## PDHonline Course E121 (3 PDH)

# Calculating Motor Start Time

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## Course Content

Large motor over current protection is normally set to trip prior to the locked-rotor safe stall time provided by the motor manufacturer but after the calculated motor start time. The locked-rotor safe stall time is determined by the manufacturer based on the heating of the rotor parts for this locked-rotor condition where the motor continuously requires a large value of inrush current. During the starting condition, an induction motor draws high values of current (the motor is a constant impedance device during the starting condition) that are very close to the motor's locked rotor value and remains at this value for the time required to start the motor. This is the reason why the locked-rotor safe stall time is used as an allowable time limit for starting the motor across the line, full voltage. For more information on modeling devices in power systems the student is referred to reference 2.

The capability to calculate motor start time for the largest motor on the electrical distribution system is important in order to evaluate the relative strength of the power system. Typically the motor manufacturer may calculate the motor starting time at a couple of selected values such as 90% or 85% and then plot the results on the time versus current curves for the supplied motor. System designers can use these starting times, but it is sometimes necessary to calculate the motor starting times using the results of a power system studies for the maximum voltage dip at minimum power system conditions. This method can then be used, using the maximum voltage dip, to avoid application problems, set motor protective devices and perform coordination studies with other protective devices on the system.

The method described is an approximation that assumes that the inertia of the power source is significantly greater (at least ten times or more) than the inertia of the driven load.

The following discussion will describe a common method for calculating the starting time for an induction motor starting full voltage, across the line.

The motor's starting time is also referred to the acceleration time. This time is important because it determines the length of time the motor must withstand stator current that exceeds its continuous rating. This time is based upon Newton's second law (force is equal to mass times acceleration) applied to rotation. This law is:

Accelerating Torque = Inertia * Angular Acceleration

The acceleration time can be calculated using the following formula:

