# Composite Load Model Project

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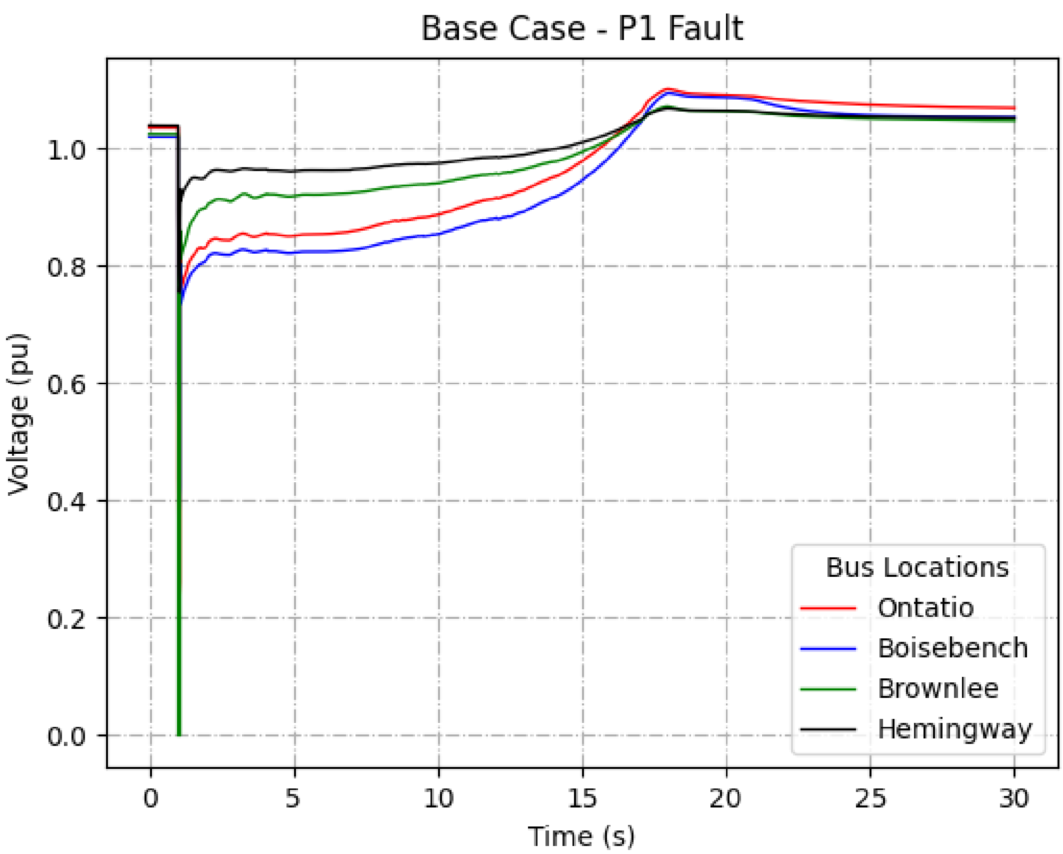
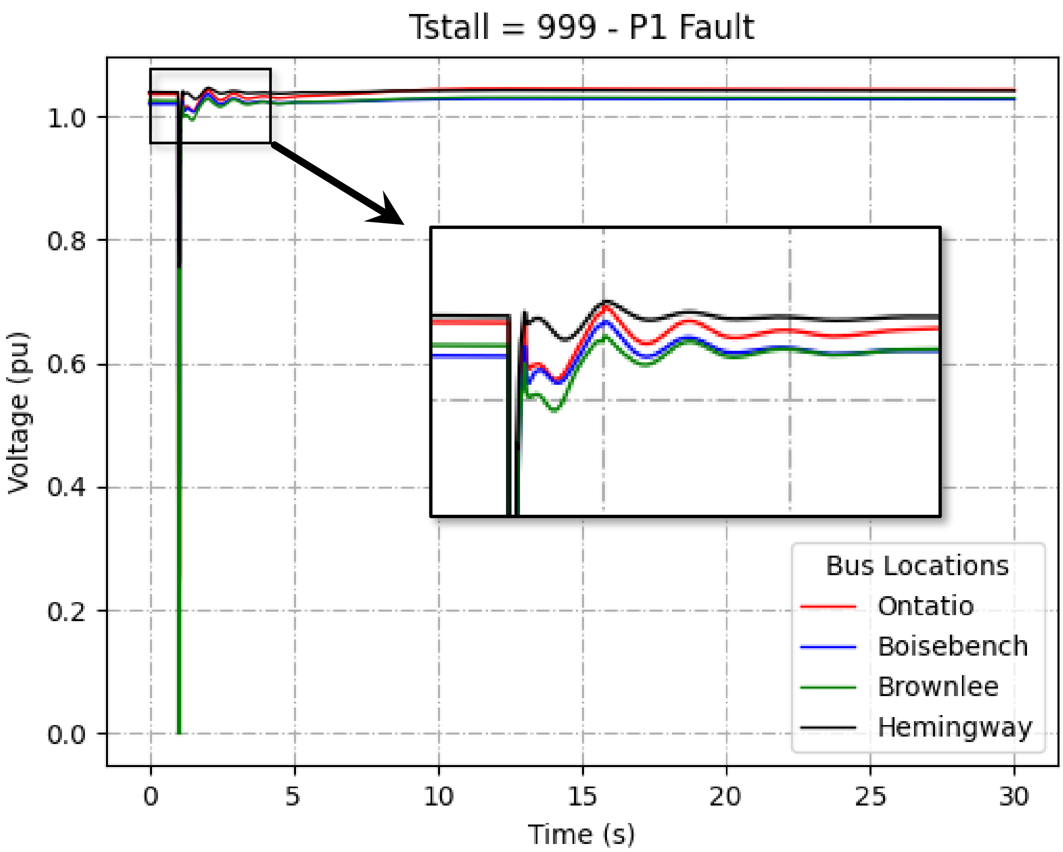
## Problem

While running some fault analysis simulations on Idaho Power's GI cases, the systems planning team has run into Voltage Recovery Violations. These violations can be seen when examining the transient stability data. When a plot of the bus voltage is generated, an FIDVR (Fault Induced Delayed Voltage Recovery) event is seen as the source of the violation.




From the plot above it is clear to see through the bus voltage that the voltage is failing to recover initially after the line fault, and then after 5-10s the voltage begins to ramp back up to nominal before it begins to finally reach stability again.

The cause of this FIDVR is believed to be caused by the stalling of single-phase motors, commonly used in residential Air-conditioning compressors. Air Conditioner compressors are highly sensitive to voltage sag due to their low inertia, making them prone to stalling under fault conditions. These single-phase motors are accounted for in the WECC Composite Load Model with the 'MotorD' parameter.




The current solution to this FIDVR violation is to change the stall time (Tstall) of the motorD component to a large number such as 999 to remove all the single-phase motor stalling from the simulation. This is a flawed approach as single-phase motor stalling is a very real concern in the protection of Idaho Power's grid. Thus, it is important to find a model that can accurately simulate these FDIVR events.

## Background

This section will provide some technical background on how the load models function and why residential air conditioners can cause FIDVR on the grid.

### Load Modeling Process

When compared to the high detail of the generator models, the load models are simple and make many assumptions and estimations. This lack of detail has not been much of a concern in the past decades due to the relatively simple loads seen in the early 2000s. However, with the increasing adoption of new technologies in the residential sector such as solar panels, heat pumps and smart thermostats, there is a growing demand for more complex and detailed load models.

The current load modeling system (CMPLDW) works by breaking down loads into several load components, 4 motor types, powered electronics, and linear resistive loads. Each load component has several different parameters that can be edited using the Load Modeling Tool. The default parameter values for these model components are set by the FERC and WECC load modeling teams. Once these components are defined, the load modeling tool will determine the appropriate proportions of these components for a given load based off some generalized assumptions of that loads composition such as a residential or commercial load.

The resulting composite load model generated by the LMDT program can then be imported into PowerWorld where those values are imported into the load model being used and used to run transient stability simulations. With this basic breakdown of the modeling process for loads, two different methods are available to alter how the loads are modeled. Either, changes can be made to the parameterization of loads, or the equations used in simulating these parameter values can be changed.

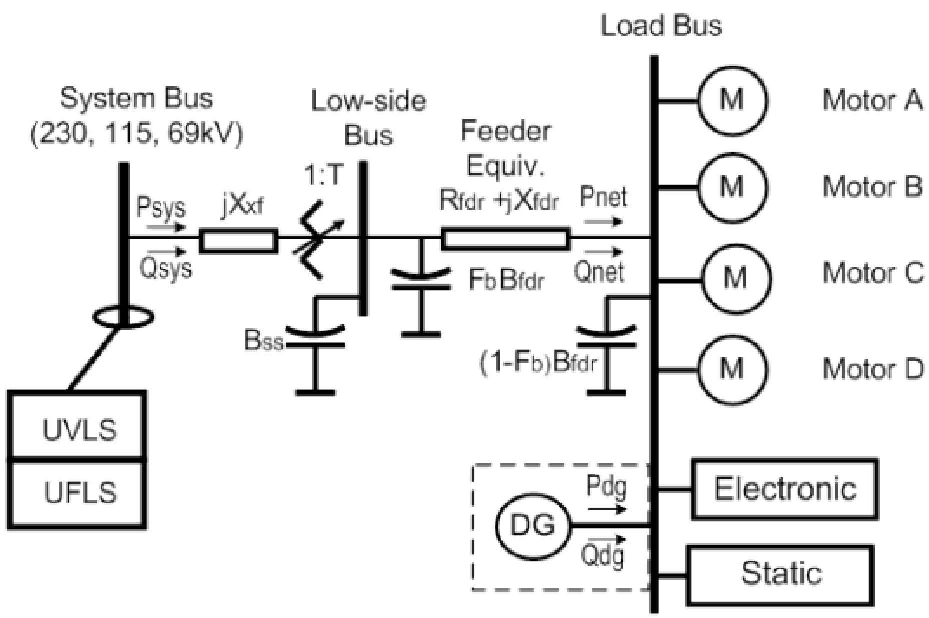



**Figure 35: Composite Load Model Structure (CMPLDW/CMLD)**

## Understanding the Load Modeling Tool

Idaho Power's Load Models are generated through the LMDT (Load Model Data Tool) created by PNNL. This is a tool that allows us to "generate composite load model parameters taking into account climate zones, season, operating hour and feeder type" **[1]**. All this data is provided and maintained by WECC and NERC.

