High-Inertia Synchronous Motor Protection and Lessons Learned

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***Abstract*—Saudi Aramco replaced existing 24,500 hp gas compressor motors at two major gas plants in Saudi Arabia with 27,000 hp, 13.2 kV electric high-inertia motors. The high-inertia motor starting time can be longer than or closer to the specified safe stall time. Therefore, for these motors, thermal model analysis is critical for adequate stator and rotor protection. Rotor thermal capacity for synchronous motors is significantly less than that of induction motors per IEEE C37.96-2000. Protection in addition to the thermal model is required in order to correctly protect these critical motors during starting.**

I. Introduction and System Overview

The scope of the project this paper discusses included the replacement of three existing motors and the plant field excitation control panels with 27,000 hp synchronous motors at a Saudi Aramco gas plant in Saudi Arabia. The compressor motors were 26 years old, had experienced frequent motor trips due to failures, and required an increasing number of shutdowns for maintenance. The failures were largely attributed to original design deficiencies and advancing age. These failures included the following:

- Interturn spatial insulation failures.
- Fan blade failures.
- Lube oil leaks.
- Defective ripple springs.
- Potential armature failures.

The new synchronous motors are capable of starting and accelerating the driven load to operating speed with 80 percent of the motor rated voltage applied to the motor terminals. The maximum locked-rotor current of the new motors cannot be more than 500 percent of the full-load rating. The existing power cables and feeder breakers were reused for connecting the new motors.

This paper discusses the tools used for the thermal model selection, custom thermal protection, relay settings, and the coordination study for these motors. This paper also provides present practices and protection guidelines for large synchronous motors.

II. Synchronous Motor Basics

The difference between an induction motor and a synchronous motor lies in the construction of the rotor, which determines whether the motor operates synchronously or asynchronously with respect to the power system. A synchronous motor, as the name implies, operates in synchronization with the system to which it is connected. This is accomplished by applying a direct current (dc) to the rotor field winding, which generates a magnetic field on the rotor that aligns with the rotating field created by the current flowing in the stator. A coupling is created between the rotor and the stator magnetic fields, causing the rotor to spin at a synchronous speed.

Induction motors, on the other hand, do not possess a field winding to create a magnetic field on the rotor. Instead, the motor relies on the relative motion between the stator rotating magnetic field and the rotor. The frequency difference between the two is the slip frequency. The relative motion induces a current on the rotor, creating a magnetic field that interacts with the stator magnetic field to create the required torque. Induction motors can be divided into two major categories: squirrel-cage and wound rotor. Synchronous motors are classified as either salient pole or round rotor (high speed).

Typically, a synchronous motor is started like an induction motor. If the motor has a separate squirrel-cage winding, that winding is used to get the motor started and to get it up to about 97 percent speed. Once the motor is started, the field can be applied and the motor can synchronize with the system. For brushless motors, the rotating assembly includes controls for applying the field at the correct time. For brushed machines, a separate field relay is required. Using the frequency of induced voltage in the field circuit during starting and the number of poles, the relay calculates the speed of the machine. When the machine reaches the desired speed and the poles are aligned, the relay flashes the field. The terminal voltage and induced field voltage have a phase shift of 90 degrees when the poles are aligned.

Just like induction motors, synchronous motors must be protected against thermal excursions during starting and running as well as fault and unbalance currents that can rapidly damage the motor. Because dc excitation and synchronous operation are fundamental for the operation of a synchronous machine, additional protection against conditions such as out-of-step and loss-of-field is required. During starting, control equipment is required to automatically apply the dc excitation field for a smooth transition from induction start to synchronous running mode. The synchronous motor thermal capability and allowable locked-rotor time (LRT) are generally much less than those of the induction motor, and special protection for the damper winding must be provided [1].

Fig. 1 shows the characteristics of a typical motor curve, displaying the locked-rotor amperes (LRA), load torque, and motor torque curve with respect to speed.

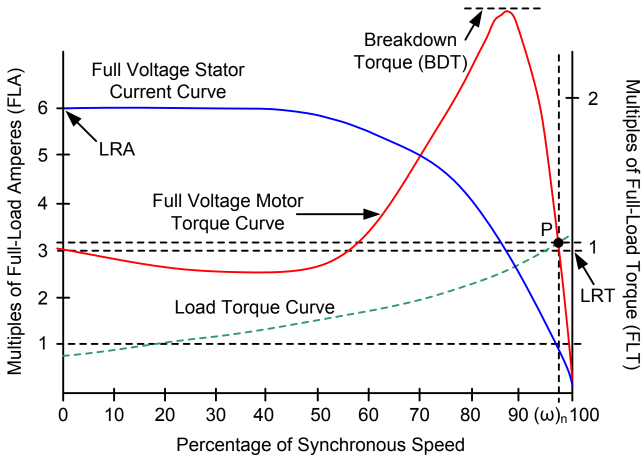

Fig. 1. Typical Motor Operating Characteristics

A. Motor Selection Criteria

Saudi Aramco standards require synchronous motors that are rated at 14,000 hp and above to be equipped with brushless excitation. The motors for the application discussed in this paper are installed in an area in which volatile, flammable gases are handled and processed. Because brush-type excitation system sparks can ignite flammable gases, only brushless excitation systems with synchronous motors are allowed.

B. Typical Motor Protection Relay

Digital relays can control, monitor, and protect induction motors, synchronous motors, adjustable speed drive (ASD) motors, and special applications such as high-inertia motors. A motor thermal element provides integrated protection for all of the following [2] [3] [4] [5]:

- Locked-rotor starts.
- Running overload.
- Unbalanced current and negative-sequence current heating.
- Repeated or frequent starts.

A digital relay dynamically calculates motor slip to precisely track motor temperature using the thermal model. The rotor resistance changes depending on slip and generates heat, especially during starting when the current and slip are the highest. By correctly calculating the rotor temperature, the thermal model reduces the time between starts. It also gives the motor more time to reach its rated speed before tripping. Advanced digital relays provide comprehensive metering and monitoring functions so that thermal model parameters can be fine-tuned and the motor can be maintained and serviced at regular intervals. The monitoring and reporting functions offer the following:

- Motor start reports and trends.
- Load-profile monitoring.
- Motor operating statistics.
- Event reports (4- or 32-samples-per-cycle resolution).
- Sequential Events Recorder (SER), with as many as 1,024 time-tagged event reports and the most recent input, output, and element transitions.

Typical motor protection elements included in a single digital relay can consist of the protection elements shown in Fig. 2. Motor protection relays offer communications and integration support with multiple protocols and programmable automation features.

III. Example Setting Calculations

This section discusses the typical settings and selection criteria for a 27,000 hp synchronous motor [1] [5] [6] [7] [8]. The protection element selection and justification for settings at the gas plant are discussed. The following protection elements are enabled:

- Phase overcurrent (50/51P).
- Neutral overcurrent (50N).
- Motor differential overcurrent (87M).
- Load jam (JAMTRIP).
- Power factor (55).
- Current unbalance (46 and 50Q).
- Phase reversal (47T).
- Overvoltage and undervoltage (27/59).
- Overfrequency and underfrequency (81).

