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Slip-Dependent Thermal Model for High Inertia Motor Protection: A Case Study

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Abstract - Protection of Induction motors can very well achieved using microprocessor based relaying technology, which tracks the accurate thermal conditions of the motor and provide adequate response to the motor control systems. In case of small and medium motors, protection can be achieved using I^2t thermal model developed according to the law of thermal equilibrium. As the most likely period of a motor to fail is during its start due to the inrush currents, protection of motors connected to high inertia loads during start require additional capability algorithms which can accurately predict the thermal capacity used(TCU). The paper introduces one such method called slip-dependent thermal model. It learns the motor characteristics during starting and modifies the starting protection characteristics accordingly. The paper describes how the concept of slip dependent positive and negative sequence resistances of the rotor is implemented in the motor thermal model in estimating the accurate thermal conditions, and hence to avoid a premature tripping during a valid start. The motor start protection setting for a high inertia motor generated in this manner using MATLAB will be presented.

Key Words: Numerical Protection, Thremal model, thermal capacity used, stall protection, locked rotor protection

1. INTRODUCTION

1.1 Numerical protection

Starting from electromechanical relays, relay technology has come a long way, with successive up gradation in the form of static electronic, digital and numerical relays. Each change brought-out its own advantages, improving the technology to such a level that the present–day numerical technology provides so many additional features other than mere protection. It's a microprocessor based technology using one or more digital signal processors (DSP) optimized for real time signal processing as well as running the protection algorithms. For faster real time processing many DSPs can run in parallel [10]. This also allows incorporating many functions into a single device which earlier used to implement using separate units.

1.2 Stall & locked rotor protection

Stall or pull out condition arise due to an increased load torque above the breakdown torque, causing the speed to reduce drastically. This occurs either when the shaft load is greater than the generated motor torque due to the suppression of motor terminal voltage or when an excessive load is applied beyond the full load torque. During this process the motor current will increase rapidly and approach locked rotor value. Along with the increase in current, the speed of the motor decreases and the impedance of the motor approaches the locked- rotor impedance.

In the conventional set up using EM relays, stall protection can be achieved with an over-current relay set to operate with inverse characteristics, detecting the current above the breakdown torque level. Since motor starting can result in a stall or locked-rotor condition, this protection is usually covered by setting the motor-starting relays above the motor-starting time-current curves and below the running and accelerating thermal limit for the motor.

Failure of a motor to accelerate when its stator is energized, called locked rotor can be caused by several types of abnormal conditions, including mechanical failure of the motor or load bearings, low supply voltage, or an open circuit in one phase of a three-phase voltage supply. When a motor stator winding is energized with the rotor stationary, the motor performs like a transformer with resistance-loaded secondary winding. Typically, stator winding currents may range from three to seven or more times the rated full-load value, depending on motor design and supply system impedance. The motor controller must be capable of interrupting locked-rotor current.

Since motors require and can tolerate high current for a limited time during acceleration, the normal practice of applying locked rotor protection is to apply an appropriate time delay in thermal protection in order to ensure that the motor is disconnected before stator insulation suffers thermal damage, or the rotor conductors melt or suffer damage from repeated stress and deformation. This approximation is done depending on the recorded trip data during starting or merely on the operator's experience. Thus, for motors where the starting time is less than the safe stall time of the motor, protection is easy to arrange. However, where motors are used to drive high inertia loads, the stall as well as the locked rotor withstand time can be less than the starting time. In these cases, an additional means must be provided to enable discrimination between the two conditions to be achieved.

