

# Estimating Key Parameters for Protection of Undocumented AC Motors

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# Estimating Key Parameters for Protection of Undocumented AC Motors

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**Abstract—This paper proposes a procedure to estimate key motor parameters for ac motors that lack manufacturer’s data. Often users lack important motor data needed to provide optimal motor performance and protection. The manufacturer may never have supplied this information, or the documentation may have been lost. This method provides motor users with a way to determine the lost or missing information.**

## 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 several key settings in order to customize them for the specific power system and motor application. Unfortunately, in the real industrial world, these crucial 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 by using motor historical data collected by the digital motor relay. Both induction and synchronous motors are addressed.

## II. MOTOR NAMEPLATE INFORMATION

For the safe operation of any ac induction 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 amperes, 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.

As we are all aware, not all motor nameplates carry this “required” information. Commissioning a motor without this data is not a “by the numbers” protection setting scenario. Even without most of the data, the following procedure can provide adequate protection for most induction 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, the starter and

cable(s) must also be capable of carrying the needed current and safely interrupting this current and stopping the motor.

## 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 motor voltage and set the under-voltage 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. CRITICAL MOTOR PARAMETERS (STARTING CURRENT)

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  $\leq 5$  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 good enough to start many loads encountered in industrial applications. Slip is  $\leq 5$  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  $\leq 5$  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 rather 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 laid out 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.

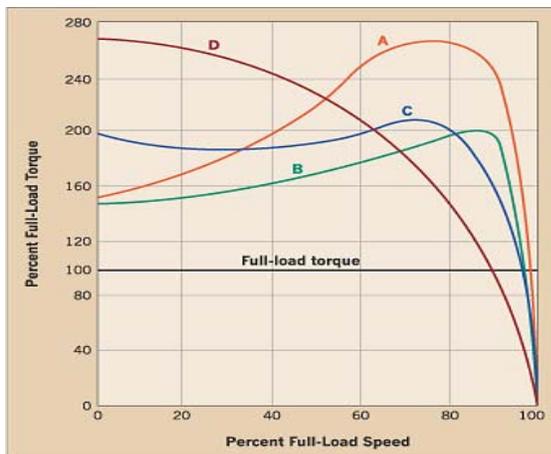


Fig. 1. Torque Is Proportional to the Square of Motor Current,  $Q = (I^2R)/S$

NEMA design codes for motors specify the locked-rotor starting current. For example, a locked-rotor Code G is a multiple of the full-load amperes of between 5.6 to 6.29.

## VI. CRITICAL MOTOR PARAMETERS TO 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 THE STARTING ELEMENT WITHOUT MANUFACTURER’S CRITICAL PARAMETERS

Settings are achieved in two iterations.

### A. Iteration 1

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

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

After the initial start process, shut down the motor and review the motor start report 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 motor start report (MSR). Allow cooling time between starts.

```

=>MSR 1 <Enter>

XXX-XXX                               Date: 01/14/2007   Time: 11:34:1794
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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•

```

Fig. 2. Example of Numerical Motor Start Report (Partial)

