Final Report

Composite Load Model Motor D Testing

Prepared for:

Australian Energy Market Operator (AEMO)

Obaidur Rahman

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Executive Summary

This project conducted extensive experimental testing to analyse the response of Motor D loads within the Composite Load Model to power system disturbances. The primary goal of the testing was to support the Australian Energy Market Operator (AEMO) in identifying and predicting potential power reduction and system stability issues arising from load behaviour during power system transient phenomena to refine their dynamic load models. The Motor D load type includes single-phase (1P) compressors in residential air-conditioning loads. These loads are characterised by constant torque load and minimal inertia, making them susceptible to stall, a characteristic with important implications for power system stability. Motor D load is also prevalent in 1P residential and light commercial refrigerator compressor motors in Australia. This project has evaluated the performance of 15 appliances, encompassing non-inverter-based air conditioners, refrigerators, freezers, a washing machine, and a dryer. Voltage sag disturbances of varying duration and depths were applied to investigate stall behaviour.

The main objectives of the tests were to assess whether the tuning parameters of Motor D require refinement and whether its composition required modification for Australian conditions. Test results indicated that most refrigerators either stalled for severe voltage sags or did not stall at all, challenging their classification within the Motor D category. Based on these results, a recommendation has been made to reclassify refrigerators to the Motor A category, significantly altering the composition of Motor D loads. Important updates to existing parameters are summarised in the Table *1*, noting that the table includes only the parameters of Model D that have been updated.

Table 1 Motor D Parameter Updates

Motor D Parameters	Description	Original	EPRI Latest	AEMO Updated 2024
compPF	power factor at 1 pu voltage	0.71	0.98	1
Vstall	Stall Voltage (pu)	0.49	0.45	0.6
Rstall	Stall Resistance (pu)	0.143	0.1	0.17
Xstall	Stall Reactance (pu)	0.143	0.1	0.07
Frst	Fraction Capable of restart (%)	0.1	0.2	0.55
Vrst	Voltage for Restart after stall (pu)	0.95	0.95	0.9
Tth	Heating time constant (s)	15	10	16

Contents

1. Introduction

Precise load modelling is essential for Network Service Providers (NSPs) and operators to evaluate power system performance under various conditions, assess network stability issues, and devise effective control solutions [1, 2]. In recent years, power systems across the world have undergone major transformations with the introduction of distributed energy resources (DERs) and modern flexible loads. When subjected to faults and other disturbances, power systems that incorporate these devices exhibit dynamic behaviour [3, 4], which traditional static load models used by NSPs and operators are not designed to capture. The present load models used in Australian industry (by the Australian Energy Market Operator and others) are frequency dependent exponential models, which last calibrated and validated by the Plant Modelling Working Group[1] in 1999, and they are not suitable to accurately model the complex dynamic behaviour of modern loads [5].

Sophisticated composite load models are now available that can capture both the dynamic and static response of loads [6]. Composite load models consider the diverse aspects of load behaviour, such as dynamic response, sensitivity to voltage changes, and response to frequency fluctuations. In order to better model the response of modern power systems, the Western Electricity Coordinating Council (WECC) has developed an advanced composite load (termed CMPLDW) model with various components, including different types of motor loads, electronic/static loads as well as the inclusion of DERs [7]. The addition of electrical distance between the transmission network and end load also allows this model to capture delayed voltage recovery events from transmission faults [8, 9]. The North American Electricity Reliability Corporation (NERC) recommends the use of the CMPLDW model for dynamic studies in power systems [10]. However, the CMPLDW model incorporates complex load characteristics which require input of as many as 133 parameters into the model. The model is constantly updated using inputs from NSPs, through utilisation of data measured during power system faults, and by means of laboratory testing of appliances.

This report presents findings from a series of bench tests conducted on Motor D type loads (as defined in Section 2.2) within the CMPLDW model. In essence, the work focussed on testing multiple Motor D loads in composite load models. The tests involved assessing the dynamic response of the loads under test when subject to voltage sags of various magnitudes and durations, along with voltage restart tests

[1] A working group established in March 1997 with Powerlink (QLD TNSP), TransGrid (NSW TNSP), ElectraNet (SA TNSP), Hyro-Electric Corporation (TAS TNSP) and Victorian Power Exchange (VIC TNSP) as members. Today, this is now known as the Power System Modelling Reference Group (PSMRG), which is convened by AEMO.

tailored for appliances including non-inverter-based air conditioners and refrigerators. These thorough evaluations aimed to understand stall behaviour and restart capabilities, providing crucial data for refining CMPLDW model parameters. The dataset obtained will play a pivotal role in in determining the RMS load model parameters and provide key details for electromagnetic transient (EMT) modelling.

2. Composite Load Model

2.1. Overall Model Structure

This section summarises the basic components of the CMPLDW load model, including overall structure, types of loads, and input parameters. The structure of the CMPLDW model is depicted in Figure 1 and consists of several key components:

1. A distribution transformer with an on-load tap changer, where the transformer impedance is represented by jXxf.
2. A substation shunt capacitor, where Bss is the susceptance in per unit (pu).
3. A single-phase equivalent model of the distribution feeders that carry power to the end-use loads (Rfdr + jXfdr). Shunt capacitors are implemented at both ends to account for reactive power losses in the feeder, ensuring that the net apparent power at the transmission bus matches that of the power flow case.
4. Six different classifications of loads which are connected to the load bus, including a combination of four different types of motors, an equivalent electronic load model, and the remaining loads combined into a static polynomial load model.

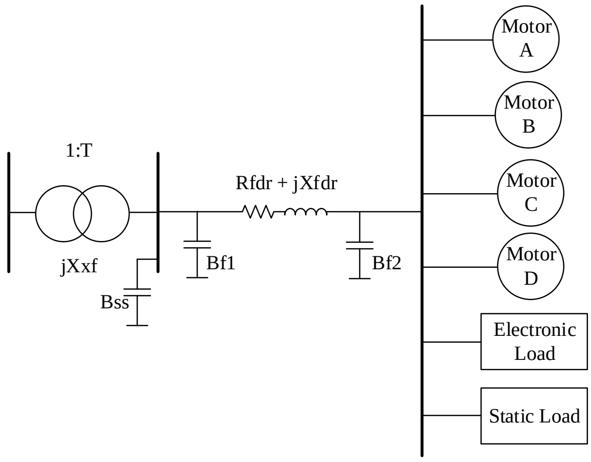

Figure 1 WECC Composite Load Model Structure

The six different classifications of load types in the CMPLDW model are summarized in Table 2.

Table 2: Classification of the different types of loads in CMPLDW

Motor A	Motor A refers to 3-phase induction motors that have high locked-rotor torque and low inertia (with a H value of 0.1 seconds) and are designed to drive constant torque loads. These types of motors are typically used in commercial and industrial air conditioning compressors and refrigeration systems.
Motor B	Motor B is a 3-phase induction motor, with high inertia (with an H value ranging from 0.25 to 1.0 seconds) and is designed to drive loads whose torque is proportional to speed squared. These motors are commonly used in commercial ventilation fans and air-handling systems, with typical ratings ranging from 4 to 19 kW.
Motor C	Motor C is a 3-phase induction motor that has low inertia (with an H value ranging from 0.1 to 0.2 seconds) and is designed to drive loads whose torque is proportional to speed squared. These motors are typically used in commercial water circulation pumps in central cooling systems, with typical ratings ranging from 4 to 19 kW.
Motor D	Motor D is a specialised performance model that is specifically designed to represent single-phase (1P) compressors used for residential air-conditioning loads. These motors have a constant torque load characteristic and minimal inertia, which can make them prone to stall. They are also commonly used in 1P residential and light commercial refrigerator compressor motors in Australia, with typical ratings ranging from 2 to 4 kW.
Power Electronic	A power electronic load refers to electronic devices used by consumers (such as computers and televisions), appliances (like dishwashers), office equipment, and variable frequency drives (VFDs) used in commercial and industrial settings.
Static	A static load represents the remaining unclassified aggregate loads, including constant impedance loads such as incandescent lighting.

2.2. Motor D

2.2.1. Overview

Motor D loads in a composite load model refer to non-inverter driven dynamic loads driven by single-phase induction motors, commonly found in appliances like air conditioners and refrigerators. These compressors may, but not exclusively, use piston, scroll, or rotary designs to achieve desired compression. Piston compressors operate by using a piston driven by a crankshaft to compress refrigerant, scroll compressors use two interleaving scrolls for continuous, smooth compression, and rotary compressors use rotating rollers to compress refrigerant in a compact, efficient manner. These compressors exhibit complex behaviours due to their dynamic response to changes in voltage and frequency, impacting the stability and performance of the power system. Accurate modelling of motor D loads involves detailed mathematical representations and parameter tuning based on experimental data to ensure realistic simulation of their start-up characteristics, operational modes, and response to electrical disturbances. Their widespread use and significant power consumption in residential and commercial settings necessitate careful consideration within composite load models to understand their influence on system stability and voltage regulation.