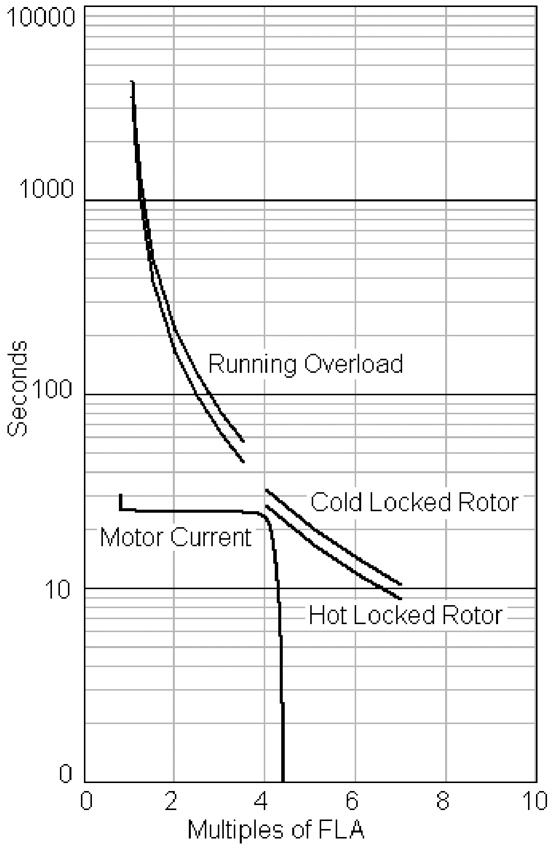

Fig.1 Thermal limit curves

2. THERMAL PROTECTION

Majority of the motor failures are either indirectly or directly caused by overloading (either prolonged or cyclic), operation on unbalanced supply voltage, or single phasing, stall or locked rotor conditions which all lead to excessive heating. The generally accepted rule is that insulation life is halved for each 10ºC rise in temperature above the rated value, modified by the length of time spent at the higher temperature. The thermal withstand capability of the motor is affected by heating in the winding prior to a fault. It is therefore important that the relay characteristic takes account of the extremes of zero and full-load pre-fault current known respectively as the 'Cold' and 'Hot' conditions [8]. Nowadays various numerical relay manufacturers uses a model called ‘thermal replica’ model which has been developed according to the principle that motor is a homogeneous body creating and dissipating heat at a rate proportional to the temperature rise.

In the normal load case, the starting time is shorter than the locked rotor time. This allows the trip time of an inverse-time overcurrent relay to be set long enough to let the motor start yet short enough to prevent the current from exceeding the locked rotor time. However, increasing moment of inertia increases the starting time and the current encroaches on the locked rotor limit as shown in Fig.1. This is the much challenging high-inertia motor starting condition where the relay overestimates the motor heating than actual and the relay cannot be set to avoid a trip. In slip-dependent thermal model, voltage and current measured by the relay and the Steinmetz model of induction motor are used to calculate the rotor resistance as a function of slip to determine the true heating during a high inertia start.

3. SLIP-DEPENDENT ROTOR THERMAL MODEL

As for majority of applications, the safe stall time defines the rotor thermal limit, the starting problem of high inertia motors can be very well managed by accurately modelling the rotor thermal conditions during starting and acceleration period. Slip- dependent thermal model introduces a new rotor thermal model which is used to modify the time-current characteristic during starting from the measured current and voltage and the supporting motor data.(Section VII).

The relay uses the calculated slip to compute the positive and negative-sequence rotor resistance throughout the motor start. Calculation of rotor resistance accurately reflects the heating that takes place in the motor during a start and results in longer allowable acceleration times before tripping than would be allowed by an I^2t thermal model.

4. THE EQUIVALENT CIRCUIT OF INDUCTION MOTOR

The sources of motor heating are the watts loss in the rotor and stator winding resistances. The resistances are shown in the Steinmetz model of the motor in Fig.2, in which R_s is the stator winding resistance and R_r is the slip-dependent rotor resistance that decreases from a high locked-rotor value to a low running value at rated speed [7].