A. Phase Overcurrent (50/51P)

For large synchronous motors, circuit breakers are selected and it is possible to use instantaneous overcurrent elements. The phase instantaneous overcurrent element is set at 1.65 times LRA per IEEE C37.96-2000 [1]. IEEE recommends a range of 1.65 to 2.5 FLA to account for asymmetrical current. This makes the instantaneous phase overcurrent element sensitive for phase faults without tripping for motor starting conditions. A time delay of 0.1 seconds (i.e., 6 cycles) is selected to avoid tripping for the transient inrush current.

IEEE C37.96-2000 [1] and NEMA MG 1-1998 [9] suggest disabling the 51P element for motor protection. The 51P element is difficult to coordinate with an upstream device because it is at the end of the line and because of the multiple overcurrent relays (cascaded) in series. In addition, the thermal element provides better thermal protection during motor starting and running. However, the 51P element was enabled as a backup for this application. The element is only enabled during motor running conditions. Phase time-overcurrent elements are set at 115 percent of the motor full-load amperes (FLA).

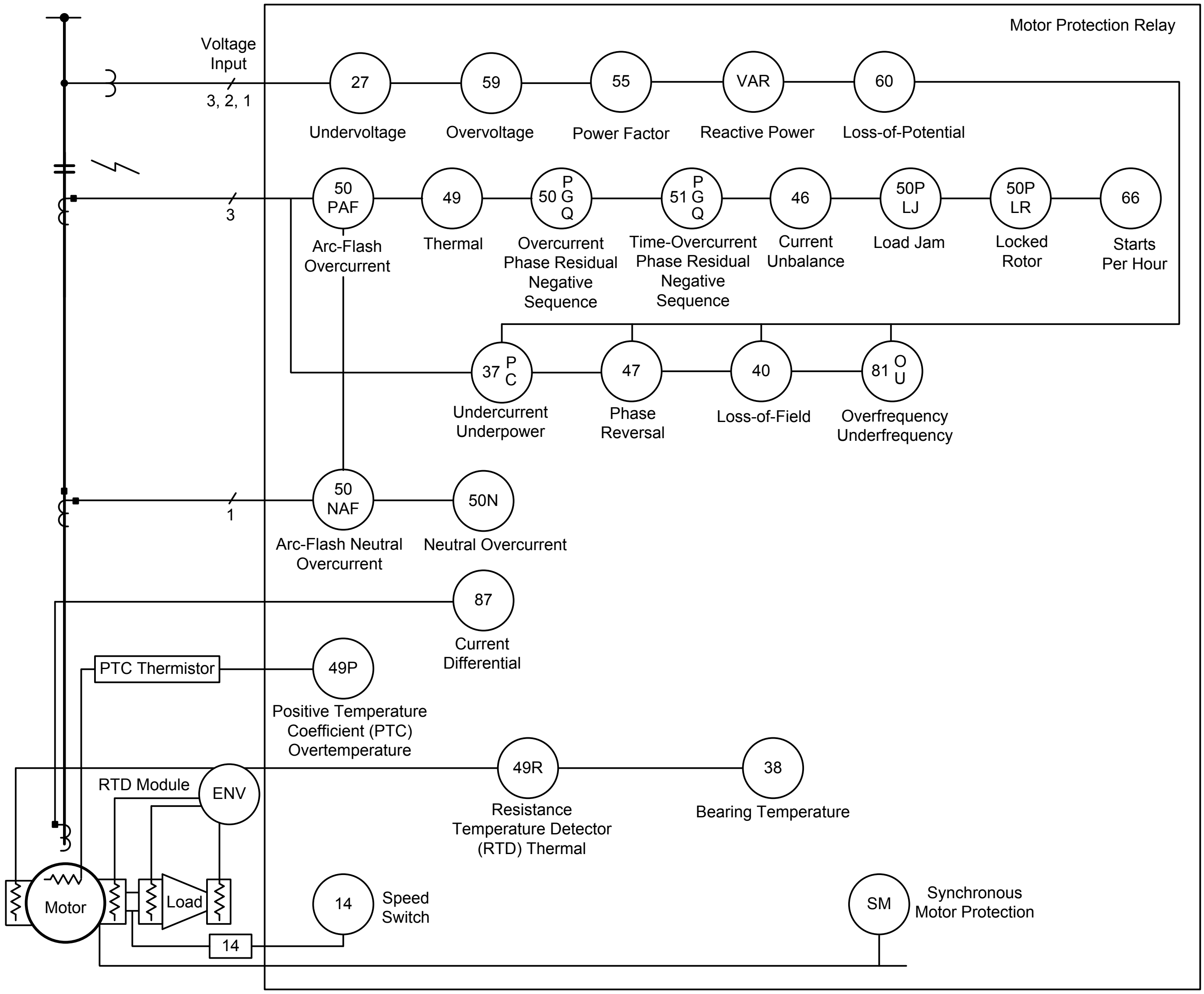

Fig. 2. Standard Features of a Motor Protection Relay

B. Neutral Overcurrent Element (50N)

The gas plant system is low-resistance grounded, with the fault current contribution limited to 400 A per 230/13.2 kV transformer, as shown in Fig. 3. Therefore, the neutral overcurrent relay setting is selected based on the minimum fault current. The motor neutral ground instantaneous overcurrent element is set at 20 A primary, which coordinates with the 200 A pickup on the transformer low-side neutral overcurrent. A time delay of 0.1 seconds (i.e., 6 cycles) is selected to avoid tripping for the inrush current.

C. Motor Differential Overcurrent Element (87M)

Differential protection is often applied to important synchronous motors as well as to most large synchronous motors. The most common connection is through a window current transformer (CT). For this application, the phase leads must pass through the CT in one direction and the neutral leads must be brought back through the CTs in the opposite direction. Because load current and CT saturation do not need to be considered for this application, the differential element can be set very sensitively. Typically, a 50/5 CT ratio is chosen with a pickup setting of 0.5 to 1.0 A secondary and a time delay of approximately 6 cycles. For this application, a pickup setting of 1.0 A was selected.

D. Load Jam Element

Synchronous motors have a high pullout torque, but if that torque is exceeded, the machine slips a pole. If a load jam occurs, the machine goes out of step, a condition that can also be detected by the 55 or VAR elements. However, load jam protection is required for this application because quick detection and isolation are important during these conditions and other motors can stall. A typical overcurrent element pickup can be 1.5 to 2.0 times the FLA with a 2-second delay. For this application, the proposed settings are 2.0 per unit. The load jam element is only enabled while in the running state, so starting currents do not affect it. This provides better protection for the motor because it trips the motor faster than the overload protection (51P) when a load jam occurs.

