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ABNORMAL STARTING OF HIGH INERTIA DRIVE INDUCTION MOTORS: A CASE FOR ROTOR THERMAL PROTECTION

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Abstract

To date it has not been possible to protect a high inertia drive motor from damaging over-temperature of an abnormal start. This is because the starting time approximates the time limit for locked rotor current. In this case, overcurrent protection must be terminated by speed detection, because it cannot distinguish locked rotor from starting current. This paper presents a novel solution to this problem in the form of a rotor thermal model derived from commonly available data.

The rotor model includes the slip-dependent heat source, thermal capacity and resistance necessary to provide the algorithm for a microprocessor based system to protect the motor through the critical starting cycle. The dynamic response of the model is temperature in units of I^2t which can be plotted on the conventional time-current plot to show the difference between the temperature and the starting current.

Introduction

This paper briefly reviews the application of time-overcurrent relays for locked rotor protection and the dilemna of the high inertia case. In this situation the duration of the starting current approaches the locked rotor time limit, but the overcurrent relay must still coordinate with the locked rotor limit. The protection is then terminated at a predetermined speed to allow the motor to start. Consequently, it has not been possible to protect the rotor during the complete starting cycle. To date even microprocessor based motor protection has implemented overcurrent characteristics which offer no improvement over conventional relays.

A. N. Eliasen [2][3] discusses the 'conflict' between high inertia drive motor capability and conventional 'relay-capability' and describes failures which can occur during starting.