$$t_a = (Wk^2 * \text{Delta N})/(308 * T_a) \quad (1)$$

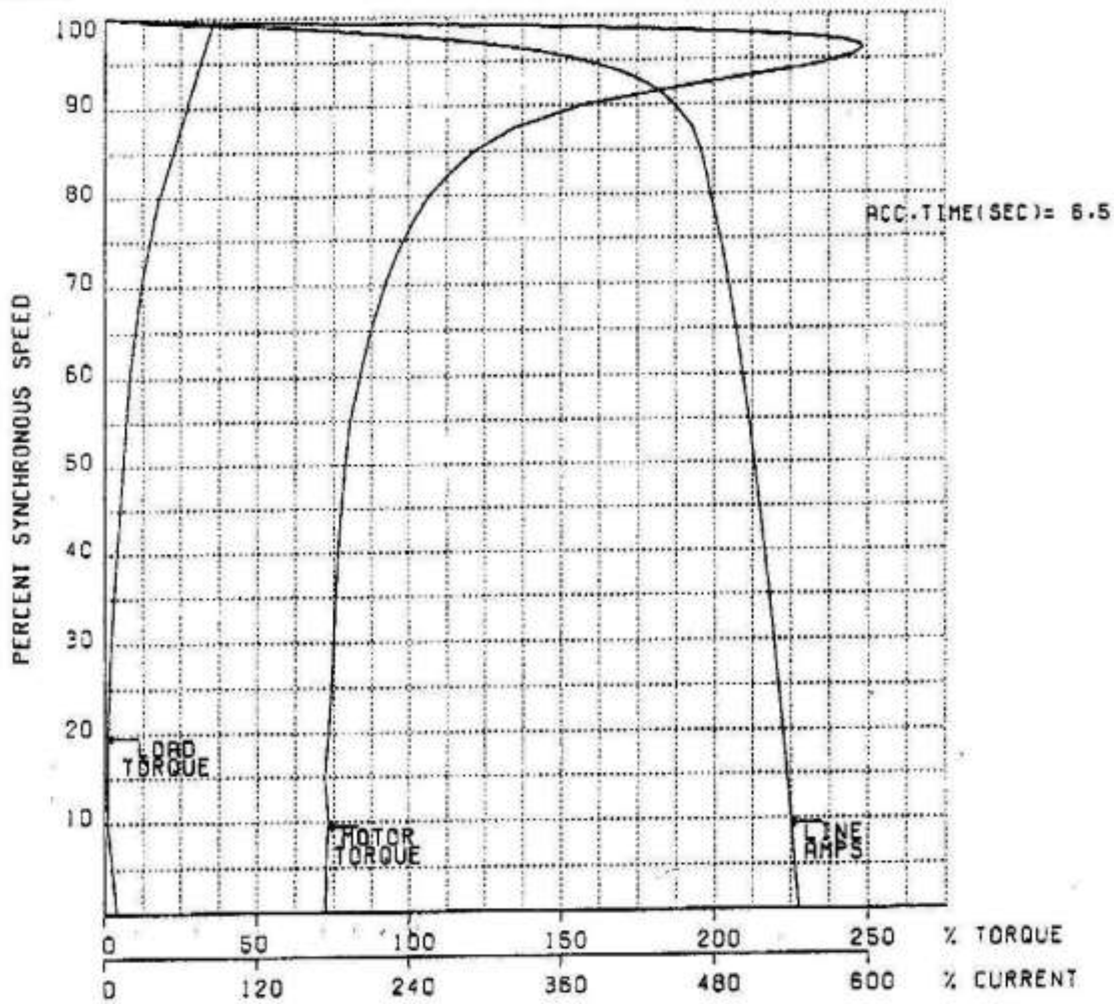
Where

$t_a$ acceleration time (seconds);
$Wk^2$ total connected inertia (lb * ft$^2$);
Delta N speed change during time $t_a$ (rev/min);
$T_a$ average accelerating torque (lb * ft) (average motor torque – average load torque);

In order to obtain these values it is necessary to request this information from the equipment manufacturer. This information is typically provided as torque versus speed curves for the induction motor and for the driven load. These curves are typically plotted using the equipment full load rating, and or rated speed. These curves must be converted to a common base or common reference scales in order to calculate the torque available for acceleration. The following motor torque versus speed curve is an example of the type of curves available from motor suppliers:

# INDUCTION MOTOR STARTING CHARACTERISTICS (CALCULATED) AT 100% LINE VOLTAGE

HP 9000 VOLTS 13200 PH 3 HZ 60 POLES 4 RPM (FL) 1785
PF 0.93 FL AMPS 332 LOCK AMPS(%) 546 RPM (SYN) 1800
FL TORQUE(LB-FT) 26470 LOCK TORQUE(%) 72
LOAD WK²(LB-FT²) 16241 MOTOR WK²(LB-FT²) 7446 FRAME 5312
LOAD CURVE APPLICATION CENT COMPRESSOR



The necessary values can be determined from the motor torque versus speed curve. Note that the torque versus speed curve for the compressor is included. The driven equipment's manufacturer typically provides the torque versus speed curve for the load. The starting condition for the driven load should be checked for initial conditions and if possible the required torque should be minimized to reduce the starting condition on the motor.

The example motor characteristics are:

Total connected $Wk^2$ 7446 lb-ft$^2$ (Motor) + 16241 lb-ft$^2$ (Compressor) = 23687 lb-ft$^2$
Full load torque = 26470 lb-ft
Synchronous speed = 1800 rpm
Full load speed = 1785 rpm

The moment of inertia of the load and the motor rotor are combined numerically to give the total lb-ft$^2$ of the mass to be accelerated. The moment of inertia is the weight in pounds of the mass times the square of its radius of gyration in feet. These values are available from the manufacturers and are usually requested of bidders as part of their proposal data.

Any difference in speed between the motor and the load, due to a pulley or gear ratio, requires the following modifications on torque and inertia.

$$T_2 = (rpm_1/rpm_2)\ (T_1)$$

$$Wk^2_2 = ((rpm_1)^2/(rpm_2)^2)\ Wk^2_1$$

Where:

$T_2$ = effective torque at motor shaft speed

$T_1$ = torque at load shaft

$Wk^2_2$ = Effective $Wk^2$ of load reflected to motor shaft speed

$Wk^2_1$ = $Wk^2$ at load shaft, including inertia of any reciprocating member

$rpm_1$ = load shaft speed

$rpm_2$ = corresponding motor shaft speed

For calculation purposes the time interval is arbitrarily selected, the smaller time interval the more accurate the approximation becomes, lets choose the following:

$t_1$ defined as the time to change speed from 0 to 10 % speed (0 to 180 rpm)
$t_2$ defined as the time to change speed from 10% to 20%
$t_3$ defined as the time to change speed from 20% to 30%
$t_4$ defined as the time to change speed from 30% to 40%
$t_5$ defined as the time to change speed from 40% to 50%
$t_6$ defined as the time to change speed from 50% to 60%
$t_7$ defined as the time to change speed from 60% to 70%
$t_8$ defined as the time to change speed from 70% to 80%
$t_9$ defined as the time to change speed from 80% to 90%
$t_{\text{full load}}$ defined as the time to change speed from 90% to 99.2%

The next step is to establish the average acceleration torque for each time interval. The torque delivered by the motor varies as the square of the applied voltage based upon nameplate voltage being 100%. For example, if the voltage dipped to 90% the torque delivered to the load would be $0.9^2$ or 0.81 of the rated voltage. The torque delivered by the motor under these conditions should not be reduced to values that are less than the required load torque. The inrush current for the motor varies proportionately with the applied voltage. Other calculations will determine the expected voltage dip when starting a large motor. The average acceleration torque is then the average motor torque minus the average load torque during each interval. The average is determine by evaluating the characteristic curve during each interval:

Ta for interval 1 is T motor average minus T load average … (0.715 – 0.03) * 26470 lb-ft = 18132 lb-ft

Then: $t_1$ = ($Wk^2$) (change in speed per unit) (rated rpm) / 308 ($T_a$)
= 23687 lb-$ft^2$ (0.1) (1800) / 308 (18132 lb-ft)
= 0.76 seconds

Ta for interval 2 is T motor average minus T load average …(0.7375 – 0.0125) * 26470 lb-ft = 19191 lb-ft

Then: $t_2$ = 0.72 seconds

Ta for interval 3 is T motor average minus T load average …(0.745 – 0.025) * 26470 lb-ft = 19058 lb-ft

Then: $t_3$ = 0.73 seconds

Ta for interval 4 is T motor average minus T load average …(0.755 – 0.0375) * 26470 lb-ft = 18992 lb-ft

Then: $t_4$ = 0.73 seconds

Ta for interval 5 is T motor average minus T load average …(0.77 – 0.06) * 26470 lb-ft = 18794 lb-ft

Then: $t_5$ = 0.74 seconds

Ta for interval 6 is T motor average minus T load average …(0.81 – 0.0625) * 26470 lb-ft = 19786 lb-ft

Then: $t_6$ = 0.7 seconds

Ta for interval 7 is T motor average minus T load average …(0.875 – 0.10) * 26470 lb-ft = 20514 lb-ft

Then: $t_7$ = 0.67 seconds

Ta for interval 8 is T motor average minus T load average …(0.99 – 0.13) * 26470 lb-ft = 22764 lb-ft

Then: $t_8$ = 0.61 seconds

Ta for interval 9 is T motor average minus T load average …(1.25 – 0.23) * 26470 lb-ft = 26999 lb-ft

Then: $t_9$ = 0.51 seconds

Ta for interval 10 is T motor average minus T load average …(2.09 – 0.35) * 26470 lb-ft = 46322 lb-ft