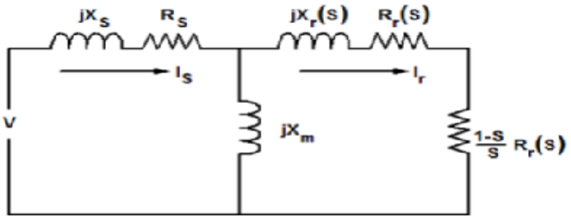

Fig.2 Steinmetz Motor Equivalent Circuit

The positive-and negative-sequence rotor resistances are given by the linear functions of slip S as follows.

$$R_1 = (R_M - R_N)S + R_N \quad \text{..... (1)}$$

$$R_2 = (R_M - R_N)(2 - S) + R_N \quad \text{...... (2)}$$

Where R_M is the locked rotor resistance and R_N is the resistance at rated speed. The relay logic estimates R_M and R_N from the known quantities defined by locked rotor current (I_L), locked rotor torque (LRQ), synchronous speed ω_{syn}, and rated speed ω_{rated} as follows.

In the Steinmetz model shown in Fig.2, the I^2r watts loss in the rotor resistor [(1-S)/S]Rr(S) is the equivalent mechanical power(P_M). Hence the torque can be calculated as,

$$Q_M = \frac{P_M}{\omega} = \frac{P_M}{1-S} = I^2 \frac{1-S}{S} R_r \frac{1}{1-S} = \frac{I^2 R_r}{S} \quad \text{......... (3)}$$

Solving for R_r in terms of torque, current and slip gives,

$$R_r = \frac{Q_M}{I^2} S \quad \text{............. (4)}$$

For locked rotor S = 1, Q_M = LRQ

$$R_r = R_M = \frac{LRQ}{I_L^2} \quad \text{....... (5)}$$

The slip S at rated load is S_N, Current I = 1 pu, and torque Q_M = 1 pu

$$R_N = S_N \quad \text{................ (6)}$$

$$R_N = \frac{\omega_{syn} - \omega_{rated}}{\omega_{syn}} \quad \text{...... (7)}$$

$$R_M = \frac{LRQ}{I_L^2} \quad \text{............... (8)}$$

The rotor resistance for any value of slip can be calculated using values taken from the plot of current and torque shown in fig.3.

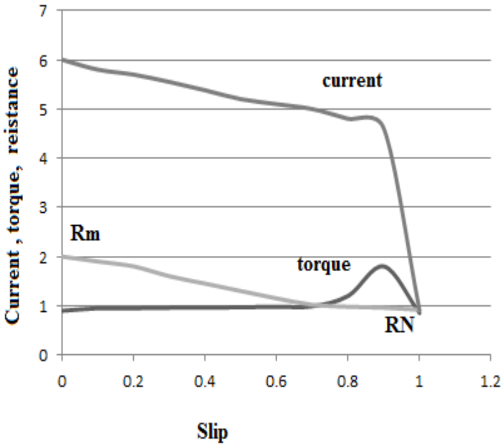

Fig.3 Motor Current, Torque, and Rotor R Plotted Versus Slip

5. CALCULATING SLIP

Relay can use the measurement of voltage and current to calculate the slip and can be used to calculate the slip dependent rotor resistance at any instant as follows.

$$Z = R + jX = \frac{V_1}{I_1} \quad \text{................ (9)}$$

From the Steimentz equivalent circuit,

$$Z = R_S + jX_S + \frac{\left(\frac{R_r}{s} + jX_r\right) . jX_m}{\frac{R_r}{s} + jX_r + jX_m} \quad \text{... (10)}$$

Expanding the equation gives,

$$Z = R_S + jX_S + \frac{\frac{R_r}{s} X_m^2 + j\left(X_m\left(\frac{R_r}{s}\right)^2 + X_r X_m (X_r + X_m)\right)}{\left(\frac{R_r}{s}\right)^2 + (X_r + X_m)^2} \quad \text{. (11)}$$

The real part of Z is,

$$R = R_S + \frac{\frac{R_r}{s} X_m^2}{\left(\frac{R_r}{s}\right)^2 + (X_r + X_m)^2} \quad \text{...... (12)}$$

Dividing by (Xm) ²

$$R = R_S + \frac{\frac{R_r}{s}}{\left(\frac{R_r}{s}\right)^2 \frac{1}{X_m^2} + \frac{(X_r + X_m)^2}{X_m^2}} \quad \text{........... (13)}$$