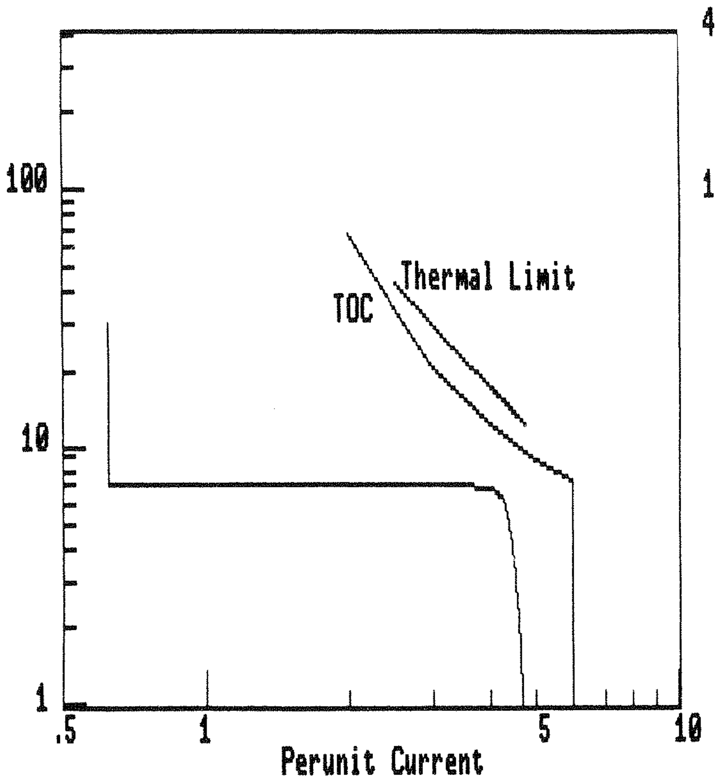

Fig. 1 Coordination of overcurrent for locked rotor protection

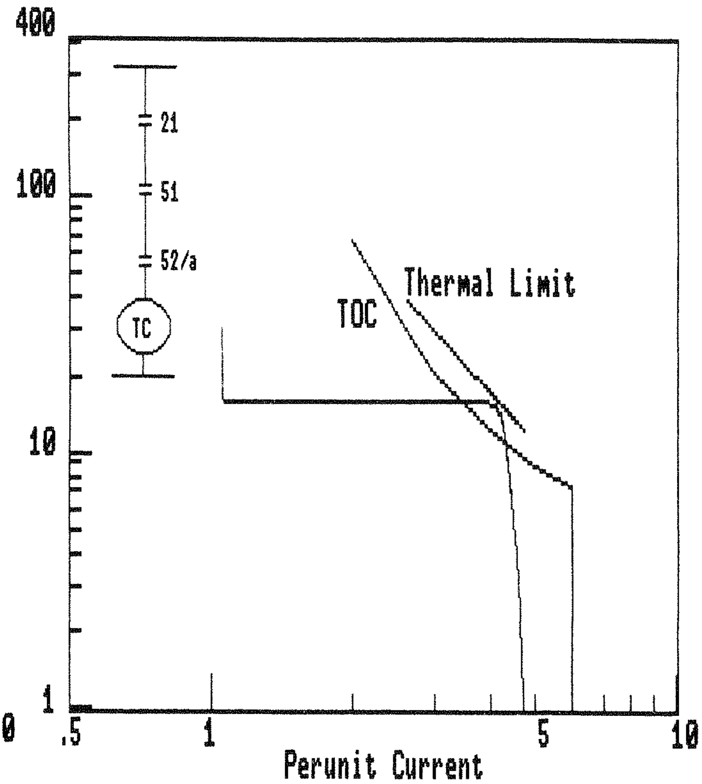

Fig. 2 High inertia case speed supervision

The dynamics of high inertia starting are analyzed using simple interactive models. As the ultimate criteria, a rotor thermal model is used to estimate the rotor temperature resulting from the starting condition. The model is constructed directly from manufacturer's data and determines the minimum information required for the application. The current and torque versus speed curves are used to determine the slip-dependent heat source and the thermal limit time-current plots determine the thermal capacity and thermal resistance of the model.

The state equations of the electrical and thermal models can be executed in real time to form the algorithm for a microprocessor based protection. The algorithm uses both voltage and current measurements and, for the first time, provides rotor thermal protection throughout the complete starting cycle.

The response of the new protection is rotor temperature and the trip value is the limit temperature expressed in units of I^2t with current in perunit. This enables the dynamic temperature resulting from a starting condition to be included as a time current plot along with the starting current and the thermal limit curve. The plot clarifies the difference between temperature and starting current and also provides for a direct comparison of the temperature with the thermal limit.

Locked Rotor Protection

Figure (1) shows a typical application of an overcurrent relay for locked rotor protection. The relay is coordinated with the thermal limit curve of the motor so that locked rotor current will be tripped before the locked rotor limit is reached. Temperature rise in the rotor is proportional to the locked rotor current squared. Consequently, the relay initiates trip to prevent the rotor from reaching a damaging temperature. At the same time the relay characteristic is set with enough time delay to allow the relay to reset and not trip when starting current drops off during a normal start.

High inertia starting is shown in Figure (2) where the load torque and/or the moment of inertia has been increased. The result is seen in the increased duration of the starting current which now approaches the limit for the locked rotor current. Here there is no choice but to coordinate the time-overcurrent characteristic with the locked rotor limit and then supervise the relay with a speed switch. The supervision in this case is shown in the inset of the figure as an under-impedance relay, device 21. The basis of this application is that the impedance looking into the machine terminals is a function of slip ranging typically from an initial value of .15 perunit ohms 87 degrees at a slip of one to near one perunit ohms 25 degrees at rated slip. The relay functions to open its contact at predetermined speed in order to prevent a trip even though the overcurrent relay closes its contact on starting current.

The impedance versus slip values for a specific application are calculated from the current and power factor versus speed curves issued for the particular motor. A typical setting is the impedance corresponding to fifty percent speed. Novel as this application is, it is unfortunate that an expense off-set mho relay, requiring both voltage and current connections, must remove rather than improve the protection.

