

Comprehensive Analysis of Induction Motor Starting in Islanded Systems Using IEEE Std 3002.7-2018 Methods

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Abstract – Induction motor starting can draw large amounts of reactive power and lead to a significant voltage dip. Due to the reduction in voltage, a motor may not be able to start, or it may negatively impact the system. This paper explores various techniques for studying the starting of induction motors. An in-depth analysis was conducted on an islanded plant to evaluate the ability of the motor to start under different system conditions. The study used static, dynamic, and transient starting methods as outlined in IEEE Std 3002.7-2018.

The paper focuses on the modeling details required for induction motor starting studies and the methods that can be applied based on data availability. It presents the results for a 12,500 hp boil-off gas compressor induction motor in an islanded liquefied natural gas facility. For the transient starting study, the induction motor characteristics and generator are validated to accurately represent the power system model. Multiple power system configurations were evaluated to assess motor starting performance under different conditions, providing practical insights into system behavior.

The results from different motor starting study techniques are compared by evaluating the starting time, reactive power drawn by the motor, voltage dip, reactive power injected by the generator, and effects on already running motors. The paper concludes with recommendations for study techniques based on data availability, project phase, and other important factors.

Index Terms – Induction Motor Starting, Exciter, Governor, Motor Starting Study (MSS), Static Starting Study (SSS), Dynamic Starting Study (DSS), Transient Starting Study (TSS)

I. INTRODUCTION

Direct-on-line induction motors (IMs) are commonly used in refinery and petrochemical power plants. These motors can be large in terms of capacity compared to the total capacity of the plant. Starting these motors can have detrimental effects on the system, other loads, and the motor itself. If these large motors are not started properly, they may be damaged due to high currents, cause power quality issues, or trip other loads in the system. Therefore, it is important to perform a motor starting study (MSS) to avoid the discussed problems and to ensure that the motor starts without any issues in the system [1].

Industrial power plants may operate in an islanded mode for reliability without any connection to the grid. These plants may have voltage and frequency stability issues [2]. Additionally, such

systems are more susceptible to adverse effects, such as a severe voltage dip and the stalling of other operating motors caused by a large motor that is starting.

This paper details an MSS on an islanded system, conducted as described in [1]. This plant has three large direct-on-line 13.2 kV IMs, each having a capacity of 12,500 hp. The paper discusses the following:

1. Modeling requirements for MSS based on data availability and required accuracy.
2. Three MSS techniques: static, dynamic, and transient.
3. Validation of the IM model using the data sheet.
4. Comparison of results obtained using the MSS techniques.
5. Recommended method based on the project phase.

II. MSS MODELING REQUIREMENTS

This section presents the modeling details required for MSSs. Proper system modeling is essential to accurately capture system behavior, such as voltage dips, reactive power drawn by the motor, frequency variations, and reactive power supplied by generators.

The system modeling should be as simple as possible while accurately representing the power system behavior. It should adopt a conservative approach while incorporating only the essential components, with noncritical elements appropriately simplified to avoid unnecessary increases in overall system complexity. The modeling details required for various components in an MSS are explained in the following subsections.

A. Direct-On-Line Induction Motor

It is important to correctly model the torque-slip characteristics of an IM as it affects the starting time. The performance of a motor, measured by parameters such as starting torque, accelerating torque, and breakdown torque, depends on torque-slip characteristics. Different IM types have different characteristics. Figure 1 shows the torque-speed characteristics of single-cage and double-cage motors with the same nameplate rating (output power, breakdown torque, and full-load speed). It shows that even though the rating is the same, the starting time is different for different cage types due to the different characteristics. The rotor resistance of a single-cage motor is

low; therefore, it has a low starting torque compared to a double-cage motor [3].

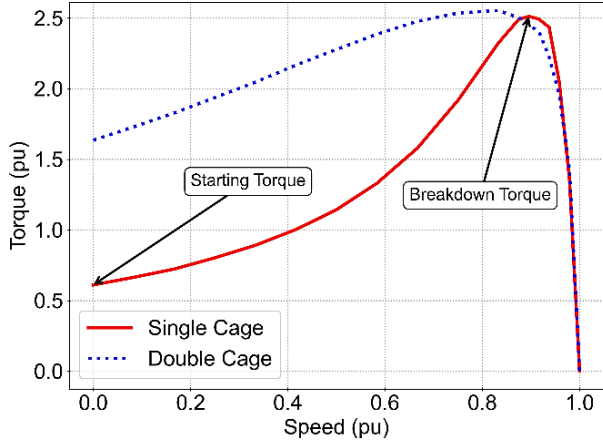


Figure 1 IM torque-speed characteristics

Figure 2, Figure 3, and Figure 4 represent the IM-equivalent circuit models for a single cage, a double cage with integrated rotors, and a double cage with independent rotors [1]. These circuits can be used for detailed analysis during motor starting. In these figures, R_s , X_s , X_m , and R_r represent stator resistance, stator reactance, magnetizing reactance, and rotor resistance, respectively. Slip is represented by s in the rotor resistance term $\frac{R_r}{s}$.

Another crucial factor that needs to be considered during MSS is the inertia of the IM, and the inertia of its driven load. Motor inertia plays an important role in determining the frequency response during starting.