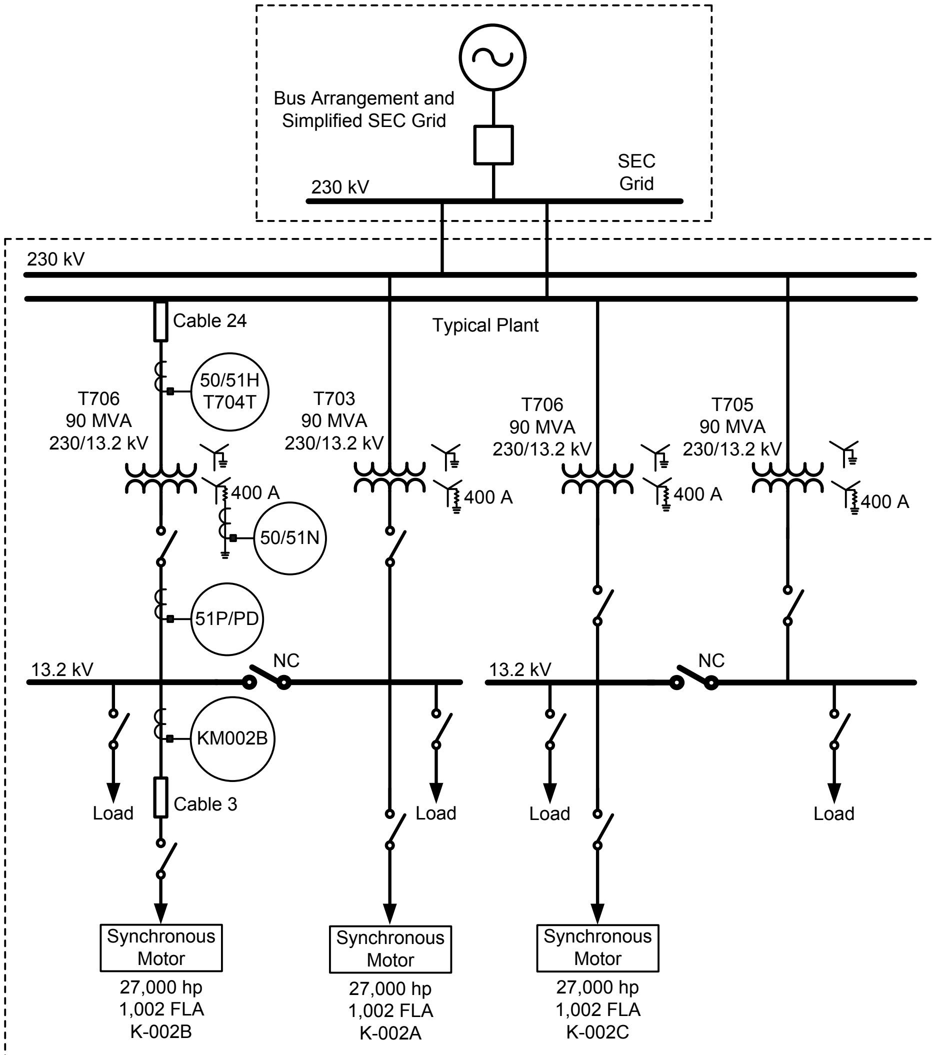

Fig. 3. System One-Line Diagram

E. Power Factor Element (55)

The power factor element is used to detect synchronous motor out-of-step or loss-of-field conditions. A synchronous motor should not get into the lagging power factor range for long periods of time. A synchronous motor should be in the unity or leading power factor (importing watts [+] and exporting VARs [–]) area during normal running conditions.

When the current of a synchronous motor lags its phase voltage by 30 degrees or more, it is either in a loss-of-field condition or it has pulled out of synchronization with the electric power system. When the synchronous motor is running and the measured lagging power factor falls below the specified value for longer than a specified time period, the relay trips. In this application, the power factor element is disabled when the motor is stopped or starting. The power factor trip pickup is selected for 0.8 to 0.9 lag with a typical 1-second delay for trip. In addition to the power factor reactive, the VAR element is also enabled with the settings based on a 0.8 to 0.9 power factor. Separate loss of excitation protection is a supplied part of the excitation panel and is wired to trip the motor breaker directly or through the protective relay if wired as an input.

F. Current Unbalance Element (46 and 50Q)

A current unbalance element protects against rotor heating caused by an unbalanced current. Negative-sequence currents flow in the motor when it is connected to a system with unbalanced voltages. Negative-sequence flow is damaging to the motor because the rotating magnetic field generated by the negative-sequence currents rotates in the opposite direction of the rotor. This relative motion results in 120 Hz of current being induced on the rotor. The magnitude of the double-line frequency current depends on the location of the fault, number of turns shorted, mutual induction, and system and motor impedance. Negative-sequence current can cause thermal damage very quickly due to the skin effect [1].

An open phase also results in positive- and negative-sequence overcurrents. Unbalance terminal voltage causes unbalance currents in the stator to flow and results in significant rotor heating. The thermal model also models the heating effect. However, current unbalance elements are also enabled in this application. A digital relay with two protection elements (46 and 50Q) was selected. The 46 element uses a maximum current deviation function, while the 50Q element operates on calculated 3I2. Each element has alarm and trip level settings.

Saudi National Grid policy requirements for system design stipulate that under normal system conditions, the three phase voltages must be balanced at 13.8 kV and higher voltages in the system, such that the negative phase-sequence voltage does not exceed 2 percent of the positive phase-sequence voltage. A maximum voltage unbalance will generate approximately 2 • 6% = 12% current unbalance.

For this application, the 46 element alarm is initiated for the 10 percent unbalance with 10 seconds of delay and a trip is initiated after a 5-second delay for a current unbalance of 20 percent or higher. The negative-sequence instantaneous overcurrent setting is selected to pick up at 40 percent of the motor FLA (400 A primary and 1.67 A secondary with 1200/5 CT), which represents around 15 percent current unbalance, and to trip the motor breaker with a 4-second delay.

G. Phase Reversal Element (47T)

The motor protection relay uses phase currents or voltages to determine whether the phase rotation of signals applied to the relay matches the phase rotation setting. If incorrect phase rotation is observed, the relay trips in 0.5 seconds.

H. Overvoltage and Undervoltage Elements (27/59)

Overvoltage elements are rarely used for motor protection because motors are typically applied at the end of a line and fed through one or more transformers. It is unlikely in most cases that the motor will experience an overvoltage condition. However, if the system is ungrounded, damaging overvoltages can be seen on the unfaulted phases in the case of a ground fault. Note that NEMA MG 1-1998 specifies that motors must be capable of operating at rated load with a variation of ±10 percent of the rated voltage.

An undervoltage element can be set in a motor protection relay to prevent starting the motor with insufficient voltage. The motor manufacturer can help determine this setting. If information is unavailable from the manufacturer, the pickup can be set to 80 percent of the nominal voltage with a time delay. This corresponds to 64 percent of the nominal starting torque, which may not be enough to start the motor. The time delay should be long enough to ensure motor disconnection before automatic transfer scheme (ATS) operation.

However, for this application, considering that Saudi Aramco standards require synchronous motors to be capable of starting and accelerating the driven load to operating speed with 80 percent of the motor rated voltage at the motor terminals—allowing for the natural rise of the voltage as the motor accelerates—undervoltage settings of 65 percent of the bus nominal voltage with no delay were selected. The undervoltage element protects the motor against a sudden restoration of the power supply by tripping the motor breaker if the supply to the motor is interrupted. This prevents the power supply from being restored out of phase with the motor generated voltage.