The LMDT software uses the following structure when defining loads:

**LMDT Structure**

**Climate Zone:**
- **NWI: Northwest Interior**
- **RMN: Rocky Mountain North**
- **HID: High Desert**
- **NVW: Northwest Valley**
- **…**

**Feeder Type:**
- **RES: Residential**
- **COM: Commercial**
- **MIX: Mixed**
- **RAG: Rural/Agriculture**

**Load Type:**
- **Res: Residential**
- **Com: Commercial**
- **Ind: Industrial**
- **Agr: Agriculture**
- **Data: Data Centers***
- **Service: Traffic Lights etc.***

**Load Source:**
- **Heating**
- **Cooling**
- **Refrig**
- **Etc.**

**Load Component:**
- **Motor A**
- **Motor B**
- **Motor C**
- **Motor D**
- **PE**
- **Res**

**Motor Data:**
- **LF: Load factor**
- **Frst: Fraction Restart**
- **Vrst: Voltage Restart**
- **Tstall: Time Stall Delay**
- **Etc.**

The specifics of how every part of the load modeling tool functions is far too long and complex to provide a full breakdown in this document. However, I have created a user guide as well as included some more detailed documentation of how the different components are calculated. This is all available in a folder located in the same location as the LMDT program file.

The areas of this tool we will be looking at for this project will fall under the Residential Load type branch of the structure shown above, as well as the motor data component. This is the section of the tool that will give us the most control over the motorD component, which is what we determined to be the source of the FIDVR.

## Composite Load Model and PowerWorld

The composite load model that is generated from with the LMDT only supplies the parameter values of the loads. PowerWorld is where the equations used to simulate the loads are located. PowerWorld defaults to the current WECC approved load model (CMPLDW) however, it does have the ability to use alternative load models.

The way that all the different load models are implemented is rather confusing and would be too much to cover in this report. However, I will be including a separate guide on how to implement the new modular load modeling system. The new load modeling system that this guide will cover is one of the most recent additions to PowerWorld and allows for the Load Models to be broken up into several different load model components, like how the LMDT program handles the loads.

This new modular approach that PowerWorld has implemented will allow us to take the same composite load model data created with the LMDT program and convert it to this new system. Once converted to this new 'CompLoad' system, several alternative load models, that have been created to replace the current approach to modeling the MotorD component of the loads, can be implemented.

## Residential AC's and FIDVR

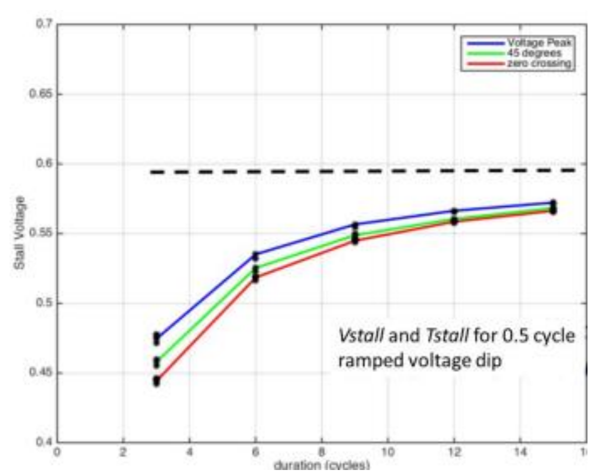
One of the largest load sources during peak hours comes from HVAC systems connected to the grid. Most of the load from these systems comes from the compressor motors. In a commercial or industrial setting this comes in the form of large 3-phase induction motors with low inertia and constant torque, defined by 'MotorA' in WECC load models **[2]**. Under/over-voltage protections come standard in most of these systems in the form of contactors that trip open when voltage exceeds the operating limits, and trip closed when a nominal voltage level is reached. These protections prevent the stalling characteristics that have been the cause of the FIDVR in simulation.

Residential HVAC systems on the other hand rely are forced to rely on single-phase compressor motors due to most residential units only being served by a single-phase line. These single-phase motors are far more problematic for the reliability of the power grid than their 3-phase counterparts. They contain the same contactor protection systems that the 3-phase motors have, however due to their single-phase nature, they have a lot harder time restarting when the contactors trip closed. This inability to restart after a voltage drop leads to prolonged stalling as the protection systems on most residential AC units are as sophisticated as something that may be seen in a commercial system.

The stalling aspect of single-phase motors has been understood for several decades. Due to the single-phase nature of the motor, when the rotor is at a standstill, the two magnetic fields present in the motor will be equal and opposite, preventing the rotor from spinning no matter how much power is sent through the coils. This means that in low inertia systems, a relatively short drop in voltage can lead to the rotor coming to a stop and putting it into a stall condition. Upon entering a stall, the motor will begin to draw more current from the grid in an attempt to recover. However due to the magnetic fields cancelling each other out, no amount of current will be able to get the motor spinning again. This ramping current draw will then continue until the thermal protection is tripped. Due to the nature of a consumer product, the sensitivity of this protection system is not very sensitive and may take up to 20s to step in and take the stalled motor off the grid.

Since this phenomenon has been known for decades, it has been accounted for in the load models for just about as long as loads have been modeled. This is to say that the current load models have no issue accurately modeling the stalling of these motors. However, what they do have trouble accurately modeling is how much of this load will actually enter a stall condition. Currently the models aggregate all of the motorD loads on a given bus into one load, and when stalling conditions are detected on that bus, it will be modeled as if every single air conditioner on that bus has stalled. In reality, it is far less binary.

Research has shown that the stall conditions vary greatly between residential AC units, and the tripping for any given is time dependent rather than binary **[2]**. This means that the current binary models are far too pessimistic and simulate an almost impossible scenario. In order to more accurately model single-phase motor stalling, a new approach needs to be taken that allows for a partial stalling of the total motorD load. This is the method that many of the new models attempt to implement into their calculations.



This is a relatively recent development so most models that attempt to simulate this new process are still considered experimental or a beta version. This report will test several of these new models to see which one works the best, however, it will be up to WECC to decide which model is the most accurate. So, the findings and suggestions made in this report may not align with what WECC decides to implement in the future.

## Testing Method

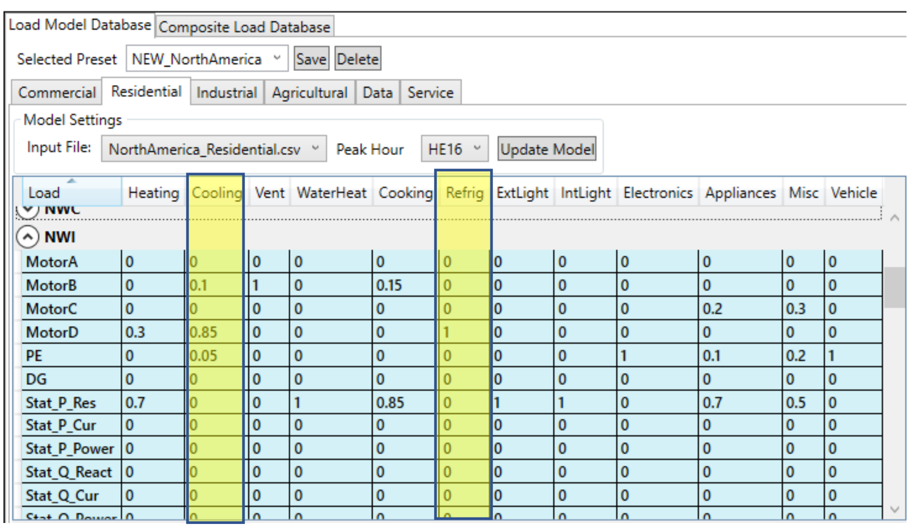
This section will cover the many different approaches that were made, and why each approach was chosen. There are two different ways that changing the load models can be approached, changing the load parameter values, or changing the load model equations being used. Both these approaches will have a direct effect on how stalling is modeled, however they do so in very different ways. Changing the parameters for the load models will simply change how much load is being modeled, while changing the load model equations changed how the loads are actually modeled. The benefits of each approach will be discussed in the conclusion of the report.

## Parameter Manipulation

Changing of the parameter values of the composite load models is done through the LMDT program. There are many different ways that the composite of the load models can be manipulated, from changing the amount of MotorD loads to the composition of the MotorD component itself.

### Test 1 – Proportion of MotorD

This first approach to try and fix the FIDVR present in simulations was to change the proportion of the motorD component present in the cooling and refrigeration of residential loads. This was done by altering the load component composition of the Cooling and Refrigeration load sources for the NWI climate zone.




| Load | Heating | Cooling | Vent | WaterHeat | Cooking | Refrig | ExtLight | IntLight | Electronics | Appliances | Misc | Vehicle |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MotorA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MotorB | 0 | 0.1 | 1 | 0 | 0.15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MotorC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.3 | 0 |
| MotorD | 0.3 | 0.85 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| PE | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0.1 | 0.2 | 1 |
| DG | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stat_P_Res | 0.7 | 0 | 0 | 1 | 0.85 | 0 | 1 | 1 | 0 | 0.7 | 0.5 | 0 |
| Stat_P_Cur | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stat_P_Power | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stat_Q_React | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stat_Q_Cur | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Four different tests were done by changing the values in the highlighted columns of the figure above, for 0%, 25%, 50%, and 75% of the motorD component. The existing motorD proportion will be split among MotorA and MotorC in an amount similar to how commercial cooling and refrigeration loads are modeled.

Knowing that the FIDVR present in the simulations was caused by excessive stalling being modeled, this approach tried to limit the amount of load considered to be from a motorD source in order to reduce its effect on the overall modeling.

**Test 2 – AC Motor Model Parameters**

The current load model in use (CMPLDW) aggregates multiple different loads, each having its own set of parameters that can be modified through the LMDT program. One of these loads' models single phase AC motors and has its own set of parameters, all of which can be found in **Appendix A**.

Based off knowing the main cause of FIDVR comes from the stalling of these single-phase motors, the parameters dealing with stalling can be targeted for testing. The parameters chosen to be tested are:

**Tstall –** Time undervoltage before stalling occurs (s)

**Frst –** Fraction of load that can restart after stalling

**Vrst –** Voltage level where restarting can begin (V pu)

**Trst** – Time to restart (s)

## Alternate Load Models

Thanks to recent updates to the PowerWorld software, it is possible to easily convert to new load models. With the addition of the 'CompLoad' feature in Version 20, the current composite load models can be separated into their different components. This tool has considerable potential to provide far more detailed load modeling in the future. What it will allow for this report is to implement new model components to replace the current model for motorD loads.

**Test 3 – INDMOT1P**

The INDMOT1P load model takes a phasor modeling approach to model single-phase A/C motors. This allows for the aggregation of 1000s of different single-phase motors into a single equation. This model does not do anything specific to model stalling, however its use may still be useful for testing and comparison purposes. The base values provided by PowerWorld **[3]** will be used for testing.