2.2.2. Component Schematic

In this section, the load type considered in this report, Motor D, will be described in detail. Motor D is derived from a 1-phase air conditioning (A/C) performance-based model developed by members of the WECC Load Modelling Task Force. The model's foundation is rooted in extensive laboratory testing of diverse A/C units. Notably, Model D is characterised by its stall behaviour and the subsequent capability to restart after fault clearance. The purpose of the Motor D load type is to depict a composite representation of numerous individual single-phase A/C compressors and their associated protective devices, as schematically illustrated in Figure 2.

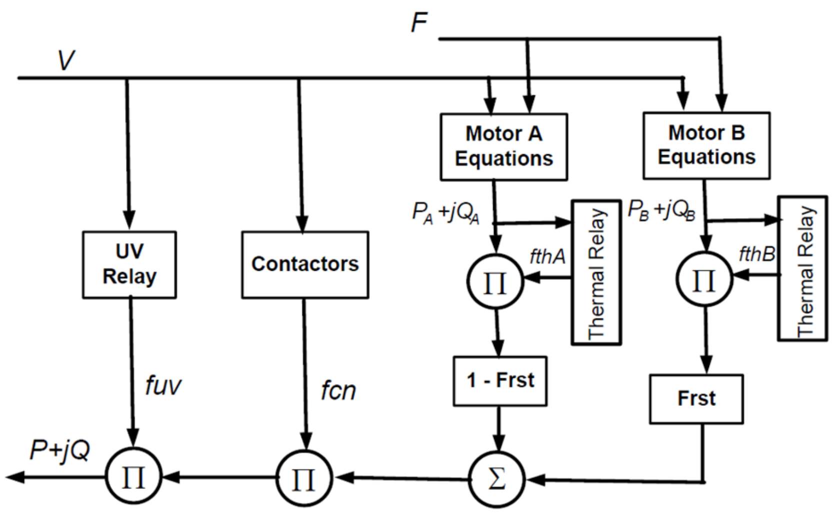

Figure 2: Motor D block diagram in the CMPLDW Model

2.2.3. Operating Principles

Motor D type is sub divided into two groups based on their stalling characteristics:

- Motor D 'A'- Those compressors that cannot restart soon after stall.
- Motor D 'B'- Those compressors that can restart soon after stall.

The performance of these motors can be represented by the equations (1) to (6).

If the supply voltage (V) is greater than 0.86pu the active (P) and reactive (Q) powers consumed by the devices can be expressed as:

$$P = P_0 * (1 + \Delta f) \tag{1}$$

$$Q = \left[Q'_0 + 6 * (V - 0.86)^2\right] * (1 - 3.3 * \Delta f) \tag{2}$$

Alternatively, if V is less than 0.86pu but greater than V_{stall}, P and Q of the motor can be obtained using:

$$P = [P'_0 + 12 * (0.86 - V)^{3.2}] * (1 + \Delta f) \tag{3}$$

$$Q = \left[Q'_0 + 11 * (0.86 - V)^{2.5}\right] * (1 - 3.3 * \Delta f) \quad (4)$$

Finally, if V is less the defined V_{stall}, the P and Q during motor stall can be calculated using the stall admittance (G_{stall}) and susceptance (B_{stall}) as shown in (5) and (6):

$$P = G_{stall} * V * V \quad (5)$$

$$Q = -B_{stall} * V * V \quad (6)$$

If the voltage drops below V_{stall} for greater T_{stall} seconds the motor stays in the stalled state, until the protection mechanism disconnects the compressor.

For ‘B’ type, if V > Vrst for t > Trst, the motor restarts.

The main purpose of testing the Motor D appliances described in this report is to investigate the possible changes that may be required in the tuning parameters of the motor D components in the CMPLDW. Some of the key parameters for the load that which will be are given below:

1. compPF- Power factor at 1 pu voltage
2. V_{stall}- Stall Voltage (pu)
3. R_{stall}- Stall Resistance (pu)
4. X_{stall}- Stall Reactance (pu)
5. F_{rst}- Fraction of load that can restart after stall
6. V_{rst}- Voltage at which restart can occur (pu)
7. T_{tt}- Heating time constant (sec)

3. Testing Procedure

3.1. Laboratory Setup

The load testing procedure utilised for this report is depicted in Figure 3. To apply the disturbances, a California Instruments (MX45-3PI 45) arbitrary programmable power supply was employed as the power source. The load under examination was connected at the output of the power supply, and the voltage and current waveforms were measured using a Keysight digital oscilloscope and processed using MATLAB software to assess the required active and reactive power responses of the devices. The MATLAB program had the capability to calculate the root mean square (rms) variations in active power (P) and reactive power (Q) when subjected to changes in magnitude, frequency, and phase angle of the supply voltage.

Figure 4 shows photographs of the laboratory setup employed for the load testing. In Figure 4 (a), the programmable power supply (waveform generator) utilised to apply the disturbances is displayed, while Figure 4(b) depicts a photograph of some of the loads in the laboratory connected to the bench testing setup.

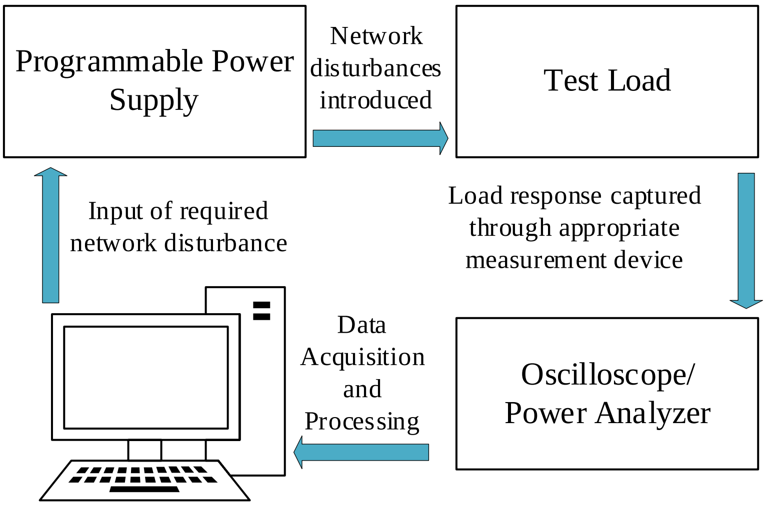

Figure 3: Schematic of Experimental Setup

(a) (b)

Figure 4: Load Testing Setup (a) Programmable Power Supply, and (b) Load under Test

3.2. Stall Tests

The testing sequence initiated with a device start-up test, focusing on capturing the initial behaviour of the appliances during startup. This test was used to distinguish the stall behaviours of the load from the motor inrush currents. Following this, a series of sag tests were performed at different depths and durations to evaluate whether the appliances would stall. After capturing the stall behaviour, the tests were repeated with smaller increments to precisely identify the voltage at which the appliance stalled. Lastly, a voltage restart test was executed to ascertain the restart voltage of the appliance.

3.2.1. Sag Tests

Table 3 shows the voltage sag disturbance characteristics applied in the testing, encompassing various durations and magnitudes to assess motor stall. These tests have been termed general sag tests in this report. Voltage magnitudes spanned from 0.8 pu to 0.2 pu, with durations of 80 ms and 120 ms. Following the identification of the motor stall point, subsequent stall tests varied the voltage magnitudes in increments of 0.02 pu to precisely pinpoint the voltage sag characteristics that precipitate a stall. This process yielded critical experimental data for the V_{stall} parameter. Additionally, as indicated in the table below, an extra sag test was conducted with a 400 ms duration at 0.2 pu to assess whether the appliance disconnects under extreme sag conditions.

Table 3: Voltage Sag Magnitude and Duration for General Sag Tests

Voltage Sag Magnitude (pu)	**Duration of Sag (ms)**		
0.8	80	120	N/A
0.7	80	120	
0.6	80	120	
0.5	80	120	
0.4	80	120	
0.3	80	120	
0.2	80	120	400

3.2.2. Voltage Restart Test

To determine the voltage restart parameters for Motor D appliances capable of restarting after a stall, voltage restart tests were performed on the appliances. In the voltage restart test, initially, a sag reduced the voltage to 0.2 pu for a duration of 120 ms. Subsequently, the voltage was restored from 0.2 pu to 0.7, 0.8, and 0.9 pu, respectively. Figure 5 illustrates the three voltage waveforms, which were used to investigate whether the restored voltage after the fault clearance was sufficient for a motor restart from stall. Here, Test 1, Test 2 and Test 3 refer to the restart tests where the voltage was restored to 0.9, 0.8 and 0.7 pu.

Including the voltage sag and voltage restart tests, overall, the testing procedure resulted in 27 tests per appliance.