Running the motor continuously under an overvoltage condition can increase the volts/Hz and can cause saturation of the air gap, resulting in the motor overheating. This was one of the suspected causes of the abnormally high rate of motor failure in one of the Saudi Aramco facilities. The high voltage maintained on the motor was intended to facilitate motor starting. Boosting the voltage for starting purposes must only be done temporarily.

I. Overfrequency and Underfrequency Elements (81)

Underfrequency protection can be used to quickly disconnect a motor in cases of power supply failure by tripping the motor breaker, which avoids energizing the motor out of synchronization in cases of fast source transfer.

Overfrequency and underfrequency elements can be programmed for tripping, alarming, and recording (e.g., SER). Settings are selected at ±5 percent of the nominal frequency with a time delay, per IEEE standards. While a second level of underfrequency and overfrequency protection is programmed for alarming, no underfrequency or overfrequency trip is programmed for this application.

IV. System One-Line Diagram and Coordination Study

As shown in Fig. 3, the 230 kV typical substation is fed from the national grid through two 230 kV lines and from a cogeneration plant through two 230 kV short lines. The load, which is mainly motors, is fed from two 90/120 MVA 230/13.2 kV transformers. These step-down transformers are solidly grounded on the high-voltage side and resistance grounded at 400 A resistance on the low-voltage side. Thus, the ground fault current is limited to 800 A on the 13.2 kV bus because the tie breaker between the two buses is operated as normally closed. One 27,000 hp motor is intended to be fed from each of these 13.2 kV buses.

System modeling and a relay coordination study were conducted using Saudi Aramco-approved electrical engineering software. The coordination study was performed to coordinate the relevant protection elements. The motor starting curves at 100 percent and 80 percent of the voltage were provided by the motor manufacturer. Fig. 4 shows the cable damage curve, transformer damage curve, motor overload curve, LRT, starting curve, and overcurrent elements. Time-overcurrent elements are disabled during starting. Neutral overcurrent elements are selected for various system operating conditions to maintain the coordination.

V. Thermal Model

Resistance temperature detectors (RTDs) are used by motor manufacturers for motor thermal protection. Inverse-time overcurrent or negative-sequence overcurrent elements are also used to detect currents that can lead to overheating. However, neither time-overcurrent elements nor RTDs can correctly track the excursions of the conductor temperature. Thermal model measurement using advanced relays that can account for slip-dependent I^2r heating of both positive- and negative-sequence current is required. The thermal model is defined by the nameplate data and thermal limit data for the motor. This mathematical model calculates the motor

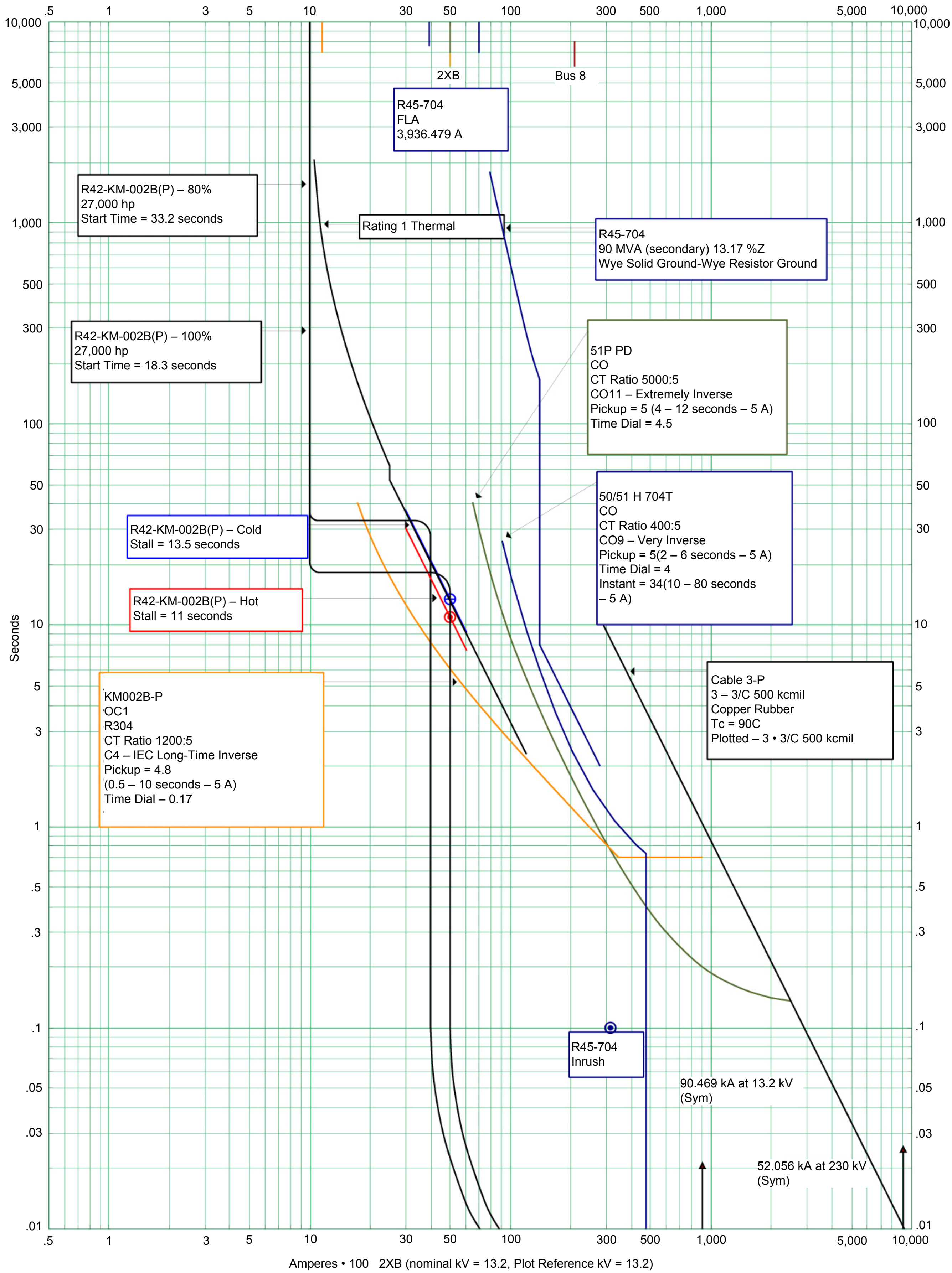

Fig. 4. 27,000 hp Synchronous Motor Curves

temperature in real time. The temperature is then compared to the thermal limit trip and alarm thresholds to prevent overheating from overload, a locked rotor, or frequent or prolonged starts. The motor manufacturer provides the thermal limit curves, also known as damage curves. Fig. 7 (shown later) shows an example of a motor starting current, starting time, hot and cold rotor current curve, and overload curve. The thermal model needs to be evaluated for both stator and rotor thermal limits. Typically, the stator is more limiting than the rotor while running overload, whereas the rotor is more limiting during starting.

