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A Services Division of Schweitzer Engineering Laboratories, Inc.

RTDS Testing Final Report
Lawrence Berkeley National Laboratory

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Section 1: EXECUTIVE SUMMARY

1.1 Introduction

Lawrence Berkeley National Laboratories hired SEL Engineering Services to provide Model Power System (MPS) Testing Services for testing the dynamic behavior of single phase air conditioner motors at a distribution feeder level. The primary purpose of this project was to develop a custom single phase induction motor model in Real Time Digital Simulator (RTDS®) and apply multiple instances of that model on a given distribution feeder to study the phenomenon of delayed voltage recovery.

The advantage to using RTDS over other modeling environments is that full flux linkages are modeled explicitly, providing more accurate results than other modeling software.

1.2 Objective

This project involves a dynamic model development and simulation study that supports a broader investigation of the effect of air conditioning and similar loads on the recovery of electric utility voltage after faults. The phenomenon of slow recovery of utility voltages is referred to as Fault Induced Delayed Voltage Recovery. From here onwards, this phenomenon will be referred as FIDVR.

This project is the result of conclusions made after extensive preliminary work which showed that it is necessary to represent both the electrical behavior of single phase capacitor motors and the driven loads in point-on-wave detail to obtain a faithful simulation of the test behavior of residential air conditioners. One of the major objectives of this project was to incorporate multiple instances of the detailed motor/load model into an electric power system simulation where these motors can be subjected to voltage disturbances that are seen in feeders experiencing the FIDVR phenomenon.

Other major objectives for this project, during a FIDVR event, are as follows:

a) To understand if all the single phase induction motors downstream on a given feeder will stall together, or if only a portion of them will stall.

b) To illustrate the sensitivity of motor stalling to pre-identified key parameters

c) To perform a large number of simulation runs along with capturing detailed plots of voltages, currents, and motor speeds throughout the system for a selection of voltage dip cases.

1.3 Summary of Results

In order to study the FIDVR phenomenon, a wide range of voltage depressions were simulated for pre-determined system conditions. With appropriate RSCAD tools, hundreds of plots were captured for various test cases.

This study provides simulations illustrating the expected behavior of motors along a feeder.

Section 2: RATIONALE OF THE SIMULATION

2.1 Delayed Voltage Recovery

In a FIDVR event, the voltages in the sub-transmission and distribution parts of a power system do not recover promptly to pre-event levels when the cause of a depression of voltages (normally an electrical fault) is removed.

A typical system configuration of concern is shown in Figure 1. A fault at a location such as point A depresses voltages throughout the load area "downstream" of the fault location. Because the fault is outside the load area, clearance of the fault does not disconnect the loads from their supply and the expectation is that load voltages will return to normal values very quickly when the fault is cleared. In FIDVR events, however, it is observed that voltages in the load area do not recover promptly when the fault is cleared. Rather, the immediate increase in voltage when the fault is cleared is smaller than expected and full recovery to normal voltage has been observed to take many seconds. A representative variation of voltage over a period of 120 seconds is shown in Figure 2.

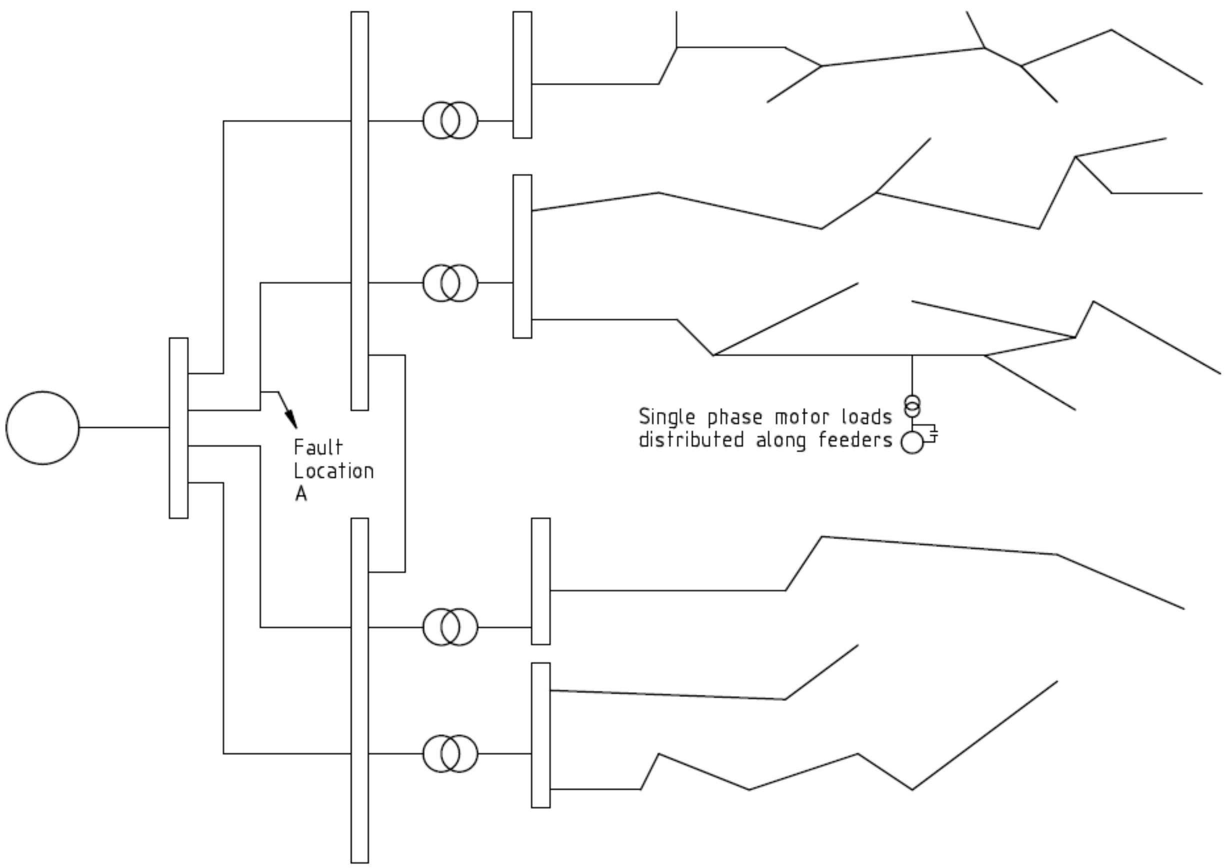


Figure 1: Typical System Configuration

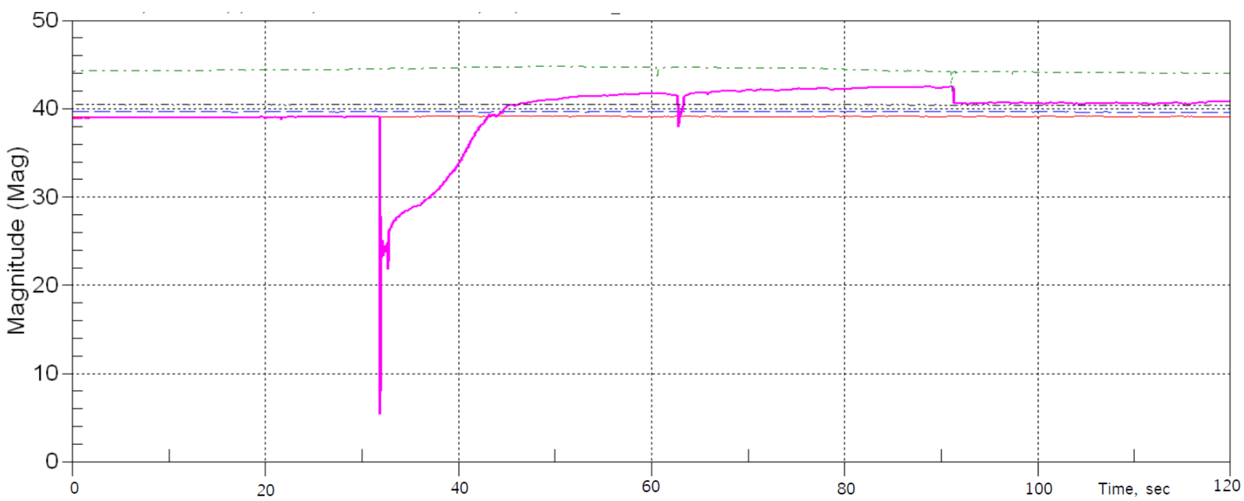


Figure 2: Representative Variation of Voltage Over a Period of 120 Seconds

2.2 Testing of Air Conditioners

The present understanding of the phenomenon is that an initiating fault depresses voltages at the terminals of motors to such a degree that they stall. The inertia constants of small motors, particularly those of driving residential air conditioner compressors, are very small (typically less than 40 milliseconds) and the run down to stall is correspondingly very quick. Faults cleared in as little as 3 cycles have been observed to cause widespread stalling.

The present understanding of the phenomenon is largely based on the testing of individual air conditioners. Tests made by Bonneville Power Administration and Southern California Edison have provided good factual information on the behavior of individual motors when the amplitude of the voltage at the terminals is varied in sudden step changes, timed ramps, and oscillations in the "electromechanical" frequency band. This testing has given a good indication of the voltage levels at which typical motors will stall, both when voltage is reduced suddenly and when it is ramped at a moderate rate. Sudden step testing has indicated that whether a motor will stall when the applied voltage is reduced suddenly to a given level is dependent on the phase of the voltage at the instant that the step is applied.

Testing by Bonneville Power Administration (BPA) and Southern California Edison has been done with the air conditioners in normally loaded conditions and hence with their single phase motors driving their normal mechanical loads. This testing has not involved the measurement of the driven load itself.

2.3 Motor Simulation

A simulation model has been developed to represent the behavior of a single motor and its driven load when subjected variations of the applied terminal voltage. This simulation model is included in this report as appendix [7.1]. It represents the electric motor at the level of electromagnetic transient simulations. Voltage, current, and flux variables are at the "point-on-wave" level and the inductances of the machine vary sinusoidally with rotor angle; mathematical rotational translations (e.g., Park's transformations) that would replace the sinusoidally varying inductances with constant values are not used. The simulation time step associated with the model is on the scale of 20 microseconds.

It is noted that electric machine models based on the rotational transformations cannot readily reproduce the presence or effects of unidirectional currents in the stator and rotor circuits while the electromagnetic transient form of model reproduces these effects explicitly. Similarly, the electromagnetic transients level model is sensitive to the phase at which the applied voltage changes, while models based on the rotational transformations cannot readily "see" this phase effect.

The same variations of terminal voltage, as used in the testing done by BPA, have been played in to the model and the resulting behavior of currents and voltages have been compared with test recordings. While the simulation model has been subjected to the played in test voltages, the absence of test recordings of load torque has made it necessary for the simulation to use assumptions regarding load torque. Based on guidance from the Air Conditioning Heating and Refrigeration Institute (AHRI) the load torque has been assumed to consist of the following:

- A component proportional to the square of speed, principally friction and windage load.
- A component varying with the angular position of the crankshaft of the driven reciprocating or scroll compressor. This load component has been assumed to have a simple triangular wave form.

The form of the load profile used in simulations is illustrated by Figure 3.

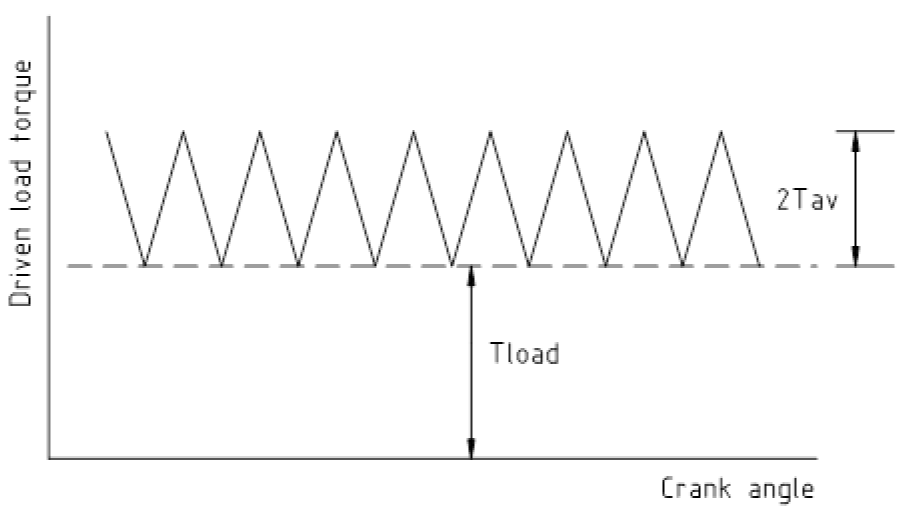


Figure 3: Load Torque Profile Used in Simulations

The single motor simulation model has been found to correspond quite well to test results, with regard to the voltage levels at which the motor will stall and to the dependence of stall on the phase of the applied voltage at the moment that the voltage is reduced suddenly.

2.4 Feeder Behavior

While the tests and simulation work so far has given a good insight into the behavior a single phase induction motor, it has not addressed the behavior of a distribution feeder or sub-transmission system whose load consists in large proportion of small motors.

Section 3: ELEMENTS OF THE SIMULATION

3.1 Single Phase Motor Model

The model is a first order forward difference implementation of an electromagnetic model of a single phase induction motor and its associated capacitor. The placement of stator and rotor windings is as shown in Figure 4. The mutual inductances between stator and rotor coils vary sinusoidally with the angular position of the rotor. The number of turns in the two stator windings is unequal. The capacitor in the second stator winding is represented explicitly. The motor is asymmetric across its d and q axes—in winding turns, wires size, applied voltage.

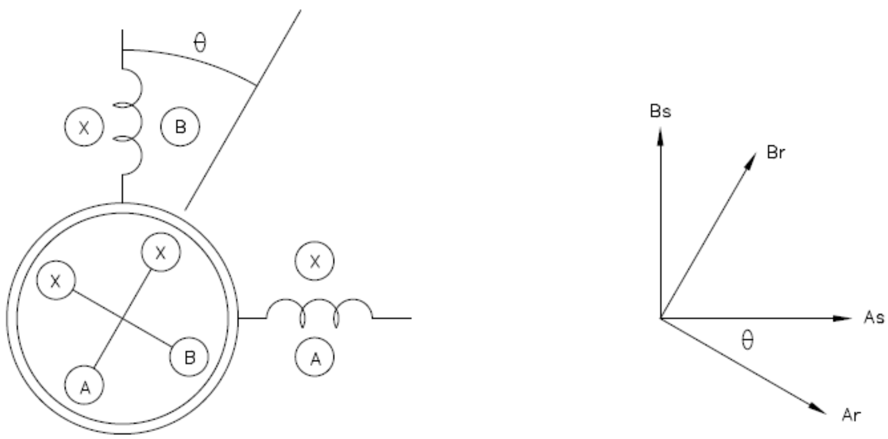


Figure 4: Induction Motor Model Recognizing Sinusoidal Variation of Mutual Inductances

Figure 5 shows a pictorial description of the motor connections in a single phase distribution circuit. It is important to note the capacitor connection to the auxiliary winding.

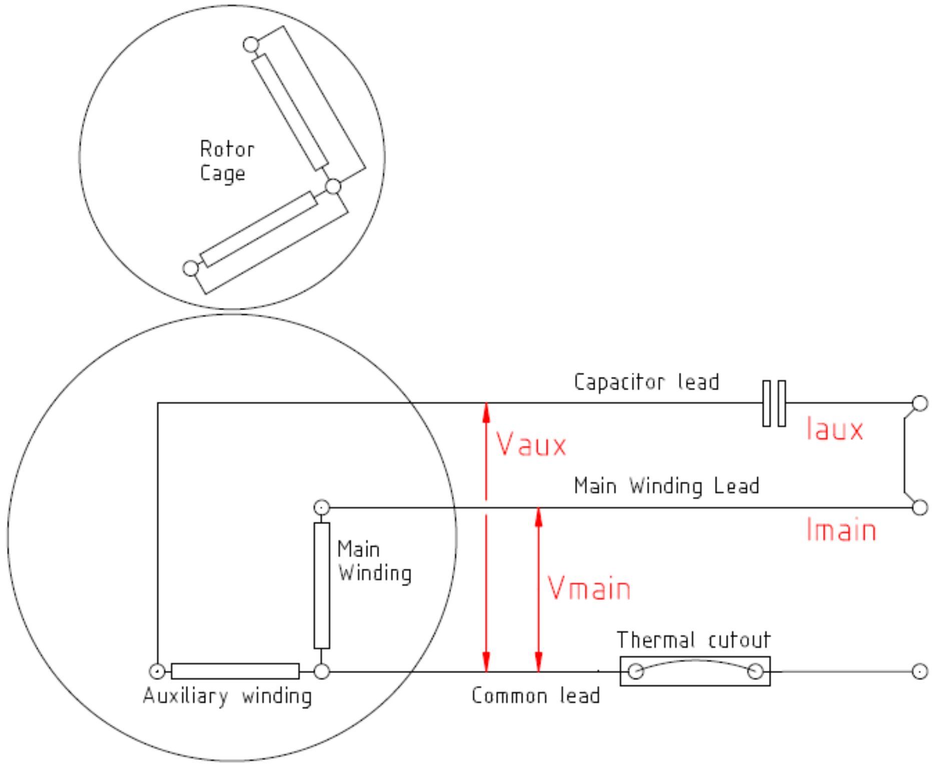


Figure 5: Pictorial Description of Motor Connections

3.2 Reciprocating Compressor Loads

As described in section 2.3 and Figure 3, the load torque consists of a component proportional to the square of speed, a component varying in a triangular waveform with crank angle, and a constant load torque "offset."

3.3 Distribution Feeder and Transformer

The distribution feeder model is made up of three phase line sections whose parameters are specified in terms of symmetrical component impedances. The three phase line sections are symmetrical in the sense of being "transposed." The symmetrical component impedances reflect the presence of a neutral wire that is effectively grounded at all locations. The single phase distribution transformers connecting load to the feeder model are connected from phase to ground. Individual blocks of load are located on radial single phase "lateral" lines. These laterals are represented by simple series impedances. Each block of load is located at the end of a lateral and consists of a single phase distribution transformer, a purely resistive load, and a single phase 230 V air conditioner motor. The motor parameters are scaled from those of an original model of a single phase motor to represent a larger concentration of motors. The feeder is connected to the 115 kV supply system by a three phase transformer. The supply transformer is rated 8 MVA, wye-wye, and grounded on both sides with zero grounding impedance.

3.4 Power Supply and Applied Voltage Dips

The three phase source in the 115 kV part of the system is operated at 121 kV. The voltage source is modeled by a strong 121 kV Thevenin source and a simple series link. The source is modeled as a three phase programmable source, thus providing control over voltage magnitude, phase, and frequency for each phase. This source voltage is programmed to play in sub-transmission and transmission events.

Section 4: BUILD UP OF THE SIMULATION

4.1 The Feeder Model

4.1.1 Circuit Configuration

The study considers the feeder shown in Figure 6. It consists of a single radial three phase distribution line from its node 3 to its node 8 where it forks into two radial three phase branches. It is represented by eight runs of three phase overhead line. The load on the feeder is concentrated at seven nodes. Each concentrated block of load consists of the following:

- 0.2 MW of constant admittance load.
- A single motor representing 177 prototype motors where each prototype motor is loaded at 4.5, 5.3, 6.0 kW in various simulation cases.