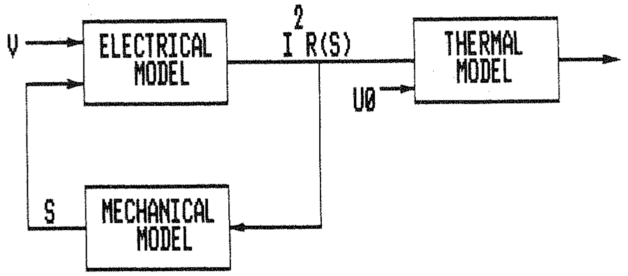

Fig. 3 Block diagram of interactive models

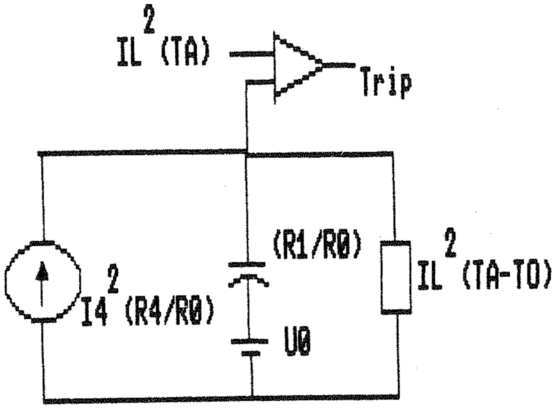

Fig. 4 Electrical analog of rotor thermal circuit

The Dynamics of Starting

Induction motor starting can be analyzed using the interactive models shown in the block diagram of Figure (3). In the electrical model, perunit voltage and slip determine the rotor current. In the mechanical model, torque developed by a component of the total power in the rotor, determines the slip. A second component of the rotor power is the input to the thermal model which determines the temperature rise over the initial rotor temperature, U0.

It is important to model the slip dependence of the rotor resistance as explained in references [1]. This is because the I^2R of the rotor decreases with decreasing slip and it is this property which accounts for the difference in heating between starting current and locked rotor current.

The electrical model is the transformer equivalent circuit of the induction motor as shown in Appendix A with stator, rotor, and mutual impedances in perunit ohms on the motor base. The mechanical model is a mathematical statement of the sum of the torques operating on the shaft including the torque developed by the rotor current, the load torque versus speed, and the moment of inertia of the rotating members. To complete the system, the thermal model includes the thermal capacity, thermal resistance of the rotor, and the slip-dependent rotor I^2R watts. The thermal model determines the rotor temperature, the ultimate limit of the system.

A recursive solution of the model equations using a finite time interval of the order of 0.2 seconds, provides the dynamic response for rotor current, torque, speed, and rotor temperature for input parameters of voltage, initial rotor temperature, load torque, and moment of inertia. The complete solution including graphics is obtained from a Basic language computer program of less than 300 statements. Such a program is listed as reference [6].

Rotor Thermal Model

The circuit shown in Figure (4) is the electrical analog of the rotor thermal model. In this circuit the heat source is shown as a constant current generator numerically equal to the I^2R watt loss in the rotor. The ability of both to retain and lose heat are represented by the thermal capacity and resistance of the rotor and are direct analogs. Temperature rise above ambient is represented as the charge voltage on the capacitor. UO is the initial charge voltage indicating the initial temperature. The limiting temperature of the rotor is UT shown as the reference of comparator monitoring the temperature U.

There has been a lively debate over what constitutes adequate induction motor application data. For the rotor, it can be taken as the minimum set of data which defines the thermal model. The required data is listed below.

Limit Temperature and Thermal Resistance

A locked rotor current, I_L, and two corresponding values of locked rotor time are needed to define the maximum temperature limit and thermal resistance. The time values needed are:

T_A: The time in seconds for the locked rotor to heat the rotor to the limiting temperature with the rotor initially at ambient temperature.

T_0: The time in seconds for the locked rotor current to heat the rotor to the limiting temperature with the rotor initially at operating temperature.

Using these parameters, the characteristic $I^2t=K$ is a slope two curve when plotted on log-log paper. By definition, all points on this curve represent the limiting temperature. Therefore, current squared times time represents temperature in the time-current plane and further, if current is in perunit, time in seconds represents temperature. Consequently, $I_L^2T_A$ is the limiting temperature, UT, in the model.

The I^2t characteristic formed using I_L and T_0 also represents the same limiting temperature. This characteristic is the familiar hot rotor limit, since it was plotted with the rotor starting from operating temperature. All points on this characteristic also represent the limiting temperature. It can be reasoned, therefore, that the difference of the cold and hot start curve, namely; $I_L^2(T_A-T_0)$, is the operating temperature. Furthermore, the operating temperature is caused by one perunit I^2 flowing in the thermal resistance. Consequently, this is also the value of the thermal resistance.