A typical induction motor draws six times the full-load current when starting. This high stator current induces a comparably high current in the rotor. The rotor resistance at zero speed is typically three times the rotor resistance when the motor is at rated speed. Thus, the I^2r heating in the rotor is approximately $6^2 \bullet 3$, or 108, times the I^2r heating when the motor runs at full load. Consequently, the motor must tolerate an extreme temperature for a limited time in order to start. Manufacturers state the motor tolerance through the maximum LRT and LRA specifications for each motor. In a similar manner, the motor manufacturer communicates the ability of the motor to operate under continuous heavy load through the service factor specification. The purpose of motor thermal protection is to allow the motor to start and run within the published guidelines of the manufacturer but trip if the motor heat energy exceeds those ratings because of overloads, negative-sequence current, or locked-rotor starting.

A. Stator and Rotor Thermal Model

The rotor thermal model includes the adiabatic thermal model for starting and a first order model for running. Fig. 5 shows the rotor resistance variation for the motor in this high-inertia motor application during starting. It is at the maximum at the start and minimum during running conditions.

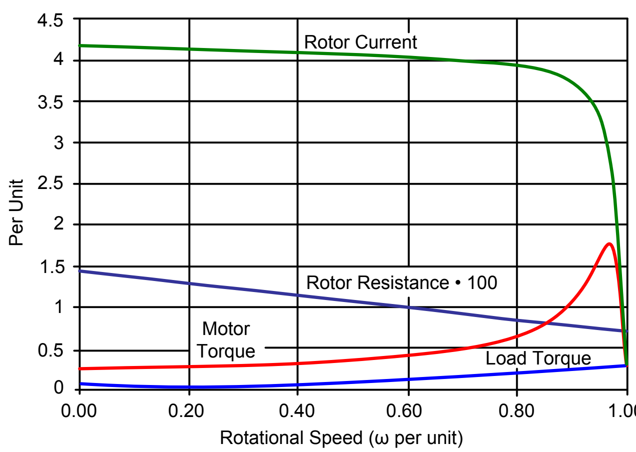

Fig. 5. Motor Starting Current and Torque

The positive and negative sequence of the rotor resistance during the starting process are defined by $R_r1(s)$ and $R_r2(s)$ simultaneously. Equation (1) shows the calculation of $R_r1(s)$ and $R_r2(s)$, respectively [1] [6].

$$
\begin{aligned}
R_r1(s) &= R_1 = (R_L - R_N) \bullet s + R_N \\
R_r2(s) &= R_2 = (R_L - R_N)(2 - s) + R_N
\end{aligned} \tag{1}
$$

where:

R_1 is the positive-sequence impedance.
R_2 is the negative-sequence impedance.
R_L is the rotor resistance during rotor lockout.
R_N is the rotor resistance at rated speed.
s is the slip.

The heat source is defined by (2) and (3), where I_1 and I_2 define the positive- and negative-sequence current. During starting (locked-rotor condition), $s = 1$ and $R_1 = R_2 = R_L$.

$$
\begin{aligned}
\text{Heat Source} &= \frac{R_1}{R_N} I_1^2 + \frac{R_2}{R_N} I_2^2 \\
\text{Heat Source} &= \frac{R_L}{R_N}(I_1^2 + I_2^2)
\end{aligned} \tag{2}
$$

During running, $s \approx 0$, $R_1 = R_N$, $R_2 = (2R_L - R_N) = 5\ R_N$, and $R_L/R_N = 3$.

$$
\begin{aligned}
\text{Heat Source} &= 3(I_1^2 + I_2^2) \\
\text{Heat Source} &= \left(I_1^2 + 5I_2^2\right) \\
\text{Heat Source} &= \left(K1\ I_1^2 + K2\ I_2^2\right)
\end{aligned} \tag{3}
$$

where:

K1 and K2 are slip-dependent factors.

If the relay is wired to read voltage, it can use the measurement of voltage and current to calculate slip *s*. The slip can then be used to determine the slip-dependent rotor resistance. The rotor model dynamically weights the heating effect of each of the negative-sequence and positive-sequence currents as a function of calculated slip. This feature prevents tripping during a start in high-inertia applications, where the motor acceleration time is longer than the LRT.

If the motor does not have advanced thermal protection logic, rotor resistance during starting cannot be calculated dynamically. The thermal model in these relays uses a conservative model and may not be able to correctly monitor the rotor thermal capacity used, which may result in a nuisance trip.

The thermal trip value is defined by the locked-rotor current and LRT using $I_L^2 \bullet T_o$. When the motor is running, it is cooling as it returns heat energy to its surroundings. The heat generated in the stator is calculated using $(I_1^2 + I_2^2)$ and is compared with $I_L^2 \bullet (T_a - T_o) \bullet SF^2$, where:

I_L is the locked-rotor current.
T_o is the operating temperature LRT.
T_a is the ambient temperature LRT.
SF is the service factor of the motor.

Therefore, for high-inertia motor protection, it is critical to select a relay that is capable of accurate thermal modeling using currents and voltages to calculate slip-dependent rotor resistance. Fig. 6 shows the stator thermal model curve for the motor.

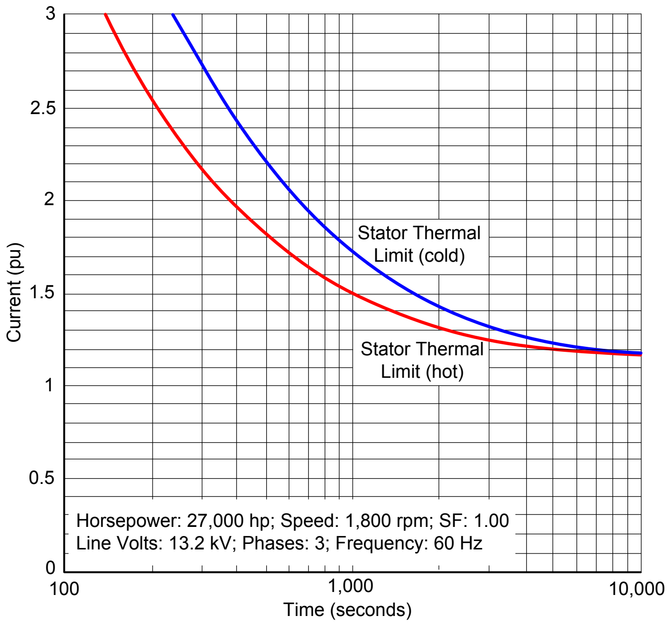

Fig. 6 Stator Thermal Limit Curve for 27,000 hp Motor

As discussed in [10], a stator thermal limit curve can be represented by (4) using the first order thermal equation. This resembles the standard inverse-time overcurrent equation, which is defined by IEEE C37.112.

$$t = TC \bullet \ln\left(\frac{I^2 - I_0^{\ 2}}{I^2 - SF^2}\right) \tag{4}$$

where:

t is the time to reach the limiting temperature.