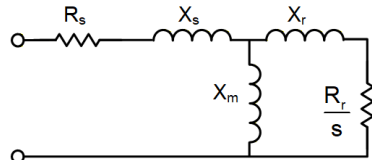


Figure 2 Single-cage IM-equivalent circuit

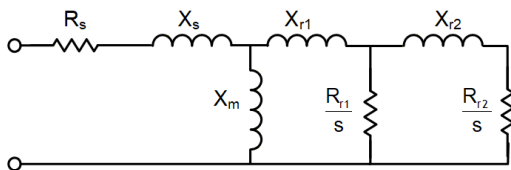


Figure 3 Double-cage IM-equivalent circuit with integrated rotors

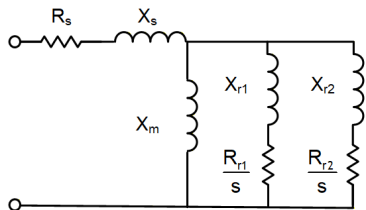


Figure 4 Double-cage IM-equivalent circuit with independent rotors

B. Generator

Accurate generator modeling is essential for MSS because the system response to higher reactive power demand during motor starting depends on this. A generator model based on generalized d-q theory is sufficient, as it accounts for armature impedance, transient and subtransient reactances, and open-circuit time constants. The inertia of the generator, including the prime mover and coupling, is important for analyzing frequency variations during motor starting. Furthermore, consideration of the capability curve of the generator is critical because, due to the large reactive power demand during motor starting, the generator may reach its steady-state or transient reactive power limit. The detailed generator model is used in Transient Starting Studies (TSSs).

In a system where utility is also connected, its impedance must be calculated based on the minimum capacity (higher impedance) to represent the worst-case scenario [1].

C. Exciter

Exciter dynamics impact the generator voltage response when a motor is started. While modeling an exciter, it is critical to also include the overexcitation limiter and underexcitation limiter, as hitting the steady-state or transient reactive power limit can result in a more severe voltage dip.

Figure 5 shows the generator voltage response for different exciter time constants T_E when a 12,500 hp IM is coupled with mechanical load and started with only one generator in the system. The voltage dip, peak, and settling time vary depending on the exciter model parameters [4]. For a higher time constant, the voltage dip is worse, and the starting time is also high. When T_E is 0.33, 1.33, and 2.33 s, the motor started in 37, 39, and 53 s, respectively.

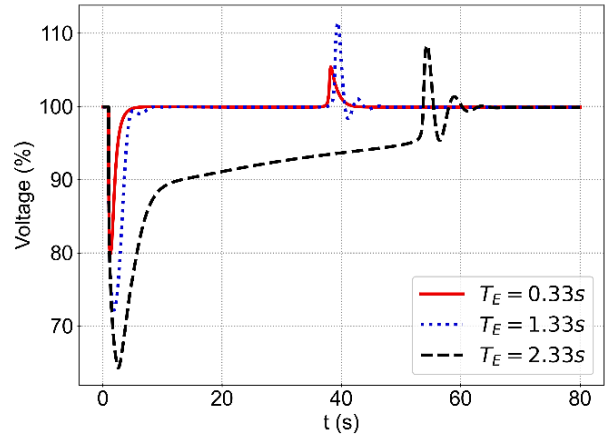


Figure 5 Generator bus voltage with different exciter time constants

As the IM approaches synchronous speed, rotor slip and rotor current decrease rapidly, leading to a sharp reduction in reactive power demand at the generator terminals. During the acceleration period, the automatic voltage regulator (AVR) increases the generator field excitation to compensate for the depressed terminal voltage caused by the motor inrush current. When the motor reactive power demand collapses near the end of the starting process, the exciter field remains temporarily

elevated due to the exciter and AVR time constants, resulting in a transient overexcitation and a voltage overshoot at the generator bus. The AVR subsequently reduces field excitation and regulates the terminal voltage back to its nominal value. These results demonstrate that exciter dynamic characteristics play a critical role in MSSs, particularly in islanded or weak power systems. Among the three starting techniques, the exciter is modeled only in the TSS.

D. Governor

Governor dynamics affect the system frequency, especially when the system is islanded. It is essential to analyze both the dip and the peak in frequency to ensure that overfrequency or underfrequency protection elements are not triggered for any loads in the system.

Figure 6 shows the frequency response for a governor with the different proportional gains K_p , when a 12,500 hp IM is coupled with mechanical load and started with only one generator in the system. The exciter time constant T_E is 0.33 s in all three scenarios.

The frequency response (i.e., frequency dip and peak) varies depending on the parameters of the governor. The frequency dip and peak are worse for lower proportional gain. When the motor is started, torque is increased with speed according to the torque-slip curve, and at $t = 27$ s, the IM reaches breakdown torque. At this point, the active power demand is high and frequency dips. After breakdown torque is crossed, the IM torque drops sharply with speed. This causes a reduction in active power demand. Because the governor responds on a slower time scale than the exciter, this reduction in active power demand cannot be immediately compensated, resulting in a brief frequency overshoot prior to motor run-up completion.

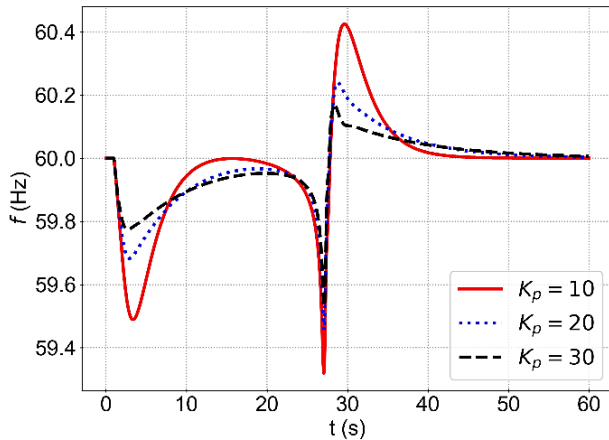


Figure 6 System frequency with different governors

It is crucial to ensure that the governor model is accurate to capture these dynamics. In a TSS, the governor is modeled, which is explained in the following sections.