### Test 4 – MOTORC

The MOTORC model is currently an experimental model for aggregating single-phase air conditioner compressor motors being created by PSLF at the request of WECC. It effectively consists of 2 parts, the first being the INDMOT1P model (excluding the saturation and a simplified version of mechanical torque). The second part has the same relay logic as the traditional LD1PAC model **[4]**.

The second part of the model is the important part of this new model. This LD1PAC logic enables the modeling of the reconnection of some of these stalled AC motors to the grid, limiting the amount of stalling being modeled on the grid. This model also accounts for the thermal protection systems of these AC units tripping the units offline after they have been stalled for a certain amount of time.

This model was tested a number of times using different parameters, the full documentation of each test will be available in **Appendix A**.

### Test 5 – INDMOT1P_PTR

Similar to the MOTORC model, the PTR model builds off the INDMOT1P, and adds onto it a set of equations that models the tripping and reconnection of stalled motors **[5]**. The PTR model differs from the MOTORC model by implementing a time dependent, progressive tripping and reconnection system. In this system, the number of stalled motors that trip offline begins increasing once the voltage drops below a set $\mathbf{V_{1off}}$ value and will continue to increase at a fixed rate as long as the voltage is below this value. The rate that the load trips offline will remain constant unless the voltage drops below the set $\mathbf{V_{td}}$ value, in which it will begin to trip offline at an increasing rate until the final $\mathbf{V_{2off}}$ value I passed.

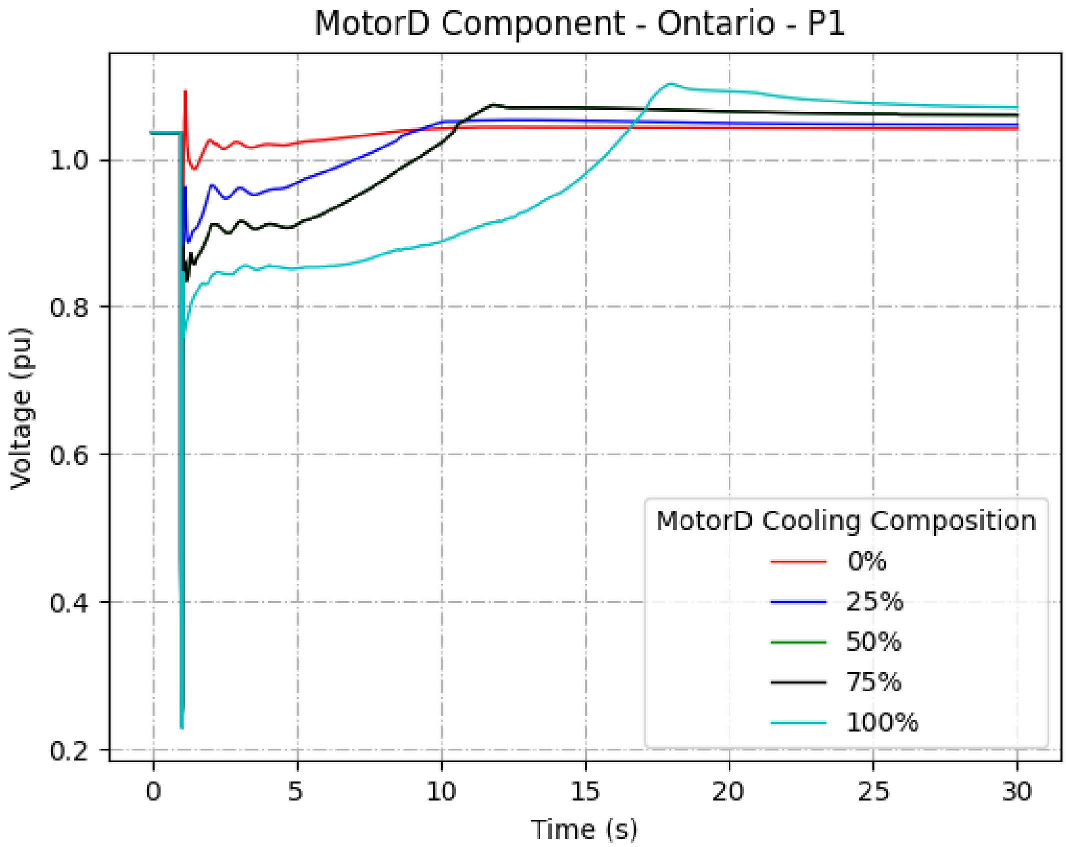
Once the voltage begins to recover, the model will enter the reconnection phase. In this phase if the voltage is above $\mathbf{V_{2on}}$ the AC motors that had previously tripped offline will begin to reconnect at a constant rate until the voltage climbs back above the $\mathbf{V_{1on}}$ voltage value.

This model has many different settings that can be changed and tested. A detailed documentation of all the different settings tested can be found in **Appendix A**.

## Results

### Test 1 –

Altering the presence of the MotorD component in the load models has a direct effect on the FIDVR event seen in fault simulations. The effect of lowering the proportion of the motorD component can be seen in the figure below, where the results from running the same simulation with 0-100% of the motorD component are plotted against each other.



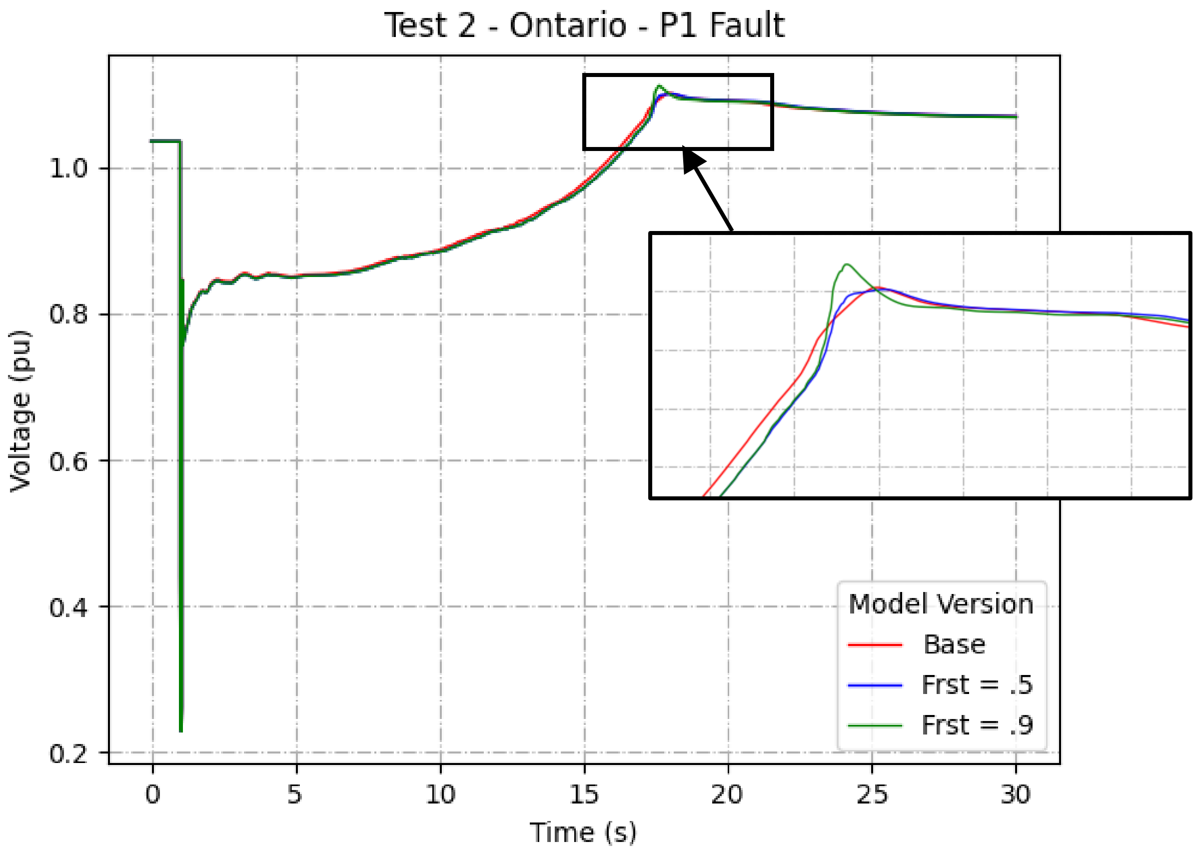

The change between each iteration is relatively consistent, showing the direct, linear relation between motorD loads and FIDVR.

While removing the amount of motorD load in the simulations does help get rid of the FIDVR events and prevents any simulations from violating the WECC standards, it is not an effective solution to the problem. This would be the equivalent of simply ignoring the very real issue of single-phase motors stalling, leaving the models effectively useless in assessing the strength of Idaho Powers grid.

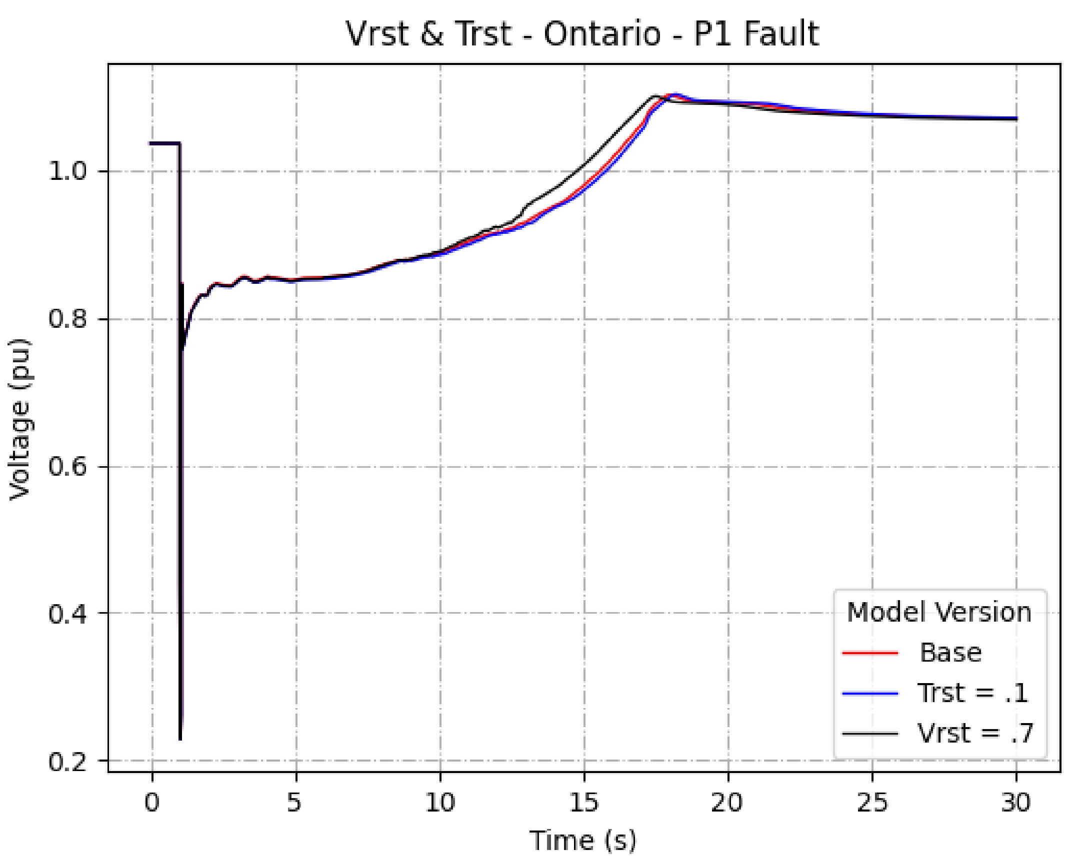
**Test 2 –**

Changing the parameters of the AC motor model being used by the CMPLDW load model had varying effects. Some of the parameters had a very large impact on the results while others had nearly none. However, by combining the alteration of multiple variables, more impactful change can be achieved.