TC (or RTC) is the stator thermal time constant.

I is the current in per unit of rated full load.

I_0 is the preload current.

SF is the service factor (maximum continuous current).

Using the 0.6 preload that is based on analysis, the calculated TC was around 48 minutes, which closely matches the TC of 50 minutes provided by the motor manufacturer. When the TC is not available, it can be calculated from the thermal limit curve [6]. Per the overload curve, three points are selected from the cold overload curve to calculate the run time constant (RTC). RTC for the three points shown in Table I was around 47 minutes for this motor using the 0.6 preload.

TABLE I
THREE POINTS SELECTED FOR RTC CALCULATIONS

Point on the Curve	Current and Corresponding Time
Point 1	I_1 = 3 times the pickup time T_1 = 250 seconds
Point 2	I_2 = 2.5 times the pickup time T_2 = 375 seconds
Point 3	2.0 times the pickup time T_3 = 650 seconds

The stator thermal curve is defined in (5).

$$RTC := \text{Ceil}\left[\frac{T_1}{\ln\left[\frac{I_1^{\ 2} - (I_0)^2}{I_1^{\ 2} - SF^2}\right]}\right]$$
$$RTC = 47 \text{ minutes} \tag{5}$$

B. *Model Motor Starting and Analysis*

The basic motor parameters and additional information based on the motor test data sheet are provided by the motor manufacturer. Once this information is available, motor starting analysis using the tools described in [9] [11] [12] can be used to analyze motor starting and thermal heating. Table II defines the general data provided for the 27,000 hp motor.

TABLE II
GENERAL MOTOR DATA

Motor Parameters	Value	Description
Horsepower	27,000 hp	Rated horsepower of the machine
Revolutions per minute	1,800 rpm	Speed at rated load
Voltage	13,200 V	Rated voltage of machine
Current	1,002 A	Current at rated load
Locked-rotor current	5 pu	Locked-rotor current

Based on the information in Table III, it can be concluded that the motor starting time is greater than the LRT (cold or hot). However, thermal model analysis suggests that for a cold start, the motor thermal capacity utilization is around 88 percent, with 23 seconds of start time. This analysis only provides preliminary results. In-service motor start results determine the actual starting time and thermal capacity utilization.

Saudi Aramco has 21,000 hp high-inertia motors at their other plants. For the purpose of analysis, results from the high inertia motor starting testing for these motors are documented and compared with the analysis of the 27,000 hp motor. Thermal model analysis for both motors was performed based on actual field data. The results and analysis are included in Section VI.

TABLE III
ADDITIONAL MOTOR DATA

Motor Parameters	Value	Description
Locked-rotor torque	28,361 lb/ft (0.36 pu)	Per data sheet
Rated torque	78,782.1 lb/ft (1 pu)	Per data sheet
Inertia of rotor	69,500 lb/ft^2 (2,928.75 kg/m^2)	Per data sheet
Inertia of load	25,557.6 lb/ft^2 (1,077.0 kg/m^2)	Per data sheet
Initial load torque	3,939.1 lb/ft (0.05 pu)	Estimated from data sheet
Final load torque	23,634.6 lb/ft (0.3 pu)	Estimated from data sheet
Hot safe stall time	11 seconds	Per data sheet
Cold safe stall time	13.5 seconds	Obtained from cold safe stall (1.2 times hot stall time)
Peak motor torque (pull-out torque)	157,564,215 lb/ft (~2 pu)	Per data sheet
Motor acceleration time (100% voltage)	18.3 seconds	Per data sheet
Motor acceleration time (80% voltage)	33.2 seconds	Per data sheet

Fig. 7 shows the locked-rotor thermal limits for different voltages for the 27,000 hp motor.

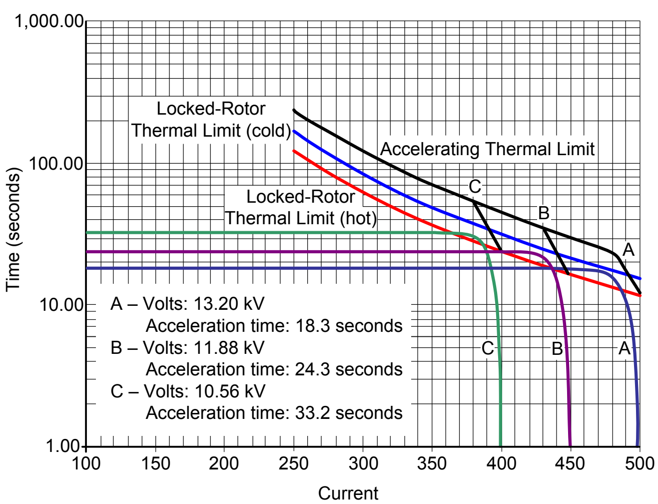

Fig. 7 Locked-Rotor Thermal Limits Versus Current

In addition to the thermal model, locked-rotor protection is also provided via the speed switch. Fig. 8 shows locked-rotor protection of the motor based on speed switch detection, which is located at the motor excitation panel. Trip time is selected to be 7 seconds at 10 percent of synchronous speed, which means that if the motor does not reach 10 percent of synchronous speed (180 rpm) within 7 seconds, the motor breaker trips.

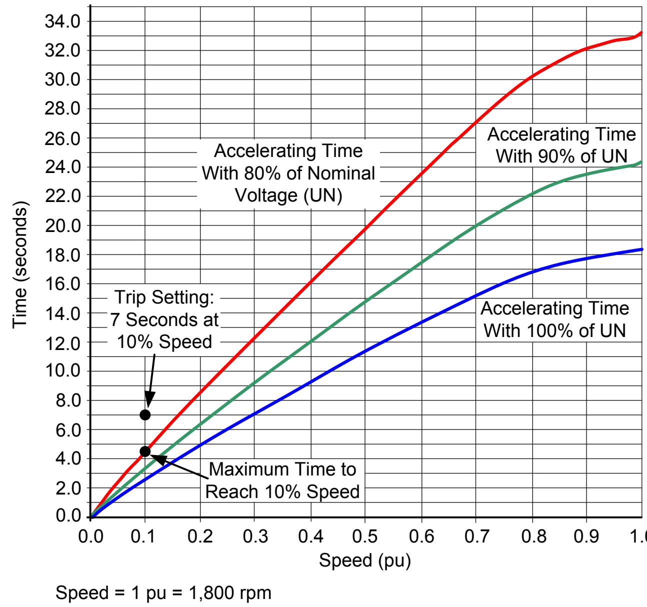

Fig. 8. Starting Time Characteristics Based on Infinite Bus (constant voltage)

VI. CUSTOM STARTING SEQUENCE

For high-inertia motors, relay and motor manufacturers provide various analysis tools and design guidelines to correctly protect the motors. However, the actual field records are very critical for design verification. It is quite possible that a motor is never started in-field during worst-case operating conditions (i.e., weak utility or source). However, careful analysis and field verification of results at a minimum is recommended.