Then: $t_{10}$ = 0.28 seconds

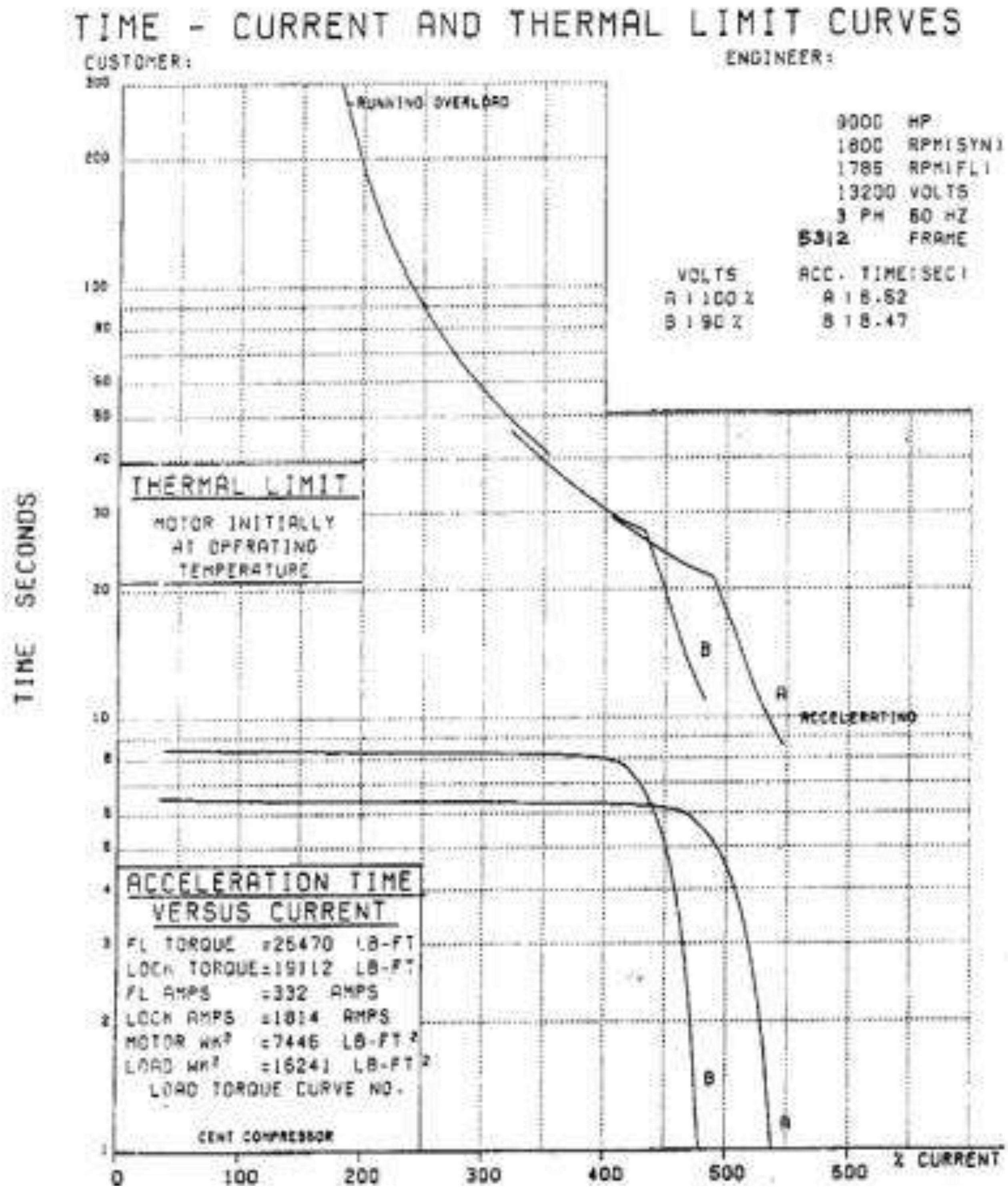
The results can the be determined as follows:

At time $t_1$= 0.76 seconds the motor is at 10% speed and at a current of 540% (which is provided on the speed versus current curve for the motor).

At time $t_1 + t_2$ = 0.76 + 0.72 = 1.48 seconds the motor is at 20% speed and at a current of 530%. This can be repeated and plotted on a time – current curve to establish the acceleration time versus current curve for the motor. All of the time intervals can be added together to obtain the starting time:

0.76 + 0.72 + 0.73 + 0.73 + 0.74 + 0.7 + 0.67 + 0.61 + 0.51 + 0.28 = 6.45

An example time – current curve is included that plots the results for 100% and 90% voltage. In this example the acceleration time is 6.52 seconds at 100% voltage, which agrees with the results of the approximation that was previously calculated. In this example the acceleration time is 8.47 seconds for 90% voltage and is accomplished by reducing the available motor torque by the square of the voltage. This technique can be used once the voltage dip is determined in order to calculate the motor starting time.




The time – current curve also provides the thermal limits for the motor during acceleration initially at operating temperature. The motor over current protection can now be selected to operate between the acceleration curve and the thermal limits to properly protect the motor during starting conditions. The over current protection should also be compared to other over current protective devices in the electrical system to insure proper coordination.

The starting of high inertia loads can sometimes lead to acceleration times that exceed the motor's thermal limits. In this case the motor manufacturer should be contacted to verify that the motor is designed for this condition and that other required protective devices are properly applied. In addition it should be verified that proper coordination with other over current devices are maintained.