For example, changing the values for both Frst and Vrst had effectively no impact on the simulation results, as seen in the figures below.

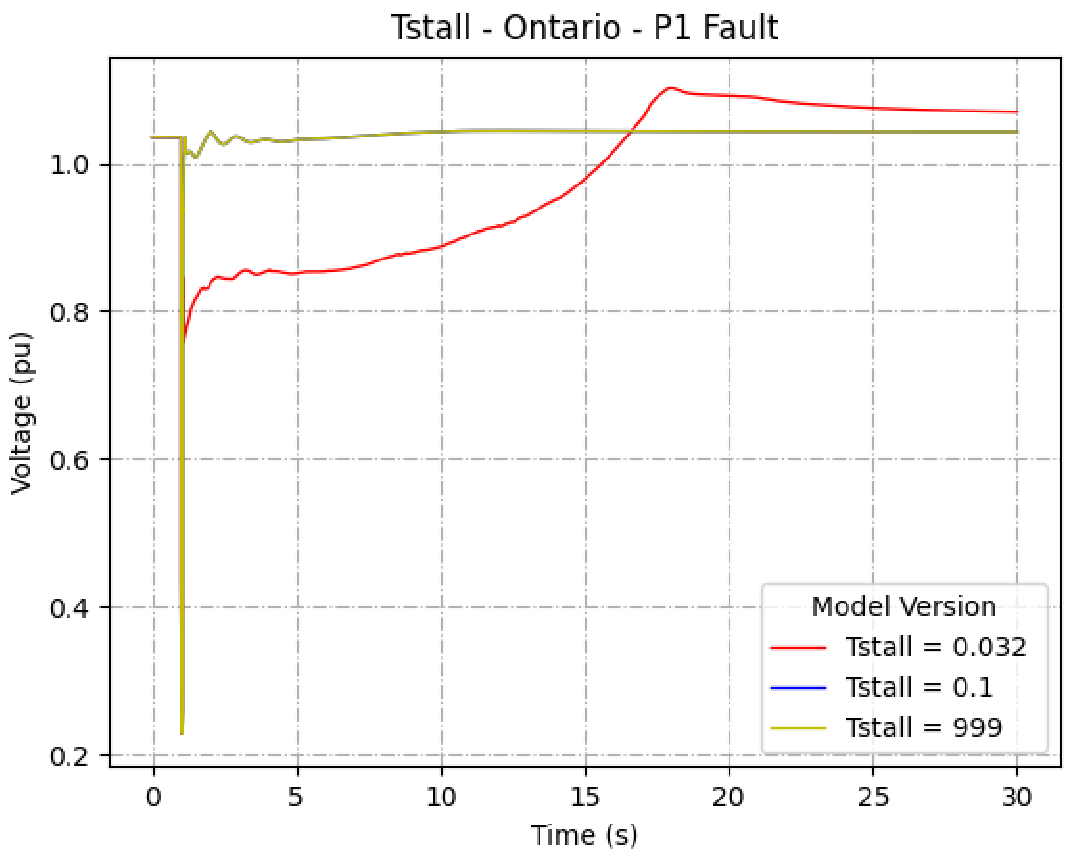


Test 2 - Ontario - P1 Fault
Voltage (pu)
Time (s)
Model Version
Base
Frst = .5
Frst = .9

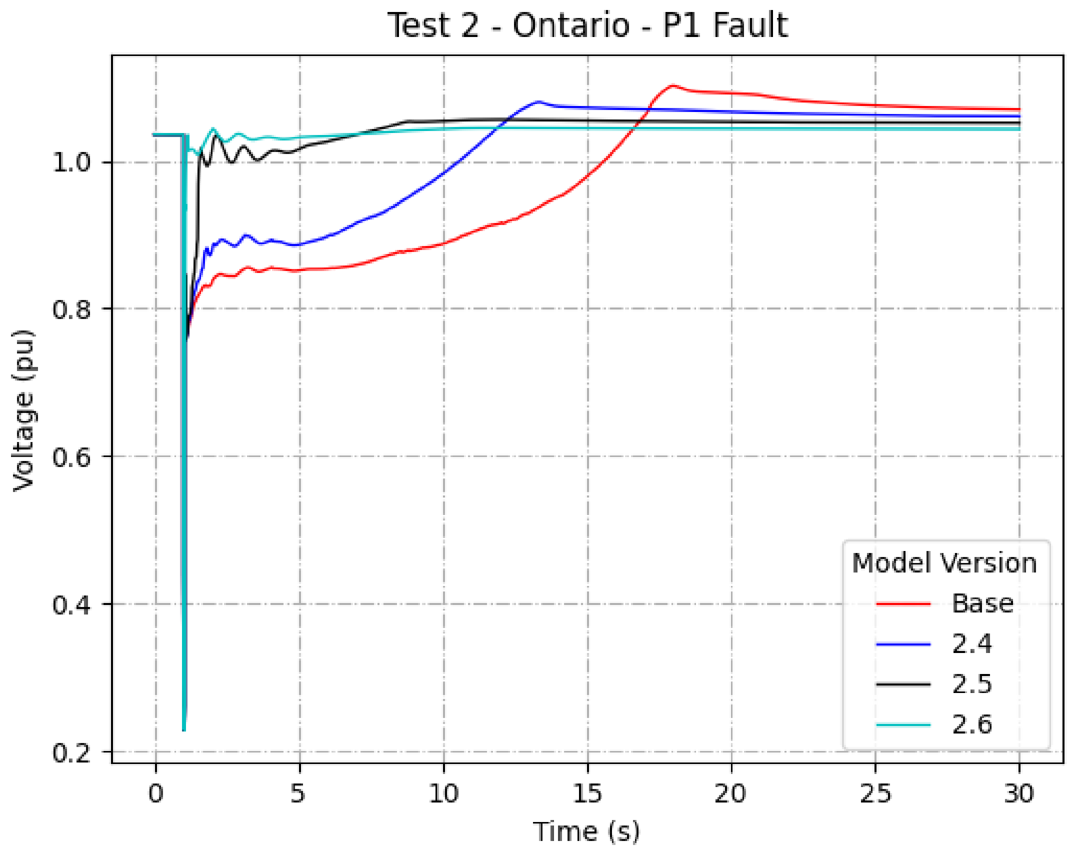
Vrst & Trst - Ontario - P1 Fault
Voltage (pu)
Time (s)
Model Version
Base
Trst = .1
Vrst = .7

Changing each of these paramaters on there own has practically no impact on the reults of the simulation. The only paramater that has any subtantial impact on its own is the Tstall paramater.




Increasing the Tstall value above a certain value (approximately as many cycles as the fault lasts) results in binary change in the results. The results from using Tstall = .1 is perfectly identical to the results from using Tstall = 999. This is because when Tstall is increased, that increases the amount of time that the voltage has to remain under the set voltage level in order to enter a stall condition. By increasing this time stalling is effectively ignored completely.

When multiple of these parameters are changed together however, a much greater impact is possible. The values chosen for these tests were chosen based off some research done into the operation of several standard residential air conditioners [x]. The figure below compares this method against the base case and the Tstall case.