The prototype motor parameters are as follows:

Friction and Windage Load Coefficient

- tload = variable parameter (4, 6, or 8 N-m)

Compressor Triangular Waveform Load Coefficient

- tav = variable parameter (12, 8, or 4 N-m)

Motor Electromagnetic Parameters

- omega = 377 and scale = 177

```
rs = 0.3/Scale                /*Stator winding resistance, ohms*/
rr = 0.3/Scale                /*Rotor winding resistance at synchronous speed, ohms*/
lm = (30/omega)/scale         /*Winding A to rotor mutual inductance, saturated, ohms*/
lmu = (30/omega)/scale        /*Winding A to rotor mutual inductance, unsaturated, ohms*/
lls = (0.5/omega)/scale       /*Winding A leakage reactance, ohms*/
llr = (0.2/omega)/scale       /*Rotor winding leakage reactance, ohms*/
nab = 1.4                     /*Ratio of winding B turns to winding A turns*/
ccap = (40e-6)*scale          /*Capacitor impedance, Henrys*/
```

Moment of inertia in Kg-m^2

- wr2 = 7800*(pi/32)*0.2*pow (.065, 4)*scale

A scale factor of 177 has been used to represent the single motor in each block of the load.

Capacitors are connected as follows:

Node 6	800/3 KVAR/phase	three phase
Node 8	1600/3 KVAR/phase	three phase
Node 11	300/1 KVAR/phase	C-phase

The three phase supply is modeled by individual programmable phase-neutral voltage sources, each with a Thevenin impedance of 0.2645 ohms, at node 1. The branch from node 1 to node 2 has individual phase series impedance of 1.32 ohms.

The supply transformer is connected wye-wye with both neutral points solidly grounded. The transformer details are as follows:

Primary Winding Voltage	121.24 kV
Secondary Winding Voltage	13.8 kV
Impedance	0.002 + j0.08 per unit on 8 MVA base

The feeder line characteristics are as follows:

Series impedance, positive sequence	0.43 + j 0.43 ohms/mile
Series impedance, zero sequence	1.70 + j 0.67 ohms/mile

The neutral of the feeder line is assumed to be well grounded at all points.

Load service transformers are connected phase-neutral, which is synonymous with phase-ground connection, given that the neutral is assumed to be effectively grounded at all points. The load service transformer details are as follows:

Primary voltage	7967 V
Secondary voltage	115/115 V center grounded
Impedance	0 + j 0.02 per unit on 1500 KVA base

The resistive load and air conditioner motor loads are connected as shown in Figure 11. The RTDS version of the feeder model is shown in Figure 7 and Figure 8. It is drawn using the RSCAD tool.

4.1.2 Feeder Loading

The feeder was set up with strongly unbalanced loading; phase C serves three loads while phases A and B serve two loads each. Phase C is very heavily loaded and has a greater than normal voltage drop from its head to the last load at bus 11. The voltages on the feeder and at the motor terminals are not constant in the pre-event conditions; they vary slightly in their fundamental-frequency amplitude as the angle dependent component of load torque, which is not synchronous with electrical voltage, slips with respect to the phase of the voltage source.

In a representative pre-event condition, the voltages at the head of the feeder and at node 8 immediately before the application of the voltage dip are shown in Table 1.1.

Table 1.1 Pre-Event Voltages

Phase	Head Voltage (kV)	Node 8 Voltage (kV)
Van	7.84	7.63
Vbn	7.87	7.45
Vcn	7.78	7.18

In this condition the voltages at the individual motor terminals immediately before the voltage dip are shown in Table 1.2.

Table 1.2 Pre-Event Voltages at Motor Terminals

Motor	Voltage (V)	Phase
1	210.1	A
2	211.3	C
3	211.3	B
4	211.0	C
5	206.0	B
6	211.0	A
7	196.7	C

4.1.3 Air Conditioner Loading

The simulations examine the behavior of the air conditioners at loadings as shown in Table 1.3:

Table 1.3 Range of Air-Conditioner Loading Levels

Nominal Power (kW)	Speed-Dependent Torque (N-m)	Triangular Torque (N-m)	Average Torque (N-m)
4.52	8	4	12
5.28	6	8	14
6.03	4	12	16

This range of power corresponds approximately to the range of power taken by a 13.00 SEER (Seasonal Energy Efficiency Ratio) rated air conditioner over an ambient temperature range of 20 degrees Fahrenheit. The triangular component of the load torque has two peaks per revolution of the motor and hence corresponds to a two-cylinder compressor.

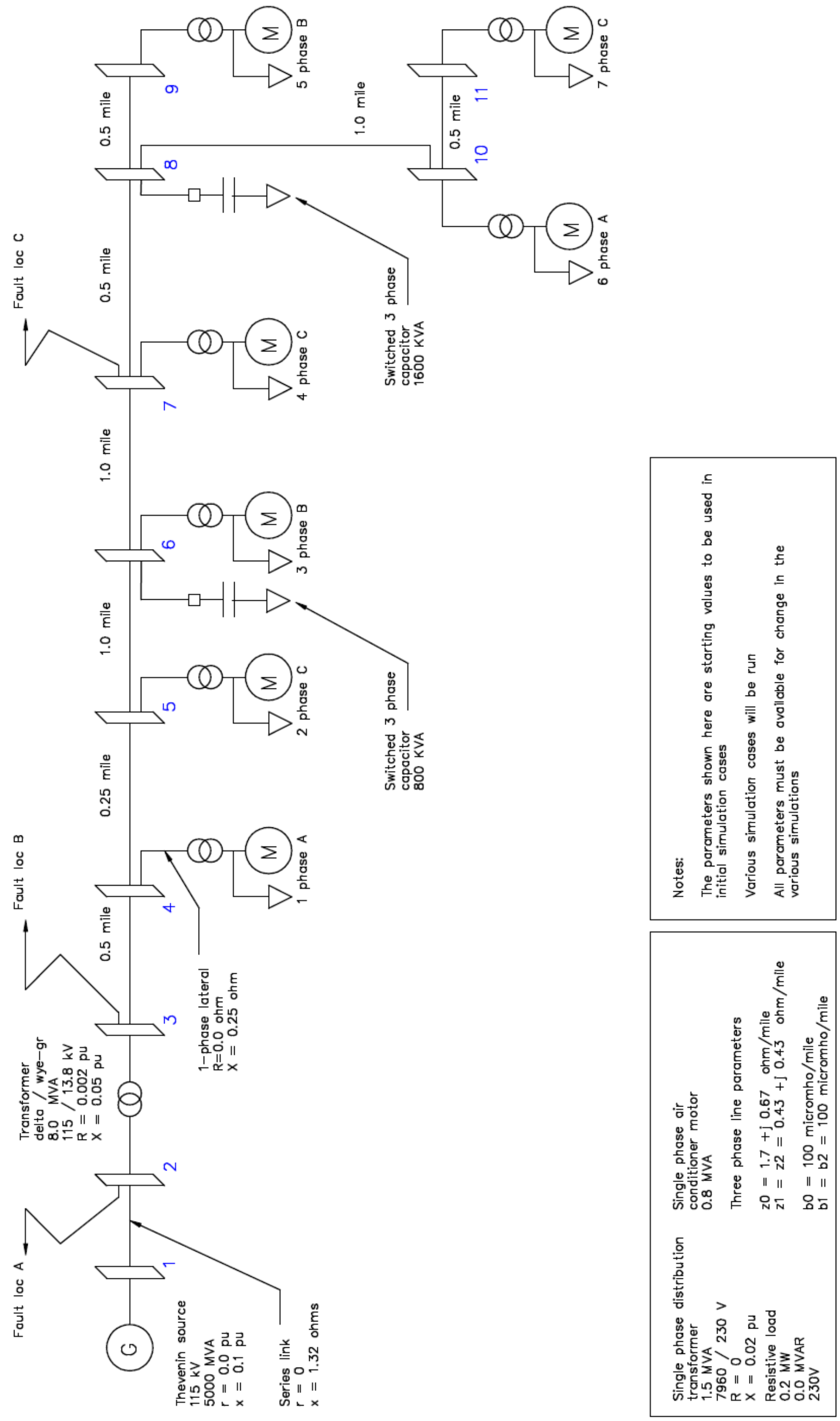


Figure 6: Feeder Layout

The feeder model in RTDS is divided between two simulator racks. Figure 7 shows the portion of the system that was modeled in rack 1. Figure 8 shows the remaining portion of the system that was modeled in rack 2.

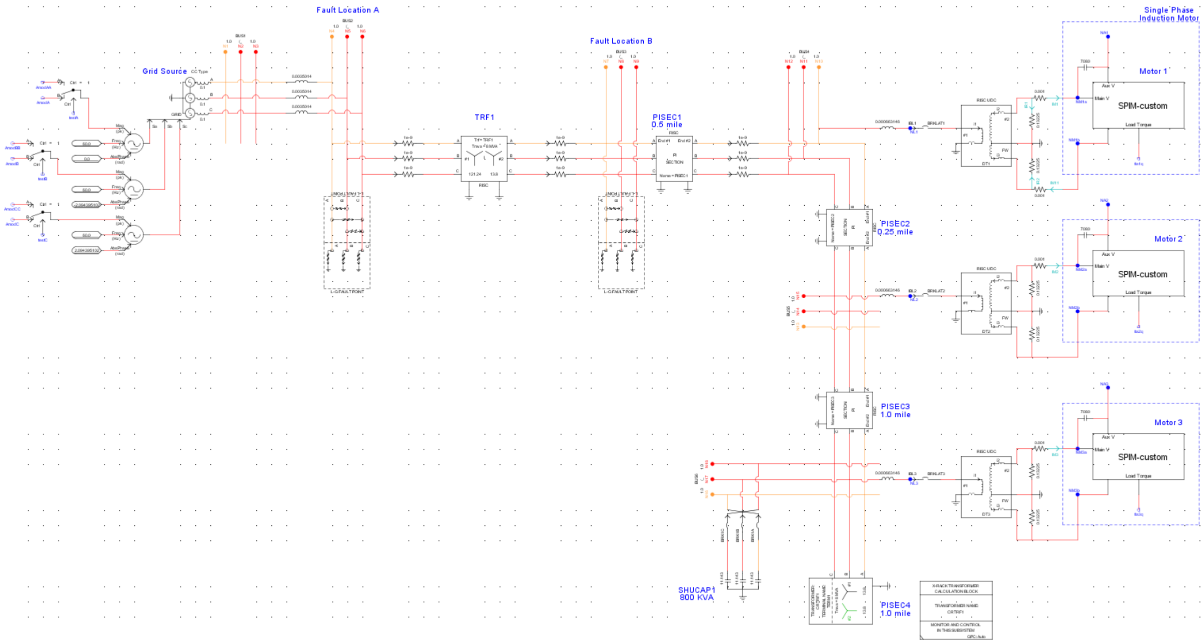


Figure 7: Feeder Model in RSCAD Subsystem 1

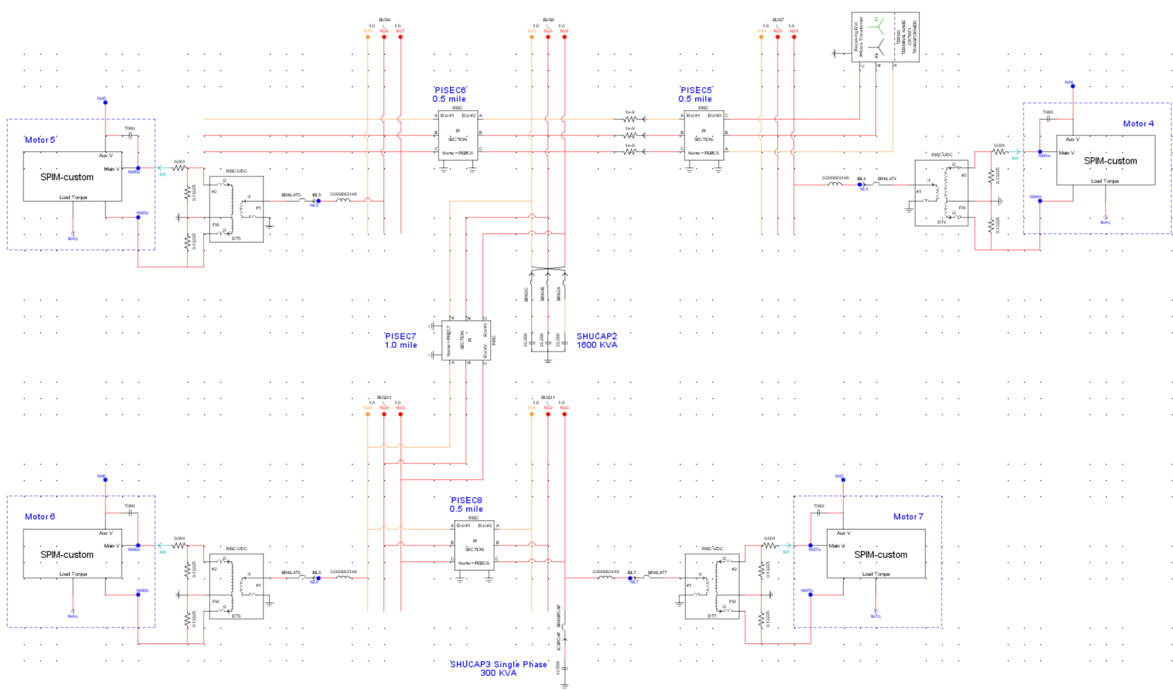


Figure 8: Feeder Model in RSCAD Subsystem 2

4.2 Real Time Digital Simulator

4.2.1 RTDS Operation

The Real-Time Digital Simulator, RTDS®, is a fully digital power system simulator capable of continuous real-time operation. It performs electromagnetic power system transient simulations with a typical simulation time step in the order of 50 microseconds utilizing a combination of custom software and hardware. RTDS is the hardware simulator and RSCAD is the windows based software suite that is used to interface with RTDS.

The RTDS hardware was designed specifically to perform hundreds of thousands of calculations in a real-time environment. The overall network solution technique employed in the RTDS is based on nodal analysis. The underlying solution algorithms are those introduced in [2]. By nature, the Dommel Algorithm allows two levels of parallel processing which are as follows:

1. Parallel processing of components connected to a common admittance matrix (i.e., within one subsystem).
2. Parallel processing of subsystems (i.e., decoupled admittance matrices).

The RTDS mimics the first level by using tightly coupled processors within a rack to solve components connected to a common admittance matrix. The second level is implemented by using separate racks to solve different simulation subsystems. In addition to being designed to execute the Dommel Algorithm in real-time, the RTDS was designed to test physical protection and control equipment. One of the main considerations of testing physical devices is the Input/Output structure. To maximize the communication bandwidth and minimize the time required, the RTDS was designed to provide the most direct route possible for I/O to be passed from the processors performing the simulation to the I/O channels.

For this project, RTDS was specifically utilized to study the behavior of multiple single phase induction motors at a point on wave detail when connected to a distribution feeder model.

4.2.2 Initialization and Sequence of Events

Each simulation was initialized by picking up the feeder, allowing the motors to run up to speed against minimal load, applying the driven loads, and allowing conditions to stabilize before applying a voltage dip. The sequence of events was as follows:

0.0 Second	Energize Feeder, Van, Vbn, Vcn = 70.0 kV L-N at Source
0.5 Second	Apply Driven Loads
1.0 Second + Phase Delay	Apply Programmed Dip in Source Voltages

Figure 9 and Figure 10 show the startup and initialization part of the simulations; this startup trajectory varies from run to run only to the extent that the different driven load profiles result in different crank-angle positions in relation to the phase of the motor terminal voltages at the instant of application of the voltage dip. For Figures 9 and 10, the x-axis is time in seconds. Figure 11 shows the connections of the single phase induction motor along with the constant admittance load to the distribution transformer.

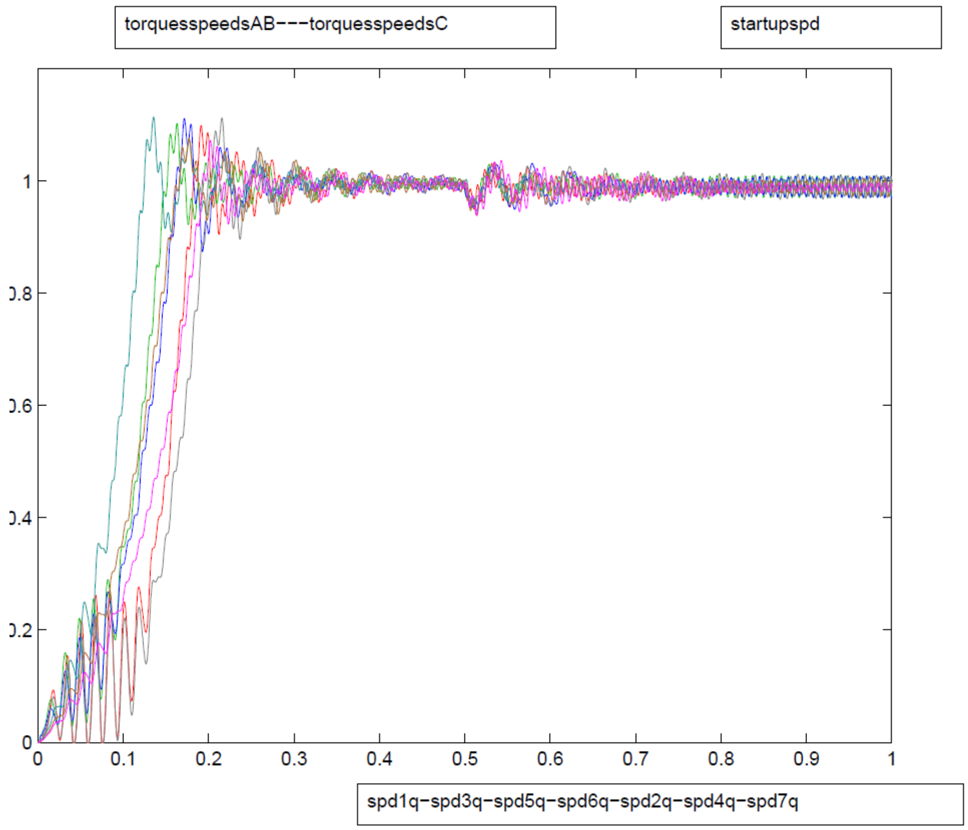


Figure 9: Startup Speeds of the Seven Motors

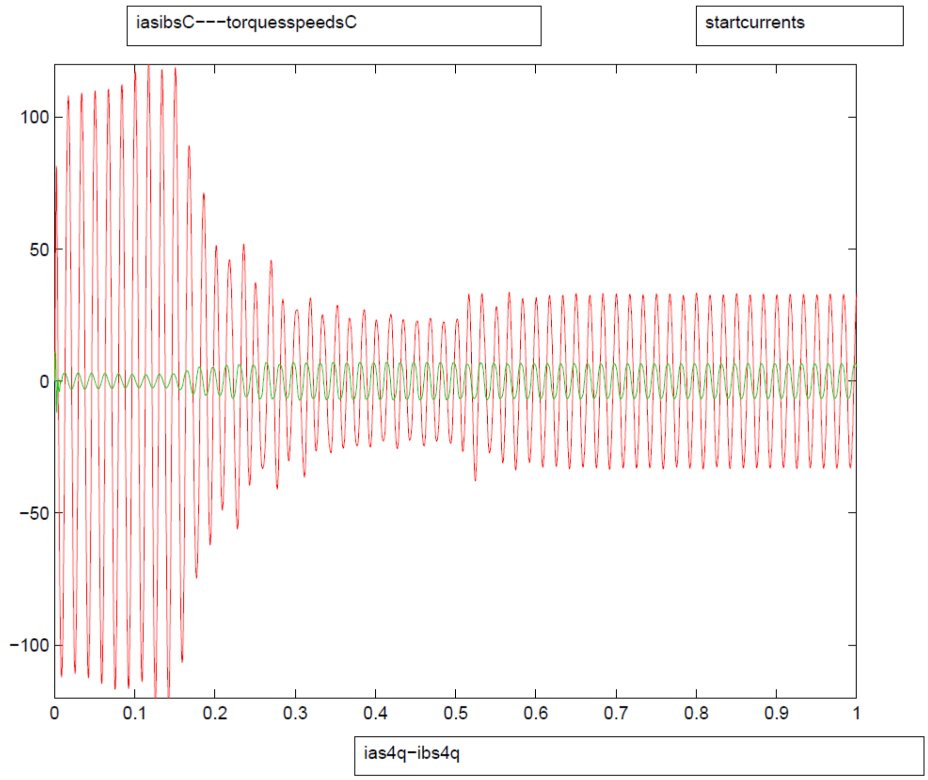


Figure 10: Startup Currents in the stator windings of a single motor

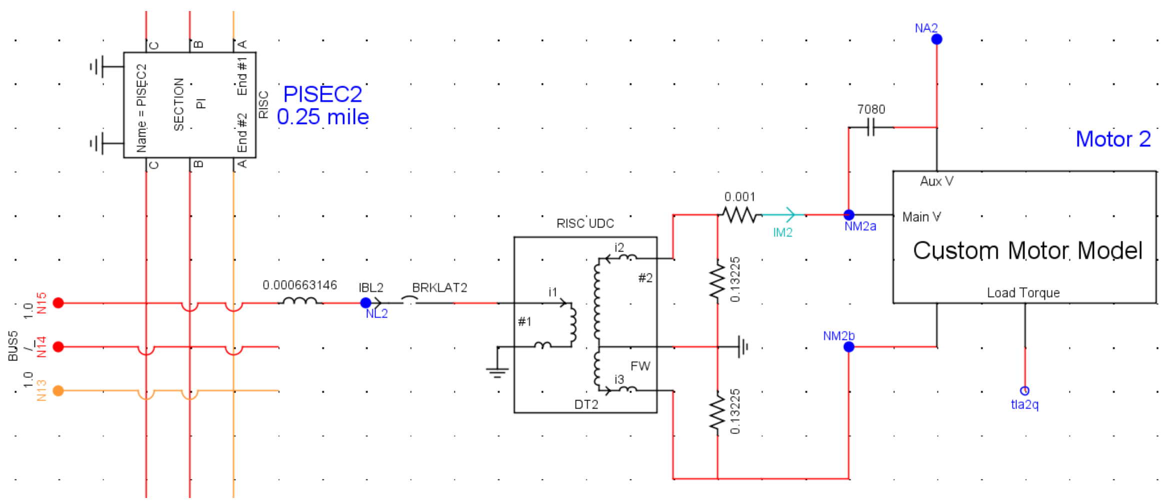


Figure 11: Connection of Each Block of Load to the Feeder Model through the Distribution Transformer