E. Transmission Line, Transformer, and Cable

Transmission lines and cables can be represented using positive-sequence impedance and shunt admittances. Transformers can be modeled using standard impedance values or based on data sheets. These impedances may affect the voltage dip during motor starting.

F. Load Modeling

The accelerating torque depends on the difference between the torque of the IM and the load. Therefore, the starting time of the IM, coupled with load, depends on the torque-speed characteristics of both the IM and the mechanical load. Hence, along with the IM, it is also important to properly model torque-speed characteristics of the load. Figure 7 shows torque-speed characteristics for various load types: centrifugal compressor, pump, and reciprocating compressor [5]. The IM response during starting may vary for different loads. The inertia of the load is an important factor—the combined inertia of the IM and the mechanical load affects the frequency response during motor starting.

When a motor is started, operating motors may stall due to a reduction in voltage. Small motors that are already running can be represented using constant MVA loads, as they will not have much impact on the system. However, large operating motors are more accurately represented using a dynamic model. Motors above 5,000 hp are considered large motors for the purpose of this study.

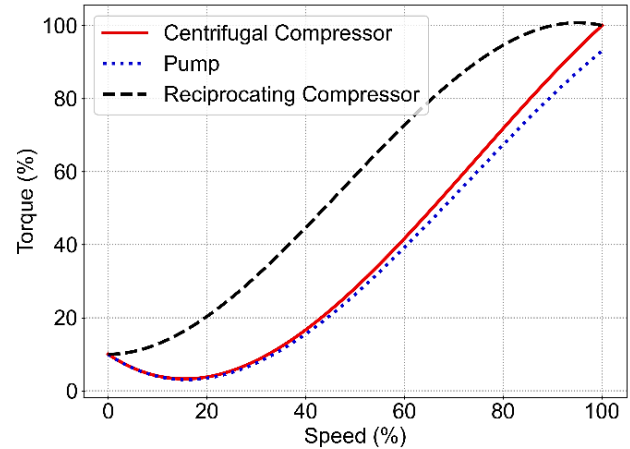


Figure 7 Load characteristics

G. Other Components

Other elements, like capacitor banks and shunt reactors, also need to be modeled for MSS, since the reactive power drawn by these elements depends on the bus voltage to which they are connected.

III. MOTOR STARTING METHODS

The instantaneous torque and starting time of an IM is given using (1) and (2), respectively [1] [6].

$$T = \frac{q_1 V^2 \left(\frac{R_r}{s} \right)}{\omega_s \left(R_s + \frac{R_r}{s} \right) + (X_s + X_r)^2} \quad (1)$$

where

- T is the instantaneous torque (Nm);
- ω_s is the angular velocity at synchronous speed (rad/s);
- $(R_s + jX_s)$ is the stator equivalent impedance (ohm);
- $\left(\frac{R_r}{s} + jX_r \right)$ is the rotor equivalent impedance (ohm);
- q_1 is the number of stator phases;
- V is the line to neutral motor terminal voltage (V).

$$t = \frac{WR^2 \left(\frac{r}{min_1} - \frac{r}{min_2} \right) 2\pi}{60gT_n} \quad (2)$$

where

- t is the motor acceleration time (s);
- WR^2 is the moment of inertia ($lbft^2$);
- g is the acceleration due to gravity ($32.2 ft/s^2$);
- $\frac{r}{min_1}, \frac{r}{min_2}$ are the revolution per minute (RPM_1 and RPM_2 , respectively) at different instants;
- T_n is the net accelerating torque ($lbft$) between RPM_1 and RPM_2 .

The torque equation is employed in dynamic and transient starting methods to perform MSS [1] [5]. These methods, along with the static starting method, are explained in the following sections.

A. Static Starting Study (SSS)

The SSS technique is the most basic among the three. In this method, the starting time of the motor is known and the locked-rotor impedance is connected to the bus during the start time. Then, load-flow calculations are performed to determine

- Bus voltages (voltage dip during start).
- Generator reactive power output.
- System currents.

After the assumed start time ends, the motor is switched to a constant MVA load representing its running condition. It is a quick, conservative method when detailed dynamic data are not available. It ignores acceleration dynamics and assumes constant increased reactive demand for the entire start time. This method is useful when IM data are not available except start time, and it is assumed that the motor will start without any issues. The generator is modeled as a constant voltage source behind transient reactance, X'_d . Other operating motors are represented as constant MVA loads.

B. Dynamic Starting Study (DSS)

In the DSS, the exciter and the governor are not modeled. The generator is represented as a constant voltage source behind X'_d . A dynamic model for the starting motors is used, while other operating motors are modeled as constant MVA loads. The following steps, which are given in IEEE Std 3002.7-2018, Section 8.1 (p. 50), are performed for this study:

1. Initialize system conditions and motor speed at zero.
2. Solve network equations for the initial voltage at $t = 0$ s.
3. Compute the motor torque and electrical quantities using the equivalent circuit (current, speed, and voltage).
4. Apply the shaft dynamic equation to update the rotor speed.
5. Recalculate the slip and motor parameters for the next time step.
6. Repeat until the motor reaches steady-state speed.

C. Transient Starting Study

This is the most accurate and detailed study technique. In this method, all the components—generator, exciter, governor, and IM—are dynamically modeled. Large operating motors can also be modeled dynamically, while other motors are represented as constant MVA loads. The following steps are performed for this study (see IEEE Std 3002.7-2018, Section 8.1 [p. 50]):

1. Initialize the system conditions and motor speed at zero.
2. Solve the network equations for the initial voltage at $t = 0$ s.
3. Compute the dynamic equations for all components (generator, exciter, governor, and motor) to determine electrical quantities.
4. Recompute the load-flow equations at the end of each time step to reflect the updated system conditions.
5. Update the system state at each time step until the steady-state speed is reached.

