor to start and still provide motor protection if the system cannot maintain voltage and support motor current demand.

IV. IMPORTANT MOTOR PARAMETERS (CURRENT UNBALANCE)

A properly operating induction motor should have balanced three-phase current. Unbalance in motor currents, caused by supply voltage unbalance, creates excessive heating in the rotor. Set the current unbalance to 24 percent with a 30-second delay. We also recommend setting the unbalance alarm at 12 percent with a 30-second delay.

Keep in mind that 1 percent voltage unbalance causes approximately 6 percent current unbalance in motors.

V. NEMA MOTOR DESIGN CLASSES

The National Electrical Manufacturers Association (NEMA) has developed specifications for so-called NEMA Design A, B, C, and D motor types [1]. These designs are based on standardizing certain motor characteristics, such as starting current, slip, and specified torque points (Fig. 1).

- **Design A** has normal starting torque (typically 150 to 170 percent of rated) and relatively high starting current. Breakdown torque is the highest of all NEMA types. It can handle heavy overloads for a short duration. Slip is ≤ 5 percent. A typical application is powering of injection-molding machines.
- **Design B** is the most numerous type of ac induction motor sold. It has normal starting torque, similar to Design A, but offers low starting current. Locked-rotor torque is sufficient to start many loads encountered in industrial applications. Slip is ≤ 5 percent. Motor

efficiency and full-load power factor are comparatively high, contributing to the popularity of the design. Typical applications include pumps, fans, and machine tools.

- **Design C** has high starting torque (greater than the previous two designs, around 200 percent), useful for driving heavy breakaway loads. These motors are intended for operation near full speed without great overloads. Starting current is low. Slip is ≤ 5 percent.
- **Design D** has high starting torque (highest of all the NEMA motor types). The starting current and full-load speed are low. High slip values (5 to 13 percent) make this motor suitable for applications with changing loads and attendant sharp changes in motor speed, such as in machinery with flywheel energy storage. Several design subclasses cover the wide slip range. This motor type is usually considered a "special order" item.

Typically, the NEMA design designation is a nameplate quantity. Using the information provided by NEMA on motor design and expected torque, we can derive a reasonable starting point for motor protection.

Although Design A and Design B motors are similar, they have some significant differences. The most commonplace of all models, the Design B motors, must comply with certain specifications in NEMA Standard MG1. These specifications limit the design to no more than 5 percent slip and place minimum limits on torque during starting and acceleration. The standards also define a maximum allowable locked-rotor current, also known as starting current. The Design A specification is identical except the motors are not limited to any maximum locked-rotor current.

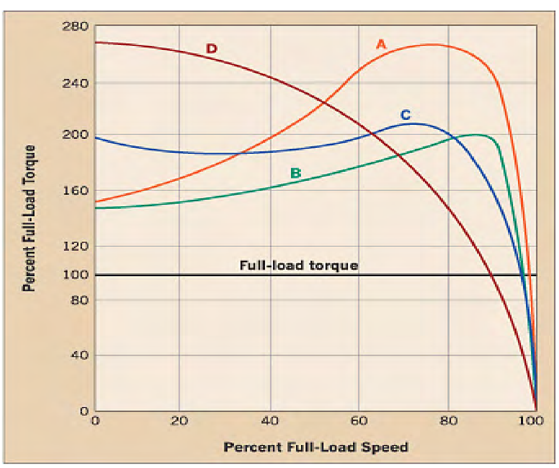

Fig. 1 Torque Is Proportional to the Square of Motor Current, $Q = (I^2R)/S$

NEMA design codes for motors specify the range of kVA per horsepower as measured at motor rated voltage and rated frequency. For example, Code G has the range of 5.6 to 6.3 kVA/HP.

VI. CRITICAL MOTOR PARAMETERS FOR THE STARTING ELEMENT (ROTOR PROTECTION)

Two parameters are required for the safe and correct protection of an ac motor during starting:

- Motor locked-rotor current (LRA)
- Safe stall time for above LRA (T_{stall})

Neither is a nameplate quantity, yet both are critical to starting, which is the most stressful and dangerous motor condition.

VII. HOW TO SET STARTING ELEMENT WITHOUT MANUFACTURER'S CRITICAL PARAMETERS

Settings are achieved in two iterations.

A. Iteration 1

For induction motors, set LRA = 6.0 • FLA and T_{stall} = 10 s.