The single phase motor is connected across the 230 volt terminals of the center-grounded secondary of the distribution transformer. The resistive loading is represented using the resistors that are connected across the 115 V. On each lateral, there is a 1 MVA load connected. Twenty percent of the load is resistive which represents lighting and other constant admittance loads. Eighty percent of the load on each lateral is represented by the single phase induction motors.

4.2.3 RTDS Solution Procedure

The simulator transient solution procedure is shown in Figure 12. For every simulation time step (20 microseconds), the motor model receives updated/new terminal voltages and solves for the Norton currents that will be injected through a Norton admittance. The motor model is solved using first order forward difference integration where as the RTDS uses trapezoidal integration for solving differential equations.

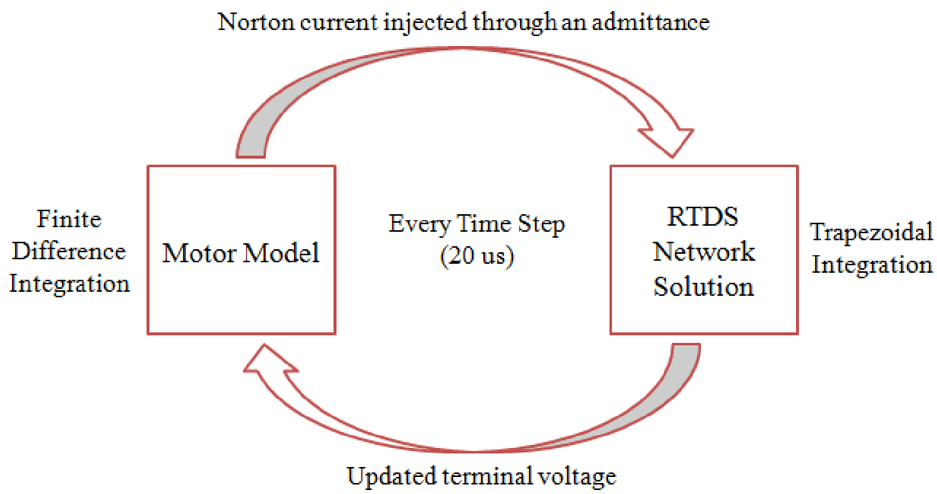


Figure 12: Transient Solution Procedure

Section 5: SIMULATION RESULTS

5.1 Motor Behavior in Steady Conditions

Because the windings of the motor have different numbers of turns and carry different currents, the torque developed by the motor contains a significant component varying at twice supply frequency. The load torque contains the triangular component associated with crank angle, which varies at a frequency of twice rotor speed. The average rotor speed is slower than synchronous. The instantaneous rotor speed is not constant but varies in accordance with the variation of electromagnetic and load torques. The waveform of driven load torque is synchronous with rotor angle therefore, it is not synchronous with the waveform of electromagnetic torque. The result of the non-synchronism of the driving and resisting torques is that the variation of rotor speed is not constant even in steady supply conditions. Instead, the variations of electromagnetic torque, load torque, and rotor speed all follow a beat frequency pattern determined by the difference between synchronous and rotor speeds. Because the wave of rotor-synchronized load torque slips in phase constantly, with respect to the phase of the supply voltage, the internal condition of the motor at the moment of inception of a disturbance is a function of the operational history of the driven load. In a real population of motors the relative phase of electromagnetic torque and load torque at the moment of inception of a supply disturbance would be largely random. In the simulations described here, the history of each block of motors from the application of the triangular torque wave until the inception of the voltage dips was not uniform. It reflected the different levels of load torque and phasing of application of the voltage dips and was not uniform from case to case, even though the supply voltage prior to the application of the voltage dip was the same in each simulations.

Figure 13 illustrates the slipping of the load torque waveform with respect to the double frequency variation of the electromagnetic torque. The load torque variation is substantially in phase with the electromagnetic torque at 0.6 second and in complete phase opposition at 0.95 second. It is evident that simulations applying voltage dips at different times (say at 1.5 seconds rather than at 1.0 second) would be expected to give slightly different results.

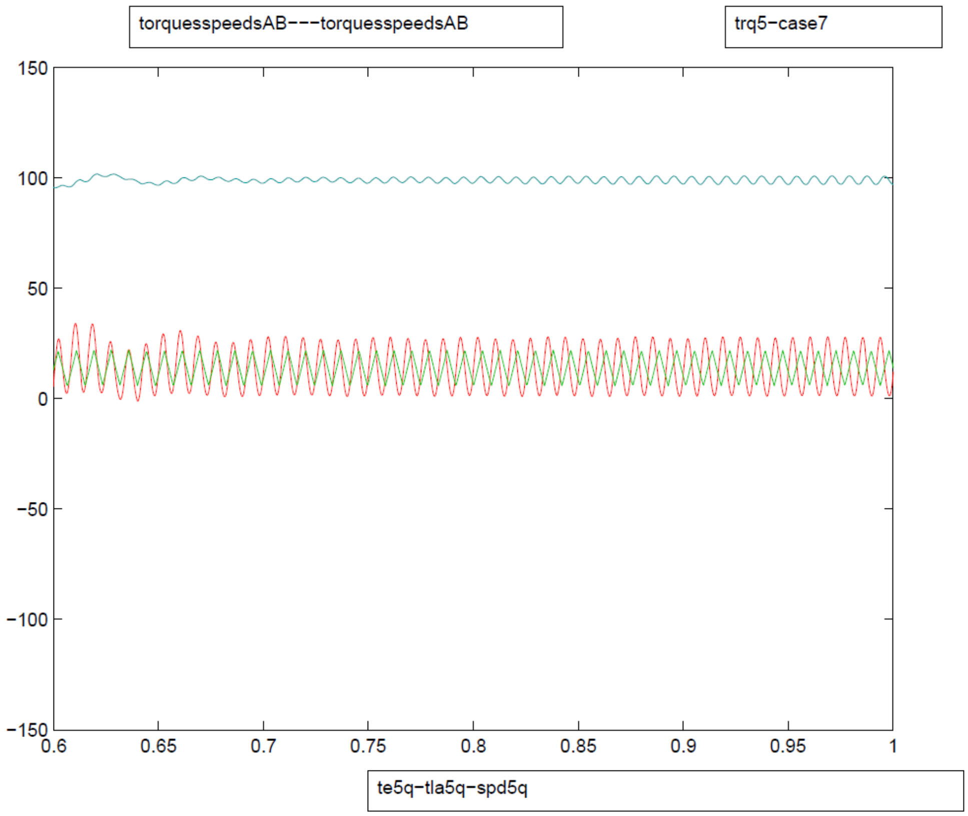


Figure 13: Slipping of Load Torque During Steady State

5.2 Mechanism of Stalling

When the motor terminal voltage is reduced suddenly, large but brief negative, decelerating excursions of the electromagnetic torque plots are shown. These components of torque are associated with the unidirectional and low frequency transient components of current that are induced in the inductive windings of the motors when voltages are changed quickly. In these simulations, where the amplitude of the supply voltage was changed suddenly, the non-sinusoidal transient components of current depend on the phase of the supply voltage at the instant of the change. Accordingly the transient variation of electromagnetic torque is strongly dependent on the phasing of the applied voltage dip. Then, as noted in the previous section, the relative phase of the supply voltage and the load torque is highly variable. Whether the motor will stall or not, at least in marginal cases, is strongly dependent on the relative phasing of the stator and rotor variables and of the initiation of the applied disturbance.

Figure 14, Figure 15, and Figure 16 all show the behavior of motors 1, 6, and 7 when the voltage in the A and C-phases of the supply is dipped from 70.0 kV to 41.2 kV for 5 cycles. Motors 1 and 6 are on the A-phase near the head and end of the feeder respectively. Motor 7 is on the C-phase at the end of the feeder.

First compare the trajectories of electromagnetic torque (red) in the three figures. The initial swings of electromagnetic torque shown in the three figures are of similar magnitude but their subsequent trajectories are very different. In the motors in the A-Phase, the subsequent swings of torque go a strongly positive, while those in the C-phase motor increase the negative side of their variation. The result is that the motor in the C-phase stalls while those in the A-Phase, whose supply voltage dip was the same reaccelerate.

In the figures, the mechanical load torque (green) and the motor speed (blue) are also shown. Close inspection of the three figures shows that the phase of the electromagnetic torque swings, relative to the load torque, is quite different between the C-phase motor and the motors in the A-Phase.

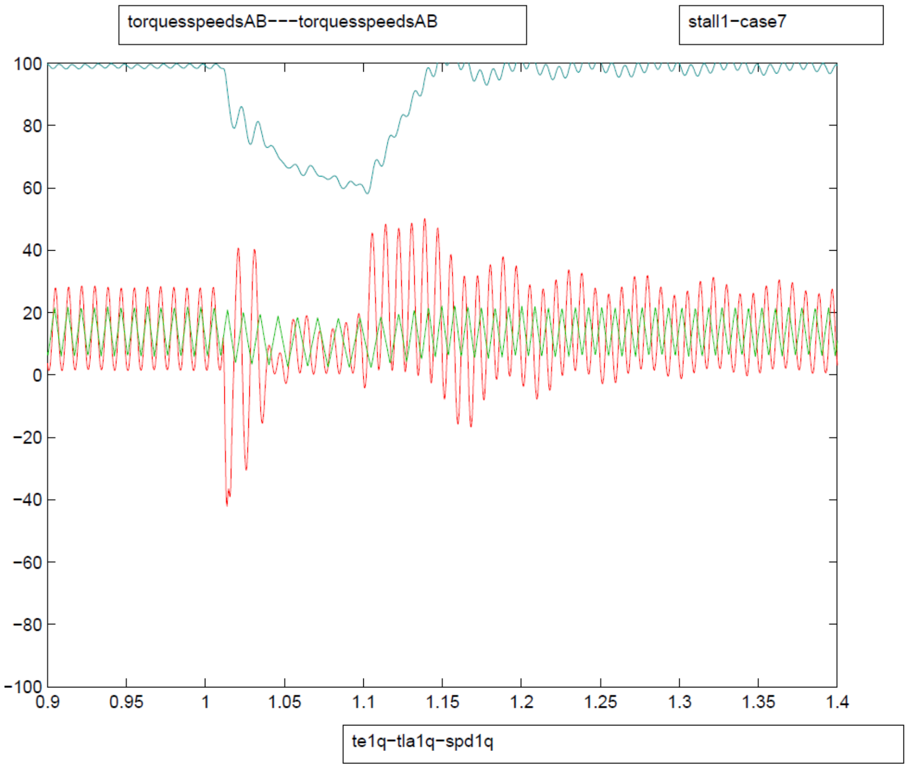


Figure 14: Behavior of Motor 1 for Voltage Dip in the A- and C-Phases

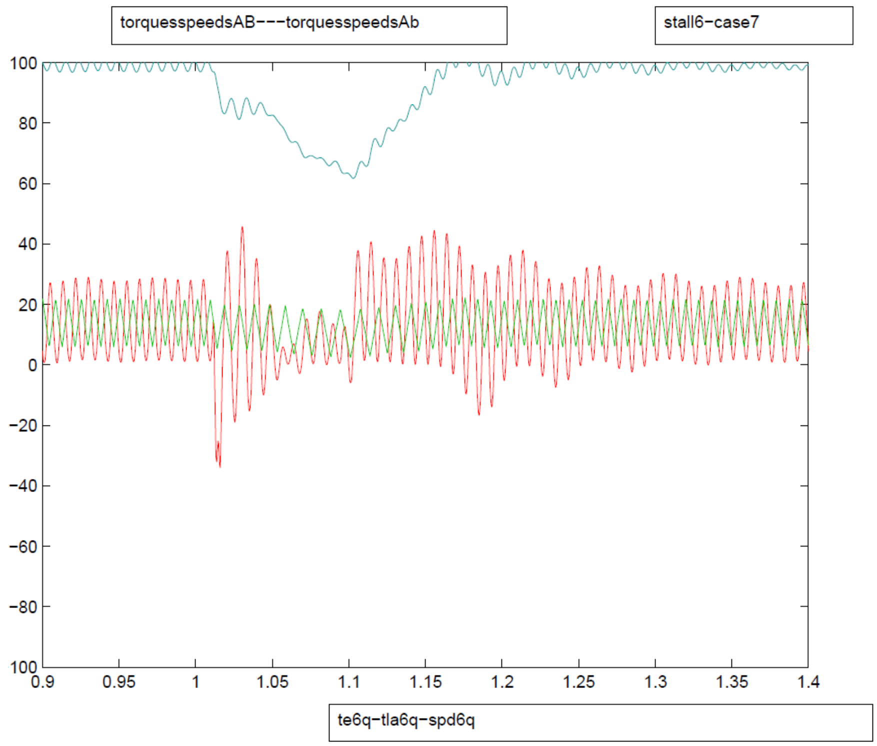


Figure 15: Behavior of Motor 6 for Voltage Dip in the A-and C-phases

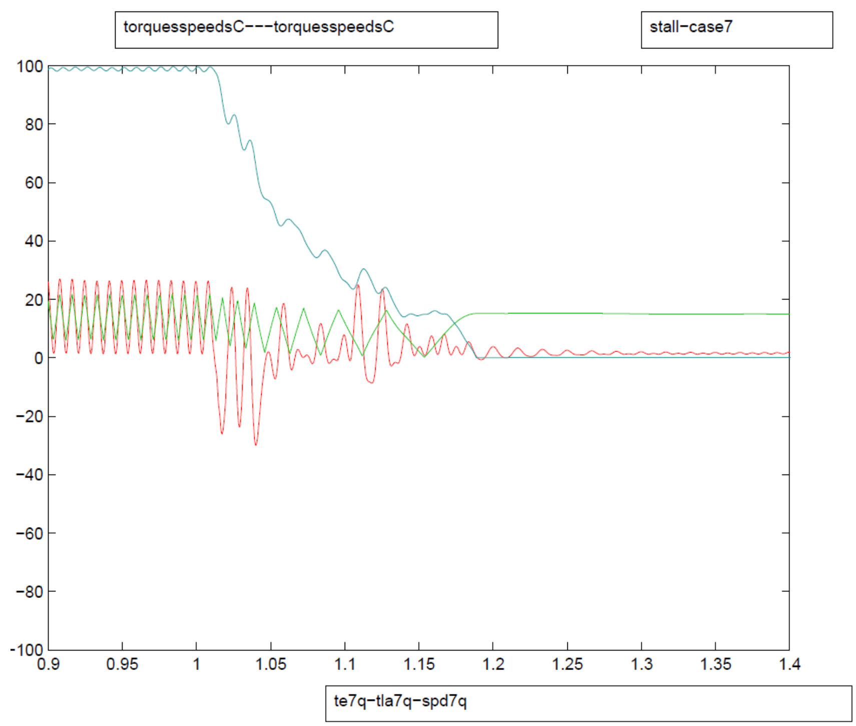


Figure 16: Behavior of Motor 7 for Voltage Dip in the A-and C-Phases

5.3 Summary of Simulation Results

Table 1.5 Batch(A)-All summarizes the overall simulation results for the first batch. It contains 240 simulations where the three phases of the supply voltage were reduced in amplitude simultaneously for different combinations of the stall-sensitive parameters. The parameters are shown in Table 1.4.

Table 1.6 Batch(B)-All summarizes the next set of simulation results. It contains 117 simulations in which the C-phase of the supply voltage was reduced in amplitude (while A and B phases were unchanged) for different combinations of the stall-sensitive parameters. For Tables 1.5 and 1.6, pale red indicates motors stalled and pale green indicates motors that did not stall.

Further, Tables 1.5 and 1.6 have been consolidated into Tables 1.7, 1.8, 1.9, 2.0, 2.1, and 2.2. Tables 1.7 Batch(A)-12 N-m, 1.8 Batch(A)-14 N-m, and 1.9 Batch(A)-16 N-m summarize simulations in which the three phases of the supply voltage were reduced in amplitude simultaneously. Tables 2.0 Batch(B)-12 N-m, 2.1 Batch(B)-14 N-m, and 2.2 Batch(B)-16 N-m describe simulations in which the C-phase of the supply voltage was reduced in amplitude while the A and B phases were unchanged. For Tables 1.7, 1.8, 1.9, 2.0, 2.1 and 2.2, colored rows in these Tables indicate simulation runs in which motors stalled. Pale yellow rows indicate runs in which multiple motors stalled. Gold shaded rows indicate cases in which only one motor stalled. The reductions of supply voltage were applied at 0, 30, 60, and 90 degree angles of the C-phase supply, as indicated by the green-shaded cells of the Tables.

The immediate indication of these six Tables is unsurprising. With the average load torque of 12 N-m the supply voltage must be very far depressed to cause motors to stall while at 14 N-m load torque some motors will stall when voltage dips only to 66 percent of pre-event level.

The parameters used for illustrating the sensitivity of motor stalling are as follows:

- Duration of voltage depression.
- Voltage during the depression (Note - This is defined by the voltage at the bottom of the dip).
- Supply Voltage Phase angle in C-phase at the instant when depression is initiated.
- Driven load parameters – These are the mechanical load parameters. Tav and Tload (See Figure 3).