IV. SYSTEM MODELING

Figure 8 presents the single-line diagram of the system with 13.8 kV and 6.9 kV substations. The system consists of four gas turbine generators (GTGs) (around 50 MVA/13.8 kV) operating in an islanded mode. During normal operation, three GTGs run in parallel with the 13.8 kV tie breaker closed. The turbine rating of each generator is around 30 MW at 89°F.

The three largest motor loads in the plant are gas compressor motors, referred to as IM 1, 2, and 3. These IMs are identical and have a rating of 12,500 hp/13.2 kV. The motors will be started direct-on-line. The IM parameters are shown in TABLE I. Dynamic models of all three IMs are included in TSS.

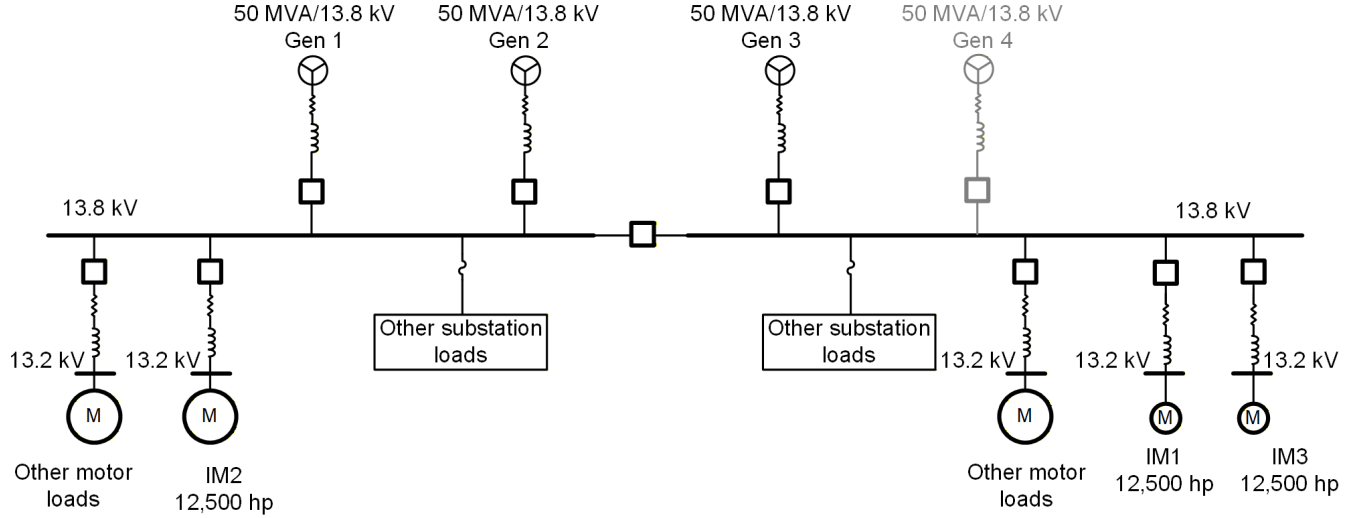


Figure 8 Single-line diagram

TABLE I
IM 1, 2, and 3 PARAMETERS

Parameter	Value
Mechanical power (hp)	12,500
Slip (%)	0.44
Power factor (pu)	0.88
Efficiency (%)	96.5
Starting torque (pu)	0.35
Maximum torque (pu)	1.65
Starting current (pu)	4
Rated voltage (kV)	13.2
Inertia (s)	3.434

A. IM Validation

The parameters for these motors are estimated using the equations given in [7], and the equivalent circuit is shown in Figure 9. In this figure, $R_s = 0.001$, $X_s = 0.2335$, $X_m = 4.835$, and $R_c = 47.99$ are stator resistance, stator reactance, magnetizing reactance, and core resistance in per unit, respectively. Furthermore, rotor reactance at full-load, rotor reactance at locked-rotor, rotor resistance at full-load, and rotor resistance (all in pu) at locked-rotor conditions are given as $X_{rfl} = 0.0974$, $X_{rlr} = 0.0153$, $R_{rfl} = 0.0043$, and $R_{rlr} = 0.0186$. These values are calculated on the MVA base of the machine.

The torque-slip characteristics of the model are compared with the data sheet, as shown in Figure 10. It can be seen that the starting torque matches that of the data sheet, and the two curves are close to each other near the operating region. The curve (model) obtained from the power system software is below the data sheet curve. This is the closest it could get to the data sheet with the estimated parameters.

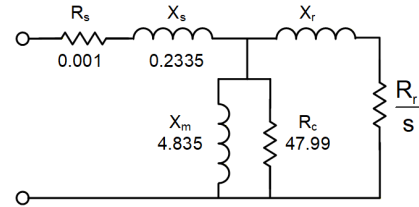


Figure 9 IM-equivalent circuit

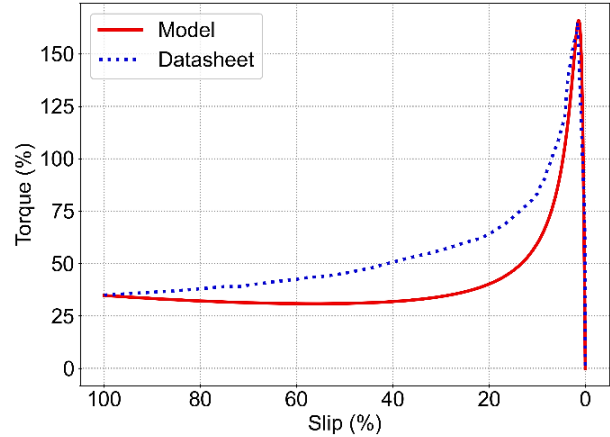


Figure 10 IM torque-slip characteristics

Figure 11 shows a comparison of the current-slip characteristics for the model and the data sheet, which are aligned near the operating region. The centrifugal compressor load is coupled to these three IMs, and Figure 12 shows torque-speed characteristics for the compressor for both the model and the data sheet.