For synchronous motors, set LRA = 4.0 • FLA and T_{stall} = 5.0 s.

After the initial start process, shut down the motor and review the motor start report (MSR) within the digital relay. Check the inrush current, voltage dip, and time to start. Confirm that the protection settings used in this first iteration are reasonably close to the actual values recorded in the motor start report. See the motor starting information as presented in either statistical or graphical format (Fig. 2 and Fig. 3).

B. Iteration 2

After confirming the initial settings and adjusting as needed, continue the commissioning process. Start the motor several times to give the relay a chance to capture the starts in the MSR. Allow cooling time between starts.

```
=>MSR 1 <Enter>

XXX-XXX                              Date: 01/14/2007    Time: 11:34:17.794
MOTOR RELAY                            Time Source: internal

FID=XXX-XXX-R200-V0-Z001001-D20031210

Date of Motor Start                        01/14/2007
Time of Motor Start                      11:21:54.298
Number of Starts                                    1
Start Time (s)                                    4.6
Start %TCU                                         40
Max Start I (A)                                   403
Min Start V (V)                                  3920
Cycle, IA (A), IB (A), IC (A), IN (A), VAB (V), VBC (V), VCA (V), %TCU

5.00, 406,404,403,0,3922,3963,3908,16.6 … … …

10.00,404,406,404,0,3925,3922,3929,16.6… … …

30.00,386,387,386,0,3930,3937,3933,20.2 … … …
•
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•
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Fig. 2 Example of Numerical Motor Start Report (Partial)

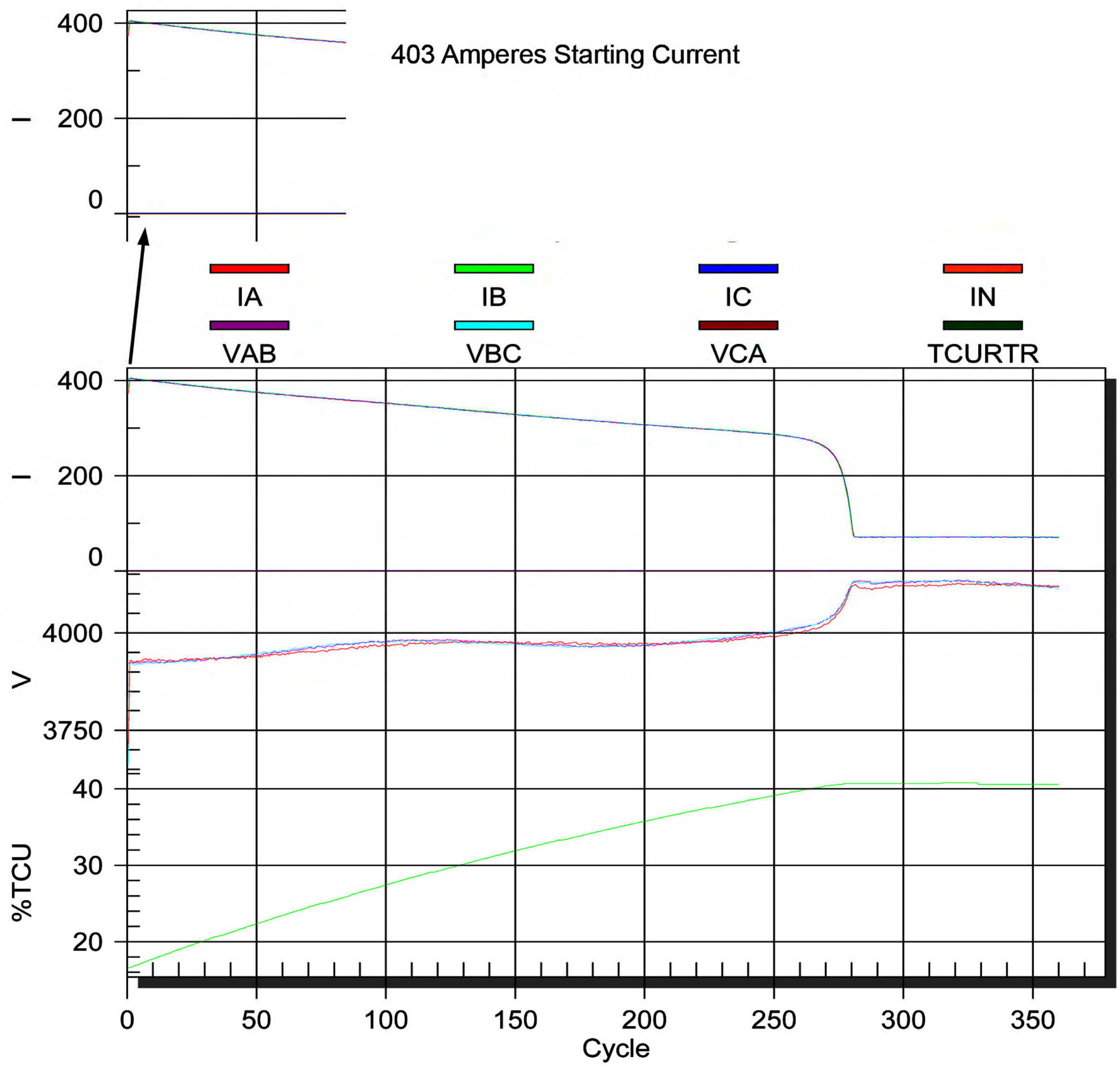

Fig. 3 Example of Graphical Motor Start Report

After starting, the relay will capture data, which include the currents, voltages, and percent thermal capacity used at prespecified intervals. The data are stored in nonvolatile memory.

After starting the motor several times, access the relay using a laptop computer, and review the MSRs.

Note the 5 cycle currents. The average of the three-phase current divided by motor FLA is the actual LRA of this motor. Replace the previously estimated quantity with this actual number.

Next, note the motor start time. Average it by adding the times and dividing by the number of MSRs used. Add 3 seconds to the start time for induction motors and 2 seconds for synchronous motors. This is your new T_{stall}. Replace the previous value with your calculated T_{stall}.

In summary, the permanent critical starting element parameters for this motor are:

LRA = (IA + IB + IC)/(3 • FLA)

T_{stall} = average start time + 3 s for induction motors

T_{stall} = average start time + 2 s for synchronous motors

After five successful starts, review the motor statistics report (Fig. 4), and use this data to adjust the protection settings if needed.