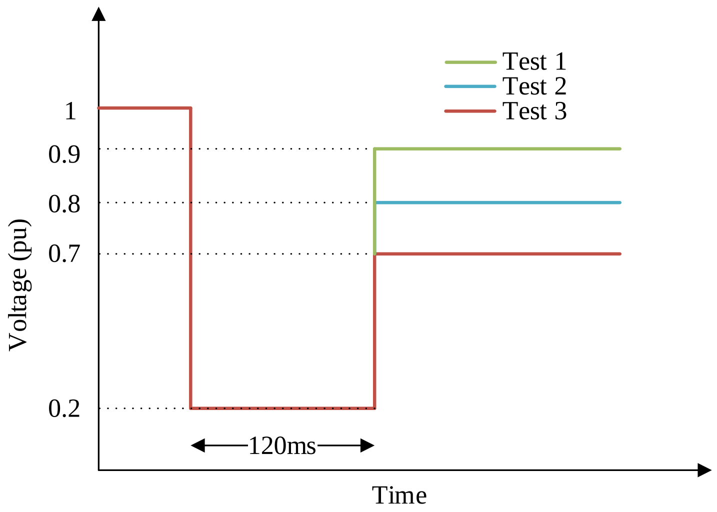

Figure 5: Tests done for Voltage Restart

3.3. List of Appliances Tested

A total of 15 appliances were tested to examine the stall behaviour of Motor D. These appliances consisted of six non-inverter-based air conditioners, including both portable and window units. Furthermore, seven refrigerators were tested, consisting of five regular top-mount units and two freezers. The final appliances were a washing machine and a dryer. Figure 6 shows photographs of some of the appliances.

Figure 6: Photographs of Tested Motor D Appliances

4. Results from Tests

In this section, the outcomes of the tests conducted are summarised. As each appliance underwent a total of 27 tests, considering the large volume of results, the key findings are presented in a tabular format, emphasising only the critical outcomes. For commercialisation purposes, the names of the appliances have been omitted from the report. The raw data of the conducted tests has been shared with AEMO through the UOW/AEMO shared repository and can be found in [11].

4.1. Air Conditioners

4.1.1. Unit 1

For Air Conditioner Unit 1, the compressor successfully restarted after stall for all general sag tests with voltage magnitudes of 0.5 pu and lower, as summarized in *Table 4*. This behaviour was observed across sag tests with durations of 80 ms and 120 ms. However, during the extreme sag test at 0.2 pu for a duration of 400 ms, the device stalled and disconnected, as illustrated in *Figure 7* (a). This unit typically consumes 865 W of real power, but during stall, real power increased to 4300 W. In voltage sag restart tests, the unit successfully restarted when the voltage was restored to 0.9 pu (depicted in *Figure 7* (b)), but it disconnected after stall when the voltage was restored to 0.8 pu and 0.7 pu.

Table 4: General Sag Test Result for Air Conditioner Unit 1

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	Stall and Restart	Stall and Restart	Stall and Restart	Stall and Restart
120	No Stall	No Stall	No Stall	Stall and Restart	Stall and Restart	Stall and Restart	Stall and Restart

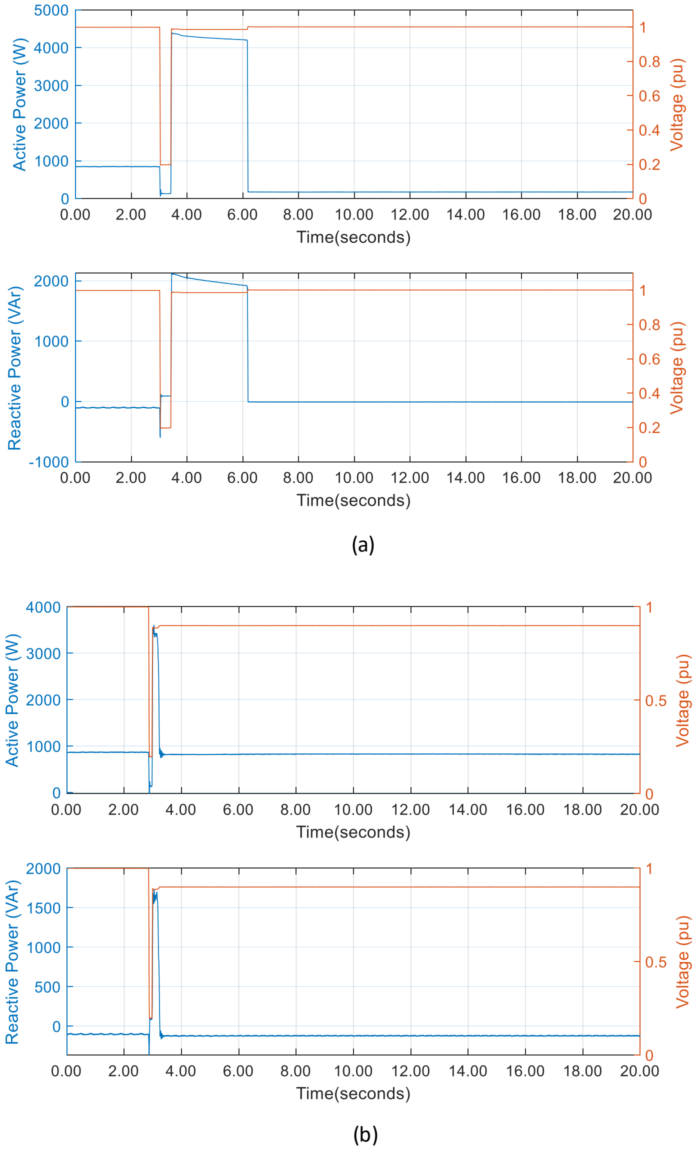

Figure 7: Results for AC 1 (a) Sag at 0.2 pu for 400 ms (b) Voltage Restored to 0.9 pu

4.1.2. Unit 2

For Air Conditioner Unit 2, the A/C successfully initiated a restart after stall for all general sag tests at 0.6 pu and below, as outlined in *Table 5*. This behaviour was consistent for sag tests with both 80 ms and 120 ms durations. However, in the extreme sag test at 0.2 pu for a duration of 400 ms, the device disconnected. While this unit typically consumes 990 W of real power, during stall, real power increased to 4400 W. For the voltage sag restart tests, the unit successfully restarted when the voltage was restored to 0.9 pu, but it disconnected after stall when the voltage was restored to 0.8 pu and 0.7 pu. The V_{stall} parameter was determined to be 0.62 pu through comprehensive sag testing, as illustrated in *Figure 8*.

Table 5: General Sag Test Result for Air Conditioner 2

Duration (ms)	Sag Voltage (pu)						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	Stall and Restart	Stall and Restart	Stall and Restart	Stall and Restart	Stall and Restart
120	No Stall	No Stall	Stall and Restart	Stall and Restart	Stall and Restart	Stall and Restart	Stall and Restart

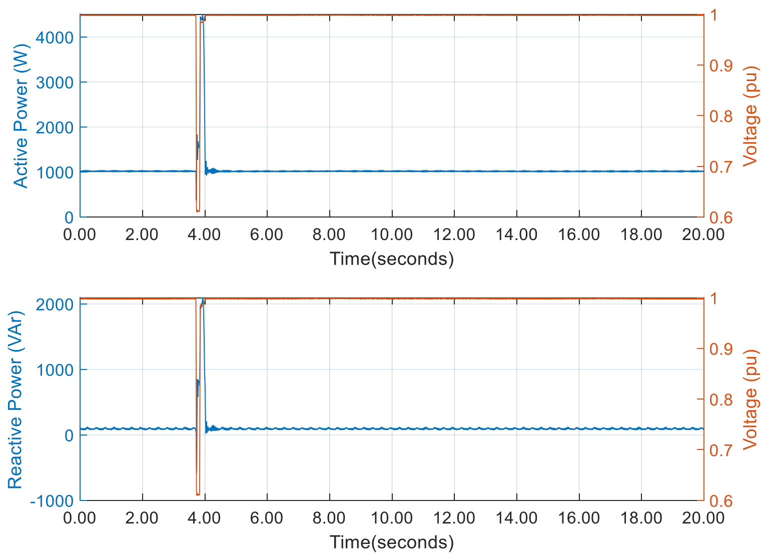

Figure 8: Detailed Sag Test for Air Conditioner 2

4.1.3. Unit 3

For Air Conditioner Unit 3, the device experienced stall and disconnection for all general voltage sag tests at 0.5 pu and below. Notably, the device could only restart for the general sag test at 0.6 pu. This pattern was consistent for both 80 ms and 120 ms durations. The summary of the general sag test results for this device is provided in

Table *6*. The test at 0.6 pu was repeated to confirm accuracy. Similar to the general sag tests, the device stalled and disconnected for the extreme 400 ms sag test. The unit could not restart in any of the voltage restart tests. During stall, the power consumption of the device increased from 1400 W to 6000 W. The stall and disconnect behaviour of A/C Unit 3 is illustrated in Figure 9 for a sag of 0.4 pu. After disconnecting, the device attempts to restart after 6 seconds but fails, repeating this cycle about 4 to 5 times before successfully reconnecting. As this study focuses on transients, only 20 seconds of data were recorded, and the full reconnection process is not shown here.