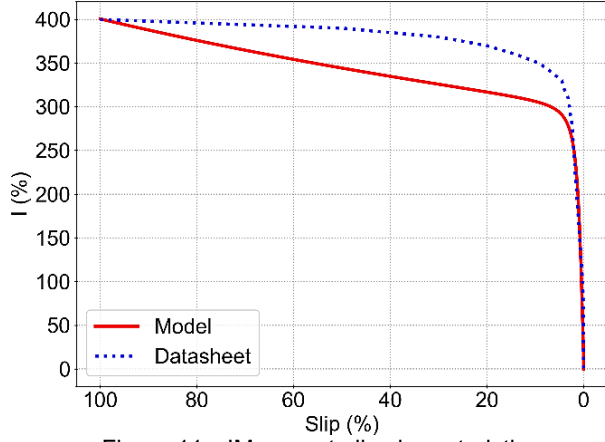


Figure 11 IM current-slip characteristics

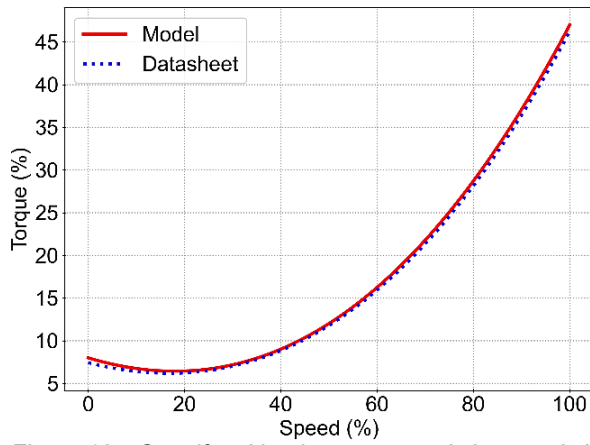


Figure 12 Centrifugal load torque-speed characteristics

The equation for load torque is given using (3). In this relation, T and ω are torque and angular velocity, in percentage.

$$T = 8 - 17\omega + 44\omega^2 + 12\omega^3 \quad (3)$$

For validation of the IM, one generator is connected to the system, while the other generators remain offline. A custom governor and an AC8C exciter are modeled for a generator. The response of the IM is shown in Figure 13, where the IM is started, and the slip, motor mechanical power (P_m), motor electrical power (P_e), reactive power (Q) drawn by the motor, terminal current (I), and terminal voltage (V) are shown. No mechanical load is coupled to the motor.

According to the data sheet, the starting time of the IM is 22 s, and the model shows a similar starting time (21.5 s). Hence, the model is close to the data sheet.

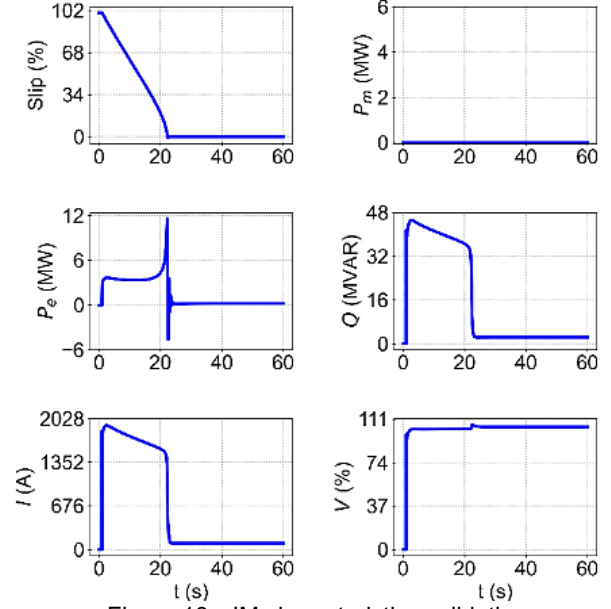


Figure 13 IM characteristics validation

B. Generator Validation

The load acceptance tests are performed on a generator, and the results are shown in Figure 14. A manufacturer-specific custom governor model, generator parameters, capability curve, and the IEEE AC8C model are used. The parameters for these models are obtained from manufacturer data sheets. The generator MW rating is 41.872 MW.

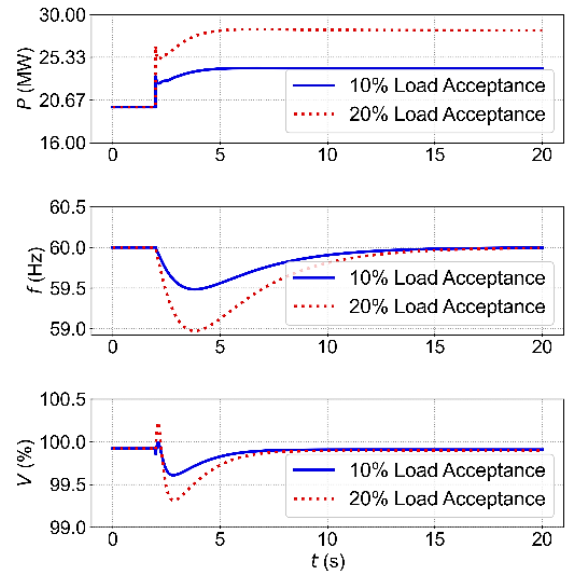


Figure 14 Generator validation

For the load acceptance test, the governor operated in isochronous mode, and 10% and 20% load steps are applied. The frequency recovers in approximately 12 s, and the voltage recovers in approximately 4 s after each load is added.