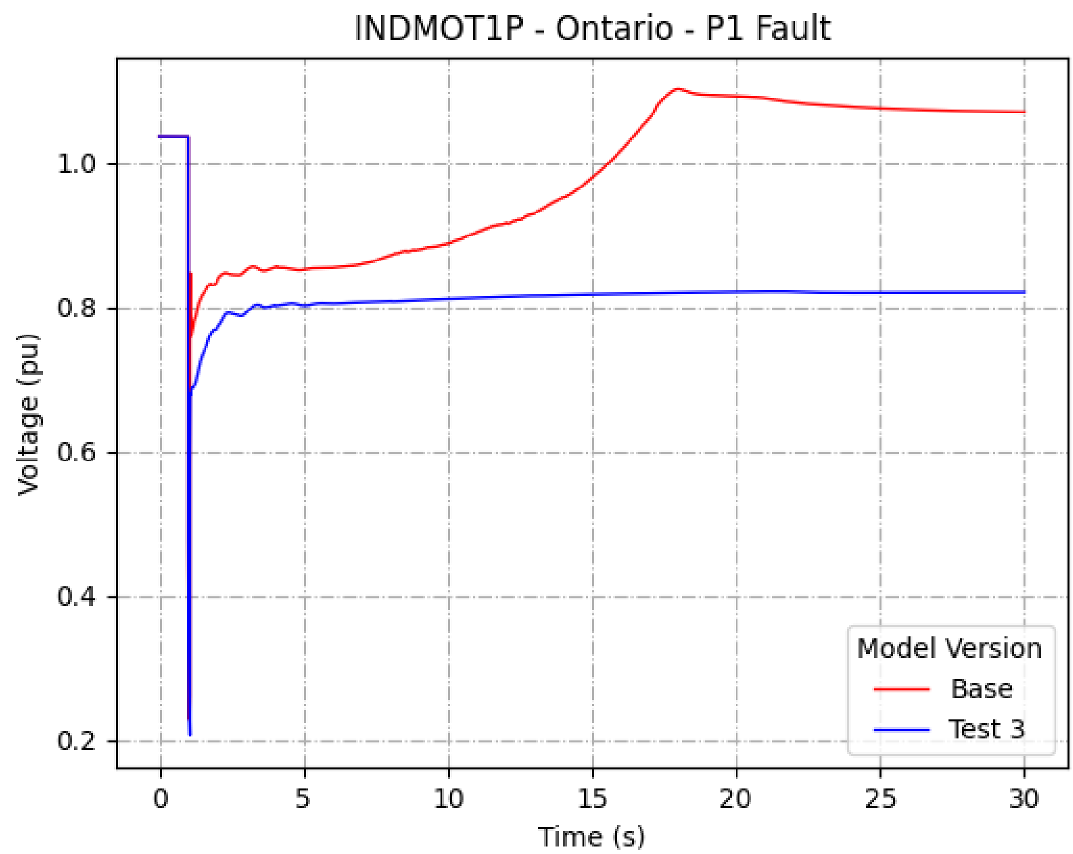


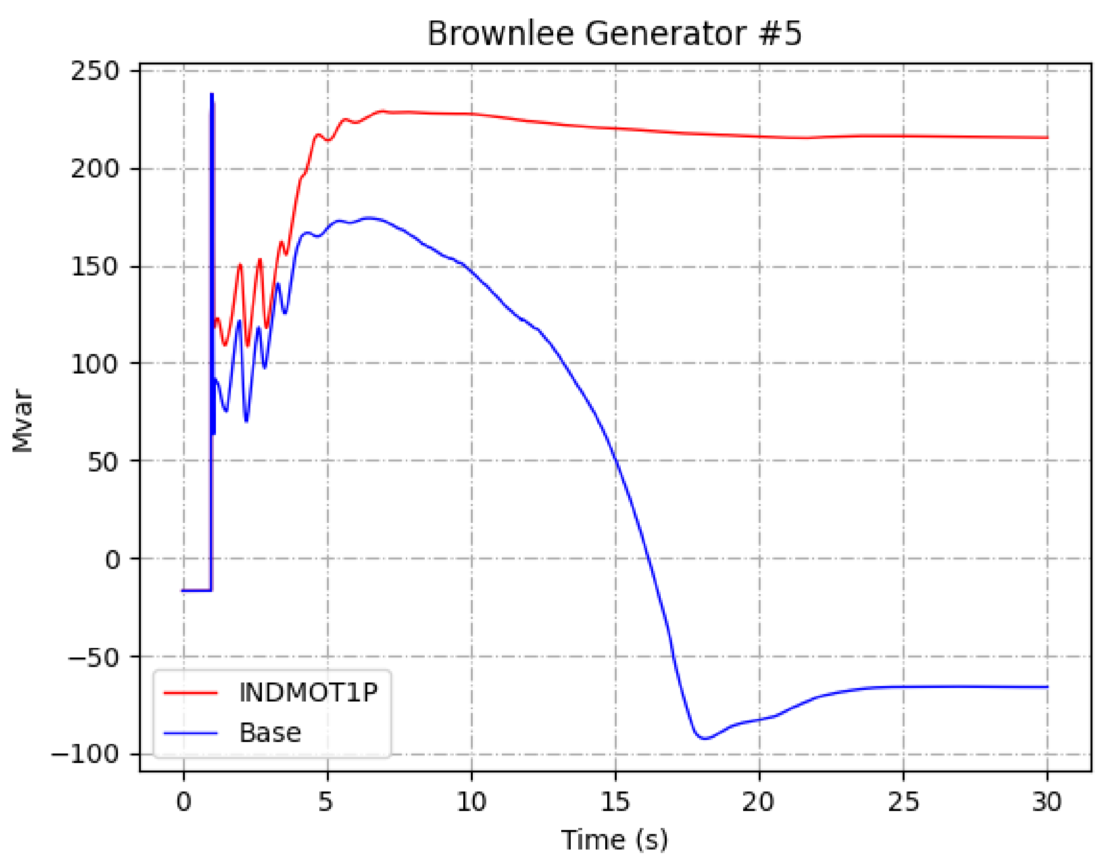

The values used in the different tested cases can be found in Appendix A. The results from the 2.5 test case provide the bets results of any test thus far. It shows the rapid voltage recovery that is much more akin to the results seen from real world fault data. While still accounting for some voltage variation that would be expected from large fault during a peak summer load case.

**Test 3 -**

The INDMOT1P load model is the foundation for both of the other models used in the following tests. It is far better at modeling the stalling of single-phase motors, but it doesn't model the tripping and restarting of those motors that recent research has shown can be expected.

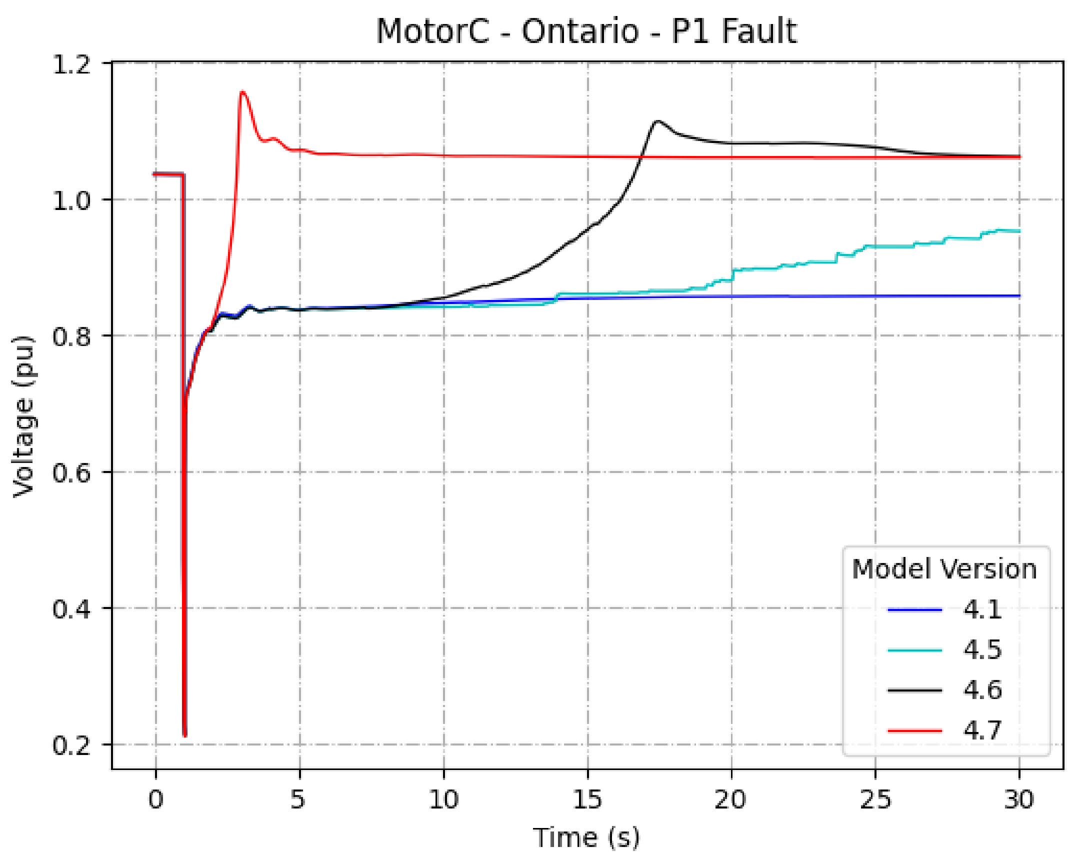
The results of implementing this model on its own doesn't provide a result any better than the current model in use. It can be seen that this model has no way of removing the stalled motors from the grid leading to a new steady state just above 80% the pre-fault voltage. This can be further seen when looking at the second figure below, showing the Mvar value on the #5 generator at Brownlee.


INDMOT1P - Ontario - P1 Fault
Voltage (pu)
Time (s)
Model Version
Base
Test 3
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30


Brownlee Generator #5
Mvar
Time (s)
INDMOT1P
Base
250
200
150
100
50
0
−50
−100
0
5
10
15
20
25
30

**Test 4 –**

The Motorc model builds off the previous load model, adding the ability to model the tripping and reconnection of stalled motors. It does this by modeling the mechanism that allows for the contactors of the motors to trip when the voltage drops below a certain level. However, this does not prevent the motor from stalling. This model was rather difficult to manipulate and many of the variables had little to no effect when changed.



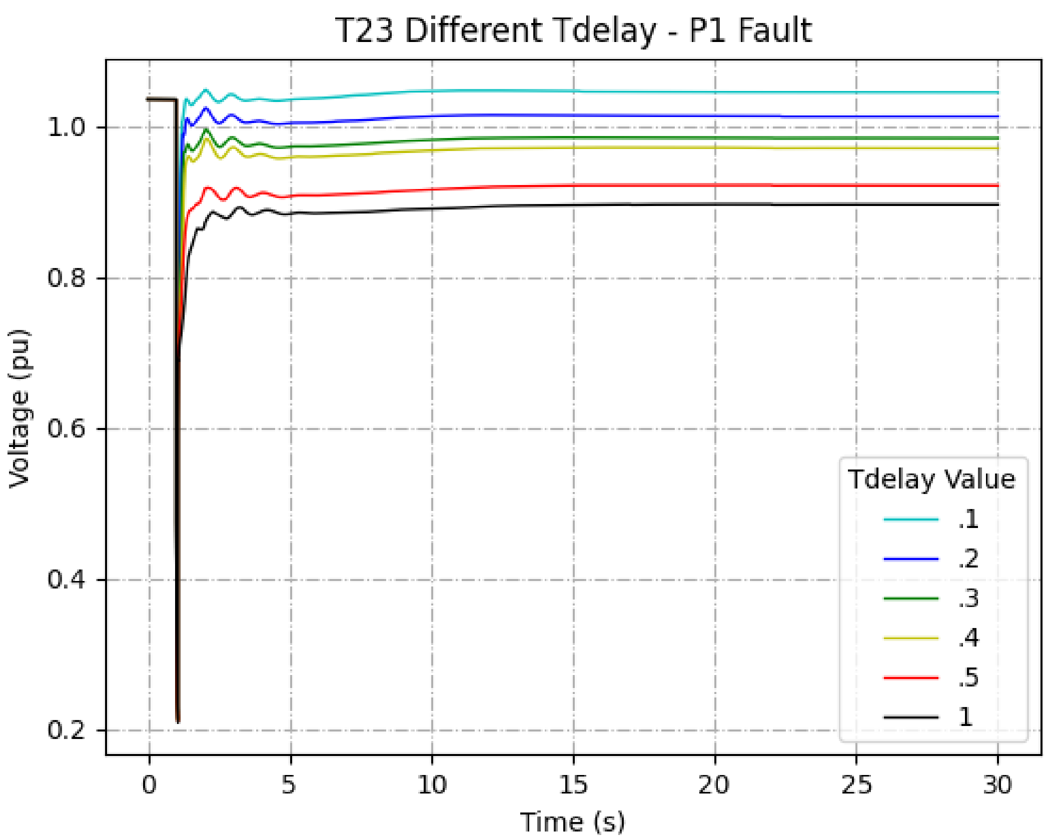

None of the results gained from using this model were very close to the expected grid response to a real-world voltage. Using the default parameter (4.1) values provided by PowerWorld returns nearly identical results to those achieved by using the INDMOT1P model. The only significant change came when the value **Tht, Th1t,** and **Th2t** were changed.