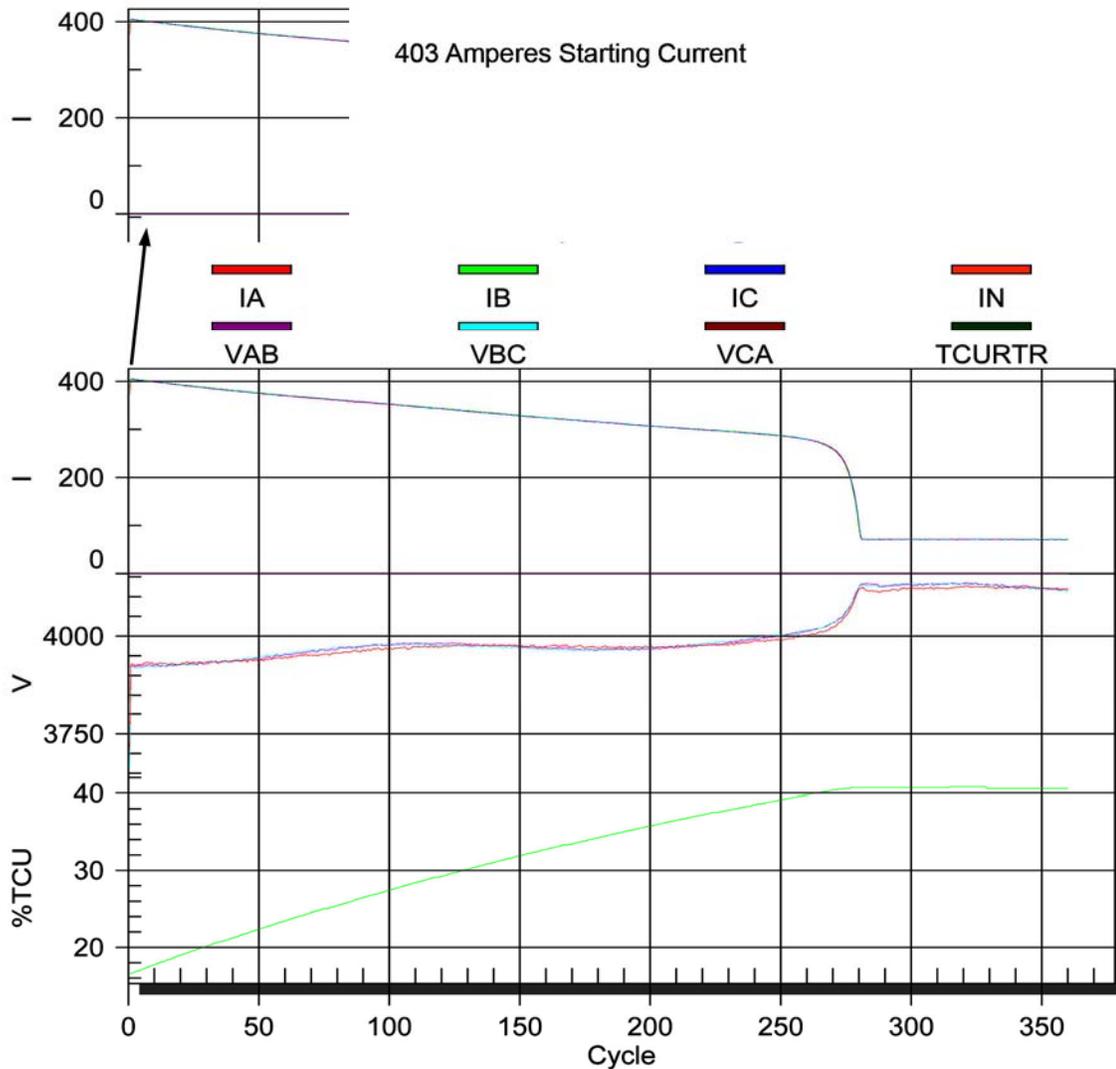


Fig. 3. Example of Graphical Motor Start Report

The relay captures 720 sets of currents, voltages, and percent thermal capacity used at programmed intervals for each start. The five latest starts are stored in nonvolatile memory.

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

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 MSR's 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 key starting element parameters for this motor are:

$$LRA = (I_A + I_B + I_C) / (3I_{FLA})$$

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

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

After five successful starts, review the motor statistics report (Fig. 4), and use these 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 TO 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  $\tau_{th}$  (RTC)

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

### IX. HOW TO SET THE 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.

Fortunately, to set the RTC, the relay will take a specific number, or it can be set in AUTO mode, where RTC is generated by the thermal model.

Set RTC = AUTO. The generated RTC turns out to be a reasonable choice, but on the conservative side.

### X. 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 (W).
- 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  $W \cdot s/^\circ C$ .
- Thermal resistance ( $R_{th}$ ): represents the heat dissipated by a motor to its surroundings. Unit of thermal resistance is  $^\circ C/W$ .
- System temperature  $U$  ( $^\circ C$ )
- Comparator: compares the calculated motor per unit (pu) temperature with a preset value based on the motor manufacturer's data.