V. SIMULATION RESULTS

In this section, the IM starting results are presented for static, dynamic, and transient study techniques. For performing MSS, three scenarios are considered, as shown in TABLE II. It should be noted that in all scenarios, IM 2 is started with a centrifugal compressor load, and its characteristics are shown in Figure 12, with a steady-state torque of 47%. Scenario 1 represents the minimum loading conditions, in which only one generator is online. Scenarios 2 and 3 represent the maximum loading conditions, in which three generators are connected. The total minimum load in the system is 15.3 MW, and the maximum load is 82.1 MW.

IM 2 is started with load. The analysis is performed using static, dynamic, and transient methods for all three scenarios (S1, S2, and S3), and the results are compared.

For S3, the pre-event generator bus voltage is set to a lower value (95%) to see if a motor can be started at a reduced generator bus voltage.

TABLE II
MOTOR STARTING SCENARIOS

Scenario	Pre-Event	Generator Bus Voltage
S1 (Minimum Loading)	Gen 1, 2: Offline Gen 3: 15.3 MW, 7.9 MVAR IM 1 running: 9.3 MW IM 3: Offline	100%
S2 (Maximum Loading)	Gen 1: 21.7 MW, 14.7 MVAR Gen 2: 30.2 MW, 14.7 MVAR Gen 3: 30.2 MW, 14.7 MVAR IM 1, 3 running: 9.3 MW each	100%
S3 (Maximum Loading)	Gen 1: 21 MW, 14.9 MVAR Gen 2: 30.2 MW, 14.6 MVAR Gen 3: 30.2 MW, 14.6 MVAR IM 1, 3 running: 9.3 MW each	95%

A. Case Study 1 – SSS

According to the IM data sheet, the start time of the motor is 22 s. Therefore, in static motor starting, the locked-rotor impedance, $Z = 0.25 pu$, is used for the starting period of 22 s, and the load-flow equations are solved. After this, the motor is represented as a constant MVA load to represent running conditions. The motor is started at $t = 5$ s. The generator bus voltage is 100% for the pre-event condition for S1 and S2, and 95% for S3.

For S1, S2, and S3, the response of IM 2 is shown in Figure 15, Figure 16, and Figure 17 for SSS, DSS, and TSS. The total simulation time for SSS is 60 s for all scenarios. For SSS, it is observed that the minimum terminal voltages for the motor are 82.4% for S1 (the minimum loading scenario) and 94.1% and 89.2% for S2 and S3 (maximum loading) (see TABLE III). The maximum reactive power drawn by IM 2 is 30.02 MVAR, 39.2 MVAR, and 35.2 MVAR for S1–S3 (see TABLE IV).