The figure above shows the effects of changing these parameters. As addressed earlier, the 4.1 version was nearly identical to the INDMOT1P model, which means that it is modeling the stalling of the motors but not the reconnection or tripping. Version 4.5 and 4.6 show the results of changing the **Th1t** and **Th2t**. 4.5 and 4.6 just have the values for each **Th#t** variable flipped. This was tested just to clarify how the modeling tool functions, so 4.5 tested when Th1t >Th2t and 4.6 tested the opposite when Th1t<Th2t. As seen in the figure above, having Th1t<Th2t is the proper way to use the model.

Version 4.7 builds off the findings of 4.6 but changes the **Tht** parameters value which determines how long a motor will stay stalled before their internal thermal protections trip them offline. The results of 4.7 are most similar to what would be expected from a real-world fault, however, the way it achieves this is through using a value for **Tht** that is far lower than what the research suggests it should be.

**Test 5 –**

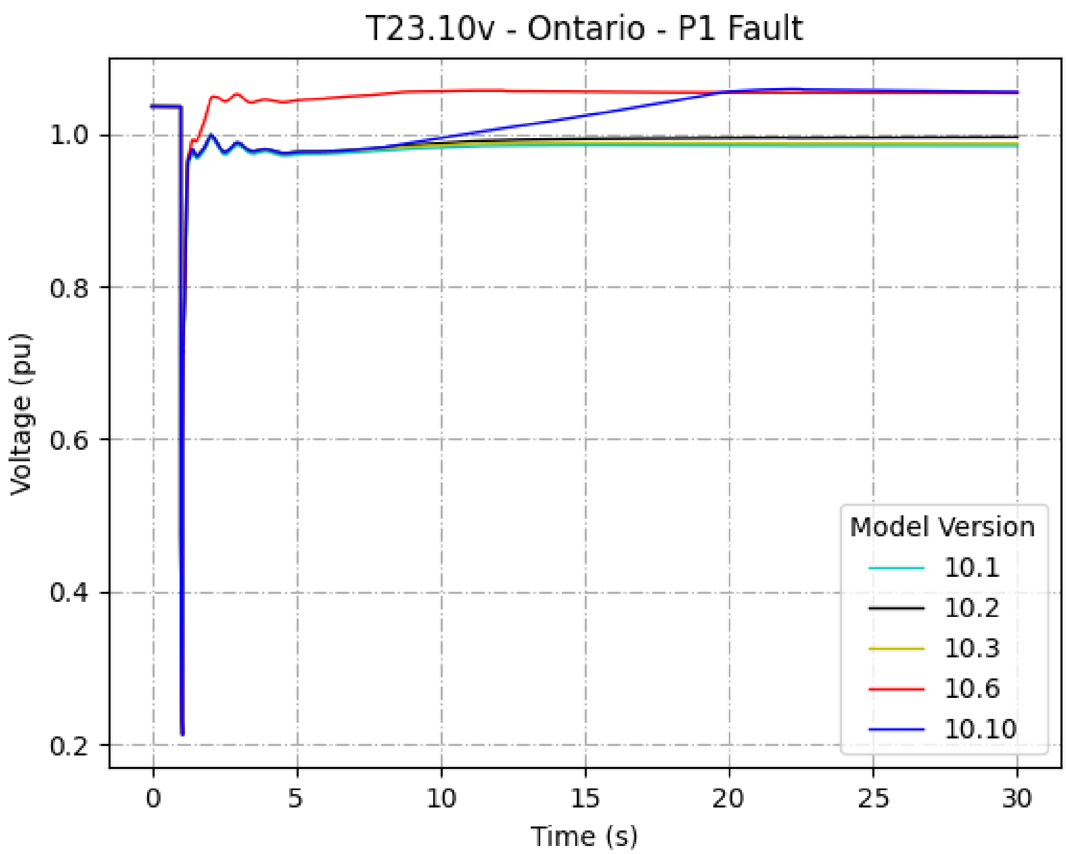
The INDMOT1P_PTR load model provided the most useful results. While many of the variables had minimal to no effect on the results, changing the **Tdelay** variable allowed for a large amount of control over the results.



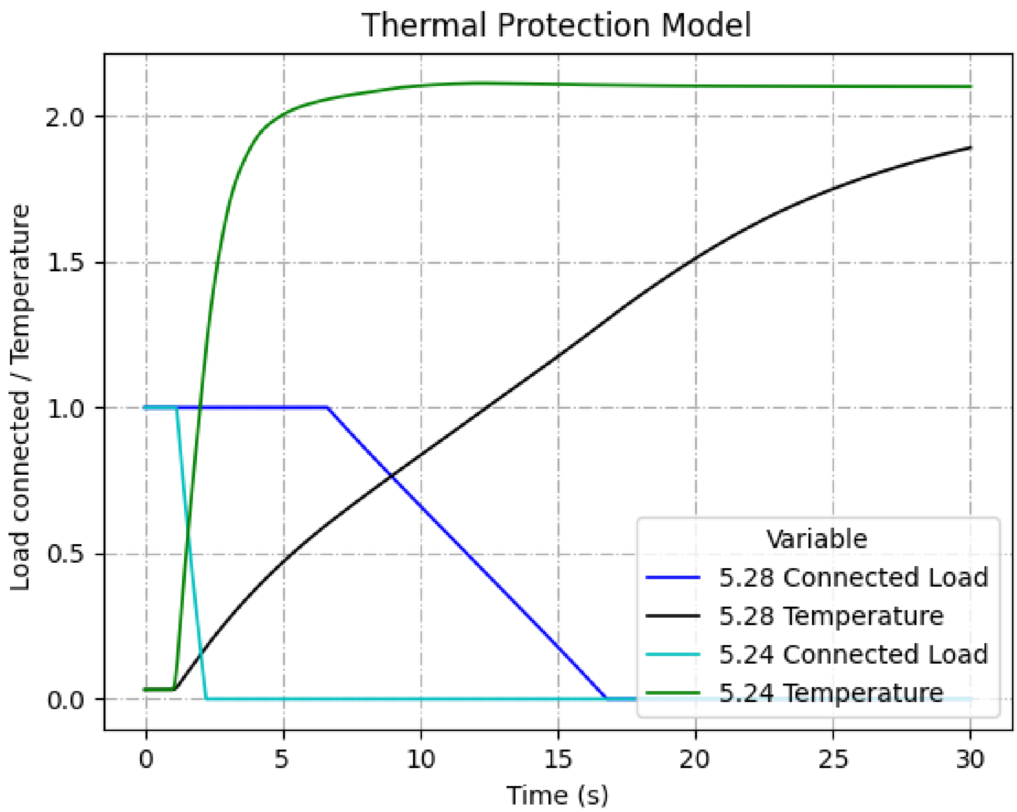

As seen in the figure above, the Tdelay value helps control the steady state voltage that the system reaches after recovering from the fault. This happens because the **Tdelay** variable handles how fast the AC motors trip off the grid and reconnect, so by lowering that time, more of the load is able to trip offline, removing the stalling motors from the grid.

After tuning the Tdelay value ( choosing Tdelay = 0.3 and Vtd = .6 ) the voltage was still unable to fully recover and became “stuck” at about 95% of its original voltage. This is most likely due to the thermal protection parameters being incorrectly set.

Through some tinkering with the **Tth, T1th** and **T2th** parameters, the simulation was tuned to have the remaining stalled units' trip offline between 6 and 16s. This 6-16s time scale was chosen to account for the large amount of variation in the sensitivity of the thermal protection units used in residential ACs.

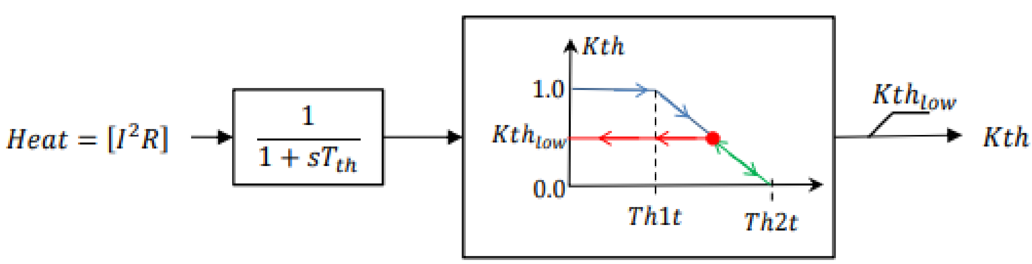


Another useful graph to help explain the cause of the different results through the manipulation of the thermal protection parameters can be seen with the figure below. This figure shows the calculated temperature of the load as well as the amount of stalled load still connected to the grid.




So, the blue lines show how much of the stalled load ( where 1 = 100% ) is connected to the grid. The black and green line shows the calculated temperature value for the selected load. This temperature value is not a direct representation of the actual temperature but rather just a scalar value that is used in calculating the thermal protection system.

If you reference the **T#th** parameter values for the respective tests (5.24 and 5.28) you can see that the load begins to trip offline when the temperature value reaches the **T1th** value and finishes tripping offline when it reaches the **T2th** value. This is helpful to understand when attempting to tune the thermal protection part of the load model. The INDMOT1P_PTR documentation also contains a useful figure that helps to explain the function of this part of the model.



The rest of the variables used in this model had only a minor impact on the results of the simulation, unless they were modified to values that are unsupported by much of the research that has been done on the issue. These parameters could be useful in fine tuning the model in order to get it as accurate as possible.

## Conclusion

Each of the models available for use in PowerWorld can be modified in order to achieve the desired results that conform to WECC voltage recovery compliance. However, the way they achieve this varies greatly. So, deciding what model works best must be done by understanding how each model handles the stalling of AC motors and comparing that to the available research on AC motors.

**Current Model**

The current WECC approved load model handles single-phase motor stalling as a single large load. This means that if the voltage level simulated at the substation level dips below a level determined by the parameters set in the model the entire load determined to be single-phase motors enters a stall condition. The reality of this event is far more complicated and less binary. This means that the current load model is far too pessimistic in its simulation of these single-phase motors.