Table 6: General Sag Test Result for Air Conditioner 3

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	Stall and Restart	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect
120	No Stall	No Stall	Stall and Restart	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect

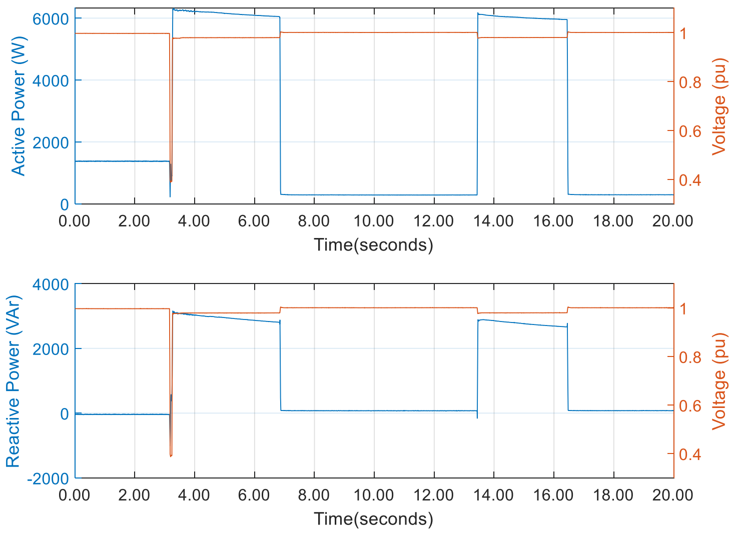

Figure 9: Response of Air Conditioner Unit 3 for 0.4 pu sag for 80ms

4.1.4. Unit 4

For Air Conditioner Unit 4, during general sag tests, the device experienced stall and disconnection for all sags at 0.6 pu and below. The power consumption of the device increased from the nominal 935 W to 3200 W during stall. *Table 7* provides a summary of the observations from the general sag tests. For the extreme sag test, the device stalled and disconnected. Following the Testing Procedure for all devices, the starting transient was recorded, and for A/C Unit 4, this is depicted in *Figure 10* (a). *Figure 10* (b) illustrates the response of A/C Unit 4, stall and disconnecting after a sag where the voltage dropped to 0.2 pu. It can be observed that the unit stalls for about 6 seconds before disconnecting, and it was unable to restart for any of the voltage restart tests as well.

Table 7: General Sag Test Result for Air Conditioner Unit 4

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect
120	No Stall	No Stall	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect

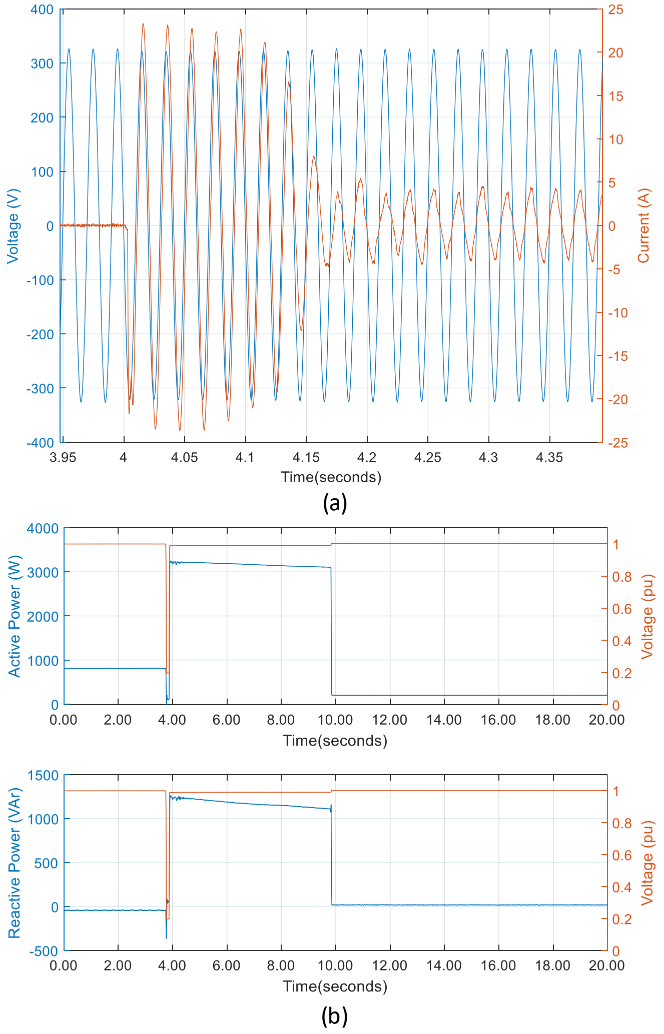

Figure 10: Results for Air Conditioner Unit 4 (a) Starting Transient (b) 0.2pu Sag for 120ms

4.1.5. Unit 5

The results obtained for A/C Unit 5 included stall and disconnection of the device for sags of 0.6 pu and lower, as depicted in *Table 8*. For the voltage restart test, the device was not able to restart for all three applied test cases. During the stall period, the device's power consumption increased from 900 W to 3.4 kW. Figure *11* shows the stall and restart of the device for a 0.6 sag for a duration of 120ms.

Table 8: General Sag Test Result for Air Conditioner Unit 5

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect
120	No Stall	No Stall	Stall and Restart	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect

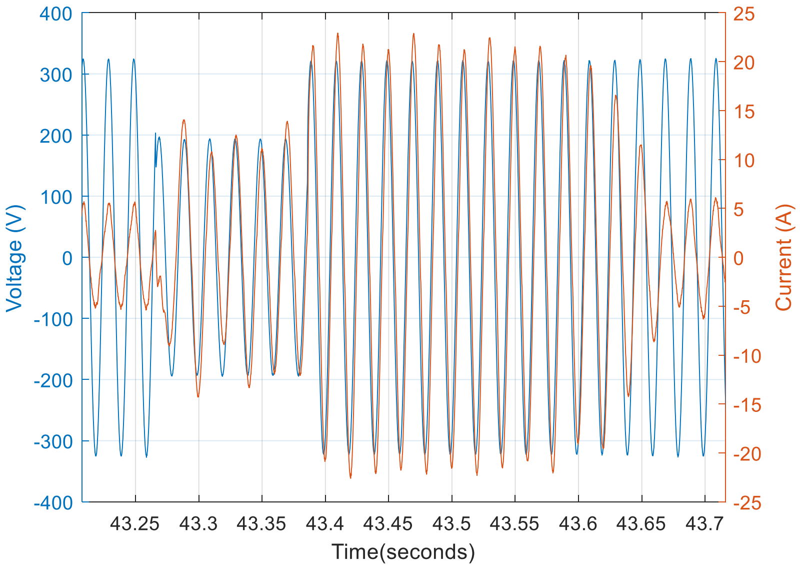

Figure 11 Response of Unit 5 for a 0.6 pu 120ms sag

4.1.6. Unit 6

This section summarises the outcomes of testing the window unit air conditioner. The results of the general sag tests are presented in *Table 9*, indicating that the unit predominantly stalls and restarts for sags of 0.5 pu and lower. However, for sags with a duration of 120 ms, A/C Unit 6 exhibited stall and disconnecting behaviour for the 0.3 pu and 0.2 pu sags. This stall and disconnect pattern persisted in the extreme sag test with a duration of 400 ms. For the voltage restart tests, the unit was unable to restart for any of the test magnitudes. During stall, the power consumption increased from 380 W to 1900 W. *Figure 12* (a) and *Figure 12* (b) depict the stall behaviour of restarting and disconnecting for 0.4 pu and 0.3 pu, respectively.