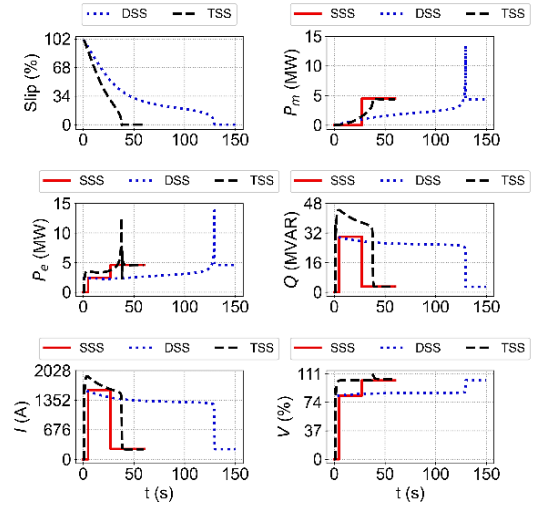


Figure 15 IM 2 response for S1

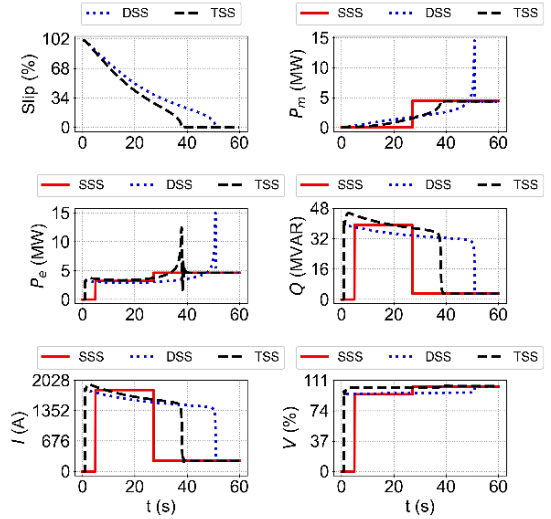


Figure 16 IM 2 response for S2

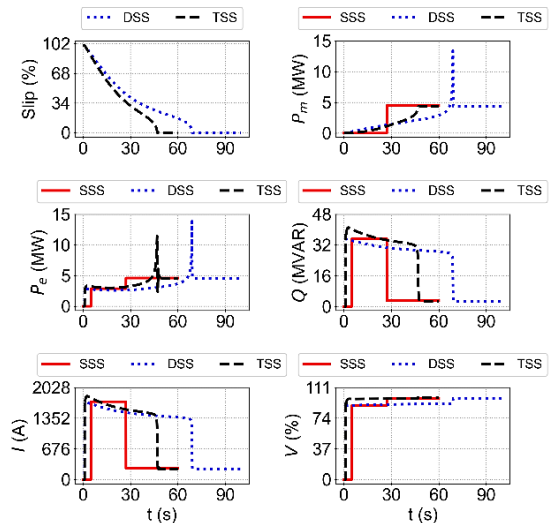


Figure 17 IM 2 response for S3

TABLE III
MSS COMPARISON (S: SSS, D: DSS, T: TSS) FOR IM 2

Scenario (Scn)	Starting Time (s)			Minimum Gen Bus Voltage (%)			Maximum Gen Bus Voltage (%)			Minimum IM Terminal Voltage (%)			Maximum IM Terminal Voltage (%)		
	S	D	T	S	D	T	S	D	T	S	D	T	S	D	T
S1*	22	128.8	37	80.7	80.5	79.9	NA	NA	105.4	82.4	82.4	81.7	NA	NA	109.7
S2	22	50.15	37	92.2	92	92	NA	NA	102.3	94.1	94.1	94.1	NA	NA	106
S3	22	68.3	46	87.4	87.2	87.2	NA	NA	97.1	89.2	89.2	89.2	NA	NA	100.7

* TSS case for S1 may not start.

TABLE IV
MAXIMUM REACTIVE POWER FOR IM AND GENERATOR FOR IM 2

Scn	Maximum IM Q (MVAR)			Maximum Gen Q (MVAR)		
	SSS	DSS	TSS	SSS	DSS	TSS
S1	30.02	30	44.4	38	37.9	52.7
S2	39.2	39.2	45.4	Gen 1: 28.1; Gen 2: 27.9; Gen 3: 27.9		28 each
S3	35.2	35.2	41.1	Gen 1: 27.1; Gen 2: 26.7; Gen 3: 26.7		27 each

The maximum reactive power injected by the generators for S1, S2, and S3 is shown in TABLE IV for all starting methods. These values do not exceed the maximum reactive power limit (40 MVAR) in any scenario for SSS. However, for S1, this value is 38 MVAR, which is close to the reactive power limit.

According to IEEE Std 3002.7-2018, Section 6.3 (p. 29), the terminal voltage during starting should not fall below 80%. Therefore, in SSS, all scenarios (S1–S3) satisfy this condition.

B. Case Study 2 – DSS

Dynamic starting results are shown in Figure 15, Figure 16, and Figure 17 for S1–S3. The motor is started at $t = 1$ s, and total simulation times are 150 s for S1, 60 s for S2, and 100 s for S3. The minimum terminal voltages of the motor are 82.4%, 94.1%, and 89.2% for S1–S3, and all are above 80% (see TABLE III). Furthermore, these values are similar to those obtained using the static starting technique.

The maximum reactive power values drawn by IM 2 are 30 MVAR, 39.2 MVAR, and 35.2 MVAR for S1–S3, which are similar to the static starting approach. The start times for IM 2 are 128.8 s, 50.15 s, and 68.3 s for S1–S3. The transient spike observed in both electrical and mechanical power signals during IM synchronization occurs regardless of load and originates from the instantaneous torque–power calculation used in the model. The spike reflected transient magnetic energy exchange rather than physical shaft power transfer.

TABLE IV shows the maximum reactive power injected by generators for the three scenarios. These values do not exceed the maximum reactive power limit. However, for S1, this value is 37.9 MVAR, which is close to the reactive power limit (40 MVAR). It should be noted that, for the minimum loading scenario, S1, if the pre-event voltage is below 97%, the motor fails to start for DSS. This occurs because IM torque is directly proportional to voltage squared, and if the available torque falls below the acceleration torque, the motor cannot accelerate and stalls. On the other hand, in S3, the available torque is greater than the acceleration torque and the motor starts.

C. Case Study 3 – TSS

Transient motor starting results are shown in Figure 15, Figure 16, and Figure 17. The motor is started at $t = 1$ s, and total simulation time is 60 s for S1–S3. It is observed that the minimum terminal voltages of the motor are 81.7%, 94.1%, and 89.2% for S1–S3. These are above 80%, as required by [1]. The maximum reactive power values drawn by IM 2 are 44.4 MVAR, 45.4 MVAR, and 41.1 MVAR for S1–S3.

The maximum reactive power injected by the generators for S1, S2, and S3 is shown in TABLE IV. For S1, the reactive power is 52.7 MVAR, which exceeds the maximum reactive power limit (40 MVAR). Also, for this scenario, the minimum generator voltage is 79.9%, which is below 80%. If this value were limited by the exciter (overexcitation limiter [OEL]), then the IM voltage dip would be lower than 81.7%, and the motor may not be able to start.

Furthermore, in TSS, the start times are 37 s, 37 s, and 46 s for S1–S3. These times are shorter than in DSS (128.8 s, 50.15 s, and 68.3) because in TSS, the exciter dynamics are considered, and the exciter acts quickly to restore voltage. This helps with maintaining higher torque, as torque is directly proportional to voltage squared. On the other hand, in DSS, voltage remains low for a longer duration. Hence, the starting time increases. Furthermore, the voltage is lowest in S1 (80.5%), and as a result, the starting time is highest (128.8 s) for DSS.

The minimum generator bus voltage and minimum IM terminal voltage are less for TSS when compared to SSS and DSS (see TABLE III) for S1. Furthermore, both DSS and TSS have less minimum generator bus voltage than SSS for S2 and S3. The maximum reactive power drawn by the IM and maximum reactive power injected by the generator are higher in TSS when compared to SSS and DSS (see TABLE IV). Therefore, TSS gives the worst-case results.