But is $\left(\frac{R_r}{s}\right)^2 \frac{1}{X_m^2}$ negligible

Let,

$$A = \langle \left(\frac{X_r + X_m}{X_m} \right)^2 \rangle \quad \text{............ (14)}$$

Using the real part of motor impedance

$$R = R_S + \frac{R_r}{A.S} \quad \text{... ... ... (15)}$$

Substituting (1) for Rr in (15) and solving for slip in terms of R_m, R_N and measured value of motor resistance R,

$$S = \frac{R_N}{A(R - R_S) - (R_M - R_N)} \quad \text{............. (16)}$$

6. ROTOR THERMAL MODEL

The safe starting time is indicated by the locked rotor curves shown in Fig. 1. The cold locked rotor characteristic specifies the time it takes the starting current to heat the rotor to the limiting temperature with the motor initially at ambient. The hot locked rotor characteristic specifies the time for starting current to heat the rotor to the limiting temperature with the motor initially at operating temperature. The limiting temperature
in units of I^2t is:

$$U_L = I_L^2 T_A \quad \text{................. (17)}$$

Where: U_L -- rotor temperature limit
I_L-- locked rotor current in per unit of FLA
TA -- safe stall time from ambient.

Since both the hot and cold characteristic represent the same limiting temperature, the operating temperature can be expressed in terms of the limiting temperature as follows:

$$U_L = I_L^2 T_O \;+ U_O \text{........................} (18)$$

$$U_O = I_L^2 (T_A \;- T_O) \text{..........................} (19)$$

Fig.4 shows the first-order thermal model that incorporates the I²t properties of the rotor thermal limit curves as well as the effect of the slip-dependent positive- and negative sequence rotor resistance on the input watts.

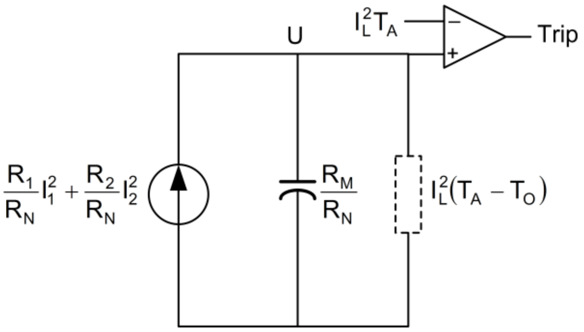

Fig.4 Slip dependent rotor thermal model

The following discrete form of the differential equation of the rotor thermal model is processed each processing interval to calculate the temperature U:

For I > 2.5

$$U_n = \left(\frac{R_1}{R_N} I_1^2 + \frac{R_2}{R_N} I_2^2\right)\frac{\Delta t}{C_{th}} + U_{n-1} \text{...} [20]$$

For I ≤ 2.5

$$U_n = \left(\frac{R_1}{R_N} I_1^2 + \frac{R_2}{R_N} I_2^2\right)\frac{\Delta t}{C_{th}} + (1 - \frac{\Delta t}{R_{th} C_{th}}) \; U_{n-1} \text{.........} (21)$$

Where: thermal capacitance, $C_{Th} = R_M / R_N$
thermal resistance, $R_{Th} = (I_L)^2 (T_A - T_O)$

I_1 and I_2 are the positive- and negative-sequence Currents, respectively. Note that the thermal resistance is only considered when the current drops below 2.5 pu, so that the calculation of temperature is adiabatic for starting current. At each sample, U_n is compared to the trip threshold and asserts the trip signal if the limiting temperature is exceeded.

7. SETTINGS OF THE THERMAL MODEL

The motor examined was a 2800KW, 6.6KV induced Draft fan. The following details were taken from the motor data sheet.