Table 9: General Sag Test Result for Air Conditioner Unit 6

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	Stall and Restart	Stall and Restart	Stall and Restart	Stall and Restart
120	No Stall	No Stall	No Stall	Stall and Restart	Stall and Restart	Stall and Disconnect	Stall and Disconnect

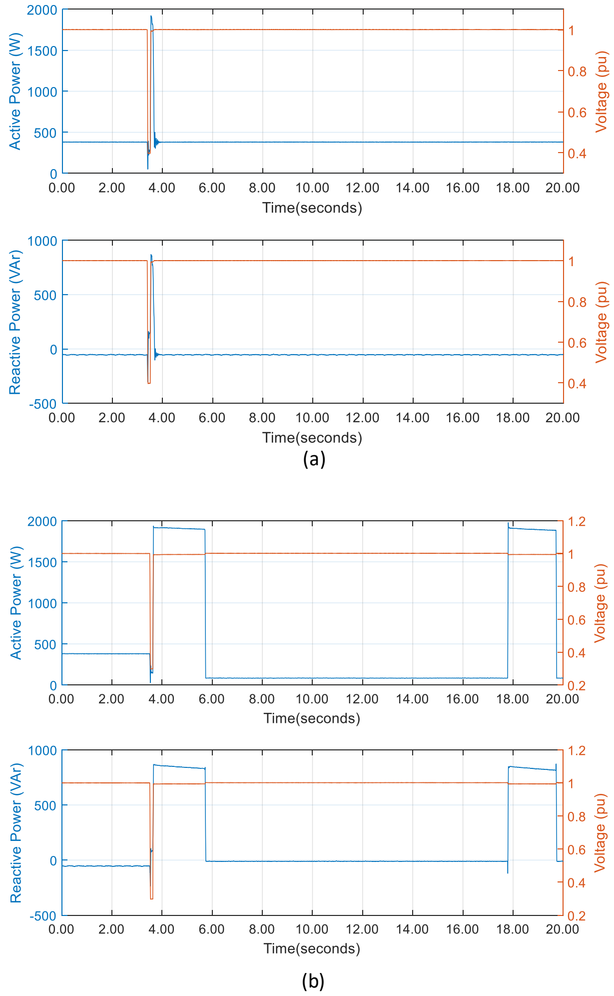

Figure 12: Response of A/C Unit 6 for a 120 ms Sag with retained voltage (a) 0.4pu (b) 0.3 pu

4.1.7. Summary of Air Conditioner Results

All the key results from the Air Conditioner Tests have been summarised in *Table 10*. Overall, it was found that three out of the six air conditioners exhibited stall and restart characteristics, while the other three exhibited stall and disconnect behaviour. A high-level observation is that the newer A/Cs mostly stalled and disconnected. Only two out of the six A/Cs were able to restart when the voltage was restored to 0.9 pu and none of the six A/Cs restarted for the 0.8 and 0.7 pu tests. The overall active power in a stall condition of the devices was found to be 4.32 pu.

Table 10: Summary of Air Conditioner Results

Load	Stall Behaviour	400ms Test	Restart Test	Stall to Nominal Power Ratio
AC 1	Stalls and Restarts for all sags below 0.5 and lower.	Stall and Disconnect	Stalls and restart for 0.9 pu.	4.97
AC 2	Stalls and Restarts for all sags below 0.6 and lower.	Stall and Disconnect	Stalls and restart for 0.9 pu.	4.44
AC 3	Stalls and Disconnects for most sags below 0.6 and lower.	Stall and Disconnect	Stalls and disconnects for all.	4.29
AC 4	Stalls and Disconnects for most sags below 0.5 and lower.	Stall and Disconnect	Stalls and disconnects for all.	3.42
AC 5	Stalls and Disconnects for all sags below 0.6 and lower.	Stall and Disconnect	Stalls and disconnects for all.	3.78
AC 6	Stalls and Restarts for most sags below 0.5 and lower.	Stall and Disconnect	Stalls and disconnects for all	5

4.2. Refrigerators & Freezers

4.2.1. Refrigerator Unit 1

Unit 1 is a brand-new non-inverter top-mount refrigerator. The results of the general sag tests are summarised in Table 11. It is observed that the device only stalled for the 0.2 pu sag test with a duration of 120 ms. For all other tests, the device experiences transient spikes in P and Q, likely from the inrush current of the motor. Figure 13 (a) illustrates the stall and restart property of the device for the specified sag, and Figure 13 (b) demonstrates that for the extreme sag, the device stalled and disconnected (not shown in the figure as it was recorded for 20 s). This refrigerator was able to restart after stall for the voltage restart test where the voltage was restored to 0.8 pu and 0.9 pu. In terms of the device starting, it had a 2.5-second delay. During the stall period, the device's power consumption increased from 90 W to 900 W

Table 11: General Sag Test Result for Refrigerator Unit 1

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall
120	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	Stall and Restart

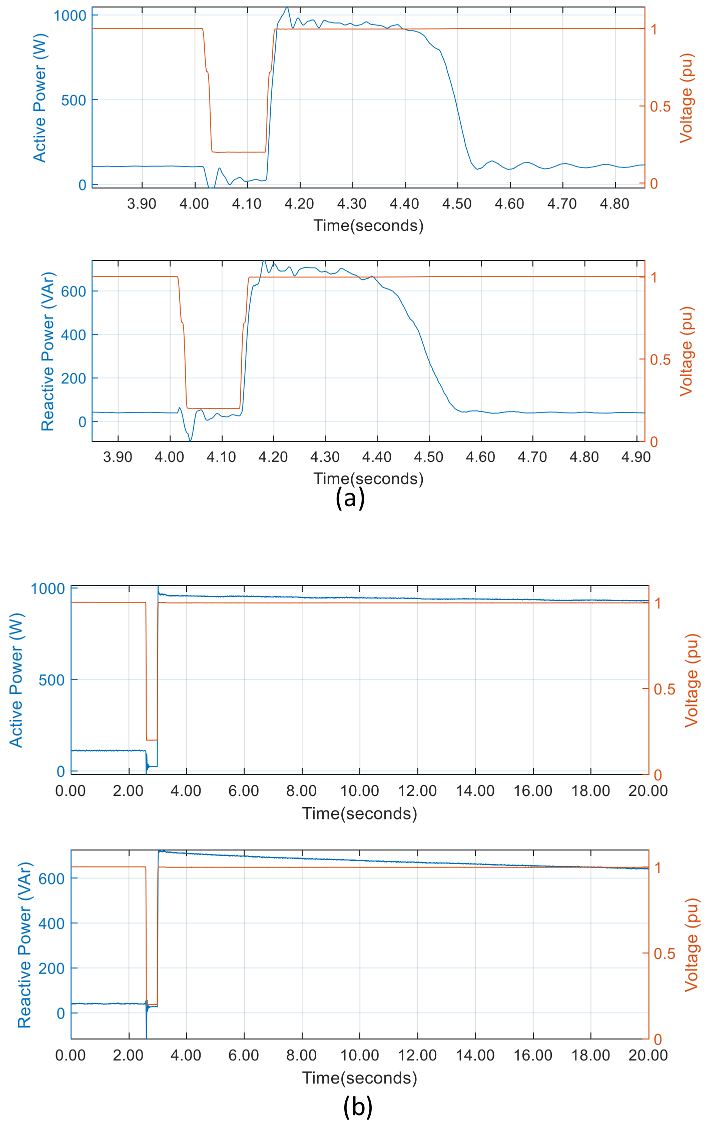

Figure 13: Results for Refrigerator Unit 1 (a) Stall and Restart for 0.2 pu Sag for 120ms (b) Extreme Sag Test Response

4.2.2. Refrigerator Unit 2

Unit 2 is an older model top-mount refrigerator. The results from the general sag tests, as demonstrated in

Table *12*, show that it only stalls and disconnects for the 120 ms duration sag test when the retained voltage was 0.2 pu. The response recorded is also shown in Figure 14. For the voltage restart test, this device stalled and disconnected for all three tests. The stall power consumed by the device was 1000 W compared to the nominal 160 W. In terms of the general starting of the refrigerator, there were no delays recorded.

Table 12: General Sag Test Result for Refrigerator Unit 2

Duration (ms)	Sag Voltage (pu)						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall
120	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	Stall and Disconnect

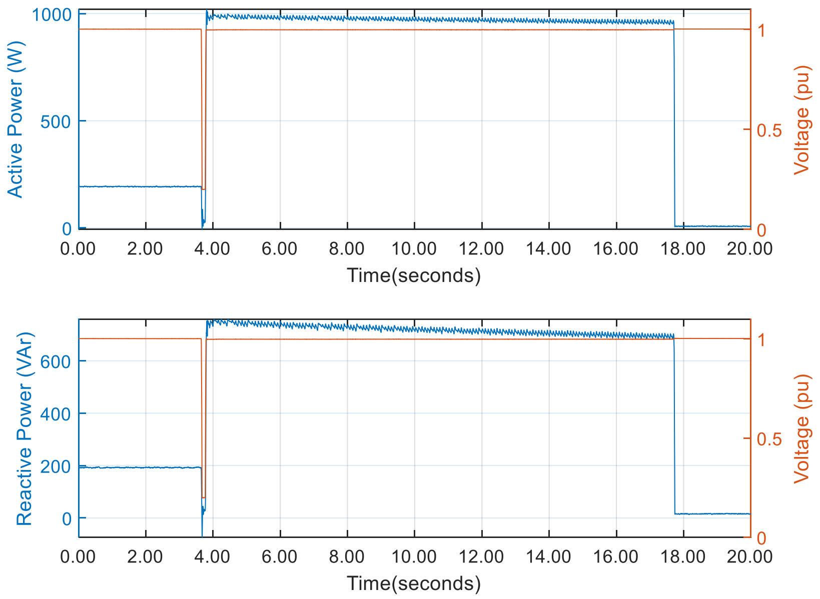

Figure 14: Stall and Disconnect Results for Refrigerator Unit 2

4.2.3. Refrigerator Unit 3

This refrigerator is one of two 2 door refrigerators evaluated in this report. This appliance demonstrated interesting power on transient behaviour as shown in Figure 15(a). It can be seen that the appliance took about 10 seconds to start consuming nominal power. For all the general sags the device was able to continue its normal operation after an inrush current. The sag test results are summarized in Table 13. The inrush current for the 120ms duration sag where the voltage is reduced to 0.2 pu is shown in Figure 15 (b). The appliance stalls and disconnects for the extreme sag test with 400ms duration.