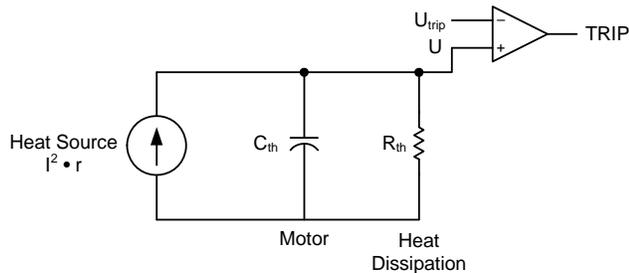


Fig. 5. First Order Thermal Model

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:

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

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.

### XI. APPLYING THE 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:

$$dU = I^2 \cdot dt \quad (pu \ ^\circ C) \quad (2)$$

The solution to this general integral is:

$$U = I^2 \cdot t \quad (pu \ ^\circ C) \quad (3)$$

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 the corresponding locked-rotor current ( $I_{LRA}$ ) can be applied to a motor.

Applying this to (3):

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

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

$$U = I_{LRA}^2 \cdot T_{STALL} \quad (pu \ ^\circ C) \quad (4)$$

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.

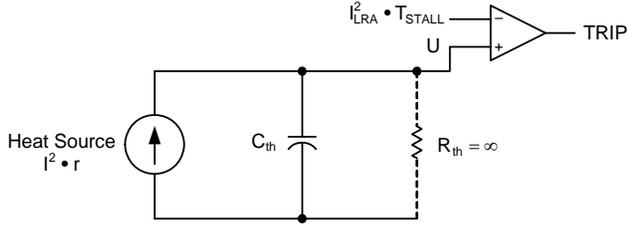


Fig. 6. Starting Element

## XII. APPLYING THE FIRST ORDER THERMAL MODEL TO A RUNNING MOTOR (STATOR PROTECTION)

Once the motor reaches full speed, the current drops, 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 yields the following solution:

$$U(t) = I_0^2 \cdot e^{-\frac{t}{\tau_{th}}} + I^2 \cdot \left(1 - e^{-\frac{t}{\tau_{th}}}\right) \quad (\text{pu } ^\circ\text{C}) \quad (5)$$

where:

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

$I_0$  = pu initial current

$I$  = pu final current

$\tau_{th}$  = motor RTC

A more useful presentation of (5) to motor relay engineers is the time ( $t$ ) in which the running element will reach temperature  $U(t)$ .

Rewriting (5) yields:

$$t = \tau_{th} \cdot \ln \left[ \frac{I^2 - I_0^2}{I^2 - U(t)} \right] \quad (\text{s}) \quad (6)$$

In plain language, (6) 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,  $U(t)$ , in question.

Two important reminders are:

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

Let us further simplify (6) 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

$SF \cdot I_{FLA}$  is considered a running overload condition. Translate this into a maximum pu temperature that the motor is designed for and can sustain at any time ( $t$ ).

$$U(t) = (SF \cdot I_{FLA})^2 \quad (\text{pu } ^\circ\text{C}) \quad (7)$$

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

$$U(t) = SF^2 \quad (\text{pu } ^\circ\text{C}) \quad (8)$$

Substituting (8) into (6) results in the final equation of the first order thermal model running element:

$$t = \tau_{th} \cdot \ln \left[ \frac{I^2 - I_0^2}{I^2 - SF^2} \right] \quad (\text{s}) \quad (9)$$

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

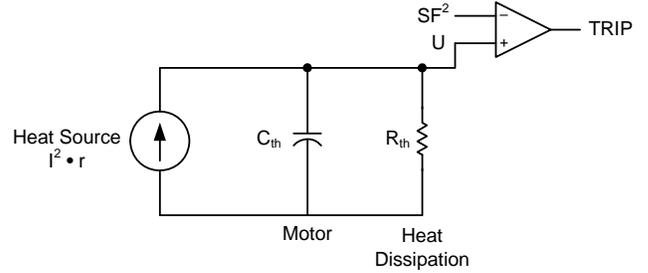


Fig. 7. Running Element

## XIII. CONCLUSION

There is no doubt that the best motor protection is achieved using the motor manufacturer's data.

However, it was demonstrated above that by using reasonable initial conditions and then tweaking them with the help of historical data captured by the relay, good motor protection can be achieved while avoiding premature process interruptions.

## XIV. 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.
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## XV. FURTHER READING

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## XVI. BIOGRAPHIES

**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.