The custom motor protection is intended to protect the motor against repetitive starts while allowing it the required time to dissipate the accumulated heat. This can result in overheating of the motor and premature failure. This protection does not normally differentiate between hot starts and cold starts, which force selection of the more conservative option, although it can limit operation.

NEMA MG 1-1998 recommends two starts in succession (coasting to rest between starts) with the motor initially at the ambient temperature or one start with the motor initially at a temperature not exceeding its rated load operating temperature. This information does not help with setting the maximum number of starts and starting interval in the relay. Large and high-voltage motor manufacturers normally supply a specific starting sequence for each motor that cannot be programmed in the relay using the allowable start and starting interval settings.

Before digital relays, Saudi Aramco was accustomed to applying the manufacturer-recommended starting logic using analog timers and auxiliary relays. Even with the installation of digital relays, many users still want the motor manufacturer starting sequence implemented. Not all relays on the market offer the flexibility and capability to have complex starting logic sequences programmed. This option can be a backup to the thermal model, which is supposed to reflect the requirements specified by the motor manufacturer. For this project, a program was developed to fully reflect the motor manufacturer starting sequence logic.

For the 27,000 hp motor, the motor manufacturer provided the custom starting sequence shown in Fig. 9. This custom sequence is programmed in the motor protection relays. When the motor is started for the first time or after, it is considered a cold motor. The motor can be in one of four states:

1. Running (no action).
2. Stopped in 2 minutes or less (second cold start).
3. Stopped after 2 minutes to 2 hours (lockout).
4. Stopped after 2 hours (one warm start).

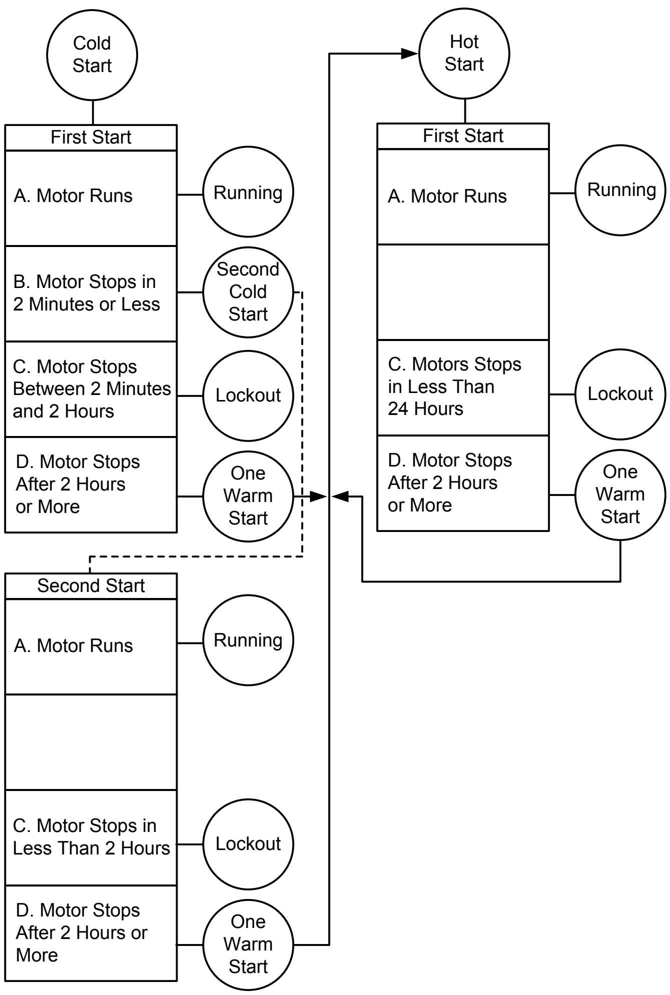

Fig. 9. Custom Starting Sequence

States 2 and 3 are critical for stator-limited motors, but not for rotor-limited motors. The motor is considered cold if it is started after 12.5 hours of motor stoppage time. For the first cold start, if the motor stops in 2 minutes or less, the second cold start is allowed. If the motor stops after 2 hours, one warm start is allowed. For motor stopping between 2 minutes and 2 hours, no start is allowed and the motor is locked out for 2 hours.

If a second cold start is allowed, then the motor can be in one of three states:

1. Running (no action).
2. Stopped after 2 hours or less (lockout).
3. Stopped after 2 hours (one warm start).

If a hot start is allowed, the motor follows the same logic as the second cold start. The front-panel display and light-emitting diodes (LEDs) are programmed for easy identification of various motor states.

VII. Field Results and Motor Starting

This section discusses the results of the 27,000 hp and 21,000 hp synchronous motor starting in the field.

A. 21,000 hp Motor Starting Results

Fig. 10 shows the starting of the 21,000 hp synchronous motor and the variation of slip, thermal capacity used, terminal voltage, and terminal current with respect to time. For the 21,000 hp motor, the starting time is 7.9 seconds (i.e., 7.9 • 60 = 474 cycles). The maximum thermal capacity used is 72 percent. The minimum voltage during starting is 11,265 V and the maximum current is 3,016 A.

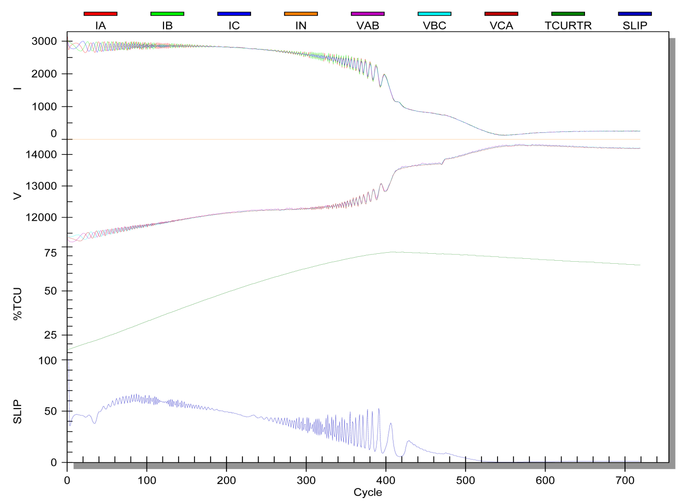

Fig. 10. 21,000 hp Motor Starting Results

Fig. 11 and Table IV show the thermal capacity analysis of the 21,000 hp motor.