Table 13: General Sag Test Result for Refrigerator Unit 3

Duration (ms)	Sag Voltage (pu)						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall
120	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall

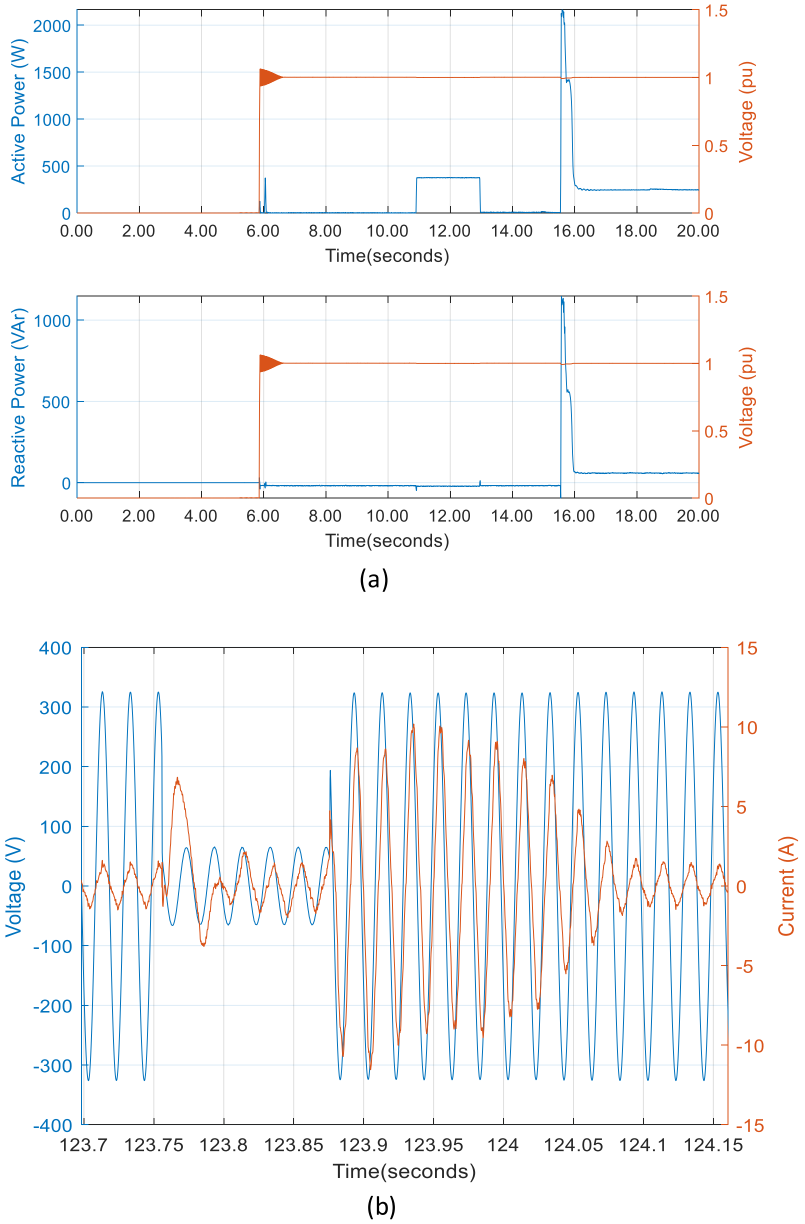

Figure 15: Results for Refrigerator Unit 3 (a) Device turn on behaviour (b) Inrush current for 0.2 pu sag for 120ms

4.2.4. Refrigerator Unit 4

Refrigerator Unit 4 is an older model top-mount unit. Unlike all the other devices tested in this project, this device did not stall for any of the tests it was subjected to. Out of the 25 appliances tested, this device was the only one that successfully rode through the extreme sag test, as shown in Figure 16. The device's nominal power consumption was 100 W and +90 VAr.

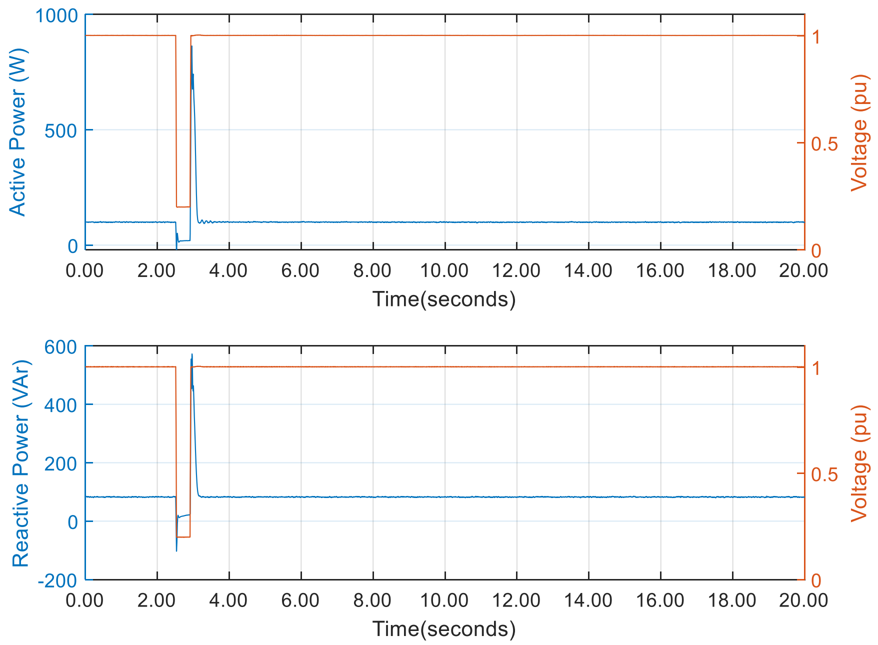

Figure 16: Refrigerator Unit 4 riding through extreme sag test

4.2.5. Refrigerator Unit 5

Refrigerator Unit 5 is a common branded, older-style refrigerator. For the general sag tests, the device rides through all the general sags. The results from the general sag tests are summarized in Table 14. The device stalled and disconnected for the extreme sag test, as shown in Figure 17 (a), and Refrigerator Unit 5 was able to restart after stall when the voltage was restored to 0.9 pu for the voltage restart tests, as shown in Figure 17 (b). During normal operation, the nominal power consumption was 160 W, which increased to 700 W during stall.

Table 14: General Sag Test Result for Refrigerator Unit 5

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall
120	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall

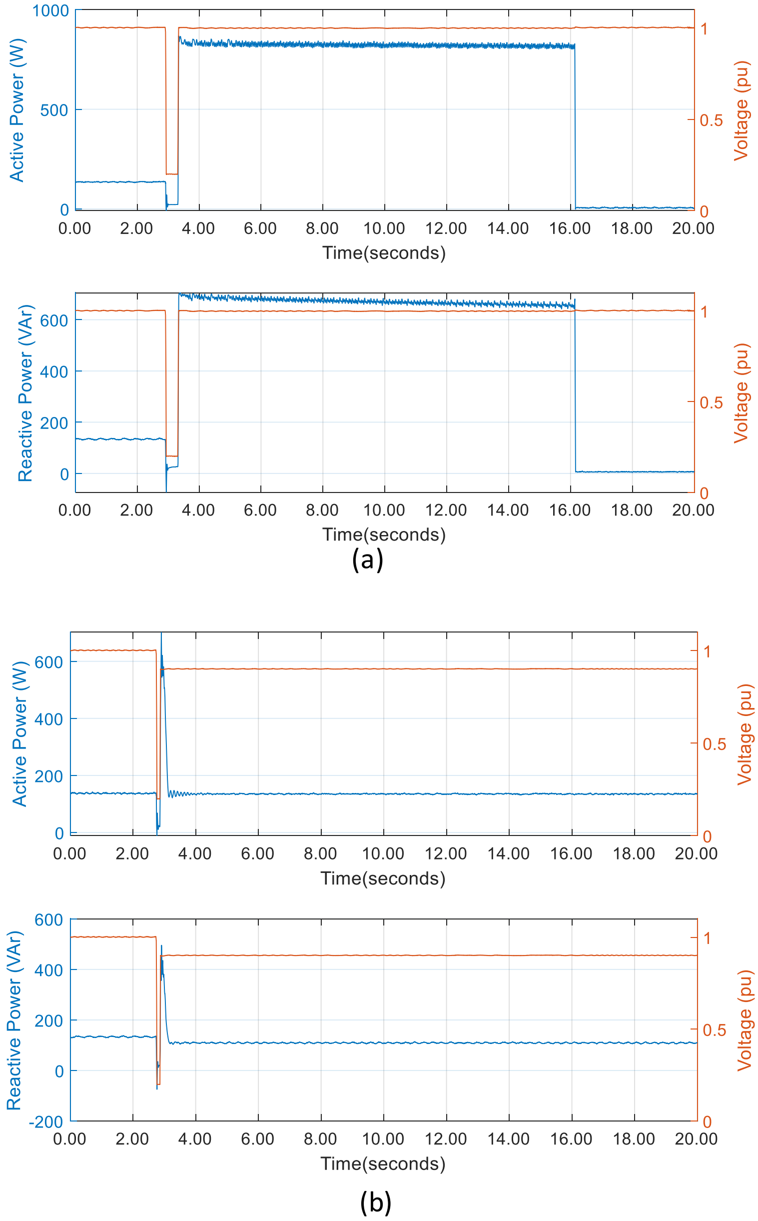

Figure 17: Results for Refrigerator Unit 5 (a) Extreme Sag Test (b) Voltage Restart Result