```
=>>MOT <Enter>

XXX-XXX                         Date: 01/14/2007    Time: 11:35:03.024
MOTOR RELAY                      Time Source: external
Operating History (elapsed time in ddd:hh:mm)  Since: 01/12/2007 11:21:54
Running Time          39:07:41
Stopped Time           9:06:17
Time Running            81.1%
Number Of Starts                             2
Number Of Emergency Starts                   0
                      Average           Peak
Start Time (s)        4.5               4.7
Max Start I (A)       405               411
Min Start V (V)       3925              3920
Start % TCU           40.9              43.5
Running % TCU         91.9              94.8
•
•
•
```

Fig. 4 Example of Motor Operating Statistics Report (Partial)

VIII. CRITICAL MOTOR PARAMETERS FOR THE RUNNING ELEMENT (STATOR PROTECTION)

Three motor parameters are required for the safe and correct protection of an ac motor while running:

- Full-load current (FLA)
- Service factor (SF)
- Thermal running time constant τ_{th} (RTC)

Of the three, only RTC is not a nameplate quantity.

IX. HOW TO SET RUNNING ELEMENT WITHOUT MANUFACTURER'S CRITICAL PARAMETERS

Set full-load current exactly as it appears on the nameplate.

If the motor has an SF of 1.0, set the relay at 1.01. If bus voltage fluctuations are a concern, this number can be increased to as high as 1.05 to compensate for increased current during reduced voltage conditions.

If the motor has an SF higher than 1.0 (1.15, 1.25, etc.), set it at that number. Do not compensate for possible reduced voltage conditions.

To set the RTC, if the relay has an AUTO mode, set RTC = AUTO. If AUTO mode is not available, set RTC = 20 minutes.

X. EXAMPLE: 400 HP PUMP MOTOR

The example motor is a 400 HP condensate extraction pump. Although this was a new motor installation, the motor manufacturer did not provide motor thermal limit curves. The only data available for this motor were taken from the motor nameplate. The nameplate data needed to set the protection were:

- Rated-load amperes = 71 A
- Locked-rotor kVA code letter = G
- Service factor = 1.0
- Time rating = continuous
- RPM at rated load (rated speed) = 1189 rpm
- Voltage = 4160 V

The initial thermal model settings for the relay are summarized in TABLE I.

TABLE I
CONDENSATE EXTRACTION PUMP MOTOR INITIAL RELAY SETTINGS

Setting	Initial Value
FLA	71 A
LRA	6 • FLA
SF	1.01
Hot Locked-Rotor Time	10 s
Undervoltage Trip	80% of Nominal
Current Unbalance Trip	24%

The motor start report is shown in Fig. 2. The actual motor acceleration time was approximately 4.6 seconds, and, as expected with a programmed 10-second safe hot locked-rotor time, the starting thermal capacity used was low, about 41 percent.

The recorded locked-rotor current was 403 A (5.7 • FLA).

Using this information, relay settings were modified to tighten the thermal protection for the motor. The final settings are shown in TABLE II.

TABLE II
CONDENSATE EXTRACTION PUMP MOTOR FINAL SETTINGS

Setting	Final Value
FLA	71 A
LRA	5.7 • FLA
SF	1.01
Hot Locked-Rotor Time	8 s
Undervoltage Trip	80% of Nominal
Current Unbalance Trip	24%