Please refer to the Table 1.4 for the parameter values used.

Table 1.4 Stall-Sensitive Parameters

Voltage at Bottom of Dip, 70 kV Nominal (kV)	Voltage Dip (%)	Voltage Phase Angle During Dip Initiation (°)	Voltage Dip Duration (cycles)	Tload (N-m)	Tav (N-m)
25.2	36	0	3	8	4
30.5	43.5	30	5	6	8
35.9	51.2	60	7	4	12
41.2	58.8	90	9	NA	NA
46.5	66.4	NA	NA	NA	NA

Table 1.5 Batch(A)-All														
Fault Duration (cycles)	**Point on Wave (°)**	**Voltage at Bottom of Dip (per unit)**			**Tload (N-m)**	**Tav (N-m)**	**Motor**							
		A-Phase	**B-Phase**	**C-Phase**			**1**	**2**	**3**	**4**	**5**	**6**	**7**
3	0	0.36	0.36	0.36	8	4	0	1	0	0	0	0	0
3	0	0.36	0.36	0.36	6	8	0	1	0	1	1	0	1
3	0	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
3	0	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
3	0	0.44	0.44	0.44	6	8	0	1	0	1	0	0	1
3	0	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
3	0	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
3	0	0.51	0.51	0.51	6	8	0	0	0	0	0	0	1
3	0	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
3	0	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
3	0	0.59	0.59	0.59	6	8	0	0	0	0	0	0	0
3	0	0.59	0.59	0.59	4	12	0	0	0	1	0	0	1
3	0	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
3	0	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
3	0	0.66	0.66	0.66	4	12	0	0	0	0	0	0	1
3	30	0.36	0.36	0.36	8	4	0	0	0	0	0	0	0
3	30	0.36	0.36	0.36	6	8	0	1	1	1	1	0	1
3	30	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
3	30	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
3	30	0.44	0.44	0.44	6	8	0	0	0	1	1	0	1
3	30	0.44	0.44	0.44	4	12	0	0	0	1	1	0	1
3	30	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
3	30	0.51	0.51	0.51	6	8	0	0	0	0	0	0	1
3	30	0.51	0.51	0.51	4	12	0	1	1	1	1	0	1
3	30	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
3	30	0.59	0.59	0.59	6	8	0	0	0	0	0	0	0
3	30	0.59	0.59	0.59	4	12	0	0	0	1	1	0	1
3	30	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
3	30	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
3	30	0.66	0.66	0.66	4	12	0	0	0	0	0	0	1
3	60	0.36	0.36	0.36	8	4	0	0	0	0	0	0	0
3	60	0.36	0.36	0.36	6	8	1	0	1	1	1	0	1
3	60	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
3	60	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
3	60	0.44	0.44	0.44	6	8	0	0	1	0	1	0	1
3	60	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1

Table 1.5 Batch(A)-All													
Fault Duration (cycles)	Point on Wave (°)	Voltage at Bottom of Dip (per unit)			Tload (N-m)	Tav (N-m)	Motor						
		A-Phase	B-Phase	C-Phase			1	2	3	4	5	6	7
3	60	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
3	60	0.51	0.51	0.51	6	8	0	0	0	0	1	0	0
3	60	0.51	0.51	0.51	4	12	1	0	1	1	1	1	1
3	60	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
3	60	0.59	0.59	0.59	6	8	0	0	0	0	0	0	0
3	60	0.59	0.59	0.59	4	12	0	0	1	0	1	0	1
3	60	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
3	60	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
3	60	0.66	0.66	0.66	4	12	0	0	0	0	0	0	1
3	90	0.36	0.36	0.36	8	4	0	0	0	0	0	0	0
3	90	0.36	0.36	0.36	6	8	1	0	1	0	1	1	1
3	90	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
3	90	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
3	90	0.44	0.44	0.44	6	8	1	0	0	0	1	0	1
3	90	0.44	0.44	0.44	4	12	1	0	1	1	1	1	1
3	90	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
3	90	0.51	0.51	0.51	6	8	0	0	0	0	0	0	0
3	90	0.51	0.51	0.51	4	12	1	0	1	1	1	1	1
3	90	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
3	90	0.59	0.59	0.59	6	8	0	0	0	0	0	0	0
3	90	0.59	0.59	0.59	4	12	0	0	0	0	1	0	1
3	90	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
3	90	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
3	90	0.66	0.66	0.66	4	12	0	0	0	0	0	0	0
5	0	0.36	0.36	0.36	8	4	0	1	0	0	0	0	1
5	0	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
5	0	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
5	0	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
5	0	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
5	0	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
5	0	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
5	0	0.51	0.51	0.51	6	8	0	1	0	1	0	0	1
5	0	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
5	0	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
5	0	0.59	0.59	0.59	6	8	0	0	0	0	0	0	1
5	0	0.59	0.59	0.59	4	12	0	1	0	1	1	1	1

Table 1.5 Batch(A)-All

Fault Duration (cycles)	Point on Wave (°)	Voltage at Bottom of Dip (per unit)			Tload (N-m)	Tav (N-m)	Motor						
		A-Phase	B-Phase	C-Phase			1	2	3	4	5	6	7
5	0	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
5	0	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
5	0	0.66	0.66	0.66	4	12	0	0	0	1	0	0	1
5	30	0.36	0.36	0.36	8	4	0	0	0	0	0	0	0
5	30	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
5	30	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
5	30	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
5	30	0.44	0.44	0.44	6	8	0	1	1	1	1	0	1
5	30	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
5	30	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
5	30	0.51	0.51	0.51	6	8	0	0	0	1	1	0	1
5	30	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
5	30	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
5	30	0.59	0.59	0.59	6	8	0	0	0	0	0	0	1
5	30	0.59	0.59	0.59	4	12	0	1	1	1	1	0	1
5	30	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
5	30	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
5	30	0.66	0.66	0.66	4	12	0	0	0	1	0	0	1
5	60	0.36	0.36	0.36	8	4	0	0	0	0	0	0	0
5	60	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
5	60	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
5	60	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
5	60	0.44	0.44	0.44	6	8	1	0	1	1	1	0	1
5	60	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
5	60	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
5	60	0.51	0.51	0.51	6	8	0	0	1	0	1	0	1
5	60	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
5	60	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
5	60	0.59	0.59	0.59	6	8	0	0	0	0	0	0	0
5	60	0.59	0.59	0.59	4	12	1	0	1	1	1	0	1
5	60	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
5	60	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
5	60	0.66	0.66	0.66	4	12	0	0	0	0	1	0	1
5	90	0.36	0.36	0.36	8	4	0	0	0	0	0	0	0
5	90	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
5	90	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1

Table 1.5 Batch(A)-All													
Fault Duration (cycles)	**Point on Wave (°)**	**Voltage at Bottom of Dip (per unit)**			**Tload (N-m)**	**Tav (N-m)**	**Motor**						
		A-Phase	**B-Phase**	**C-Phase**			**1**	**2**	**3**	**4**	**5**	**6**	**7**
5	90	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
5	90	0.44	0.44	0.44	6	8	1	0	1	1	1	1	1
5	90	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
5	90	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
5	90	0.51	0.51	0.51	6	8	1	0	0	0	1	0	1
5	90	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
5	90	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
5	90	0.59	0.59	0.59	6	8	0	0	0	0	0	0	0
5	90	0.59	0.59	0.59	4	12	1	0	1	1	1	1	1
5	90	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
5	90	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
5	90	0.66	0.66	0.66	4	12	0	0	0	0	1	0	1
7	0	0.36	0.36	0.36	8	4	0	1	0	0	0	0	1
7	0	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
7	0	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
7	0	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
7	0	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
7	0	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
7	0	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
7	0	0.51	0.51	0.51	6	8	0	1	0	1	1	1	1
7	0	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
7	0	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
7	0	0.59	0.59	0.59	6	8	0	0	0	1	0	0	1
7	0	0.59	0.59	0.59	4	12	1	1	1	1	1	1	1
7	0	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
7	0	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
7	0	0.66	0.66	0.66	4	12	0	0	0	1	1	0	1
7	30	0.36	0.36	0.36	8	4	0	0	0	0	1	0	1
7	30	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
7	30	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
7	30	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
7	30	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
7	30	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
7	30	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
7	30	0.51	0.51	0.51	6	8	0	1	1	1	1	0	1
7	30	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1

Table 1.5 Batch(A)-All													
Fault Duration (cycles)	**Point on Wave (°)**	**Voltage at Bottom of Dip (per unit)**			**Tload (N-m)**	**Tav (N-m)**	**Motor**						
		A-Phase	**B-Phase**	**C-Phase**			**1**	**2**	**3**	**4**	**5**	**6**	**7**
7	30	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
7	30	0.59	0.59	0.59	6	8	0	0	0	1	0	0	1
7	30	0.59	0.59	0.59	4	12	1	1	1	1	1	1	1
7	30	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
7	30	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
7	30	0.66	0.66	0.66	4	12	0	0	0	1	1	0	1
7	60	0.36	0.36	0.36	8	4	0	0	1	0	1	0	0
7	60	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
7	60	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
7	60	0.44	0.44	0.44	8	4	0	0	0	0	1	0	0
7	60	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
7	60	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
7	60	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
7	60	0.51	0.51	0.51	6	8	1	0	1	1	1	0	1
7	60	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
7	60	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
7	60	0.59	0.59	0.59	6	8	0	0	0	0	1	0	1
7	60	0.59	0.59	0.59	4	12	1	1	1	1	1	1	1
7	60	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
7	60	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
7	60	0.66	0.66	0.66	4	12	0	0	0	1	1	0	1
7	90	0.36	0.36	0.36	8	4	0	0	0	0	1	1	0
7	90	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
7	90	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
7	90	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
7	90	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
7	90	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
7	90	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
7	90	0.51	0.51	0.51	6	8	1	0	1	1	1	1	1
7	90	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
7	90	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
7	90	0.59	0.59	0.59	6	8	0	0	0	0	1	0	1
7	90	0.59	0.59	0.59	4	12	1	0	1	1	1	1	1
7	90	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
7	90	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
7	90	0.66	0.66	0.66	4	12	0	0	0	0	1	0	1

Table 1.5 Batch(A)-All														
Fault Duration (cycles)	Point on Wave (°)	Voltage at Bottom of Dip (per unit)			Tload (N-m)	Tav (N-m)	Motor						
		A-Phase	B-Phase	C-Phase			1	2	3	4	5	6	7
9	0	0.36	0.36	0.36	8	4	1	1	1	1	1	0	1
9	0	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
9	0	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
9	0	0.44	0.44	0.44	8	4	0	0	0	0	0	0	1
9	0	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
9	0	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
9	0	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
9	0	0.51	0.51	0.51	6	8	1	1	1	1	1	1	1
9	0	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
9	0	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
9	0	0.59	0.59	0.59	6	8	0	0	0	1	1	0	1
9	0	0.59	0.59	0.59	4	12	1	1	1	1	1	1	1
9	0	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
9	0	0.66	0.66	0.66	6	8	0	0	0	0	0	0	1
9	0	0.66	0.66	0.66	4	12	0	0	0	1	1	0	1
9	30	0.36	0.36	0.36	8	4	0	1	1	1	1	0	1
9	30	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
9	30	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
9	30	0.44	0.44	0.44	8	4	0	0	0	0	0	0	1
9	30	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
9	30	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
9	30	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
9	30	0.51	0.51	0.51	6	8	1	1	1	1	1	1	1
9	30	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
9	30	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
9	30	0.59	0.59	0.59	6	8	0	0	0	1	1	0	1
9	30	0.59	0.59	0.59	4	12	1	1	1	1	1	1	1
9	30	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
9	30	0.66	0.66	0.66	6	8	0	0	0	0	0	0	1
9	30	0.66	0.66	0.66	4	12	0	0	0	1	1	0	1
9	60	0.36	0.36	0.36	8	4	1	0	1	0	1	0	1
9	60	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
9	60	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
9	60	0.44	0.44	0.44	8	4	0	0	0	0	1	0	0
9	60	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
9	60	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1

Table 1.5 Batch(A)-All													
Fault Duration (cycles)	**Point on Wave (°)**	**Voltage at Bottom of Dip (per unit)**			**Tload (N-m)**	**Tav (N-m)**	**Motor**						
		A-Phase	**B-Phase**	**C-Phase**			**1**	**2**	**3**	**4**	**5**	**6**	**7**
9	60	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
9	60	0.51	0.51	0.51	6	8	1	0	1	1	1	1	1
9	60	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
9	60	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
9	60	0.59	0.59	0.59	6	8	0	0	0	1	1	0	1
9	60	0.59	0.59	0.59	4	12	1	1	1	1	1	1	1
9	60	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
9	60	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
9	60	0.66	0.66	0.66	4	12	0	0	1	1	1	0	1
9	90	0.36	0.36	0.36	8	4	0	0	1	0	1	1	1
9	90	0.36	0.36	0.36	6	8	1	1	1	1	1	1	1
9	90	0.36	0.36	0.36	4	12	1	1	1	1	1	1	1
9	90	0.44	0.44	0.44	8	4	0	0	0	0	0	0	0
9	90	0.44	0.44	0.44	6	8	1	1	1	1	1	1	1
9	90	0.44	0.44	0.44	4	12	1	1	1	1	1	1	1
9	90	0.51	0.51	0.51	8	4	0	0	0	0	0	0	0
9	90	0.51	0.51	0.51	6	8	1	0	1	1	1	1	1
9	90	0.51	0.51	0.51	4	12	1	1	1	1	1	1	1
9	90	0.59	0.59	0.59	8	4	0	0	0	0	0	0	0
9	90	0.59	0.59	0.59	6	8	0	0	0	0	1	0	1
9	90	0.59	0.59	0.59	4	12	1	1	1	1	1	1	1
9	90	0.66	0.66	0.66	8	4	0	0	0	0	0	0	0
9	90	0.66	0.66	0.66	6	8	0	0	0	0	0	0	0
9	90	0.66	0.66	0.66	4	12	0	0	0	1	1	1	1

Table 1.6 Batch(B)-All													
Fault Duration (cycles)	**Point on Wave (°)**	**Voltage at Bottom of Dip (per unit)**			**Tload (N-m)**	**Tav (N-m)**	**Motor**						
		A-Phase	**B-Phase**	**C-Phase**			**1**	**2**	**3**	**4**	**5**	**6**	**7**
3	0	1	1	0.36	8	4	0	0	0	0	0	0	0
3	0	1	1	0.36	6	8	0	1	0	1	0	0	1
3	0	1	1	0.36	4	12	0	1	0	1	0	0	1
3	0	1	1	0.44	8	4	0	0	0	0	0	0	0
3	0	1	1	0.44	6	8	0	1	0	1	0	0	1
3	0	1	1	0.44	4	12	0	1	0	1	0	0	1
3	0	1	1	0.51	8	4	0	0	0	0	0	0	0
3	0	1	1	0.51	6	8	0	0	0	0	0	0	1
3	0	1	1	0.51	4	12	0	1	0	1	0	0	1
3	0	1	1	0.59	8	4	0	0	0	0	0	0	0
3	0	1	1	0.59	6	8	0	0	0	0	0	0	1
3	0	1	1	0.59	4	12	0	0	0	1	0	0	1
3	0	1	1	0.66	8	4	0	0	0	0	0	0	0
3	0	1	1	0.66	6	8	0	0	0	0	0	0	0
3	0	1	1	0.66	4	12	0	0	0	0	0	0	1
3	30	1	1	0.36	8	4	0	0	0	0	0	0	0
3	30	1	1	0.36	6	8	0	1	0	1	0	0	1
3	30	1	1	0.36	4	12	0	1	0	1	0	0	1
3	30	1	1	0.44	8	4	0	0	0	0	0	0	0
3	30	1	1	0.44	6	8	0	0	0	1	0	0	1
3	30	1	1	0.44	4	12	0	1	0	1	0	0	1
3	30	1	1	0.51	8	4	0	0	0	0	0	0	0
3	30	1	1	0.51	6	8	0	0	0	0	0	0	1
3	30	1	1	0.51	4	12	0	1	0	1	0	0	1
3	30	1	1	0.59	8	4	0	0	0	0	0	0	0
3	30	1	1	0.59	6	8	0	0	0	0	0	0	0
3	30	1	1	0.59	4	12	0	0	0	1	0	0	1
3	30	1	1	0.66	8	4	0	0	0	0	0	0	0
3	30	1	1	0.66	6	8	0	0	0	0	0	0	0
3	30	1	1	0.66	4	12	0	0	0	0	0	0	1
3	60	1	1	0.36	8	4	0	0	0	0	0	0	0
3	60	1	1	0.36	6	8	0	0	0	1	0	0	1
3	60	1	1	0.36	4	12	0	1	0	1	0	0	1
3	60	1	1	0.44	8	4	0	0	0	0	0	0	0
3	60	1	1	0.44	6	8	0	0	0	0	0	0	1
3	60	1	1	0.44	4	12	0	1	0	1	0	0	1

Table 1.6 Batch(B)-All													
Fault Duration (cycles)	**Point on Wave (°)**	**Voltage at Bottom of Dip (per unit)**			**Tload (N-m)**	**Tav (N-m)**	**Motor**						
		A-Phase	**B-Phase**	**C-Phase**			**1**	**2**	**3**	**4**	**5**	**6**	**7**
3	60	1	1	0.51	8	4	0	0	0	0	0	0	0
3	60	1	1	0.51	6	8	0	0	0	0	0	0	1
3	60	1	1	0.51	4	12	0	0	0	1	0	0	1
3	60	1	1	0.59	8	4	0	0	0	0	0	0	0
3	60	1	1	0.59	6	8	0	0	0	0	0	0	0
3	60	1	1	0.59	4	12	0	0	0	1	0	0	1
3	60	1	1	0.66	8	4	0	0	0	0	0	0	0
3	60	1	1	0.66	6	8	0	0	0	0	0	0	0
3	60	1	1	0.66	4	12	0	0	0	0	0	0	1
3	90	1	1	0.36	8	4	0	0	0	0	0	0	0
3	90	1	1	0.36	6	8	0	0	0	1	0	0	1
3	90	1	1	0.36	4	12	0	1	0	1	0	0	1
3	90	1	1	0.44	8	4	0	0	0	0	0	0	0
3	90	1	1	0.44	6	8	0	0	0	0	0	0	1
3	90	1	1	0.44	4	12	0	1	0	1	0	0	1
3	90	1	1	0.51	8	4	0	0	0	0	0	0	0
3	90	1	1	0.51	6	8	0	0	0	0	0	0	1
3	90	1	1	0.51	4	12	0	0	0	1	0	0	1
3	90	1	1	0.59	8	4	0	0	0	0	0	0	0
3	90	1	1	0.59	6	8	0	0	0	0	0	0	0
3	90	1	1	0.59	4	12	0	0	0	1	0	0	1
3	90	1	1	0.66	8	4	0	0	0	0	0	0	0
3	90	1	1	0.66	6	8	0	0	0	0	0	0	0
3	90	1	1	0.66	4	12	0	0	0	0	0	0	1
5	0	1	1	0.36	8	4	0	0	0	0	0	0	1
5	0	1	1	0.36	6	8	0	1	0	1	0	0	1
5	0	1	1	0.36	4	12	0	1	0	1	0	0	1
5	0	1	1	0.44	8	4	0	0	0	0	0	0	0
5	0	1	1	0.44	6	8	0	1	0	1	0	0	1
5	0	1	1	0.44	4	12	0	1	0	1	0	0	1
5	0	1	1	0.51	8	4	0	0	0	0	0	0	0
5	0	1	1	0.51	6	8	0	1	0	1	0	0	1
5	0	1	1	0.51	4	12	0	1	0	1	0	0	1
5	0	1	1	0.59	8	4	0	0	0	0	0	0	0
5	0	1	1	0.59	6	8	0	0	0	0	0	0	1
5	0	1	1	0.59	4	12	0	1	0	1	0	0	1