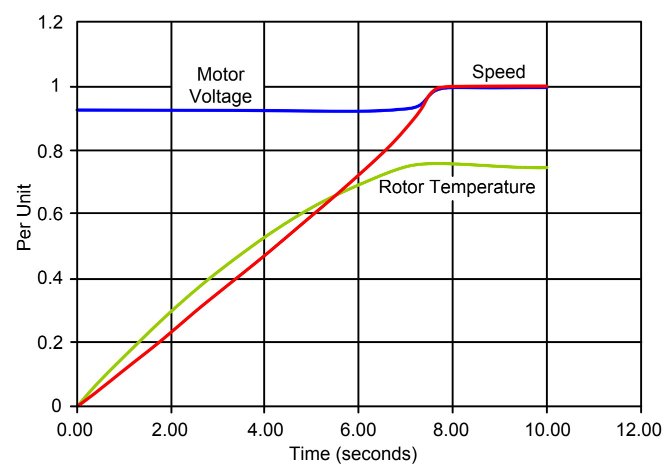

Fig. 11. 21,000 hp Motor Starting Thermal Results

TABLE IV
COMPARISON OF 21,000 HP MOTOR RESULTS

Quantity	Field Results	Analysis
Starting time (seconds)	7.9	7.5
Starting current (A)	3,016	2,984
Voltage (% of nominal)	85	90
Starting thermal (%)	72	76

B. 27,000 hp Motor Starting Results

This section discusses the comparison of the field results and the software analysis for the 27,000 hp motor. Fig. 12, Table V, and Table VI show the thermal capacity analysis of the 27,000 hp motor and the starting time. From previous analysis, it was established that the 27,000 hp motor can have issues with rotor thermal capacity if the motor is started hot during weak system conditions. Additional comparison for this 27,000 hp motor showed that contingency cases, such as outage of one 230/13.2 kV transformer or a motor start during weak system conditions, prolonged the starting time, which results in higher thermal capacity requirements. However, the actual motor start in the field was done with unloaded conditions and load inertia decoupled during good system conditions. The motor was started cold. The field results indicate a starting time of 13.8 seconds with around 63 percent thermal capacity during starting. The thermal analysis also shows a starting time of 13.8 seconds with 62 percent thermal capacity utilization. This provides good confidence in the thermal analysis. Voltage drop and starting current results are also comparable and error is less than 5 percent between the two results.

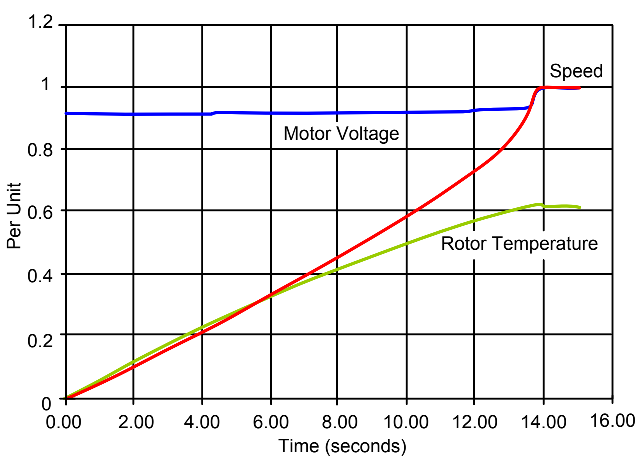

Fig. 12. 27,000 hp Motor Starting Thermal Results

TABLE V
COMPARISON OF 27,000 HP MOTOR RESULTS

Quantity	Field Results	Analysis
Starting time (seconds)	13.8	13.8
Starting current (A)	4,700	4,464
Voltage (% of nominal)	95	92
Starting thermal (%)	63	61.8

TABLE VI
FIELD RESULTS FOR 27,000 HP MOTORS

Motor Starting Function	KM002A	KM002B
Learned acceleration time	13.8 seconds	13.8 seconds
Learned starting current	4,701	4,642
Learned starting capacity	65%	61%
Learned acceleration time	13.5 seconds	13.0 seconds
Last starting current	4,500	4,661
Last starting capacity	00	58

It can be observed from the motor data sheet that a starting time of 18.3 seconds at 100 percent voltage is applicable when the 27,000 hp motor is started loaded. The inertias for the loaded and unloaded machine are listed in Table III. If the motor is started loaded, the starting time for the motor is 18.9 seconds with almost 85 percent thermal capacity utilization. The starting time closely matches the motor test results. Fig. 13 shows the software analysis of the 27,000 hp motor loaded start.

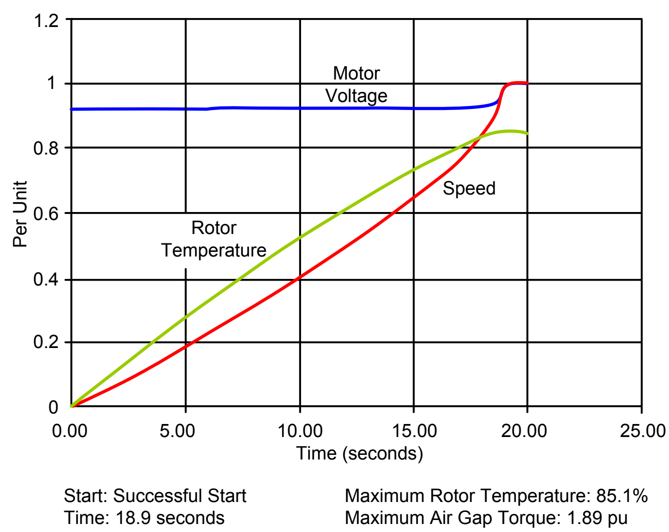

Fig. 13. 27,000 hp High-Inertia Motor Starting Example

Thus, it was concluded that preliminary motor analysis with the tools available can provide good information about the rotor thermal model. The results, however, need to be closely compared with the field test. Saudi Aramco has standard operating guidelines for starting large motors and additional protection, such as a speed switch, ensures the motor is not locked and that the motor is tripped if the speed does not reach 10 percent (i.e., 180 rpm) in 7 seconds.

VIII. CONCLUSION

High-inertia synchronous motors are very critical components for the operation of Saudi Aramco plants. These motors operate in harsh environments continuously, so adequate design and protection are required. Using analysis tools currently available, it is possible to calculate the thermal model for the stator and rotor correctly. The correlation of field starting and running analysis with the calculations provides good confidence. Advanced relays can provide accurate motor starting data, including the rotor and stator thermal capacity and can help reduce the time between starts for these critical motors. This paper discusses protection guidelines for synchronous motors and some of the tools available for high-inertia motor thermal capacity modeling. A speed switch and programming of the custom starting sequence per the motor manufacturer provides additional protection for these large motors.

IX. Acknowledgment

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XI. Biographies

Faouzi Jebali received his BS from Ecole Polytechnique of Montreal in 1986. He has broad experience in the field of power system design studies, operations, and protection. He served nearly 14 years working as a protection engineer for Canadian consulting firms and for the power industry before joining Saudi Aramco in 2001. Faouzi is working in the Power System Engineering Department (Power System Studies and Protection Unit) of Saudi Aramco as an Engineering Specialist. He is responsible for conducting protection and power system studies, supplying support to Saudi Aramco facilities, conducting investigations of power interruption and equipment failures, and contributing to Saudi Aramco standards.

Kamal Garg is a protection supervisor in the engineering services division of Schweitzer Engineering Laboratories, Inc. (SEL). He received his MSEE from Florida International University and India Institute of Technology, Roorkee, India, and his BSEE from Kamla Nehru Institute of Technology, Avadh University, India. Kamal worked for POWERGRID India for seven years and Black & Veatch for five years at various positions before joining SEL in 2006. Kamal has experience in protection system design, system planning, substation design, operation, remedial action schemes, synchrophasors, testing, and maintenance. Kamal is a licensed professional engineer in the United States and Canada.

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