D. Effects on the Operating IM

In all scenarios, IM 1 runs at full load (9.3 MW) in the pre-event condition (that is, before IM 2 is started). Figure 18 shows the effect on IM 1 for S1–S3 when IM 2 is started. Only in TSS are the already running motors, IM 2 and IM 3, modeled dynamically. Therefore, the results shown in Figure 18 are obtained using TSS. IM 3 behaved the same as IM 1 because both are connected to the same bus except in S1, in which IM 3 is offline.

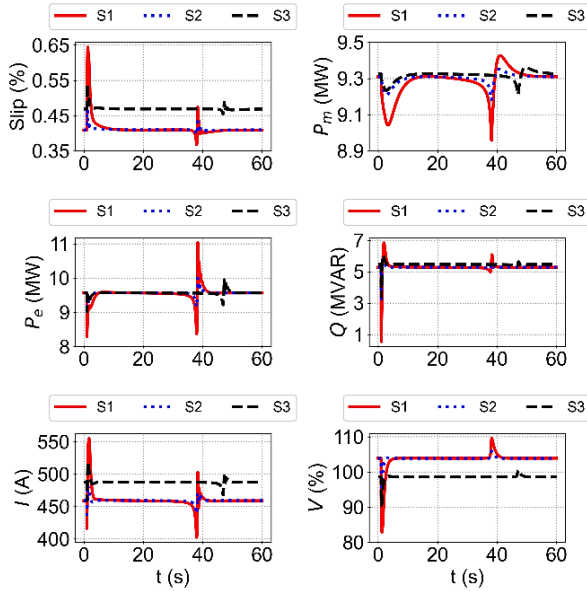


Figure 18 Operating IM 1 response for S1–S3 (TSS)

During the IM 2 starting, the IM 1 slip increased slightly. The peak slip values are 0.64%, 0.46%, and 0.54% for S1–S3. The minimum terminal voltages are 82.9%, 95.6%, and 90.5% for S1–S3. According to IEEE Std 3002.7-2018, Section 6.3 (p. 29), the minimum allowable voltage for an already operating motor is 70%; therefore, all scenarios satisfied this criterion. The highest reactive power values are 6.8 MVAR, 5.8 MVAR, and 6.0 MVAR for S1–S3, which show only minor deviation from the steady-state value of 5.3 MVAR.

VI. CONCLUSION

This paper compares static, dynamic, and transient motor starting analysis methods per IEEE Std 3002.7-2018 for an islanded system. The study demonstrates that accuracy improves with modeling detail: SSS offers quick, conservative estimates suitable for early project phases; DSS provides medium accuracy when motor data are available (intermediate project phase); and TSS delivers the most accurate results by modeling generator, exciter, and governor dynamics (final project phase). TSS predicted a start time close to the data sheet value and revealed worst-case voltage dips and reactive power demands, making it essential for final design verification.

A summary of key differences in assumptions, accuracy, data requirements, pros, cons, and typical use cases is provided in TABLE V. This comparison serves as a practical guide for selecting the appropriate study technique based on project phase and available data.

Although the TSS is performed later, in the final phase of the project when all required data become available, it is still essential to perform it with sufficient lead time before commissioning, especially for large motors, so that any design flaws can be corrected with minimal impact on the project.

TABLE V
DIFFERENCES BETWEEN MSS TECHNIQUES

Aspect	Static Starting Study	Dynamic Starting Study	Transient Starting Study
Assumptions	Motor remains at locked-rotor condition for entire start time; start time taken from data sheet; generator modeled as constant voltage source behind X'_d ; other motors as constant MVA loads.	Motor acceleration modeled step-by-step using torque-slip and inertia; generator modeled as constant voltage source behind X'_d ; exciter and governor not modeled; other motors as constant MVA loads.	Full dynamic modeling of motor, generator, exciter, and governor; includes AVR and governor response; large operating motors can be modeled dynamically.
Accuracy	Low to medium (ignores acceleration dynamics).	Medium (captures motor acceleration but ignores generator, exciter, and governor dynamics).	High (is the most realistic voltage dip and reactive power behavior).
Data Requirements	Minimal: motor locked-rotor impedance, start time, generator X'_d .	Motor equivalent circuit and inertia; generator X'_d .	Detailed motor data plus generator including inertia, exciter, and governor parameters and dynamic models.
Pros	Quick and simple; useful in early project phase; conservative results for voltage dip (voltage is low and constant for entire starting period, reactive power demand is high and constant for entire starting period).	More realistic than SSS; good for intermediate phase when motor data are available; predicts actual start time.	Most accurate; captures AVR and governor effects; identifies worst-case reactive power and voltage dips; captures effect on operating motors.
Cons	Cannot predict failure-to-start accurately; ignores system dynamics.	Misses exciter and governor influence; may misjudge voltage recovery; simplified generator model.	Requires extensive data and modeling effort; computationally intensive; longer study time.
Typical Use Case	Early phase: feasibility checks when detailed data are unavailable.	Intermediate phase: motor data available but generator, exciter, and governor data are missing.	Final phase: detailed system data available; most accurate analysis required.

The detailed modeling in TSS and the comparison of results indicate that SSS and DSS provide medium accuracy, whereas TSS offers high accuracy. This accuracy classification (low, medium, or high) is based on the level of modeling details per [1] and simulation results obtained for different techniques. The results have not yet been validated against field data; this validation will be conducted in the future once the plant is constructed.

In terms of efficiency, SSS is faster and requires less computational burden. DSS requires an IM dynamic model, while TSS includes the IM, governor, and exciter dynamic models. Therefore, TSS requires more computational burden, validation efforts, and study time compared to DSS.

Finally, it can be inferred that the motor starting analysis is important to determine whether soft starting or a review of protection settings are required if system conditions (e.g., undervoltage, etc.) are violated. This helps with the proper commissioning of the plant.

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VIII. VITAE

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