Table 1.6 Batch(B)-All													
Fault Duration (cycles)	**Point on Wave (°)**	**Voltage at Bottom of Dip (per unit)**			**Tload (N-m)**	**Tav (N-m)**	**Motor**						
		A-Phase	**B-Phase**	**C-Phase**			**1**	**2**	**3**	**4**	**5**	**6**	**7**
5	0	1	1	0.66	8	4	0	0	0	0	0	0	0
5	0	1	1	0.66	6	8	0	0	0	0	0	0	0
5	0	1	1	0.66	4	12	0	0	0	1	0	0	1
5	30	1	1	0.36	8	4	0	0	0	0	0	0	1
5	30	1	1	0.36	6	8	0	1	0	1	0	0	1
5	30	1	1	0.36	4	12	0	1	0	1	0	0	1
5	30	1	1	0.44	8	4	0	0	0	0	0	0	0
5	30	1	1	0.44	6	8	0	1	0	1	0	0	1
5	30	1	1	0.44	4	12	0	1	0	1	0	0	1
5	30	1	1	0.51	8	4	0	0	0	0	0	0	0
5	30	1	1	0.51	6	8	0	0	0	1	0	0	1
5	30	1	1	0.51	4	12	0	1	0	1	0	0	1
5	30	1	1	0.59	8	4	0	0	0	0	0	0	0
5	30	1	1	0.59	6	8	0	0	0	0	0	0	1
5	30	1	1	0.59	4	12	0	1	0	1	0	0	1
5	30	1	1	0.66	8	4	0	0	0	0	0	0	0
5	30	1	1	0.66	6	8	0	0	0	0	0	0	0
5	30	1	1	0.66	4	12	0	0	0	1	0	0	1
5	60	1	1	0.36	8	4	0	0	0	0	0	0	0
5	60	1	1	0.36	6	8	0	1	0	1	0	0	1
5	60	1	1	0.36	4	12	0	1	0	1	0	0	1
5	60	1	1	0.44	8	4	0	0	0	0	0	0	0
5	60	1	1	0.44	6	8	0	0	0	1	0	0	1
5	60	1	1	0.44	4	12	0	1	0	1	0	0	1
5	60	1	1	0.51	8	4	0	0	0	0	0	0	0
5	60	1	1	0.51	6	8	0	0	0	1	0	0	1
5	60	1	1	0.51	4	12	0	1	0	1	0	0	1
5	60	1	1	0.59	8	4	0	0	0	0	0	0	0
5	60	1	1	0.59	6	8	0	0	0	0	0	0	1
5	60	1	1	0.59	4	12	0	0	0	1	0	0	1
5	60	1	1	0.66	8	4	0	0	0	0	0	0	0
5	60	1	1	0.66	6	8	0	0	0	0	0	0	0
5	60	1	1	0.66	4	12	0	0	0	1	0	0	1
5	90	1	1	0.36	8	4	0	0	0	0	0	0	0
5	90	1	1	0.36	6	8	0	1	0	1	0	0	1
5	90	1	1	0.36	4	12	0	1	0	1	0	0	1

Table 1.6 Batch(B)-All														
Fault Duration (cycles)	Point on Wave (°)	Voltage at Bottom of Dip (per unit)			Tload (N-m)	Tav (N-m)	Motor						
		A-Phase	B-Phase	C-Phase			1	2	3	4	5	6	7
5	90	1	1	0.44	8	4	0	0	0	0	0	0	0
5	90	1	1	0.44	6	8	0	0	0	1	0	0	1
5	90	1	1	0.44	4	12	0	1	0	1	0	0	1
5	90	1	1	0.51	8	4	0	0	0	0	0	0	0
5	90	1	1	0.51	6	8	0	0	0	0	0	0	1
5	90	1	1	0.51	4	12	0	1	0	1	0	0	1
5	90	1	1	0.59	8	4	0	0	0	0	0	0	0
5	90	1	1	0.59	6	8	0	0	0	0	0	0	1
5	90	1	1	0.59	4	12	0	0	0	1	0	0	1

Table 1.7 Batch(A)-12 N-m

Simulations With Average Torque = 12 N-m

Fault Duration (ms)	Phase (°)	Source V in Dip (kV) A	B	C	Tsp (N-m)	Ttr (N-m)	Stalled Motors M1 A	M2 C	M3 B	M4 C	M5 B	M6 A	M7 C	Stalled Motors Total	A	B	C
0.05	0	25	25	25	8	4	0	1	0	0	0	0	0	1	0	0	1
0.05	0	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	0	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	0	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	0	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	0	25	25	25	8	4	0	1	0	0	0	0	1	2	0	0	2
0.083	0	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	0	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	0	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	0	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	0	25	25	25	8	4	0	1	0	0	0	0	1	2	0	0	2
0.117	0	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	0	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	0	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	0	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	0	25	25	25	8	4	1	1	1	1	1	0	1	6	1	2	3
0.15	0	31	31	31	8	4	0	0	0	0	0	0	1	1	0	0	1
0.15	0	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	0	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	0	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	25	25	25	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	30	25	25	25	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	30	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	30	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	30	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	30	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	30	25	25	25	8	4	0	0	0	0	1	0	1	2	0	1	1
0.117	30	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0

Table 1.7 Batch(A)-12 N-m																	
Simulations With Average Torque = 12 N-m																	
Fault Duration (ms)	Phase (°)	Source V in Dip (kV)					Stalled Motors							Stalled Motors			
					Tsp	Ttr	M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C	(N-m)	(N-m)	A	C	B	C	B	A	C		A	B	C
0.117	30	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	30	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	30	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	30	25	25	25	8	4	0	1	1	1	1	0	1	5	0	2	3
0.15	30	31	31	31	8	4	0	0	0	0	0	0	1	1	0	0	1
0.15	30	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	30	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	30	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	25	25	25	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	60	25	25	25	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	60	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	60	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	60	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	60	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	60	25	25	25	8	4	0	0	1	0	1	0	0	2	0	2	0
0.117	60	31	31	31	8	4	0	0	0	0	1	0	0	1	0	1	0
0.117	60	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	60	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	60	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	60	25	25	25	8	4	1	0	1	0	1	0	1	4	1	2	1
0.15	60	31	31	31	8	4	0	0	0	0	1	0	0	1	0	1	0
0.15	60	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	60	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	60	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	25	25	25	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0

Table 1.7 Batch(A)-12 N-m

Simulations With Average Torque = 12 N-m

Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp	Ttr	Stalled Motors M1	M2	M3	M4	M5	M6	M7	Stalled Motors Total			
		A	B	C	(N-m)	(N-m)	A	C	B	C	B	A	C		A	B	C
0.05	90	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	90	25	25	25	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	90	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	90	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	90	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.083	90	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	90	25	25	25	8	4	0	0	0	0	1	1	0	2	1	1	0
0.117	90	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	90	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	90	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.117	90	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	90	25	25	25	8	4	0	0	1	0	1	1	1	4	1	2	1
0.15	90	31	31	31	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	90	36	36	36	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	90	41	41	41	8	4	0	0	0	0	0	0	0	0	0	0	0
0.15	90	47	47	47	8	4	0	0	0	0	0	0	0	0	0	0	0

Table 1.8 Batch(A)-14 N-m

Simulations With Average Torque = 14 N-m

Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors								Stalled Motors		
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.05	0	25.2	25.2	25.2	6	8	0	1	0	1	1	0	1	4	0	1	3
0.05	0	30.5	30.5	30.5	6	8	0	1	0	1	0	0	1	3	0	0	3
0.05	0	35.9	35.9	35.9	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	0	41.2	41.2	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	0	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	0	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.0833	0	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.0833	0	35.9	35.9	35.9	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	41.2	41.2	41.2	6	8	0	0	0	0	0	0	1	1	0	0	1
0.0833	0	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.1166	0	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	0	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	0	35.9	35.9	35.9	6	8	0	1	0	1	1	1	1	5	1	1	3
0.1166	0	41.2	41.2	41.2	6	8	0	0	0	1	0	0	1	2	0	0	2
0.1166	0	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.15	0	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	0	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	0	35.9	35.9	35.9	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	0	41.2	41.2	41.2	6	8	0	0	0	1	1	0	1	3	0	1	2
0.15	0	46.5	46.5	46.5	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	30	25.2	25.2	25.2	6	8	0	1	1	1	1	0	1	5	0	2	3
0.05	30	30.5	30.5	30.5	6	8	0	0	0	1	1	0	1	3	0	1	2
0.05	30	35.9	35.9	35.9	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	30	41.2	41.2	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	30	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	30	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.0833	30	30.5	30.5	30.5	6	8	0	1	1	1	1	0	1	5	0	2	3
0.0833	30	35.9	35.9	35.9	6	8	0	0	0	1	1	0	1	3	0	1	2
0.0833	30	41.2	41.2	41.2	6	8	0	0	0	0	0	0	1	1	0	0	1
0.0833	30	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.1166	30	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	30	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	30	35.9	35.9	35.9	6	8	0	1	1	1	1	0	1	5	0	2	3
0.1166	30	41.2	41.2	41.2	6	8	0	0	0	1	0	0	1	2	0	0	2
0.1166	30	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.15	30	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	30	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	30	35.9	35.9	35.9	6	8	1	1	1	1	1	1	1	7	2	2	3

Table 1.8 Batch(A)-14 N-m

Simulations With Average Torque = 14 N-m																			
Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors								Stalled Motors		
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.15	30	41.2	41.2	41.2	6	8	0	0	0	1	1	0	1	3	0	1	2
0.15	30	46.5	46.5	46.5	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	60	25.2	25.2	25.2	6	8	1	0	1	1	1	0	1	5	1	2	2
0.05	60	30.5	30.5	30.5	6	8	0	0	1	0	1	0	1	3	0	2	1
0.05	60	35.9	35.9	35.9	6	8	0	0	0	0	1	0	0	1	0	1	0
0.05	60	41.2	41.2	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	60	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.0833	60	30.5	30.5	30.5	6	8	1	0	1	1	1	0	1	5	1	2	2
0.0833	60	35.9	35.9	35.9	6	8	0	0	1	0	1	0	1	3	0	2	1
0.0833	60	41.2	41.2	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.1166	60	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	60	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	60	35.9	35.9	35.9	6	8	1	0	1	1	1	0	1	5	1	2	2
0.1166	60	41.2	41.2	41.2	6	8	0	0	0	0	1	0	1	2	0	1	1
0.1166	60	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.15	60	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	60	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	60	35.9	35.9	35.9	6	8	1	0	1	1	1	1	1	6	2	2	2
0.15	60	41.2	41.2	41.2	6	8	0	0	0	1	1	0	1	3	0	1	2
0.15	60	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	90	25.2	25.2	25.2	6	8	1	0	1	0	1	1	1	5	2	2	1
0.05	90	30.5	30.5	30.5	6	8	1	0	0	0	1	0	1	3	1	1	1
0.05	90	35.9	35.9	35.9	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	90	41.2	41.2	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	90	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.0833	90	30.5	30.5	30.5	6	8	1	0	1	1	1	1	1	6	2	2	2
0.0833	90	35.9	35.9	35.9	6	8	1	0	0	0	1	0	1	3	1	1	1
0.0833	90	41.2	41.2	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.1166	90	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	90	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.1166	90	35.9	35.9	35.9	6	8	1	0	1	1	1	1	1	6	2	2	2
0.1166	90	41.2	41.2	41.2	6	8	0	0	0	0	1	0	1	2	0	1	1
0.1166	90	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0

Table 1.8 Batch(A)-14 N-m																	
Simulations With Average Torque = 14 N-m																	
Fault Duration (ms)	**Phase (°)**	**Source V in Dip (kV)**			**Tsp (N-m)**	**Ttr (N-m)**	**Stalled Motors**								**Stalled Motors**		
							M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**Total**			
		A	**B**	**C**			**A**	**C**	**B**	**C**	**B**	**A**	**C**		**A**	**B**	**C**
0.15	90	25.2	25.2	25.2	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	90	30.5	30.5	30.5	6	8	1	1	1	1	1	1	1	7	2	2	3
0.15	90	35.9	35.9	35.9	6	8	1	0	1	1	1	1	1	6	2	2	2
0.15	90	41.2	41.2	41.2	6	8	0	0	0	0	1	0	1	2	0	1	1
0.15	90	46.5	46.5	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0

Table 1.9 Batch(A)-16 N-m

Simulations With Average Torque - 16 N-m

Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors								Stalled Motors		
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.05	0	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.05	0	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.05	0	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.05	0	41.2	41.2	41.2	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	0	46.5	46.5	46.5	4	12	0	0	0	0	0	0	1	1	0	0	1
0.0833	0	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	0	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	0	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	0	41.2	41.2	41.2	4	12	0	1	0	1	1	1	1	5	1	1	3
0.0833	0	46.5	46.5	46.5	4	12	0	0	0	1	0	0	1	2	0	0	2
0.1166	0	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	0	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	0	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	0	41.2	41.2	41.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	0	46.5	46.5	46.5	4	12	0	0	0	1	1	0	1	3	0	1	2
0.15	0	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	0	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	0	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	0	41.2	41.2	41.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	0	46.5	46.5	46.5	4	12	0	0	0	1	1	0	1	3	0	1	2
0.05	30	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.05	30	30.5	30.5	30.5	4	12	0	0	0	1	1	0	1	3	0	1	2
0.05	30	35.9	35.9	35.9	4	12	0	1	1	1	1	0	1	5	0	2	3
0.05	30	41.2	41.2	41.2	4	12	0	0	0	1	1	0	1	3	0	1	2
0.05	30	46.5	46.5	46.5	4	12	0	0	0	0	0	0	1	1	0	0	1
0.0833	30	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	30	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	30	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	30	41.2	41.2	41.2	4	12	0	1	1	1	1	0	1	5	0	2	3
0.0833	30	46.5	46.5	46.5	4	12	0	0	0	1	0	0	1	2	0	0	2
0.1166	30	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	30	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	30	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	30	41.2	41.2	41.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	30	46.5	46.5	46.5	4	12	0	0	0	1	1	0	1	3	0	1	2
0.15	30	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3

Table 1.9 Batch(A)-16 N-m

Simulations With Average Torque - 16 N-m

Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors								Stalled Motors		
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.15	30	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	30	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	30	41.2	41.2	41.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	30	46.5	46.5	46.5	4	12	0	0	0	1	1	0	1	3	0	1	2
0.05	60	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.05	60	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.05	60	35.9	35.9	35.9	4	12	1	0	1	1	1	1	1	6	2	2	2
0.05	60	41.2	41.2	41.2	4	12	0	0	1	0	1	0	1	3	0	2	1
0.05	60	46.5	46.5	46.5	4	12	0	0	0	0	0	0	1	1	0	0	1
0.0833	60	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	60	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	60	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	60	41.2	41.2	41.2	4	12	1	0	1	1	1	0	1	5	1	2	2
0.0833	60	46.5	46.5	46.5	4	12	0	0	0	0	1	0	1	2	0	1	1
0.1166	60	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	60	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	60	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	60	41.2	41.2	41.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	60	46.5	46.5	46.5	4	12	0	0	0	1	1	0	1	3	0	1	2
0.15	60	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	60	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	60	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	60	41.2	41.2	41.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	60	46.5	46.5	46.5	4	12	0	0	1	1	1	0	1	4	0	2	2
0.05	90	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.05	90	30.5	30.5	30.5	4	12	1	0	1	1	1	1	1	6	2	2	2
0.05	90	35.9	35.9	35.9	4	12	1	0	1	1	1	1	1	6	2	2	2
0.05	90	41.2	41.2	41.2	4	12	0	0	0	0	1	0	1	2	0	1	1
0.05	90	46.5	46.5	46.5	4	12	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	90	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	90	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.0833	90	41.2	41.2	41.2	4	12	1	0	1	1	1	1	1	6	2	2	2
0.0833	90	46.5	46.5	46.5	4	12	0	0	0	0	1	0	1	2	0	1	1
0.1166	90	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	90	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3

Table 1.9 Batch(A)-16 N-m																	
Simulations With Average Torque - 16 N-m																	
Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors								Stalled Motors		
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.1166	90	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.1166	90	41.2	41.2	41.2	4	12	1	0	1	1	1	1	1	6	2	2	2
0.1166	90	46.5	46.5	46.5	4	12	0	0	0	0	1	0	1	2	0	1	1
0.15	90	25.2	25.2	25.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	90	30.5	30.5	30.5	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	90	35.9	35.9	35.9	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	90	41.2	41.2	41.2	4	12	1	1	1	1	1	1	1	7	2	2	3
0.15	90	46.5	46.5	46.5	4	12	0	0	0	1	1	1	1	4	1	1	2

Table 2.0 Batch(B)-12 N-m

Simulations With Average Torque – 12 N-m

Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors							Stalled Motors			
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.05	0	70	70	25.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	0	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	0	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	0	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	0	70	70	46.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	0	70	70	25.2	8	4	0	0	0	0	0	0	1	1	0	0	1
0.0833	0	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	0	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	0	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	0	70	70	46.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	70	70	25.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	30	70	70	46.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	30	70	70	25.2	8	4	0	0	0	0	0	0	1	1	0	0	1
0.0833	30	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	30	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	30	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	30	70	70	46.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	70	70	25.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	60	70	70	46.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	70	70	25.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	70	70	46.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	70	70	25.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.05	90	70	70	46.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	70	70	25.2	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	70	70	30.5	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	70	70	35.9	8	4	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	70	70	41.2	8	4	0	0	0	0	0	0	0	0	0	0	0

Table 2.1 Batch(B)-14 N-m

Simulations With Average Torque = 14 N-m

Fault Duration (ms)	Phase (°)	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors							Stalled Motors			
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.05	0	70	70	25.2	6	8	0	1	0	1	0	0	1	3	0	0	3
0.05	0	70	70	30.5	6	8	0	1	0	1	0	0	1	3	0	0	3
0.05	0	70	70	35.9	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	0	70	70	41.2	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	0	70	70	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	0	70	70	25.2	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	70	70	30.5	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	70	70	35.9	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	70	70	41.2	6	8	0	0	0	0	0	0	1	1	0	0	1
0.0833	0	70	70	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	30	70	70	25.2	6	8	0	1	0	1	0	0	1	3	0	0	3
0.05	30	70	70	30.5	6	8	0	0	0	1	0	0	1	2	0	0	2
0.05	30	70	70	35.9	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	30	70	70	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	30	70	70	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	30	70	70	25.2	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	30	70	70	30.5	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	30	70	70	35.9	6	8	0	0	0	1	0	0	1	2	0	0	2
0.0833	30	70	70	41.2	6	8	0	0	0	0	0	0	1	1	0	0	1
0.0833	30	70	70	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	60	70	70	25.2	6	8	0	0	0	1	0	0	1	2	0	0	2
0.05	60	70	70	30.5	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	60	70	70	35.9	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	60	70	70	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	60	70	70	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	60	70	70	25.2	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	60	70	70	30.5	6	8	0	0	0	1	0	0	1	2	0	0	2
0.0833	60	70	70	35.9	6	8	0	0	0	1	0	0	1	2	0	0	2
0.0833	60	70	70	41.2	6	8	0	0	0	0	0	0	1	1	0	0	1
0.0833	60	70	70	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	90	70	70	25.2	6	8	0	0	0	1	0	0	1	2	0	0	2
0.05	90	70	70	30.5	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	90	70	70	35.9	6	8	0	0	0	0	0	0	1	1	0	0	1
0.05	90	70	70	41.2	6	8	0	0	0	0	0	0	0	0	0	0	0
0.05	90	70	70	46.5	6	8	0	0	0	0	0	0	0	0	0	0	0
0.0833	90	70	70	25.2	6	8	0	1	0	1	0	0	1	3	0	0	3
0.0833	90	70	70	30.5	6	8	0	0	0	1	0	0	1	2	0	0	2
0.0833	90	70	70	35.9	6	8	0	0	0	0	0	0	1	1	0	0	1
0.0833	90	70	70	41.2	6	8	0	0	0	0	0	0	1	1	0	0	1