4.2.6. Freezer Unit 1

Freezer Unit 1 is an older model freezer. The results of the general sag tests are shown in Table 15, indicating that the appliance was able to ride through all the general sag tests without stalling and only exhibited inrush currents. During stall, the power consumption increased from 130 W to 580 W. The response from the 120 ms duration 0.2 pu sag depicted in *Figure 18* (a). This freezer was able to restart when the voltage was restored to 0.9 pu, as shown in *Figure 18* (b). However, for the extreme sag test, the freezer stalled and disconnected.

Table 15 General Sag Test Results Freezer 1

Duration (ms)	Sag Voltage (pu)						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall
120	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall	No Stall

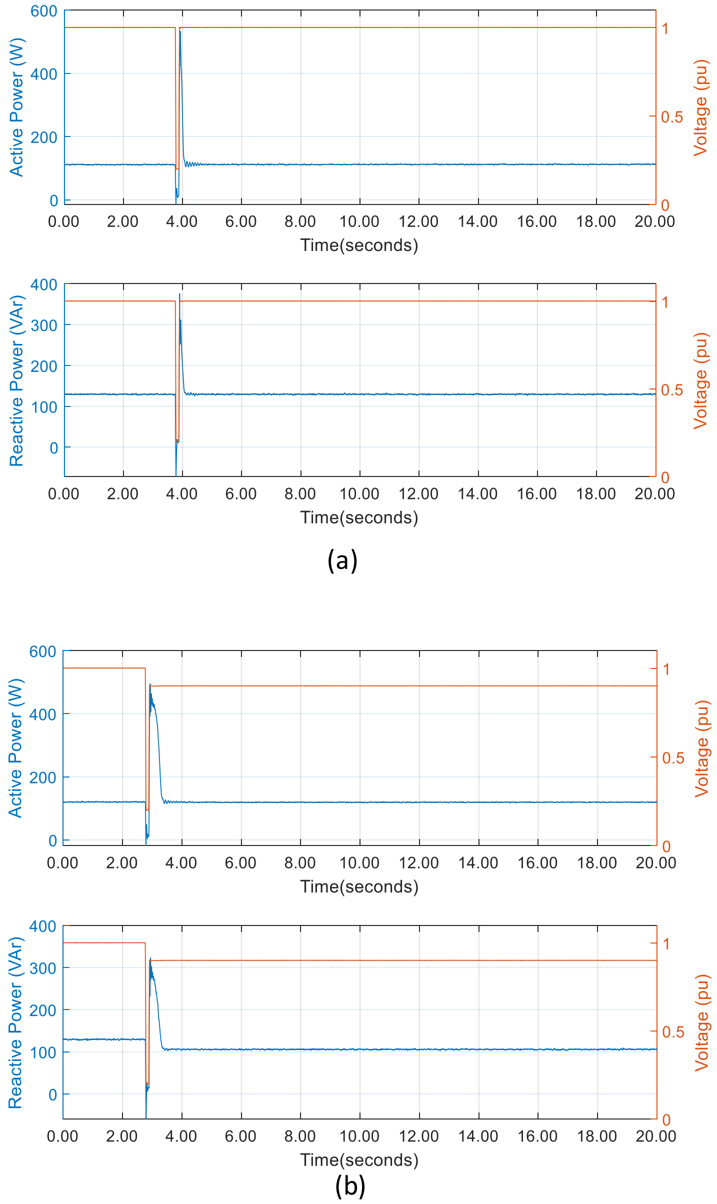

Figure 18: Freezer Unit 1 Results (a) Sag for 120ms at 0.2 pu (b) Voltage Restored to 0.9 pu

4.2.7. Freezer Unit 2

Freezer Unit 2 is a brand-new device. In response to the general sag tests, where the retained voltage was lower than 0.4 pu, the device stalled and disconnected. The summary of the general sag test results is shown in Table 16. For an 80 ms sag with voltage dropping to 0.4 and 0.3 pu, both the restart and disconnect responses of the device are shown in *Figure 19* (a) and *Figure 19* (b), respectively. Freezer Unit 2 also disconnected for the extreme sag test applied. The device was not able to restart for any of the voltage restart tests.

Table 16: General Sag Test Results for Freezer Unit 2

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	No Stall	Stall and Restart	Stall and Disconnect	Stall and Disconnect
120	No Stall	No Stall	No Stall	No Stall	Stall and Disconnect	Stall and Disconnect	Stall and Disconnect

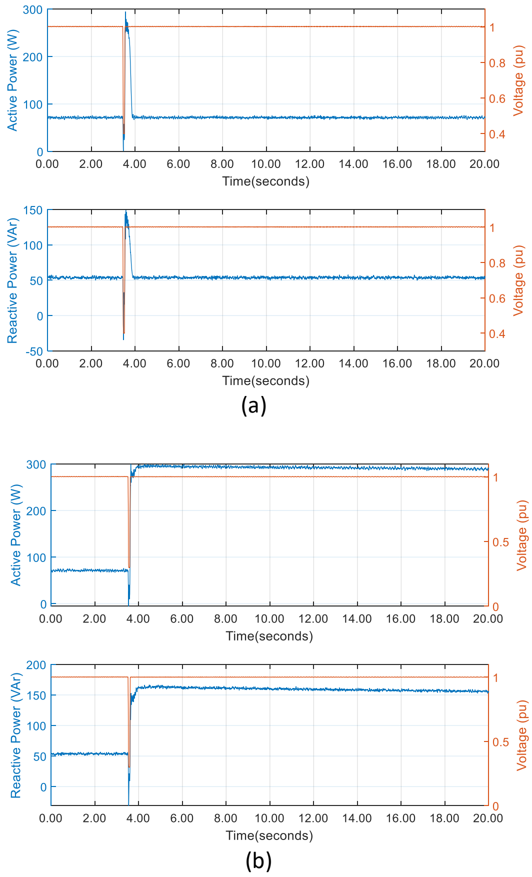

Figure 19: Freezer Unit 2 results for General Sag Test for 80 ms with retained voltage (a) 0.4 pu (b) 0.3 pu

4.2.8. Summary of Results for Refrigerators

Table 17 presents a comprehensive overview of key responses for the tested refrigerators and freezers. It is observed that regular refrigerators, in general, did not exhibit stall characteristics. Out of the five loads tested, only two demonstrated stall behaviour when subjected to a sag with a retained voltage of 0.2 pu. This observation challenges their classification within the Motor D category in the CMPLDW model. To demonstrate this, the active aggregated responses for the 6 ACs and 7 fridge/freezer responses for a 0.4 pu voltage sag, 80 ms duration, are shown in Figure 19. It can be clearly seen that while the blue graph of A/Cs demonstrates the response expected from a Motor D load, the fridges mostly ride through the faults. In the test results, these fridges and freezers demonstrate a significant inrush current (and subsequently increased active and reactive power) for a short duration immediately following the fault as the motor returns to nominal speed. This behaviour is best represented by the Motor A component of the CMPLDW model, as Motor A exhibits the highest inrush current.

Therefore, based on these test results, it is recommended that refrigerators be reclassified to the Motor A category. This category is specifically intended to represent refrigeration systems, albeit in three-phase systems. This proposed reclassification aligns more accurately with the observed behaviour during voltage sag tests. As for freezers, they exhibited similar behaviour to the other refrigerators where stall behaviour was only observed in the most severe sags of 0.2 pu. This resulted in the refrigerators also being classified in the Motor A category.