Slip Dependent Heat Source

The skin effect of the slip frequency reduces the rotor resistance and therefore the heat input during the acceleration. The change in resistance as a function of slip is given by the manufacturer's data in the form of the current and torque versus speed curves. Since these curves define the current and torque for every value of slip, the perunit rotor resistance can be calculated using the equation for torque, Q, in terms of current, resistance and slip:

$$Q=I^2R/S \tag{1}$$

Thus, $R = (Q/I^2)S$ and the calculations carried out for data from a 6000 HP motor results in the linear resistance versus slip characteristic shown in Figure (5). Although the starting current remains high during acceleration, the reduction in heat input is evident since the rotor resistance decreases to only a third of its locked rotor value at rated slip.

The rotor resistance as a function of slip is conveniently expressed using the end value resistances, R_1 and R_0, which are the resistance at slip one and slip zero respectively. As a matter of convenience, rated slip can be used for zero slip without serious error. Consequently, R_0 = rated slip and:

$$R_4 = (R_1-R_0)S + R_0 \tag{2}$$

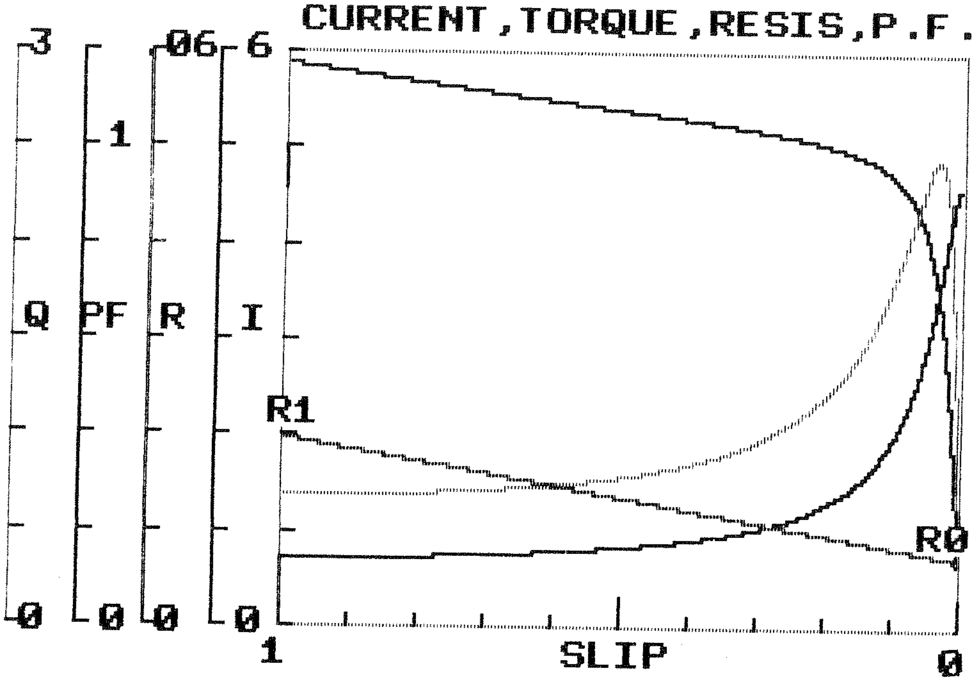

Fig. 5 Current, torque, P.F., and rotor resistance vs. slip

The slip dependent heat source in the thermal model is, therefore

$$I_4^2R_4/R_0 \qquad (3)$$

where I_4 is rotor current, and the resistances are as defined. Here, the rotor heat source has been expressed in perunit of the I^2R loss at rated current simply by dividing the equation by R_0. Using the novel speed algorithm described in reference [1], the slip, S, in equation (2) can be derived from voltage and current measurements at the terminals of the motor. The slip is given by:

$$S = R_0/[A(R-R_3)-(R_1-R_0)] \qquad (4)$$

Where R is the real part of the V/I calculation using the measured voltage and current, R_3 is the perunit stator resistance, and the factor, A, is the ratio of stator to rotor current magnitude. Consequently, the slip dependent rotor heat source is determined by input terminal voltage and current and by the resistances: R_0, R_1, and the stator resistance, R_3.

Temperature Plots in the Time-Current Plane

As shown by the block diagram of Figure (3), the thermal model monitors the rotor's slip dependent heat input for any condition of electrical input and mechanical load. It's output is the resulting temperature which is then compared directly to the thermal limit or a predetermined lower value as the trip criteria.