Table 2.2 Batch(B)-16 N-m

Simulations With Average Torque = 16 N-m																
Fault Duration (ms)	Phase	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors							Stalled Motors			
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.05	0	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	0	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	0	70	70	35.9	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	0	70	70	41.2	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	0	70	70	46.5	4	12	0	0	0	0	0	0	1	1	0	0	1
0.0833	0	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	70	70	35.9	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	70	70	41.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	0	70	70	46.5	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	30	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	30	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	30	70	70	35.9	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	30	70	70	41.2	4	12	0	0	0	1	0	0	1		0	0	2
0.05	30	70	70	46.5	4	12	0	0	0	0	0	0	1	1	0	0	1
0.0833	30	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	30	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	30	70	70	35.9	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	30	70	70	41.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	30	70	70	46.5	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	60	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	60	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	60	70	70	35.9	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	60	70	70	41.2	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	60	70	70	46.5	4	12	0	0	0	0	0	0	1	1	0	0	1
0.0833	60	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	60	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	60	70	70	35.9	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	60	70	70	41.2	4	12	0	0	0	1	0	0	1	2	0	0	2
0.0833	60	70	70	46.5	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	90	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.05	90	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3

Table 2.2 Batch(B)-16 N-m

Simulations With Average Torque = 16 N-m

Fault Duration (ms)	Phase	Source V in Dip (kV)			Tsp (N-m)	Ttr (N-m)	Stalled Motors							Stalled Motors			
							M1	M2	M3	M4	M5	M6	M7	Total			
		A	B	C			A	C	B	C	B	A	C		A	B	C
0.05	90	70	70	35.9	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	90	70	70	41.2	4	12	0	0	0	1	0	0	1	2	0	0	2
0.05	90	70	70	46.5	4	12	0	0	0	0	0	0	1	1	0	0	1
0.0833	90	70	70	25.2	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	90	70	70	30.5	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	90	70	70	35.9	4	12	0	1	0	1	0	0	1	3	0	0	3
0.0833	90	70	70	41.2	4	12	0	0	0	1	0	0	1	2	0	0	2

Section 6: COMMENTARY AND CONCLUSIONS

6.1 Results Obtained

The numerical values of voltage, load torque, and duration of dip appearing in this study cannot be regarded as a useful guide as to whether motors on a real feeder would stall. They are useful as an indication of the relative effect of the many parameters that can affect the stalling or reacceleration of motors. They give support to the following largely qualitative conclusions:

- The likelihood that motors will stall is strongly related to their loading. Where the load is air conditioning this leads to strong correlation of stalling with high ambient temperature.
- Stalling of air conditioner motors does not require a long duration of voltage dip. With moderate loading, most or all motors will stall in a 9 cycle dip, and some will stall in a dip of only 3 cycles.
- It is quite credible that nearly all motors on a feeder will stall in a dip as brief as 3 cycles when their driven loads are near maximum.

The summation of the above points is that the behavior of motors indicated by a limited number of point-on-wave motor models connected to a very simplified distribution feeder model supports the conclusions indicated by work with a single instance of the model; stalling depends on a very wide range of factors and can occur very quickly in relation to the time scale of bulk electric system disturbances.

This, in turn, supports the emerging deduction from field experience that stalling of air conditioner motors must be expected to occur not only following longer than normal electric system faults, but in the wake of very normal and properly cleared disturbances.

6.2 The RTDS Approach to Simulation

The simulation exercise described here was an initial experiment in the application of the RTDS simulator to an exploratory investigation where the direction that results would take was essentially unknown. The suitability of the RTDS for the type of work undertaken was "to be discovered." With the experiment at its present stage of evolution the following notes can be made:

- The majority of the time and effort expended in the experiment was in the integration of the single phase motor model into the RTDS machinery. This integration task involved learning about the mechanics of the interface between the RTDS and user-created modeling code.
- The ability of the RTDS simulator to adapt the topology of the feeder being simulated, the sizing of feeder components, and the sizing of motors represented by the motor models was found to be limited. A part of this inflexibility was associated with the use of multiple instances of the user-written motor model.
- Presumably because of the small integration time step used (20 microseconds), the RTDS was not able to run the simulations in real time. Also, it is important to note that the RTDS was running in non real-time as the model was more developmental and not optimized.

6.3 Next Steps

It appears that the handling of motor behavior in simulations of the bulk electric system will have to have its basis in statistical understanding of the prevalence of motor-stalling events. Given the high cost of the RTDS machinery, and the statistical nature of the factors affecting the behavior of the motors, the statistical understanding will have to come from field experience, rather than from simulations.

It will be very desirable to have the RTDS machinery available for focused studies. In particular, it will be desirable to obtain data from a well instrumented feeder and to be able to simulate the response of that feeder to played-in recordings of events. This calls for the incorporation of the single-phase motor model into the kernel of the RTDS machinery in a way that will allow simulations using many instances of the model to run in real time.

The large expense of RTDS machinery makes it desirable to have parallel implementation of the single phase motor model in EMTP-type general purpose simulation programs such as PSCAD.

Section 7: APPENDIX

7.1 Mathematical Description of Single Phase Induction Motor Model

Subject: Difference Equation form of Single phase induction motor model

By: J. Undrill

Date: 4 November 2011

1 Introduction

This memo describes a finite difference implementation of an electromagnetic model of a single phase induction motor and its associated capacitor. This form of the model is intended to be used in large-scale simulation of a distribution feeder in which many instances of the motor-model will be connected to point-on-wave electrical models of the feeder and conventional resistive-indictive-capacitive loads.

2 Load model

We consider the load torque, T_{load}, to consist of a small component proportional to the square of speed plus a relatively much larger component varying in a triangular wave form with crank angle.

3 Motor model

The single phase induction motor is modeled at the level of electromagnetic transients. The placement of stator and rotor windings is as shown in figure 1. The mutual inductances between stator and rotor coils vary sinusoidally with the angular position of the rotor. The number of turns in the two stator windings are unequal. The capacitor in the 'second' stator winding is represented explicitly.

The flux linkage model is implemented by the position dependent matrix

$$\begin{vmatrix} \psi_{as} \\ \psi_{bs} \\ \psi_{ar} \\ \psi_{br} \end{vmatrix} = \begin{vmatrix} L_m + L_s & 0 & L_m cos\theta & L_m sin\theta \\ 0 & N^2 L_m + L_s & -NL_m sin\theta & NL_m cos\theta \\ L_m cos\theta & -NL_m sin\theta & L_m + L_r & 0 \\ L_m sin\theta & NL_m cos\theta & 0 & L_m + L_r \end{vmatrix} \begin{vmatrix} i_{as} \\ i_{bs} \\ i_{ar} \\ i_{br} \end{vmatrix} \quad (1)$$

The angle θ appearing in (1) is the physical angular position of the rotor winding centerline relative to the stator structure. It must be noted that, unlike the 'rotor angle' used in three phase machine analysis, this angle is always increasing at a rate only slightly less than the synchronous speed of the power system.

Differentiating (1) results in

$$\begin{vmatrix} d\psi_{as}/dt \\ d\psi_{bs}/dt \\ d\psi_{ar}/dt \\ d\psi_{br}/dt \end{vmatrix} = L_{rs} \begin{vmatrix} di_{as}/dt \\ di_{bs}/dt \\ di_{ar}/dt \\ di_{br}/dt \end{vmatrix} + A_{rs} \begin{vmatrix} i_{as} \\ i_{bs} \\ i_{ar} \\ i_{br} \end{vmatrix} \quad (2)$$

Where L_{rs} is the matrix in equation (1) and

$$Ars = \begin{vmatrix} 0 & 0 & -\omega L_m sin\theta & \omega L_m cos\theta \\ 0 & 0 & -\omega NL_m cos\theta & -\omega NL_m sin\theta \\ -\omega L_m sin\theta & -\omega NL_m cos\theta & 0 & 0 \\ \omega L_m cos\theta & -\omega NL_m cos\theta & 0 & 0 \end{vmatrix} \quad (3)$$

1

The inductances appearing in the above matrices are not constant, but must be varied as a function of flux in order to represent saturation of the stator and rotor iron. This variation is approximated as follows

$$\Psi_m = \sqrt{\psi_{as}^2, \psi_{bs}^2} \tag{4}$$

$$L_m = L_{mu}/(1 + S(\psi_m)) \tag{5}$$

where S is the standard saturation function defined by its values at nominal and 1.2 times nominal flux, S_1, S_{12}.

The standard differential equations relating flux, voltage, and current are

$$\frac{d\psi_{as}}{dt} = v_a - R_s i_{as} \tag{6}$$

$$\frac{d\psi_{bs}}{dt} = v_b - R_s i_{bs} \tag{7}$$

$$\frac{d\psi_{ar}}{dt} = -R_r i_{ar} \tag{8}$$

$$\frac{d\psi_{br}}{dt} = -R_r i_{br} \tag{9}$$

Equations (6) thru (9) can be rewritten in matrix form as

$$\frac{d\Psi}{dt} = V - RI \tag{10}$$

then (2) can be substituted to give

$$L_{rs}\frac{dI}{dt} + A_{rs}I = V - RI \tag{11}$$

Equation (11) is the required definition of the time derivatives of the state variables describing the electrmagnetic behavior of the motor.

Integration of the differential equations for simulation can be handled by the users choice of integration algorithm. For this discussion, it is useful to rework (11) into a difference equationform by using the forward difference approximation

$$\frac{dI^n}{dt} = \frac{i^n - i^o}{h} \tag{12}$$

where h is the integration time step.

Substituting (12) into (11) gives the integration of the system differential equations as

$$(L_{rs} + hA_{rs} + hR)I^n = L_{rs}I^o + hV \tag{13}$$

The matrices L_{rs} and A_{rs} must be rebuilt at each step before (13) is solved for I^n.

Equation (13) handles the simulation of the electromagnetic behavior of the motor. The motion of the rotor requires calculation of the electromagnetic torque, the load torque, and thence the speed and angular position of the rotor windings.

The stator and rotor flux linkages are calculated by (1). The air gap flux, as needed to calculate torque, is then obtained by

$$\psi_{am} = \psi_{as} - L_s i_{as} \tag{14}$$

2

$$\psi_{bm} = \psi_{bs} - N^2 L_s i_{bs} \tag{15}$$

and the electromagnetic torque is then

$$T_e = \psi_{am}(-i_{ar} sin\theta + i_{br} cos\theta) - \psi_{bm}(i_{ar} cos\theta + i_{br} sin\theta) \tag{16}$$

The supply voltage, v_a is applied to the main winding. The voltage v_b applied to the second stator winding is given by

$$v_b = v_a - \frac{q_{cap}}{C_{cap}} \tag{17}$$

The capacitor is described by

$$\frac{dq_{cap}}{dt} = i_{bs} \tag{18}$$

This motor model gives an explicit representation of the several components of the electromagnetic torque developed by the motor, among them

- a unidirectional (useful) component
- an alternating component at slip frequency
- an alternating component at a frequency of $(2\omega_s - \omega_r)$.

The motion of the rotor and variation of the angle describing mutual inductances are described by

$$\frac{d\omega}{dt} = \frac{T_e - T_{load}}{H_r} \tag{19}$$

$$\frac{d\theta}{dt} = \omega \tag{20}$$

Where H_r is the polar moment of inertia of the rotor.

A last refinement is to recognize that the effective resistance of the rotor is a function of the frequency of rotor currents and hence of slip. The variation of rotor resistance is approximated as

$$R_{cage} = R_r(5 - 4\omega/\omega_o) \tag{21}$$

4 Simulations

4.1 Base Case Simulation - Voltage Dip Initiated at Zero of AC Wave

Simulations were made of a sequence as follows:

- the motor was switched on at $t = 0.$ and allowed to accelerate against a load of $1.0\omega_r^2$
- then allowed to run against the speed dependent component of load until $t = 0.5$

- the major component of load commenced at $t = 0.5$ taking load in triangular from 1N-m to 25N-m, for an average of 13N-m
- at $t = 2.0$ the supply voltage was reduced from 230V (RMS) to 115V
- at $t = 2.0833$ (after 5 cycles) the supply voltage was raised to 207V

Figure 2 shows the behavior of the motor over the 3 second simulation period. The rotor accelerates to full speed in less than half a second and settles at nearly synchronous speed, drawing a low current, until the main load is applied at 0.5 seconds. Terminal current stabilizes in less than a second at just under 20 amps and the rotor currents take up their characteristic slip frequency form.

Figure 3 shows the variation of stator currents, electrical torque, mechanical torque, and speed, on an expanded scale at the voltage dip. When the supply voltage is reduced to half-value at $t = 2.0$ the electrical torque (blue) goes to a large negative value for approximately 20 msec and then oscillates about a near-zero value. When voltage is restored the electrical torque is not sufficient to overcome the mechanical torque requirement of the stalled compressor and the motor does not restart. The current drawn from the supply goes to its locked rotor value of approximately 6 times full load current.

4.2 Sensitivity to timing of event initiation

Figure 4 shows the behavior of torques and speed when the voltage dip is initiated at the peack of the AC voltage wave, rather than at the zero as for figures 2 amd 3. Now the initial dip in electrical torque (blue) is still apparent but is smaller than seen in figure 3. The electrical torque during the following part of the voltage dip has a significant unidirectional component and there is a strong positive (reaccelerating) torque as soon as voltage is restored. The rotor reaccelerates rapidly.

5 Commentary

This memo extends the indication of the earlier memo on the subject and confirms the two main points:

- very brief depressions of voltage can cause stalling
- however, stalling is not the inevitable result of a brief depression of voltage

6 Terminology

L_{mu}	Winding A to Rotor mutual inductance, unsaturated, ohms
L_m	Winding A to Rotor mutual inductance, saturated, ohms
L_s	Winding A leakage reactance, ohms
L_r	Rotor winding leakage reactance, ohms
N	Ratio of winding B turns to winding A turns
R_s	Stator winding resistance, ohms
R_{cage}	Effective rotor winding resistance at nonsynchronous running speed, ohms
R_r	Rotor winding resistance at synchronous running speed
C_{cap}	Capacitor impedance, ohms

wr2	Rotor moment of inertia, Kg-m2
T_e	Electromagnetic torque, Newton-m
T_{load}	Load torque, Newton-m
n	Shaft speed, per unit
ω_o	Synchronous speed and frequency
S_1	Saturation factor at nominal flux level
S_{12}	Saturation factor with flux at 1.2 times nominal level

5

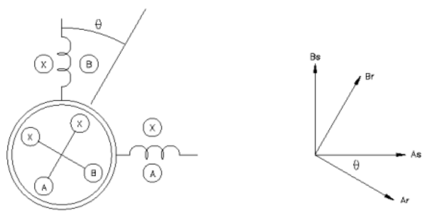


Figure 1: Induction motor model recognizing sinusoidal variation of mutual inductances

6

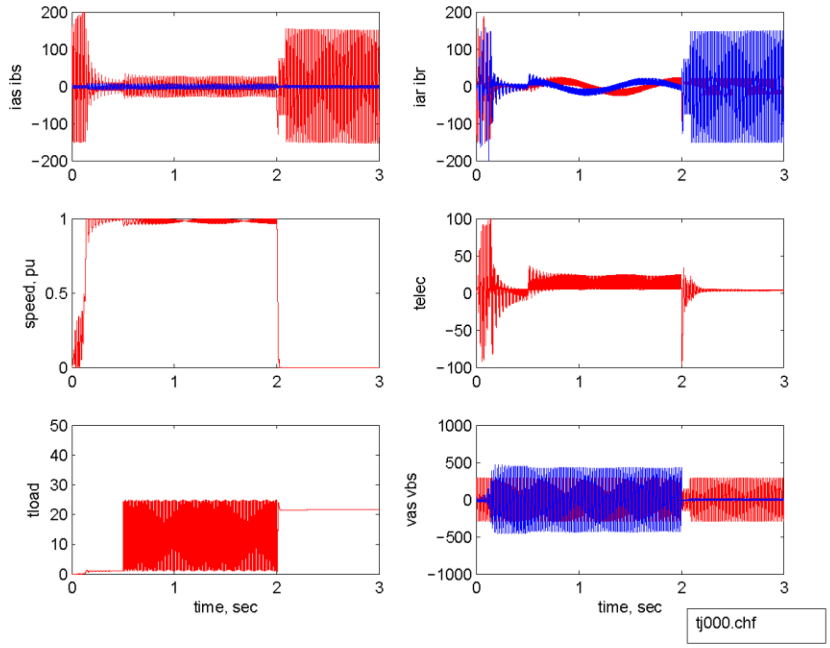


Figure 2: Response of motor in base case simulation

7

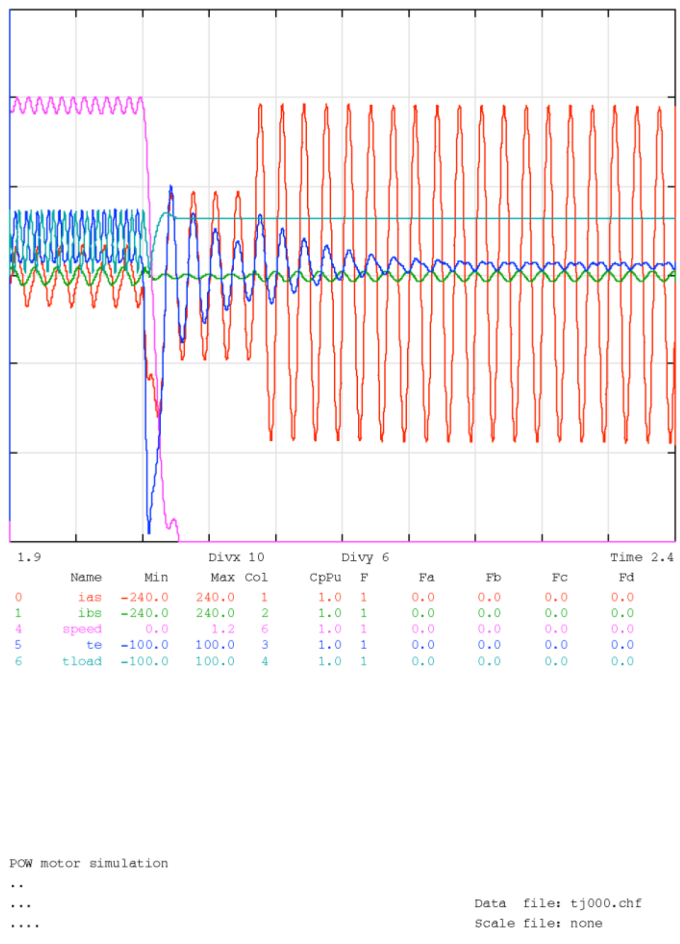
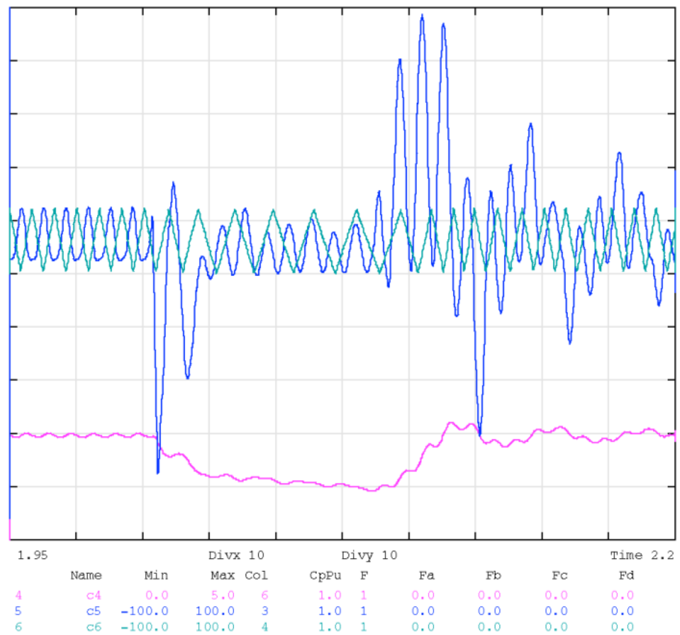


Figure 3: Response of motor in base case simulation - expanded scale at voltage dip

8



POW motor simulation
..
...
....
.....