7.1 For rotor model

Table-1 Motor specifications

Motor Parameter	Assigned Value
Synchronous speed, ω_{syn}	1500 rpm
Rated speed, ω_{rated}	1486 rpm
Locked Rotor Current, I_L	6pu
Locked Rotor Torque, LRQ	0.7 Pu
Cold Rotor Limit, T_A	17.0 sec.
Hot Rotor Limit, T_O	12.0 sec

The relay monitors voltage and current to determine the motor Z and calculates R_M and R_N. The real part of Z is then used to derive slip and calculate the slip-dependent rotor positive-and negative-sequence resistance.

$$R_N = \frac{\omega_{syn} - \omega_{rated}}{\omega_{syn}} = \frac{1500 - 1486}{1500} = 0.00933$$

$$R_M = \frac{LRQ}{I_L^2} = \frac{0.7}{6^2} = 0.01944$$

The speed algorithm applied to the relay is as follows

Total resistance of the motor,

$$R = Real\ part\ of\ \frac{(V_1)}{(I_1)}$$

V_1 and I_1 are the voltage and current measured at each processing interval

$$A = \langle(\frac{X_r + X_m}{X_m})^2\rangle = (\frac{0.35 + 3.5}{3.5})^2 = 1.21$$

R_M, A and the initial value of R measured during start is used to determine the stator resistance R_S:

$$R_s = R_{initial} - \frac{R_M}{A} \quad \ldots\ldots\ldots\ldots\ldots (22)$$

Then for any value of measured resistance R the corresponding slip can be calculated as,

$$S = \frac{R_N}{A(R-R_S)-(R_M-R_N)}$$

And the positive and negative sequence resistances:

$$R_1 = (R_M - R_N)S + R_N$$

$$R_2 = (R_M - R_N)(2 - S) + R_N$$

A simulation of the motor start was performed in MATLAB software to see how closely the actual quantities measured by the relay tracked with the simulated data based on the known motor parameters. The simulated parameters like positive sequence resistance, negative sequence resistance, slip, and thermal capacity used show the successful start of the motor, as shown in the Figures below.

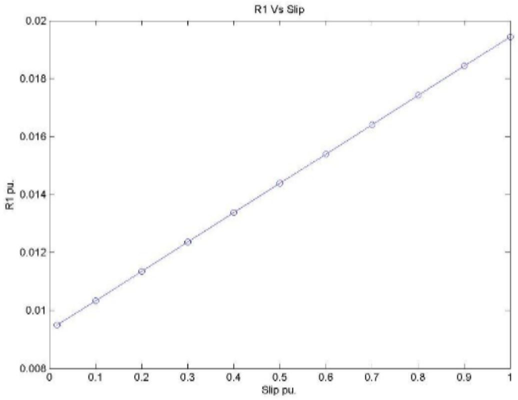

Fig.5 Motor resistance, R_1 during start

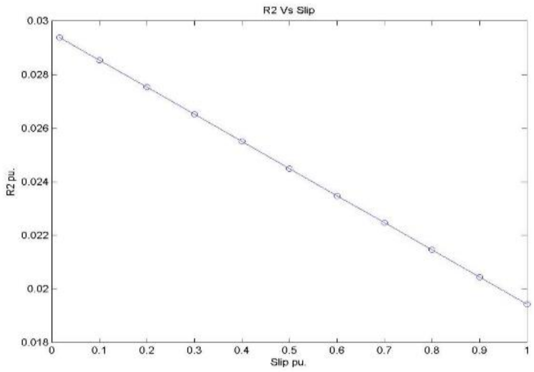

Fig. 6 Rotor resistance, R_2 during start

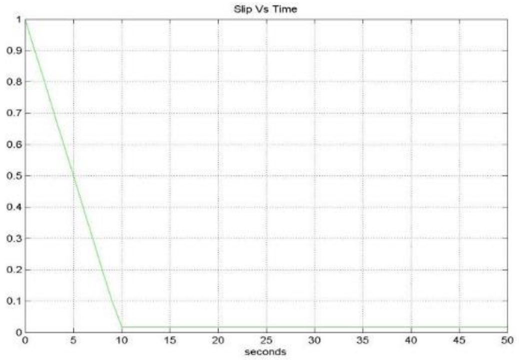

Fig. 7 Motor slip during start

Fig.5, Fig.6 & fig.7 show the variations in rotor positive and negative rotor resistances and slip during the moment of starting to the acceleration period. The rotor thermal status is estimated using the first order differential equation mentioned in equations no. 20 and 21.