XI. PROTECTING THE MOTOR—AN OVERVIEW OF THE FIRST ORDER THERMAL MODEL [2] [3]

Fig. 5 illustrates the first order thermal model. The major components of the model are as follows:

- Heat source: heat flow from the source is I^2r watts (J/s).
- Thermal capacitance (C_{th}): represents a motor that has the capacity (C_{th}) to absorb heat from the heat source. Unit of thermal capacitance is J/°C.
- Thermal resistance (R_{th}): represents the heat dissipated by a motor to its surroundings. Unit of thermal resistance is °C/W.
- System temperature is U (°C).
- Comparator: compares the calculated motor per unit (pu) temperature with a preset value based on the motor manufacturer's data.

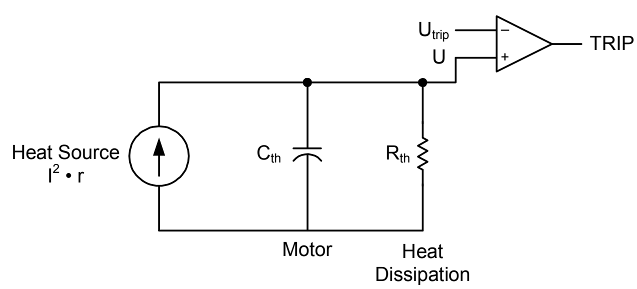

Fig. 5 First Order Thermal Model

Qualitative analysis of this model states that heat produced by the heat source is transferred to the motor, which dissipates the heat to the surrounding environment.

Quantitative analysis is defined by a first order linear differential equation similar to a parallel RC electrical circuit and is:

$$I^2 r = C_{th} \bullet \frac{dU}{dt} + \frac{U}{R_{th}} \qquad (W) \qquad (1)$$

Motors are comprised of two major components—stator and rotor.

The stator's function is to produce a rotating magnetic field (at line frequency) in the air gap and induce voltage in the rotor bars that produces current flow in those bars.

Rotor current produces a magnetic field of its own. The rotor magnetic field is at 90 degrees to the air-gap magnetic field, thus generating torque tangential to the rotor surface and producing rotational force, which turns the shaft.

Because the construction of the stator and rotor is different, so is their thermal characteristic. To accommodate this major difference in stator and rotor thermal properties, the first order thermal model was refined into the following two elements:

- Starting element, which protects the rotor during the starting sequence.
- Running element, which protects the stator when the motor is up to speed and running.

Tripping of the motor switches from one element to the other at 2.5 times the rated full-load current of the motor.

XII. APPLYING FIRST ORDER THERMAL MODEL TO MOTOR STARTING (ROTOR PROTECTION)

It is widely accepted that the starting sequence of an ac motor is regarded as an adiabatic (lossless) process. Starting deposits an immense amount of heat (up to a hundred times the rated heating) in rotor bars, while the duration of the starting sequence is magnitudes shorter than motor thermal time constants. Thus, any heat deposited in the rotor will not dissipate to the surroundings during the starting sequence. (It will dissipate later when the motor is up to speed and running.)

Applying this assumption to the first order thermal model depicted in Fig. 5, we are effectively saying that the thermal resistance of the motor during starting is infinity ($R = \infty$).

Substituting this condition into (1) and converting it into pu quantities by substituting $r = C_{th} = 1$ yields:

$$dU = I^2 \bullet dt \qquad (\text{pu } ^\circ\text{C}) \qquad (2)$$

The solution to this general integral is:

$$U = I^2 \bullet t \qquad (\text{pu } ^\circ\text{C}) \qquad (3)$$