Data file: tj090.chf
Scale file: none

Figure 4: Response of motor with voltage dip initiated at maximum of AC wave - expanded scale at voltage dip

9

7.2 Instructions for Navigating Through the DVD and Viewing the Simulation Results

a) After putting the DVD in your computer, go to **My Computer** and open the DVD called **SEL FIDVR 2012**.

b) The simulation results have been grouped into four folders, they are as follows:
   - Batch(A)_Results
   - Batch(B)_Results
   - ExcelSheets(Motor_Stall_Flags)
   - Explanatory_Case_Results

c) Open the folder called **Batch(A)_Results**. This folder contains two sub folders separating the simulation plots and motor stall flagging results.

d) Open the folder called **Flags_A**. In here there is a .csv file that contains the motor stall flag information without any formatting applied. This file can be used for analysis using standard .CSV tools.

   Note: The .csv file contains additional runs where Tload and Tav of 2 N-m and 16 N-m were used. These runs can be safely ignored as they represent unrealistic, (high) load torque scenarios. They were generated as a result of some initial testing.

e) Go back to the main view and open the folder called **ExcelSheets(Motor_Stall_Flags).** In here you will find a Microsoft® Excel® file called **Batch(A)-All.xlsx**. This Excel sheet gives a high-level overview of the 240 simulations that were performed in Batch A. The simulation parameters have been color coded to help quickly identify the case of interest. This file corresponds to Table 1.5.

f) Go back to the **Batch(A)_Results** and open the folder called **Plots_A**. In here you will find 5,760 files of simulation results. Out of these, 1,920 .jpeg files are the results. These can be used for quick analysis and review of what happened in every run. The rest of the files are COMTRADE format files of the same results. The RTDS stores the COMTRADE plots in IEEE C37.111-1991 *Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems* compliant files. Each COMTRADE plot consists of two files, a configuration file and a data file.

g) The COMTRADE plots may be viewed using SEL-5601 Analytic Assistant software. Alternatively, a free COMTRADE viewer called TOP® is available from Electrotek Concepts© at http://www.pqsoft.com/top/on the World Wide Web.

h) Also, MATLAB® code templates are available online that allow plotting via MATLAB plotter.

i) These COMTRADE plots are useful in analyzing each simulation run in detail. They can also be used to reproduce tests for further analysis by playing them into a relay via a relay test system capable of replaying COMTRADE files.

The files on the DVD can be related to specific simulation runs by examination of the following eight components of the file names: ***AAA_BBB_CCC_DDD_EEE_FFF_GGG_HHH***. Definitions are as follows:

AAA, indicates which variables are contained in the file
BBB is the fault duration,
CCC is the voltage phase at fault initiation,
DDD is the voltage at the bottom for phase A (on a nominal of 70 kV L-N),
EEE is the voltage at the bottom for phase B (on a nominal of 70 kV L-N),
FFF is the voltage at the bottom for phase C (on a nominal of 70 kV L-N),
GGG is the value of torque proportional to square of speed,
HHH is the value of torque varying in triangular waveform.

An example file name is as follows:

Bus2PH_0.05_0_35.9_35.9_35.9_4.0_12.0

This file contains the Bus 2 phase RMS quantities for the case where the fault duration was 5 cycles, C-phase voltage was at 0 degrees during the time of fault initiation, voltage at bottom of dip was 35.9 kV for A-, B-, and C-phases and the Tload was 4 N-m and Tav was 12 N-m.

In the simulation results DVD, you will find three different extensions for every file name. The first one is a .jpeg which represents a snapshot of the RTDS results as shown on the simulator output. The second one is a .cfg which corresponds to the COMTRADE configuration file. The last one is a .dat which corresponds to the COMTRADE data file.

Therefore, for every simulation (or for every run), there will be three corresponding files. For the above example, the three file names would be as follows:

Bus2PH_0.05_0_35.9_35.9_35.9_4.0_12.0.jpeg
Bus2PH_0.05_0_35.9_35.9_35.9_4.0_12.0.cfg
Bus2PH_0.05_0_35.9_35.9_35.9_4.0_12.0.dat

j) Please follow the above steps for navigating through the second batch of runs called **Batch(B)_Results**. The main differences between Batch A and Batch B results are shown in Table 2.3.

Table 2.3 Differences between Batch A and Batch B simulations

Batch	**Fault Durations Tested (cycles)**	**Voltage Phase Angles During Dip Initiation (degrees)**	**Variation in Voltage Amplitudes Tested (kV)**	**Driven Load Parameters Tested**	
				Tload (N-m)	**Tav (N-m)**
A	3, 5, 7, 9	0, 30, 60, 90	Phases A, B & C	8, 6, 4	4, 8, 12
B	3, 5	0, 30, 60, 90	Only phase C	8, 6, 4	4, 8, 12

k) Also, the DVD contains additional excel sheets of the results along with some explanatory case results.

l) Please see Table 2.4, which describes the channels contained in the plots.

Table 2.4 Description of file names and channels

AAA (first component of file names)	**File Name Description**	**Channels Involved**	**Channel Descriptions**
Bus2PH	Bus 2 Phase Quantities (RMS)	B2VARMS, B2VBRMS, B2VCRMS, B2IARMS, B2IBRMS, B2ICRMS	Bus 2 phase A, B and C voltages and currents
Bus2SC	Bus 2 Symmetrical Components	B2V1, B2V2, B2V0, B2I1, B2I2, B2I0	Bus 2 voltages and currents sequence quantities
Bus3PH	Bus 3 Phase Quantities (RMS)	B2VARMS, B3VBRMS, B2VCRMS, B21ARMS, B31BRMS, B3ICRMS	Bus 3 phase A, B and C voltages and currents
Bus3SC	Bus 3 Symmetrical Components	B3V1, B3V2, B3V0, B3I1, B3I2, B3I0	Bus 3 voltages and currents sequence quantities
ElecTorque	Electromagnetic Torques	te1q, te2q, te3q, te4q, te5q, te6q, te7q	Electromagnetic torques of motors 1 to 7
Instantaneous	Point on wave quantities	N4, N5, N6	Voltages at Bus 2 (A-, B- and C-phases)
		STPIA, STPIB, STPIC	Currents flowing out of Bus 2 (A-, B- and C-phases)
		N7, N8, N9	Voltages at Bus 3 (A-, B- and C-phases)
		STSIA, STSIB, STSIC	Currents flowing into of Bus 2 (A-, B- and C-phases)
		N22, N23, N24	Voltages at Bus 8 (A-, B- and C-phases)
		I78A, I78B, I78C	Currents flowing into of Bus 8 (A-, B- and C-phases)

MotorTerminalVolts	Terminal voltages of motors	NM1, NM2, NM3, NM4, NM5, NM6, NM7	Terminal voltages of motors 1 to 7
Speeds	Motor speeds	Motor 1, Motor 2, Motor 3, Motor 4, Motor 5, Motor 6, Motor 7	Per unit speeds of motors 1 to 7

7.3 RTDS Parameters

Please see below for the model parameters used in RTDS.

<u>Source</u>

$$Z_{base} = \frac{V^2_{base(L-L)}}{S_{base(3\emptyset)}} = \frac{115^2}{5000} = 2.645\ \Omega$$

$$Z_{actual} = Z_{p.u.} * Z_{base} = j0.1 * 2.645 = 0.2645\ \Omega$$

The above Zactual has been used as positive-sequence impedance (Z1) in the RTDS source model.

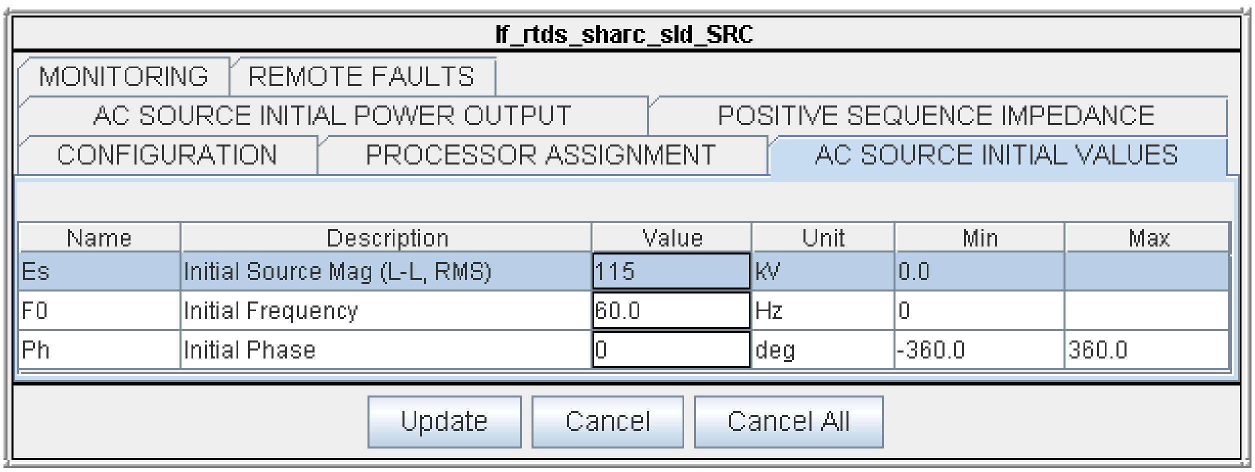


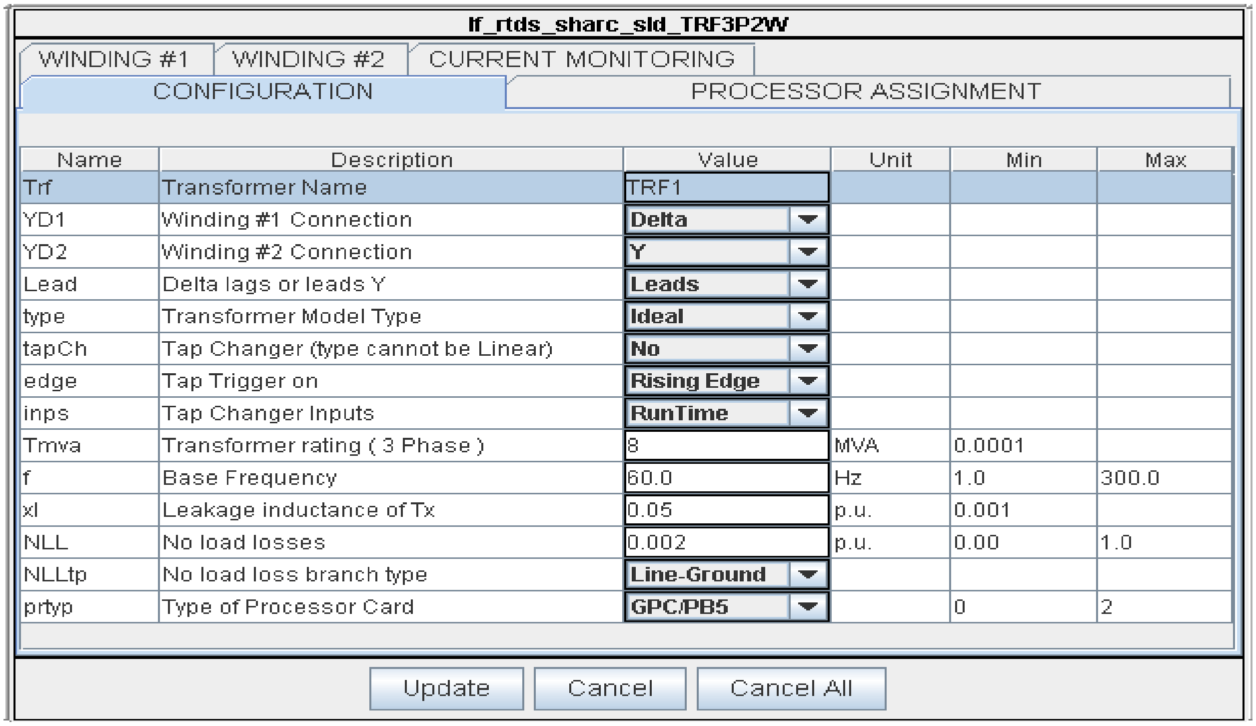
Figure 17: Source Parameters

<u>Series Link</u>

$$jX_L = \omega L = 1.32\ \Omega$$
$$L = \frac{1.32}{2\pi f} = 0.0035014\ H$$

<u>Supply Transformer</u>

Winding#1 is set to 121.24 kV (L-L) and Winding#2 is set to 13.8 kV (L-L)



Name	Description	Value	Unit	Min	Max
Trf	Transformer Name	TRF1			
YD1	Winding #1 Connection	Delta			
YD2	Winding #2 Connection	Y			
Lead	Delta lags or leads Y	Leads			
type	Transformer Model Type	Ideal			
tapCh	Tap Changer (type cannot be Linear)	No			
edge	Tap Trigger on	Rising Edge			
inps	Tap Changer Inputs	RunTime			
Tmva	Transformer rating (3 Phase)	8	MVA	0.0001	
f	Base Frequency	60.0	Hz	1.0	300.0
xl	Leakage inductance of Tx	0.05	p.u.	0.001	
NLL	No load losses	0.002	p.u.	0.00	1.0
NLLtp	No load loss branch type	Line-Ground			
prtyp	Type of Processor Card	GPC/PB5		0	2

Figure 18: Supply Transformer Parameters

<u>Three phase line parameters (feeder)</u>

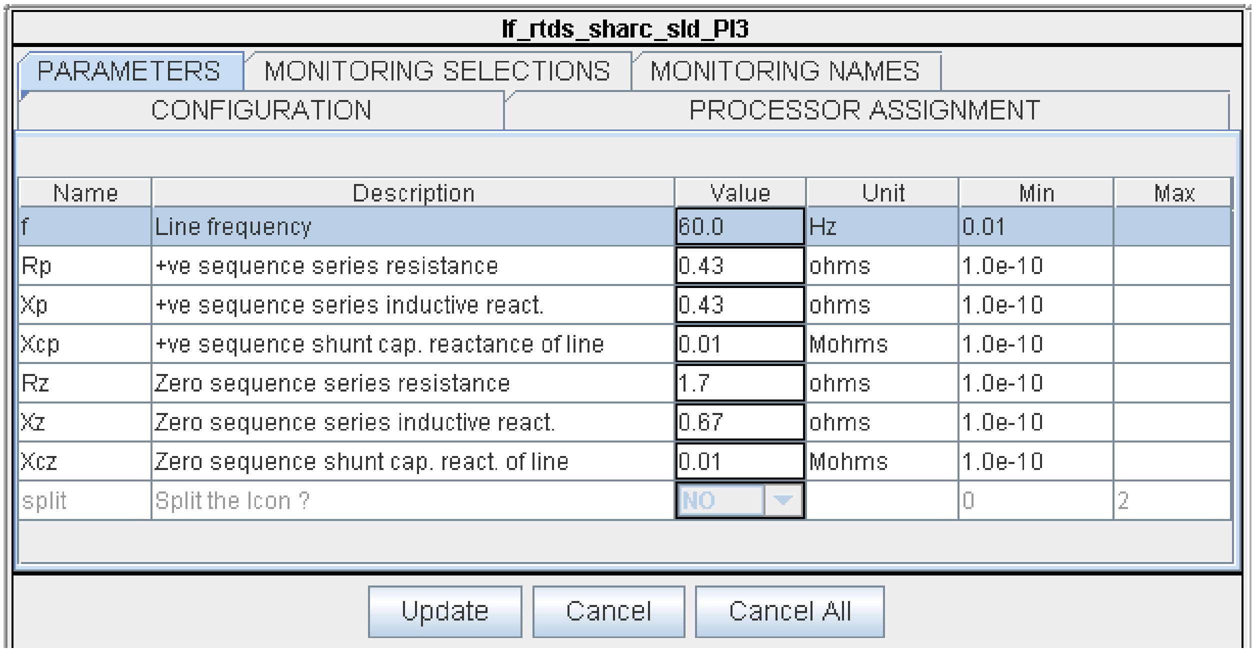
Given,

$$Z_0 = 1.7 + j0.67 \frac{\Omega}{mile}$$
$$Z_1 = 0.43 + j0.43 \frac{\Omega}{mile}$$
$$B_0 = 100 \frac{micromho}{mile}$$
$$B_1 = B_2 = 100 \frac{micromho}{mile}$$

Susceptance for capacitors is expressed by the following:

$$B_c = \omega C = \frac{1}{X_c}$$
$$X_{C0} = \frac{1}{B_0} = 0.01 \frac{M\Omega}{mile}$$
$$X_{C1} = \frac{1}{B_1} = 0.01 \frac{M\Omega}{mile}$$

The Z and B parameters have been multiplied by the respective feeder lengths and entered into the PI section settings. A typical PI section settings looks like the following:



lf_rtds_sharc_sld_PI3

PARAMETERS | MONITORING SELECTIONS | MONITORING NAMES

CONFIGURATION | PROCESSOR ASSIGNMENT

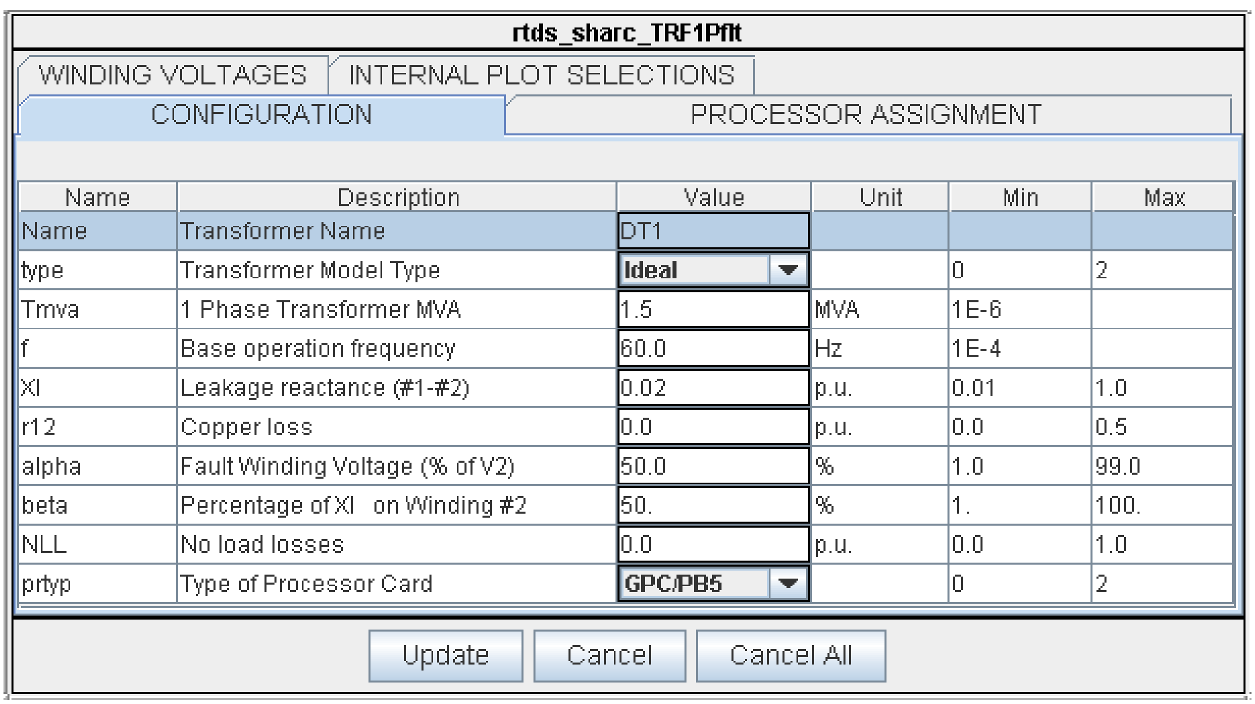
Name	Description	Value	Unit	Min	Max
f	Line frequency	60.0	Hz	0.01	
Rp	+ve sequence series resistance	0.43	ohms	1.0e-10	
Xp	+ve sequence series inductive react.	0.43	ohms	1.0e-10	
Xcp	+ve sequence shunt cap. reactance of line	0.01	Mohms	1.0e-10	
Rz	Zero sequence series resistance	1.7	ohms	1.0e-10	
Xz	Zero sequence series inductive react.	0.67	ohms	1.0e-10	
Xcz	Zero sequence shunt cap. react. of line	0.01	Mohms	1.0e-10	
split	Split the Icon ?	NO		0	2