While more realistic results can be achieved through the current model (Test 2.4, 2.6) the way it achieves this effectively ignores the issue of staling completely. Test 2.6 sets the **Tstall** variable to 999 meaning that for a single-phase motor to begin stalling it would have to be connected to an undervoltage supply of power for 999s. This is effectively just ignoring the issue of stalling completely, which is obviously far from an ideal solution. Test 2.4 on the other hand does allow for some of the stalling to be modeled through changing the parameters that deal with the motors ability to restart after starting to stall. Test 2.4 assumes that 90% of stalled load is able to restart normal operation in only 0.1s after the supplied voltage has risen back above 0.6Vpu. These conditions are far too optimistic and do not align with the single-phase motor properties that have been observed in past research.

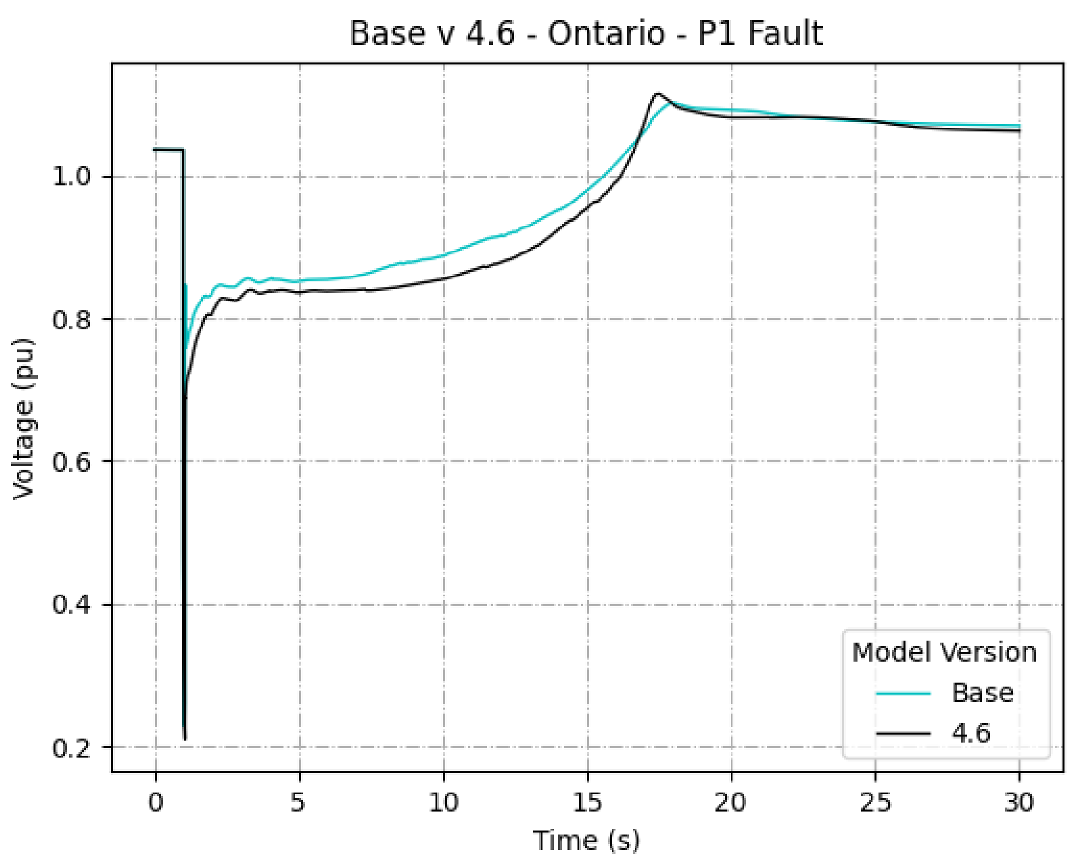
**INDMOT1P**

This load model was created to improve on the current modeling system by treating the load seen from single-phase motors as an aggregation of many different loads rather than a single large load like the current model does. Unlike the current CMPLDW model where stalling is mainly determined by several different parameters such as **Tstall** and **Vstall**, this model calculates stalling through more advanced modeling of the internal properties of the motor. In theory this is a big upgrade from the current load model, however, this model appears unable to model the internal protections present in these motors that disconnects them from the grid after they begin to stall. This leads to the model beingly the most pessimistic of all the models available, as the amount of stalled load stays consistent for the entire 30s that these simulations tested. This model is an effective base for other models to be built on top of, but it is not useful on its own in its current state.

**MotorC**

The "motorc" load model is the model currently being developed in collaboration with WECC. It allows for more realistic modeling of the tripping and reconnection mechanics that have been observed in recent studies of residential air conditioners. Finding any progress made by the WECC LMTF regarding the implementation of this model is hard to come by. Currently it seems that they have created and tested this model, and determined it is able to model these AC loads more accurately, however, they still need to do more detailed testing of the model to prove its accuracy. The specific parameter settings that WECC has chosen thus far for the motorc load model are not shared publicly and It seems as though this issue is rather low on their project list. So, this means that this model may become the standard sometime in the suture, however, as of now this doesn't seem like the best model choice.

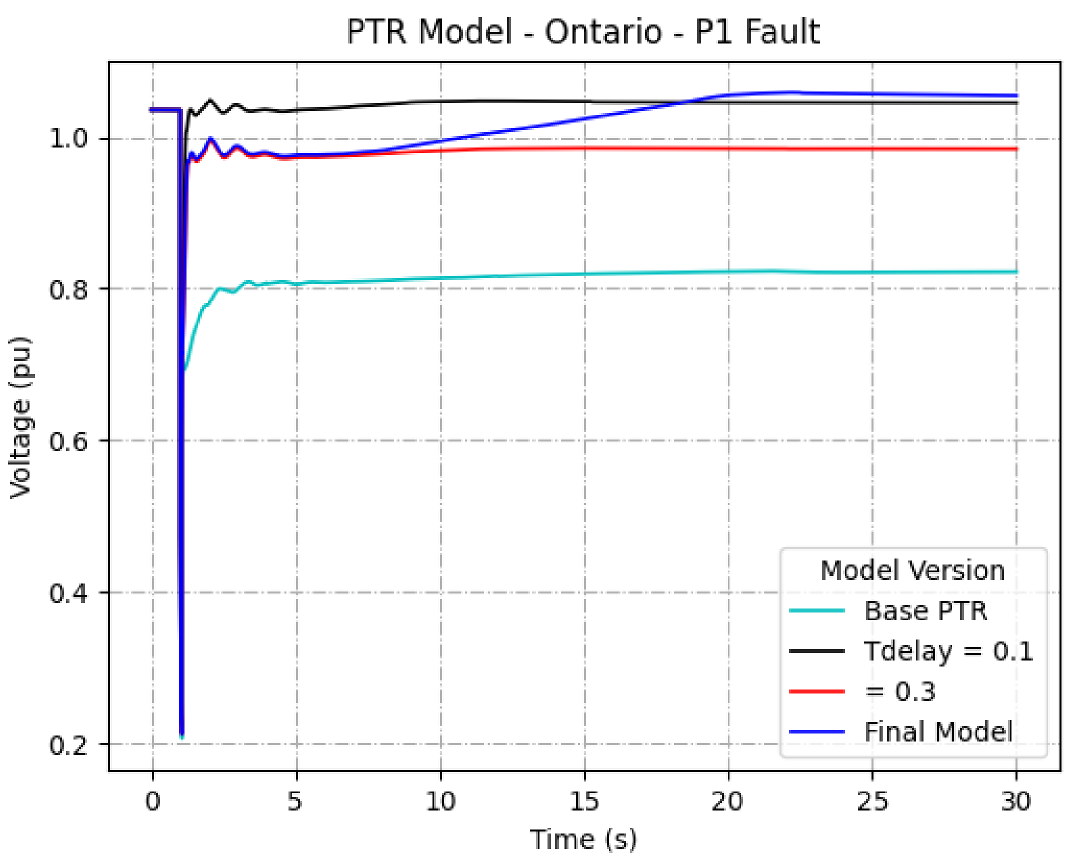
Many of the variables in this model have seemingly no impact on the results of the simulations when realistic values that agree with recent research are used. The default parameters given in PowerWorld prove inadequate in modeling the recovery of many different stalled motors after a undervoltage event. The only variables that allow for the stalling of the motors to be removed from the grid is the thermal protection components. The properties of the thermal protection circuits present in most residential ACs varies greatly, but there has been enough research done on the issue that some average values can be chosen. When these averages are used such as in Test 4.6, the result is nearly identical to that achieved with the current base model.




While this may provide a better representation of the stalling of many different single-phase motors, it is still far too pessimistic when compared to any historical fault data that the Idaho Power gird has experienced. In order to get results that are closer to the historical fault data, the **Tht** parameter must be lowered from 10s to 1s or less. This is a choice that is unsupported by any research done on the properties of residential ACs, making it a less than ideal choice for use in any accurate simulation of the power grid.

**INDMOT1P-PTR**

Similar to the MotorC load model, this model builds off the INDMOT1P load model, adding some new parameters that attempt to model the tripping and reconnection of stalled single-phase motors more accurately during one of these fault events. Taking a different approach than the MotorC model, this model uses a method that allows for motors to trip offline upon seeing low voltage and reconnect when voltage levels return to normal. This appears to be a far more effective way to model stalling single-phases motors. Much like observed in the historical fault data, this model allows for rapid voltage recovery while still accounting for a minor increase in Mvar load that would be expected from a number of stalled residential ACs.




Unlike other models, this model builds off the findings of some recent research on the topic that shows many residential ACs end up tripping offline when voltage rapidly drops below around .6 Vpu. The proportion and speed at which these units are able to trip offline varies greatly depending on the manufacturer, but a model that takes an average from these values should be more than adequate for comparatively large simulations. This report found that the best results were achieved when the parameter values of Test 5.28 (Final Model) were used. These values were chosen based off the findings of a study done by the EPRI (Electric Power Research Institute) [2].

**Conclusion**

All of these models are able to accurately model the stalling of a single-phase motor load, however, they struggle when trying to model several thousand motors spread across hundreds of miles. This is a very difficult property to accurately model for many different reasons. The main issue is that all the research that is used in building these models is based off studies that test the undervoltage response of single AC units under very specific load conditions. The issue with this approach is that it does not take into account the variation of voltage across a distribution feeder.

The voltage will not be a single consistent value across the entire feeder as there are a number of different systems such as voltage rectifiers and cap banks spread across several miles of distribution lines. Without a better understanding of the voltage response across the distribution lines, increasing the accuracy of these load models can only be done through more guess and check.