Motor manufacturers supply rotor thermal limit information as part of motor data. The rotor thermal limit is expressed in terms of the maximum time (T_{STALL}) that corresponding locked-rotor current (I_{LRA}) can be applied to a motor.

Applying this to (3):

$$I = I_{LRA} \qquad (\text{pu locked-rotor amperes})$$

$$t = T_{STALL} \qquad (\text{safe stall time, seconds})$$

$$U_{trip} = I_{LRA}^2 \bullet T_{STALL} \qquad (\text{pu } ^\circ\text{C}) \qquad (4)$$

Comparing this maximum permissible temperature of $I_{LRA}^2 \bullet T_{STALL}$ with a measured temperature $I^2 \bullet t$ during a start:

$$I^2 \bullet t = I_{LRA}^2 \bullet T_{STALL}$$

Solving for t results in a curve of maximum allowable rotor temperature for any current I > 2.5 FLA. Thus, t is the tripping time t_{trip} :

$$t_{trip} = \frac{I_{LRA}^2}{I^2} \bullet T_{STALL} \qquad (5)$$

Incorporating all of the above changes to Fig. 5 results in the starting element of the first order thermal model as illustrated in Fig. 6.

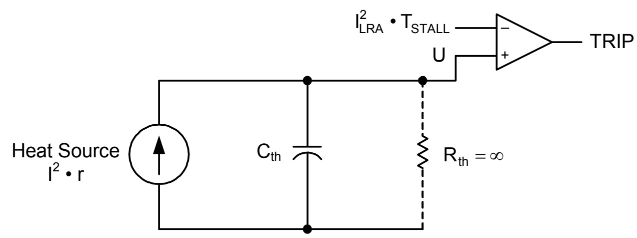

Fig. 6 Starting Element

XIII. APPLYING FIRST ORDER THERMAL MODEL TO RUNNING MOTOR (STATOR PROTECTION)

Once the motor reaches full speed, the current decreases, and the motor is in the running state, the first order thermal model switches tripping from the starting element to the running element.

Equation (1) and Fig. 5 apply to the running element. Equation (1) is a first order linear differential equation. Rearranging, converting to pu, and solving the equation yields the following solution:

$$U(t) = I_0^2 \bullet e^{-\frac{t}{\tau_{th}}} + I^2 \bullet \left(1 - e^{-\frac{t}{\tau_{th}}}\right) \qquad (\text{pu } ^\circ\text{C}) \qquad (6)$$

where:

U(t) = pu temperature as a function of time

I_0 = pu initial current (when overload occurs)

I = pu overload current

τ_{th} = motor RTC (thermal running time constant)

A more useful presentation of (6) to motor relay engineers is the time (t) in which the running element will reach temperature U(t).

Rewriting (6) yields:

$$t = \tau_{th} \bullet \ln\left[\frac{I^2 - I_0^2}{I^2 - U(t)}\right] \qquad (s) \qquad (7)$$

In plain language, (7) states that the time it takes to reach U(t) is calculated by multiplying the motor RTC by the natural logarithm of the difference between final pu temperature and initial pu temperature, divided by the difference between final pu temperature and the pu temperature at time t.

Two important reminders are:

- The base for this pu system is motor full-load current.
- A valid range for U(t) is between initial pu temperature I_0^2 and final pu temperature I^2.

Let us further simplify (7) to make it more suitable for motor protection applications.

Manufacturers state the SF of the machine on every motor nameplate. Even though the exact interpretation of the SF is vague, one thing is certain—any motor current greater than SF • FLA is considered a running overload condition. Translate this into U_{trip}, a maximum pu temperature that the motor is designed for and can sustain:

$$U(t) = U_{trip} = (SF \bullet I_{FLA})^2 \qquad (\text{pu } °\text{C}) \qquad (8)$$