Update | Cancel | Cancel All

Figure 19: PI Section Parameters

Single Phase Distribution Transformer

Winding#1 is set to 7.967 kV (L-N) and winding#2 is set to 230 V.



rtds_sharc_TRF1Pflt

WINDING VOLTAGES | INTERNAL PLOT SELECTIONS

CONFIGURATION | PROCESSOR ASSIGNMENT

Name	Description	Value	Unit	Min	Max
Name	Transformer Name	DT1			
type	Transformer Model Type	Ideal		0	2
Tmva	1 Phase Transformer MVA	1.5	MVA	1E-6	
f	Base operation frequency	60.0	Hz	1E-4	
Xl	Leakage reactance (#1-#2)	0.02	p.u.	0.01	1.0
r12	Copper loss	0.0	p.u.	0.0	0.5
alpha	Fault Winding Voltage (% of V2)	50.0	%	1.0	99.0
beta	Percentage of Xl on Winding #2	50.	%	1.	100.
NLL	No load losses	0.0	p.u.	0.0	1.0
prtyp	Type of Processor Card	GPC/PB5		0	2

Update | Cancel | Cancel All

Figure 20: Distribution Transformer Parameters

Resistive Load

Given,

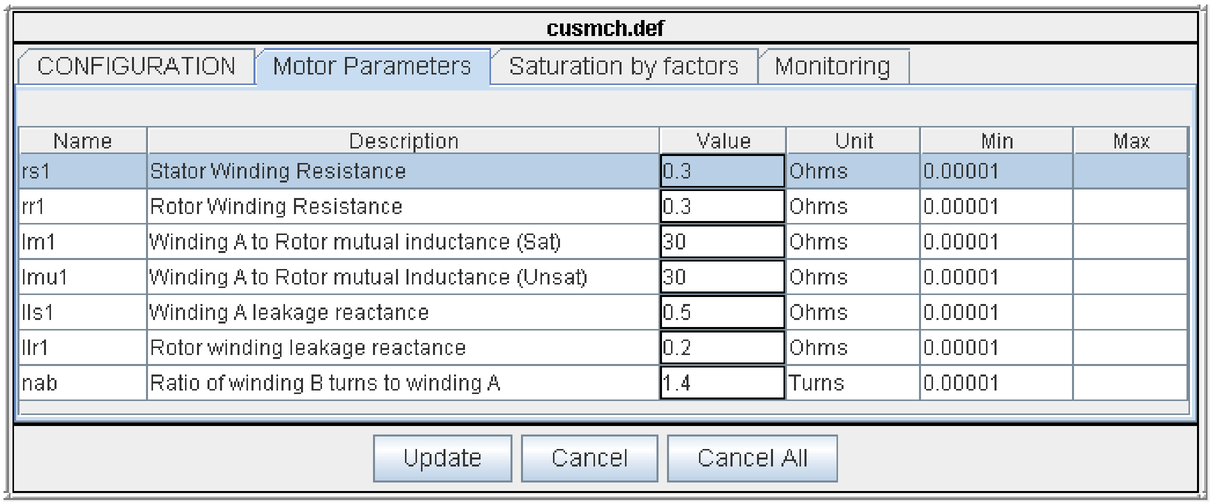
P = 0.2 MW

This load has been equally distributed across the two 115 V circuits on the secondary side of the distribution transformer.

$$R = \frac{V^2}{P} = \frac{115^2}{0.1 * 10^6} = 0.13225\ \Omega$$

Single Phase Motor Load

The motor parameters are shown below. These parameters are internally scaled by the scale factor.



Name	Description	Value	Unit	Min	Max
rs1	Stator Winding Resistance	0.3	Ohms	0.00001	
rr1	Rotor Winding Resistance	0.3	Ohms	0.00001	
lm1	Winding A to Rotor mutual inductance (Sat)	30	Ohms	0.00001	
lmu1	Winding A to Rotor mutual Inductance (Unsat)	30	Ohms	0.00001	
lls1	Winding A leakage reactance	0.5	Ohms	0.00001	
llr1	Rotor winding leakage reactance	0.2	Ohms	0.00001	
nab	Ratio of winding B turns to winding A	1.4	Turns	0.00001	

Figure 21: Custom Motor Parameters

The saturation for the single phase motor model is described by factors. The saturation factors are the same across all the motors. They are 0.03 (S at nominal) and 0.1 (S at 1.2 times nominal).

Shunt Capacitors

$$Q_{C(3\emptyset)} = \omega C_{an} V_{LL}^2$$

Three phase shunt capacitor bank on bus 6

$$C_{an} = \frac{Q_{C(3\emptyset)}}{\omega V_{LL}^2} = \frac{800 * 1000}{2\pi * 60 * 13.8 * 13.8 * 10^6} = 11.143\ \mu F$$

Three phase shunt capacitor bank on bus 8

$$C_{an} = \frac{Q_{C(3\emptyset)}}{\omega V_{LL}^2} = \frac{1600 * 1000}{2\pi * 60 * 13.8 * 13.8 * 10^6} = 22.286\ \mu F$$

Single phase shunt capacitor bank on bus 11 phase C

$$C_{an} = \frac{Q_{C(1\emptyset)}}{\omega V_{LN}^2} = \frac{300 * 1000}{2\pi * 60 * 7.967 * 7.967 * 10^6} = 12.559\ \mu F$$

Series Impedance of single phase lateral

$$jX_L = \omega L = 0.25\ \Omega$$

$$L = \frac{0.25}{2\pi f} = 0.000663146\ H$$

7.4 Details of Custom Motor Model in RSCAD

The motor mode in RTDS has been built using the C builder tool. The tool is available within the RSCAD software suite.

The custom component developed by the user is usually interfaced by specifying impedance at the nodes to which the component is connected and by providing current injections into those nodes.

1. Within C builder, certain methodology has to be adopted for defining component constants, variables, drawings and code. Here are some high-level steps followed for creating the custom component (single phase motor). All these steps are performed within the C builder.
2. In the drawing area, sketch the custom component utilizing the basic shapes.
3. Under the Parameters tab, define the parameters that are constants. These can be changed by the user within the draft if needed.
4. Under the IO Points/Nodes tab, create the inputs and outputs needed for the component to be utilized in the draft. These inputs and outputs can be used in the draft for connecting sliders where variables can be changed in real-time during simulation.
5. Under the C File Associations, utilize the template to start writing the component code in C like language. The code file is mainly divided into three sections
    a. STATIC – In this section, all the variable names that are going to be used in the code are declared
    b. RAM – This section is used for initializing the required variables and creating all the constants. Anything defined under the RAM section will be only executed once before the start of the simulation.
    c. CODE – This section is further divided into different zones.
        i. BEGIN_TO: In this zone, all the code required to calculate the current injections for the next time step is executed.
        ii. T0_T2: In this zone, rest of the code is executed. The code executed under this zone is typically used for calculating quantities such as flux linkages, torque etc. that are not required in producing the injection currents.
6. Under the C File Associations, also create variables required for current injections, conductance matrix, monitoring, etc.

Please see Figure 22 for a screenshot of the C builder tool. It shows the custom single phase induction motor model that was created for this project. It has three power system nodes (Main winding voltage input, Aux winding voltage input and neutral) and a single control input (Load torque).

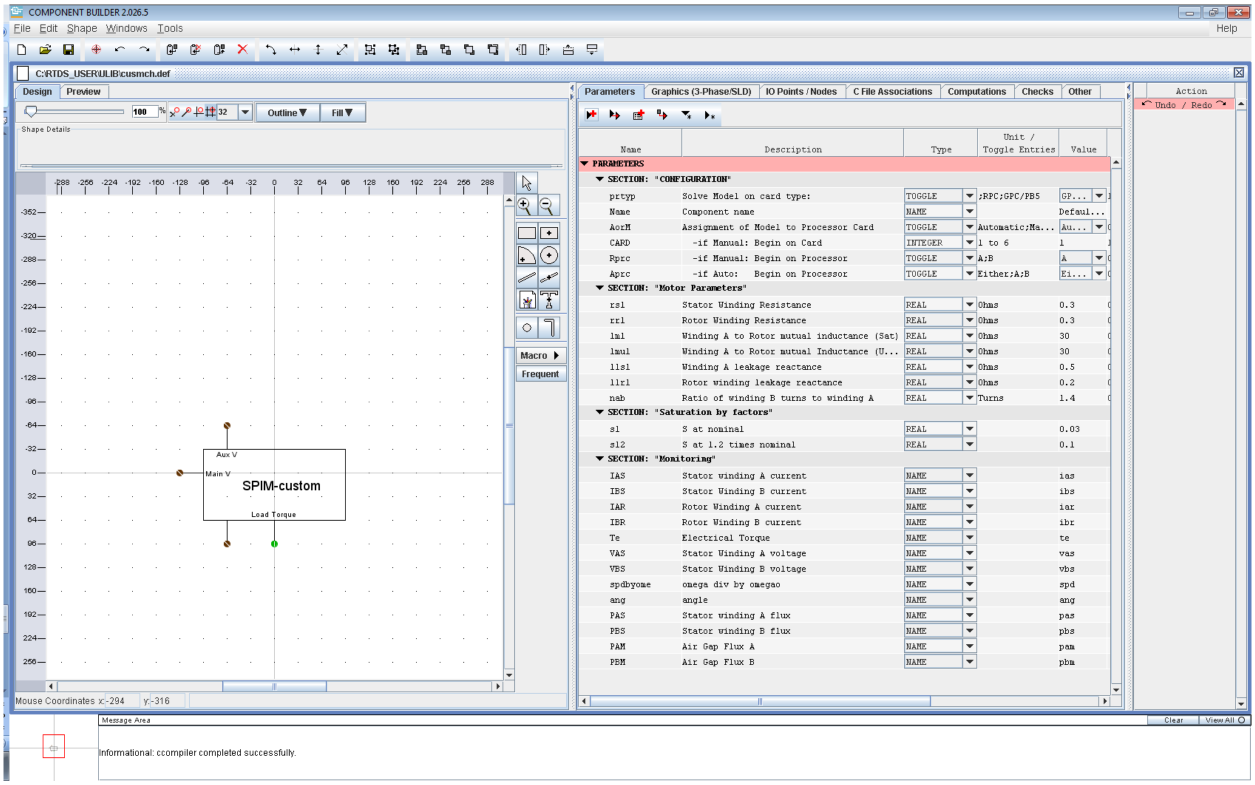


Figure 22: Main Layout of the C-Builder Tool

Figure 23 shows a single instance of the custom motor model being used in the draft file. Multiple instances of the same model can be connected to a power system model if needed.

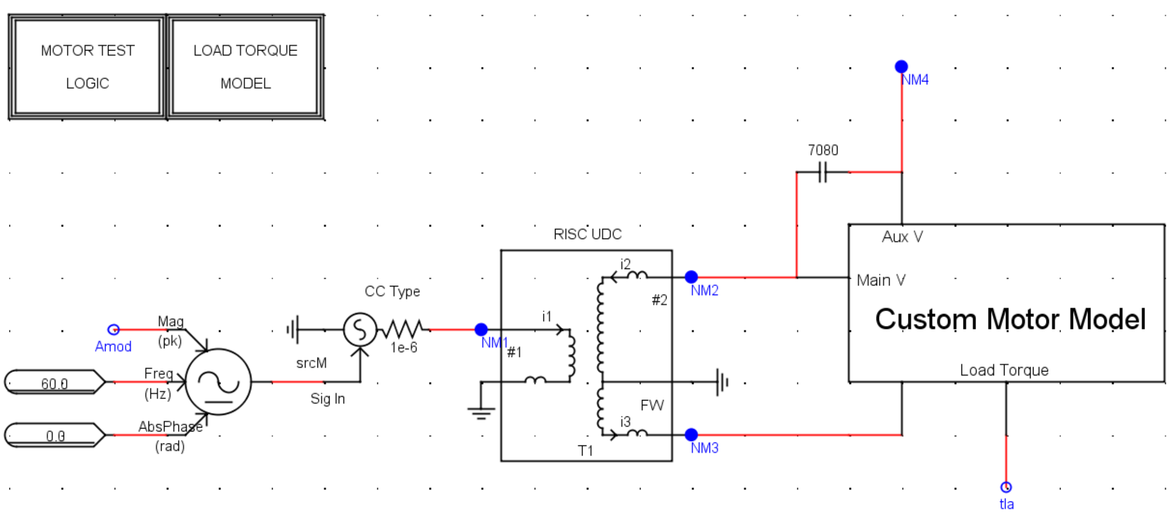


Figure 23: Connection of Motor to a Single Phase Source Through Distribution Transformer

Figure 24 shows the load torque model for a single instance of the induction motor. This has been modeled using the discrete control system components available in RSCAD library.

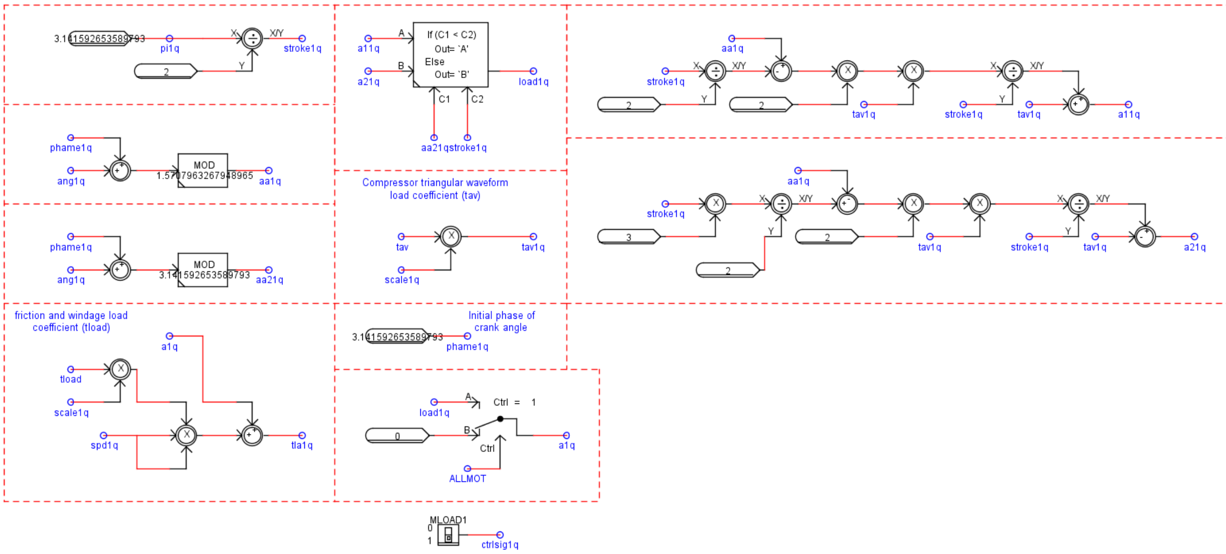


Figure 24: Load Torque Model

The load torque model is external to the custom built motor model. While the motor model has been built using the C builder tool, the load torque model has been created in the draft using built-in library functions. This gives us the flexibility to change parameters in the load torque model during simulations and also easily modify existing (or) create new & additional logic as needed without needing to change the motor model.

7.5 Sequence of Events implementation in RSCAD

Figure 25 shows the RSCAD implementation of the sequence of events. The same sequence of events has been used for all the simulations performed under this project.

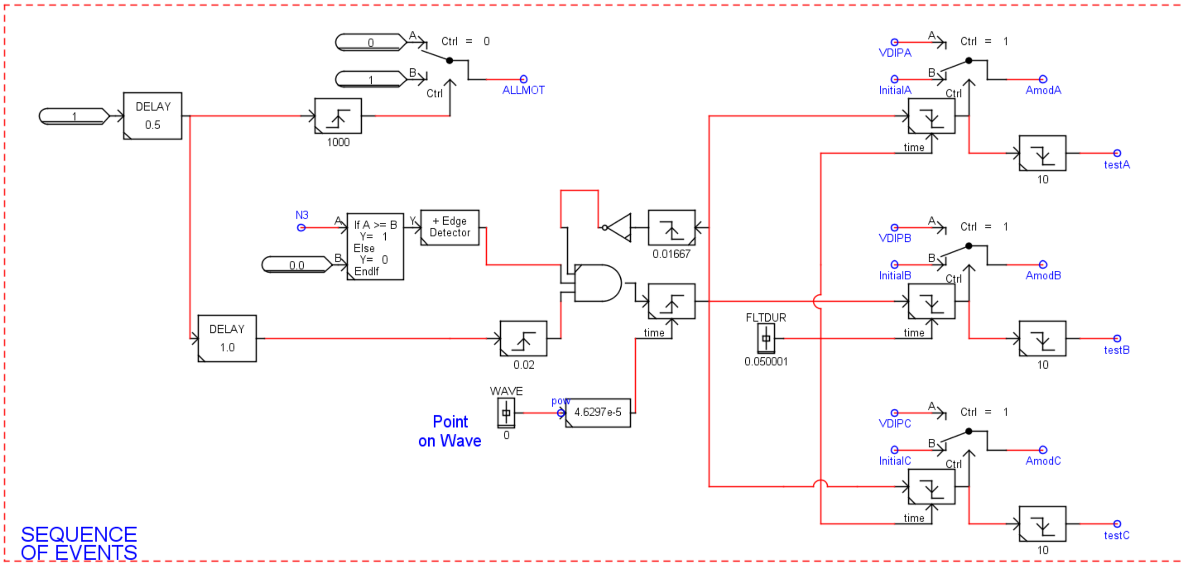


Figure 25: Sequence of Events Implementation in RTDS

7.6 Plot Captures

For all the plots that have been captured in the different batches of runs, there will a ±10-millisecond delay in their starting times. It is due to the un-deterministic network latency between the RTDS simulator and the computer sending the commands for automatic plot captures. Since RTDS starts its plots at t = 0 (even if the plots are elapsed in time), a small phase difference might appear between starting voltages in different cases.

Section 8: REFERENCE

1. Information available at: http://www.rtds.com
2. H.W. Dommel, "Digital computer solution of electromagnetic transients in single- and multi-phase networks," IEEE Trans. on Power App. and Syst., Vol. PAS-88 (4), pp. 388-398, 1969.