# Appendix A

Documentation of Tested Model Configurations

## Test 1 – MotorD component

### 1.1 - 0%

| Load | Cooling | Refrig |
|---|---|---|
| MotorA | 0.8 | 1 |
| MotorB | .1 | 0 |
| MotorC | .05 | 0 |
| MotorD | 0 | 0 |
| PE | .05 | 0 |

### 1.2 - 25%

| Load | Cooling | Refrig |
|---|---|---|
| MotorA | 0.6 | 0.8 |
| MotorB | .1 | 0 |
| MotorC | .05 | 0 |
| MotorD | 0.2 | 0.2 |
| PE | .05 | 0 |

### 1.3 - 50%

| Load | Cooling | Refrig |
|---|---|---|
| MotorA | 0.4 | 0.5 |
| MotorB | .1 | 0 |
| MotorC | .05 | 0 |
| MotorD | 0.4 | 0.5 |
| PE | .05 | 0 |

### 1.4 - 75%

| Load | Cooling | Refrig |
|---|---|---|
| MotorA | 0.2 | 0.2 |
| MotorB | .1 | 0 |
| MotorC | .05 | 0 |
| MotorD | 0.6 | 0.8 |
| PE | .05 | 0 |

## Test 2 – AC Motor Parameters

**2.1 – Frst** = .5

**2.2 – Frst** = .9

**2.3 – Vrst** = .7

**2.4 – Vrst** = .6
**Frst** = .5
**Trst** = .1

**2.5 - Vrst** = .6
**Frst** = .9
**Trst** = .1

**2.6 – Tstall** = 999

**2.7 – Tstall** = .1

**2.8 – Tstall** = .03

## Test 3 – INDMOT1P Load Model

**3.1 – INDMOT1P**

## Test 4 – MotorC Load Model

**4.1 –** Default Motorc

**4.2 -**

| | | | |
|---|---|---|---|
| $V_{c1on}$ | 0.525 | | |
| $V_{tr1}$ | 0.56 | $T_{tr1}$ | 0.25 |
| $V_{tr2}$ | 0.49 | $T_{tr2}$ | .05 |

**4.3 -**

| | | | |
|---|---|---|---|
| $V_{c1on}$ | 0.525 | $T_{tr1}$ | 0.25 |
| $V_{tr1}$ | 0.56 | $T_{tr2}$ | .05 |
| $V_{tr2}$ | 0.49 | $A_{sat}$ | 0 |
| | | $B_{sat}$ | 0 |

**4.4 -**

| | | | |
|---|---|---|---|
| $V_{c1on}$ | 0.6 | $T_{tr1}$ | 1 |
| $V_{tr1}$ | 0.75 | $T_{tr2}$ | .13 |
| $V_{tr2}$ | 0.55 | $A_{sat}$ | 0 |
| | | $B_{sat}$ | 0 |

**4.5 -**

| | | | |
|---|---|---|---|
| $V_{tr1}$ | 0.75 | $T_{tr1}$ | 1 |
| $V_{tr2}$ | 0.55 | $T_{tr2}$ | .13 |
| $T_{th}$ | 10 | $A_{sat}$ | 0 |
| $T_{h1t}$ | .45 | $B_{sat}$ | 0 |
| $T_{h2t}$ | .7 | | |

**4.6 -**

| | | | |
|---|---|---|---|
| $V_{tr1}$ | 0.75 | $T_{tr1}$ | 1 |
| $V_{tr2}$ | 0.55 | $T_{tr2}$ | .13 |
| $T_{th}$ | 10 | $A_{sat}$ | 0 |
| $T_{h1t}$ | .7 | $B_{sat}$ | 0 |
| $T_{h2t}$ | .45 | $F_{uvr}$ | 0% |

**4.7 -**

| | | | |
|---|---|---|---|
| $V_{tr1}$ | 0.75 | $T_{tr1}$ | 1 |
| $V_{tr2}$ | 0.55 | $T_{tr2}$ | .13 |
| $T_{th}$ | 1 | $A_{sat}$ | 0 |
| $T_{h1t}$ | .7 | $B_{sat}$ | 0 |
| $T_{h2t}$ | .45 | | |

**4.8 -**

| | | | |
|---|---|---|---|
| $V_{tr1}$ | 0.75 | $T_{tr1}$ | 1 |
| $V_{tr2}$ | 0.55 | $T_{tr2}$ | .13 |
| $T_{th}$ | 1 | $A_{sat}$ | 0 |
| $T_{h1t}$ | .7 | $B_{sat}$ | 0 |
| $T_{h2t}$ | .45 | $F_{uvr}$ | 20% |

## Test 5 – INDMOT1P_PTR Load Model

**5.1 –**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.45 | $V_{1on}$ | 0.5 |
| $V_{2off}$ | 0.35 | $V_{2on}$ | 0.4 |

| | | | |
|---|---|---|---|
| $V_{td}$ | 0.5 | $T_{delay}$ | 1 |
| $F_{recon}$ | 1 | $T_{recon}$ | 4 |

**5.2 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.56 | $V_{1on}$ | 0.5 |
| $V_{2off}$ | 0.45 | $V_{2on}$ | 0.4 |
| $V_{td}$ | 0.56 | $T_{delay}$ | 0.1 |
| $F_{recon}$ | .5 | $T_{recon}$ | 4 |

**5.3 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.65 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 1 |
| $F_{recon}$ | 0.65 | $T_{recon}$ | 4 |

**5.4 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 1 |
| $F_{recon}$ | 1 | $T_{recon}$ | 4 |

**5.5 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.56 | $V_{1on}$ | 0.6 |
| $V_{2off}$ | 0.45 | $V_{2on}$ | 0.5 |
| $V_{td}$ | 0.56 | $T_{delay}$ | 0.1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.6 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.1 |
| $F_{recon}$ | 1 | $T_{recon}$ | 4 |

**5.7 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.8 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.9 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.5 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.10 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.5 |
| $F_{recon}$ | 1 | $T_{recon}$ | 4 |

**5.11 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.2 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.12 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.3 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.13 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.4 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.14 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |

| | | | |
|---|---|---|---|
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 2 |

**5.15 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.16 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.17 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.9 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.6 |
| $V_{td}$ | 0.55 | $T_{delay}$ | 0.1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.18 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.9 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.6 |
| $V_{td}$ | 0.75 | $T_{delay}$ | 1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |

**5.19 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.9 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.6 |
| $V_{td}$ | 0.75 | $T_{delay}$ | 1 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 0.5 |

**5.20 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.6 | $T_{delay}$ | 0.5 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |
| $T_{th}$ | 10 | $T_{h1t}$ | 0.5 |
| | | $T_{h2t}$ | 4.3 |

**5.21 –**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.6 | $T_{delay}$ | 0.5 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |
| $T_{th}$ | 10 | $T_{h1t}$ | 1.3 |
| | | $T_{h2t}$ | 10 |

**5.22 –**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.6 | $T_{delay}$ | 0.5 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |
| $T_{th}$ | 1 | $T_{h1t}$ | 1.3 |
| | | $T_{h2t}$ | 4.3 |

**5.23 -**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.6 | $T_{delay}$ | 0.5 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |
| $T_{th}$ | 1 | $T_{h1t}$ | 0.5 |
| | | $T_{h2t}$ | 10 |

**5.24 –**

| | | | |
|---|---|---|---|
| $V_{1off}$ | 0.75 | $V_{1on}$ | 0.75 |
| $V_{2off}$ | 0.55 | $V_{2on}$ | 0.55 |
| $V_{td}$ | 0.6 | $T_{delay}$ | 0.5 |
| $F_{recon}$ | 0.5 | $T_{recon}$ | 4 |
| $T_{th}$ | 1 | $T_{h1t}$ | 0.1 |
| | | $T_{h2t}$ | 4.3 |

**5.25 –**

| | | | |
|---|---|---|---|
| **$V_{1off}$** | 0.75 | **$V_{1on}$** | 0.75 |
| **$V_{2off}$** | 0.55 | **$V_{2on}$** | 0.55 |
| **$V_{td}$** | 0.6 | **$T_{delay}$** | 0.5 |
| **$F_{recon}$** | 0.5 | **$T_{recon}$** | 4 |
| **$T_{th}$** | 10 | **$T_{h1t}$** | 0.1 |
| | | **$T_{h2t}$** | 1.2 |

**5.26 –**

| | | | |
|---|---|---|---|
| **$V_{1off}$** | 0.75 | **$V_{1on}$** | 0.75 |
| **$V_{2off}$** | 0.55 | **$V_{2on}$** | 0.55 |
| **$V_{td}$** | 0.6 | **$T_{delay}$** | 0.5 |
| **$F_{recon}$** | 0.5 | **$T_{recon}$** | 4 |
| **$T_{th}$** | 10 | **$T_{h1t}$** | 0.6 |
| | | **$T_{h2t}$** | 1.1 |

**5.27 –**

| | | | |
|---|---|---|---|
| **$V_{1off}$** | 0.75 | **$V_{1on}$** | 0.75 |
| **$V_{2off}$** | 0.55 | **$V_{2on}$** | 0.55 |
| **$V_{td}$** | 0.6 | **$T_{delay}$** | 0.5 |
| **$F_{recon}$** | 0.5 | **$T_{recon}$** | 4 |
| **$T_{th}$** | 10 | **$T_{h1t}$** | 0.6 |
| | | **$T_{h2t}$** | 1.2 |

**5.28 –**

| | | | |
|---|---|---|---|
| **$V_{1off}$** | 0.75 | **$V_{1on}$** | 0.75 |
| **$V_{2off}$** | 0.55 | **$V_{2on}$** | 0.55 |
| **$V_{td}$** | 0.6 | **$T_{delay}$** | 0.5 |
| **$F_{recon}$** | 0.5 | **$T_{recon}$** | 4 |
| **$T_{th}$** | 10 | **$T_{h1t}$** | 0.6 |
| | | **$T_{h2t}$** | 1.3 |

## References


[1] PNNL-29592, Open-Source High-Fidelity Aggregate Composite Load Models of Emerging Load Behaviors for Large-Scale Analysis

[2] EPRI, Technical Reference on the Composite Load Model

[3] Load Characteristic INDMOT1P
https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Load%20Characteristic%20INDMOT1P.htm?tocpath=Transient%20Stability%20Add-On%20(TS)%7CTransient%20Models%7CLoad%7CCharacteristic%7C_____13

[4] Load Characteristic LD1PAC
https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Load%20Characteristic%20LD1PAC.htm?tocpath=Transient%20Stability%20Add-On%20(TS)%7CTransient%20Models%7CLoad%7CCharacteristic%7C_____16

[5] Load Characteristic INDMOT1P_PTR
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