Because I_{FLA} = 1 pu, the above expression is further simplified to:

$$U_{trip} = SF^2 \qquad (\text{pu } °\text{C}) \qquad (9)$$

Substituting (9) into (7) results in the final equation of the first order thermal model running element. It represents the maximum time a motor can spend under an overload condition, thus t = t_{trip} .

$$t_{trip} = \tau_{th} \bullet \ln\left[\frac{I^2 - I_0^2}{I^2 - SF^2}\right] \qquad (\text{s}) \qquad (10)$$

The running element of the thermal model is shown in Fig. 7.

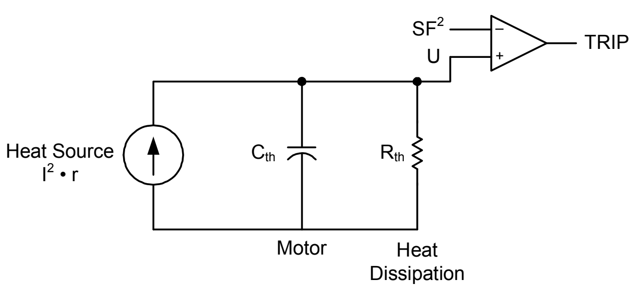

Fig. 7 Running Element

Combining the starting and running trip times on one graph (Fig. 8) illustrates a typical response curve of the first order thermal model.

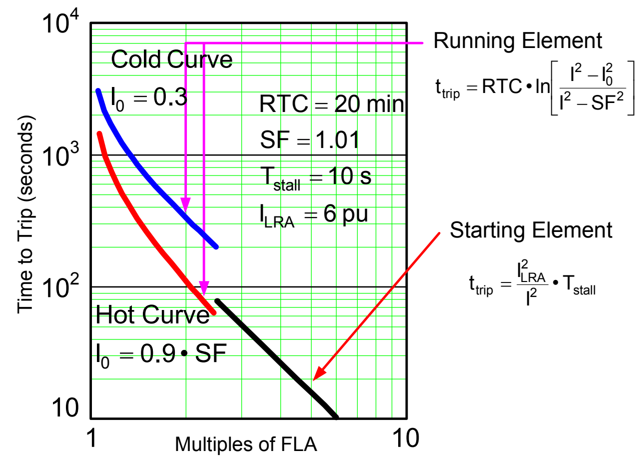

Fig. 8 Thermal Model Response Curve

XIV. CONCLUSION

There is no doubt that the best motor protection is achieved using the motor manufacturer’s data. However, using reasonable initial conditions and then refining them with historical data captured by the relay, good motor protection can be achieved while avoiding premature process interruptions.

XV. REFERENCES

[1] NEMA, *Motors and Generators*, National Electrical Manufacturers Association Standard MG-1-1998, New York, 1998.

[2] S. E. Zocholl, “Tutorial: From the Steinmetz Model to the Protection of High Inertia Drives,” proceedings of the 33rd Annual Western Protective Relay Conference, Spokane, WA, October 2006.

[3] S. E. Zocholl, *AC Motor Protection*, Schweitzer Engineering Laboratories, Inc., pp. 6–21, 2004.

XVI. FURTHER READING

S. E. Zocholl, E. O. Schweitzer, and A. Aliaga-Zegarra, “Thermal Protection of Induction Motors Enhanced by Interactive Electrical and Thermal Models,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, No. 7, July 1983.

S. E. Zocholl and G. Benmouyal, “On the Protection of Thermal Processes,” *IEEE Transactions on Power Delivery*, vol. 20, issue 2, pp. 1240–1246, April 2005.

IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Motors, IEEE Standard 620-1996.

XVII. VITAE

Edward A. Lebenhaft received his B.A.Sc. in Electrical Engineering from the University of Toronto in 1972. He spent 18 years with Ontario Hydro constructing and designing nuclear power plants. In the following 14 years, Ed was a regional manager for Multilin (eventually to be bought out by GE). After a brief retirement, Ed joined Schweitzer Engineering Laboratories, Inc. in October 2004, where he is currently a field application engineer dealing with motor protection. Ed is a registered Professional Engineer in South Carolina.

Mark Zeller received his B.S. from the University of Idaho in 1985. He has broad experience in industrial power system maintenance, operations, and protection. Upon graduating, he worked over 15 years in the pulp and paper industry, where he worked in engineering and maintenance with responsibility for power system protection and engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. in 2003, he was employed by Fluor to provide engineering and consulting services for Alcoa. He has been a member of IEEE since 1985.

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