Table 17: Summary of Refrigerator and Freezer Tests

Load	General Stall Test Key Observations	400ms Test	Restart Test	General Observations
Unit 1	Stalls and restarts for 0.2 sag.	Stall and Disconnect	Stalls and restarts for 0.9 and 0.8 pu.	Generally, no stall except for very deep sags. Power increases from nominal 95 W to 900W. There is about a 2.5 second delay when starting.
Unit 2	Stalls and disconnects for 0.2 sag 120ms.	Stall and Disconnect	Stalls and disconnects for all.	Generally, no stalls except 0.2 pu 120ms. Power increases from nominal 160 W to 1000W. No delay in starting
Unit 3	No stall	Stall and Disconnect	Stalls and restarts for 0.9 pu.	Generally, no stalls. Power increases from nominal 190 W to 580W. There is about a 10 second delay when starting.
Unit 4	No stall	Ride Through	Rides through for 0.9, 0.8 and 0.7 pu restarts.	Generally, only fridge to ride through all tests. Nominal power of 100W and +90VAr
Unit 5	No stall	Stall and Disconnect	Stalls and restarts for 0.9 pu.	Generally, no stall. Power increases from nominal 160 W to 700W
Freezer 1	No stall	Stall and Disconnect	Stalls and restarts for 0.9 pu.	Generally, no stall. Power increases from nominal 130 W to 580W during the 400ms test.
Freezer 2	Stalls and disconnects for 0.3 sag and lower.	Stall and Disconnect	Stalls and disconnects for all.	Generally, stall and disconnects for the deep sags only. Power increases from nominal 70 W to 310W.

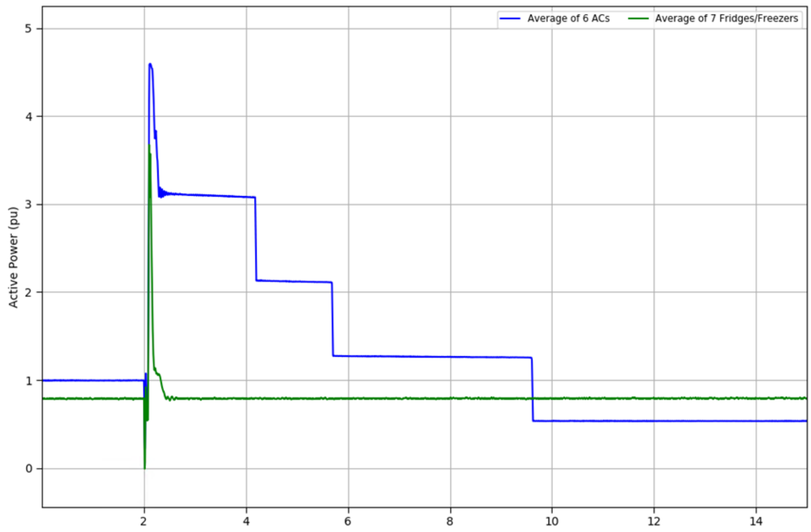

Figure 20: Aggregated response of ACs and Fridges for a 0.4 pu sag for a duration of 80ms

4.3. Dryer

The dryer, which has been tested is an older-styled model. This appliance displayed distinct behaviour compared to the other devices. Unlike the other appliances, the dryer disconnected without stall or exhibiting any inrush characteristics. The results from the general sag tests are presented in *Table 18*. It was observed that the manual turn-off button of the dryer tripped for any sags where the voltage dropped below 0.6 pu. Following disconnection, the dryer had to be manually turned back on. The device responded similarly in all other voltage restart tests and the extreme sag test.

Table 18: Dryer General Sag Results

Duration (ms)	**Sag Voltage (pu)**						
	0.8	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**
80	No Stall	No Stall	No Stall	Disconnect	Disconnect	Disconnect	Disconnect
120	No Stall	No Stall	No Stall	Disconnect	Disconnect	Disconnect	Disconnect

5. Updates to the CMPLDW Parameters

Following the CMPLDW model update in November 2022, EPRI, the organization overseeing international load/DER models, made adjustments to the default Motor D settings. These outcomes of the testing presented in this report suggest that the parameters should be subject to further refinement. The proposed changes to Motor D parameters are outlined in Table XVIII below, with a focus on aligning parameters with the Australian load composition. The updated response of the Motor D model in PSSE is depicted in Figures 19 and 20 for real and reactive power response respectively. The updated response, represented by green lines, closely matches the average response of the Air Conditioner sag test results. The disturbance chosen for this plot was a 0.2 pu depth sag for a duration of 80 ms.

Table 19: Proposed parameter changes for Motor D loads

Motor D Parameters	Description	Original	EPRI Latest	AEMO Updated 2024
compPF	power factor at 1 pu voltage	0.71	0.98	1
Vstall	Stall Voltage (pu)	0.49	0.45	0.6
Rstall	Stall Resistance (pu)	0.143	0.1	0.17
Xstall	Stall Reactance (pu)	0.143	0.1	0.07
Frst	Fraction Capable of restart (%)	0.1	0.2	0.55
Vrst	Voltage for Restart after stall (pu)	0.95	0.95	0.9
Tth	Heating time constant (s)	15	10	16

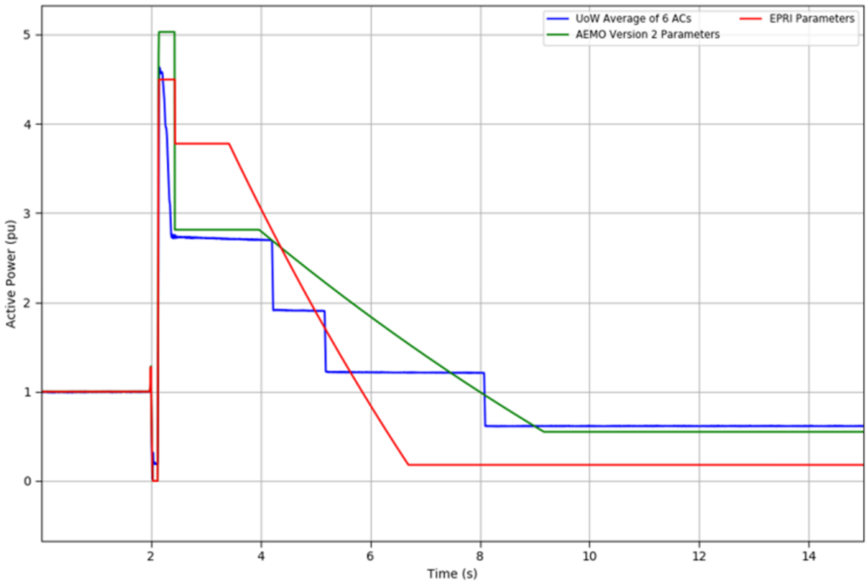

Figure 21: Active Power Response of Motor D with updated parameters

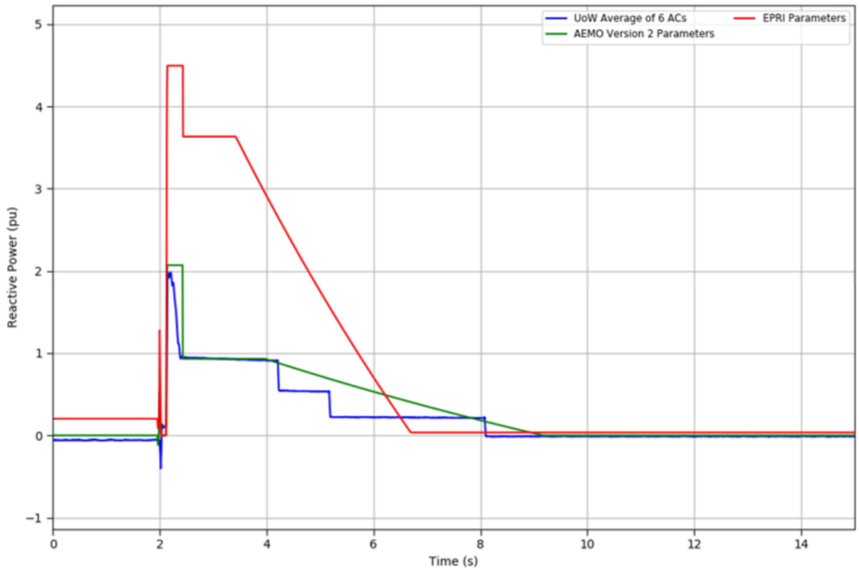

Figure 22: Reactive Power Response of Motor D with updated parameters

6. Conclusion

The experimental testing carried out in this project focussed on characterising the dynamic response of Motor D type loads within the Composite Load Model to voltage sags, tailored for the Australian context. This investigation aimed to aid the Australian Energy Market Operator (AEMO) in predicting power reduction and system stability issues resulting from load behaviour during transient power system events. Motor D, representing 1P compressors in residential air-conditioning loads, exhibited characteristics prone to stall, particularly under sag disturbances. Common in Australian residential and light commercial refrigerator compressor motors, 15 appliances containing this type of motor – including air conditioners, refrigerators, freezers, washing machines, and dryers – were exposed to voltage sag disturbances of varying depth and duration in order to better understand stall behaviour.

The primary objectives were to refine Motor D tuning parameters and assess any need for modification in the Australian context. Results revealed that most refrigerators either stalled at more severe voltage sags (below 0.2 pu) or did not stall at all, challenging their classification within the Motor D category. Consequently, it is recommended that refrigerators and freezers be reclassified as a Motor A load type. These adjustments to Motor D parameters enhance its accuracy and relevance for use in power system studies involving the Australian grid.

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