It is clear from the example of the thermal limit curve that a specific temperature is represented by an I^2t curve when plotted as a time-current characteristic. Therefore, the representation of the operating temperature is obtained by dividing the constant, $I^2(T_A-T_0)$, by a value of current squared and plotting the resulting value of time, t, for the corresponding value of current. The time range between this curve and the thermal limit curve shows the range of rotor temperature which can result from valid starting conditions. Furthermore, the temperature response of the thermal model can be plotted as a dynamic time-current characteristic using the same procedure.

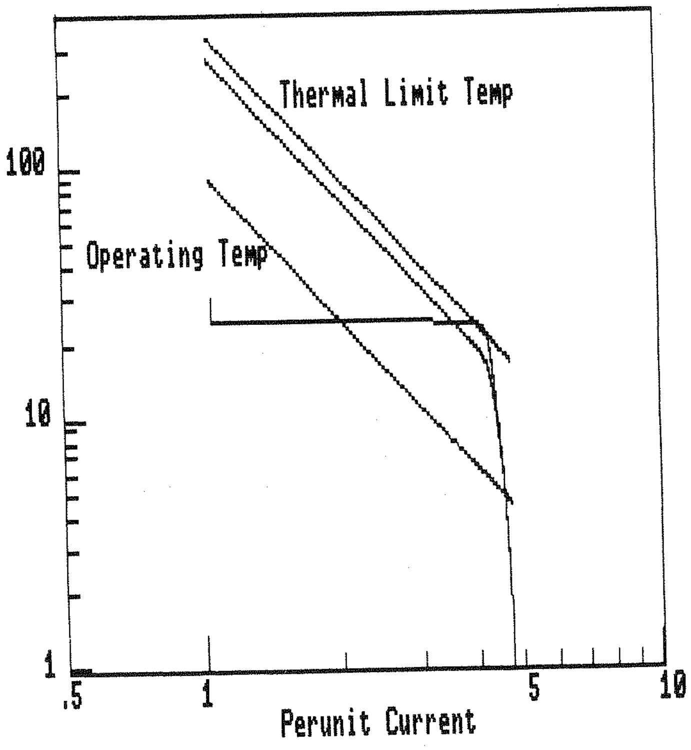

Fig. 6 Dynamic Temperature and Starting Current U0=0

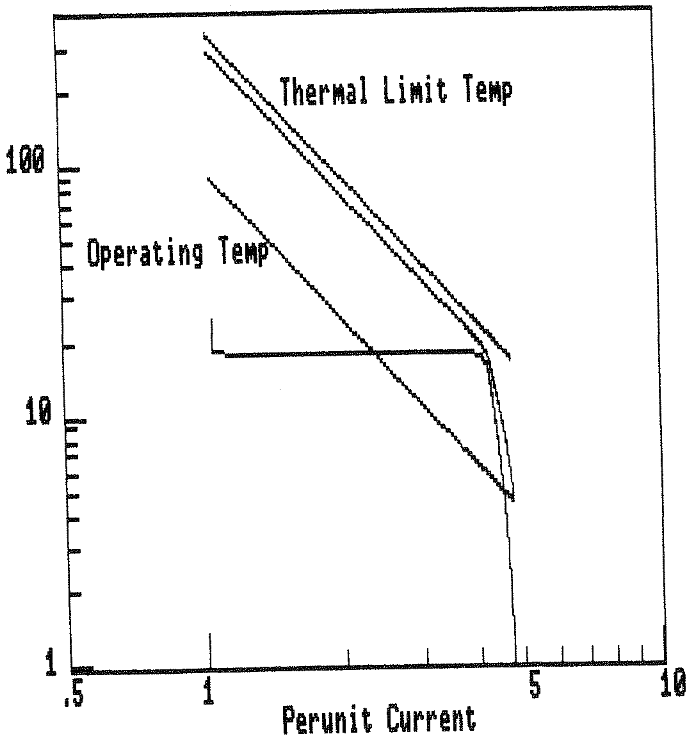

Fig. 7 Dynamic Temperature and Starting Current U0 = Operating Temperature

The temperature is obtained by updating the heat input to the state equation of the thermal model and calculating over a finite time interval. The temperature is expressed in units of I^2t which is then divided by the square of the current corresponding to the heat input. Time values obtained in this manner are plotted against corresponding values of current to obtain the dynamic temperature characteristic. The dynamic characteristic is shown in Figure (6) for the high inertia case previously plotted in Figure (2). The plot shows that the rotor temperature as a result of the start is in the range between the operating temperature and thermal limit of the motor.