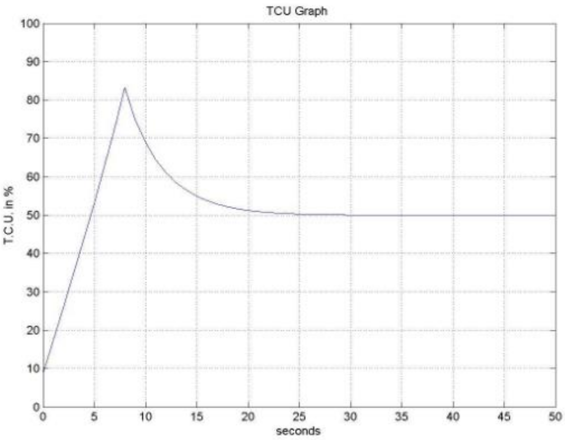

Fig.8 Plot of actual thermal capacity used

Fig. 8 shows the successful start of the motor where Rr decreases, and the temperature reaches only 80 % of the limiting temperature at the time of acceleration.

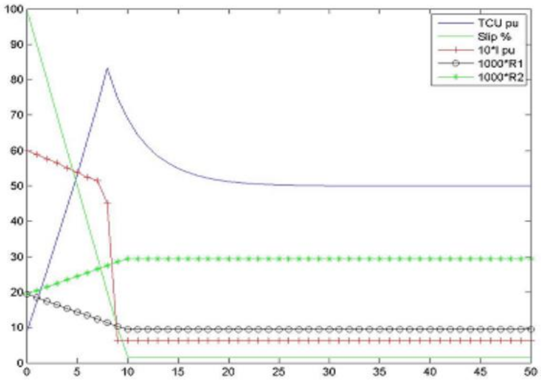

Fig.9 Motor starting showing thermal model emulating the rotor temperature

8. ANALYSIS & RECOMMENDATIONS

Characteristics plotted above are the simulation results obtained for various parameters that decide the starting performance of the motor. For better estimation of the temperature, rotor resistance is resolved into its positive and negative components. Analysis done on the graph lead to following conclusions.

1) As the motor gears to rated speed rotor resistance varies from a maximum value at unity slip to 1/3rd at rated speed.

2) During the acceleration period Positive sequence resistance decreases while negative sequence resistance increase, indicating the prominence of rotor heating.

3) Slip varies from maximum one to the minimum rated slip during acceleration time.

4) In the thermal capacity used (TCU) plot, it is seen that, the actual motor acceleration time is around 7.5 sec, and as expected with a programmed 12-seconds safe hot locked rotor time, the thermal capacity used was only 83 %.

5) When the simulation is tried with I^2t model, the heating risen up to almost 100% within 7 seconds itself. If the same motor was attempted to start with a 12 seconds LRTHOTI setting, for locked rotor protection, the relay would have stopped the attempt at 7 second itself, by detecting a locked rotor condition, as the heating would have become 100%. This overestimation is avoided in the slip-dependent model as it is able to calculate the true I^2rt instead of simply I^2t.(here the timings are very near to each other as the motor torque is comparatively lower for a high inertia class, and the situation more or less depend on the load conditions).

6) Figure 8 shows the successful start of the motor, with a true TCU calculation, as expected. As it is seen that the motor reaches its rated speed at around 7 seconds, the locked rotor time setting can be modified to a value slightly higher than the acceleration time obtained from the slip dependent-model.

9. CONCLUSION

In case of high starting torque motors optimum protection can be achieved by slip-dependent thermal motor. It has been observed that the rotor resistance varies considerably during the starting period which facilitates the modification in the protection scheme. During the acceleration period, the positive sequence resistance decreases and negative sequence resistance increases indicating the predominance of losses over the actual output during start. MATLAB simulation results on the derived model shows that, during the acceleration period the thermal capacity used (TCU) calculated by the relay reaches only around 80%, indicating a possible successful start of the motor, by setting the relay with a higher starting time than the mentioned LRTHOTI in the data sheet.

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