Consideration of the thermal model with U0 equal zero will show that the dynamic temperature and the time-current plots are identical for the locked rotor case and that these two plots deviate when there is acceleration. This is the effect of the changing rotor resistance during acceleration and is clearly seen in Figure (6) where the temperature plot deviates from the plot of the starting current.

The representation of rotor initial temperature is an important feature of the thermal model. Figure (6) shows a cold start and it is evident that the motor would have reached the thermal limit had it been started from operating temperature. The importance of the initial temperature is shown in Figure (7) where the moment of inertia has been reduced to accommodate a start from operating temperature.

The dynamic temperature characteristics in Figure (6) and (7) show at a glance the effectiveness of rotor thermal protection to monitor the rotor throughout difficult starting and/or running conditions.

Conclusions

A review of present practice has shown that simple overcurrent protection, save for the obvious locked rotor conditions, leaves the rotor unprotected and especially during the critical starting periods. For the first time, a thermal model has been constructed which provides this type of protection and in accordance with manufacturer supplied data.

Rotor-thermal protection is made possible by modeling the rotor slip-dependent heat source in addition to the thermal capacity and resistance of the rotor. It has also been shown that the model parameters are specified by the manufacturer in the form of the following data:

1. Locked rotor current, I_L
2. Corresponding locked rotor times, T_A, and T_0
3. Current and torque versus slip curves
4. Stator resistance

The time discrete state equations of the model together with a novel speed algorithm are implemented in a microprocessor based protection package to provide the rotor thermal protection along with the usual complement of functions required for the protection of large motors.

APPENDIX A - Induction Motor Electrical Models

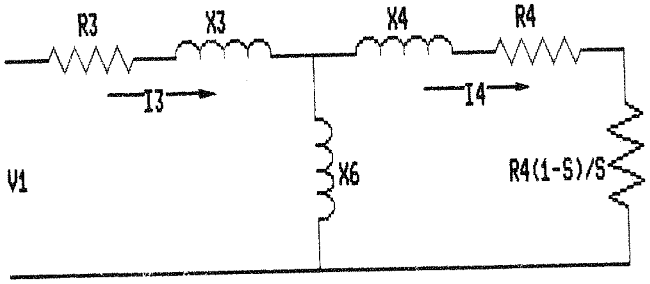

Figure A1. Positive Sequence electrical model

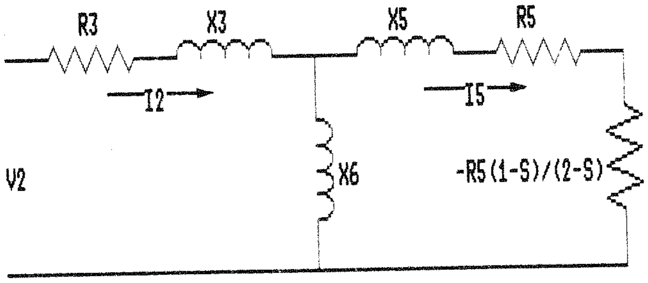

Figure A2. Negative Sequence electrical model

V1	Positive sequence terminal voltage
I1	Positive sequence stator current
I4	Positive sequence rotor current
V2	Negative sequence terminal voltage
I2	Negative sequence stator current
I5	Negative sequence rotor current
R3+jX3	Stator impedance
R4+jX4	Positive sequence rotor impedance (slip dep.)
R5+jX5	Negative sequence rotor impedance (slip dep.)
X6	Mutual reactance
S	Positive sequence slip
2-S	Negative sequence slip

Although not used in above discussion of motor starting, negative sequence heating of the rotor is given as:

$$I_5^2(R_5/R_0)$$

Where:

$$R_5=(R_1-R_0)(2-S)+R_0$$

and used as an additional input to the model in order to account for unbalanced current operation.

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