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under Contract DE-AC05-76RL01830

Grid Friendly^{TM} Device Model Development and Simulation

N Lu

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November 2009

Pacific Northwest NATIONAL LABORATORY

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Pacific Northwest National Laboratory

Richland, Washington 99352

Summary

This report presents models for simulating the dynamic effects of populations of Grid Friendly™ water heater controllers on power grid dynamic performance. The models represent either (1) an under-voltage response or (2) an underfrequency response that can be conducted by populations of autonomously responsive water heaters. These models were applied to several test cases supplied by the client, and simulations of these test cases were conducted using General Electric (GE) Positive Sequence Load Flow (PSLF) software. A three-feeder test bed was used to quantify the effectiveness of the responses and the sensitivity of the schemes to device penetration and parameter settings. Then, five historic system events within the Bonneville Power Administration (BPA) power grid were studied to evaluate the impact of the autonomous under-voltage and underfrequency response schemes.

Concerning simulations of the under-voltage-responsive water heaters, the study demonstrated that the feeder voltage in the test cases normally recovered at a higher voltage for the case having voltage-responsive water heaters than it would without such responsive loads. The test cases using under-voltage-responsive water heaters also resulted in a faster recovery of the grid system frequency. However, the presence of voltage-responsive water heaters did not resolve the slow voltage recovery phenomena caused by the stalling of 1-phase air conditioner motors.

Concerning simulations using under-frequency-responsive water heaters, an underfrequency-responsive device model was formulated as had been done for the voltage-responsive water heaters; however, the underfrequency test case simulations were found to be unreliable. A fundamental limitation apparently exists in the inability of the EPCGEN module, in which the device model was created, to receive the frequency parameter from the main PSLF simulation codes. This frequency parameter was not available to the EPCGEN module during the simulation. Efforts to calculate a useable, stable representation of system frequency for these simulations were unsuccessful.

New EPCGEN models were developed for the frequency-responsive and voltage-responsive water heaters in the study. This report describes the models and how they may be implemented. Many additional simulation files were made available to the client in electronic format to accompany this report.

Acknowledgment

This report was prepared with support from Bonneville Power Administration. The authors thank Paul Ferron of Bonneville Power Administration for providing PSLF base cases and measurement data to reproduce the fault cases.

Contents

1.0 Introduction

In late 2007, the Bonneville Power Administration (BPA) contracted Pacific Northwest National Laboratory (PNNL) to complete a research project titled "Grid-Responsive Demand-Side Control Using Grid Friendly™ Appliance Technologies" [Hammerstrom 2009, DeSteese and Hammerstrom 2009]. Cosponsors included Portland General Electric (PGE) and Puget Sound Energy (PSE). The project focused on applications of the Grid Friendly™ Appliance (GFA) controller, which is an autonomous controller that was designed to advise devices like appliances concerning valuable demand-side grid services that should be conducted. The controller bases its advice on observations it makes from the ac voltage signal. Electric tank water heaters were selected to be controlled by the GFA controller in this project.

Two autonomous responses are addressed herein. First, an under-voltage-responsive water heater is able to recognize sudden reductions in feeder circuit voltage at each water heater and may curtail any electric load that is being consumed by the water heater. These under-voltage events are usually induced by nearby electrical faults. An under-voltage response is necessarily specified by the set of voltage thresholds at which the responsive water heaters would respond. The set of voltages at which the curtailment would be released must also be specified. Additionally, any delays prior to the water heater load becoming curtailed or again released must be specified. For example, a delay may be intentionally imposed prior to curtailing water heater loads to avoid responses during the fault itself. Much longer and randomized delays should be imposed prior to the release of curtailments in order to re-establish diversity of the water heater loads and soften what could otherwise be an abrupt reintroduction of a large aggregated electrical load into the already stressed grid region.

An autonomous underfrequency load shed should be similarly specified by its thresholds and any delays that are imposed on the device's responses.

Dynamic simulations must be conducted to predict the effects that populations of responsive water heaters could have on power grids during under-voltage and underfrequency events. This report addresses using the industry recognized General Electric (GE) positive sequence load flow (PSLF) toolset. In this study, PNNL created models for the responsive GFA water heaters and conducted dynamic simulations that would predict how large populations of such controlled populations of water heaters would react to and perhaps mitigate any of several under-voltage or underfrequency test cases provided to PNNL by BPA.

2.0 The Model of the Under-Voltage Response Scheme

As shown in Figure 1, the designed under-voltage response of a GFA water heater is as follows: When the system voltage changes from V_{th1} to V_{th2}, an increasingly large fraction of the water heaters turn off until all have been turned off. Each specific water heater turns itself off at a single voltage threshold, the set of which are evenly distributed between the two voltages V_{th1} and V_{th2}. The water heaters begin their recovery similarly between V_{rh2} and V_{rh1}. However, the recovery is followed by a randomized time delay that is imposed to re-establish load diversity within the water heater population.

An individual responsive load will follow strictly the logic described above. A corresponding control state diagram is shown in Figure 2(a). However, to model the aggregate GFA water heater response at the feeder or transmission level, an aggregated model that simulates the hundreds and thousands of GFA water heaters needs to be developed. The biggest difference between the individual and the aggregated models is that an individual GFA water heater has deterministic parameters for its triggering voltage thresholds and delay timer settings; an aggregate GFA water heater model needs to accurately represent the distributions of all the individual GFA water heaters' thresholds and time delays.

To do so, we applied a discretized approach to divide all the GFA water heaters into a number of groups, or *bins*. Each bin has fixed triggering voltage thresholds that represent a fraction of the distribution of thresholds between V_{th1} and V_{th2} and between V_{rh2} and V_{rh1}. These subtle difference are shown in the state transition diagram of the aggregated controller model of Figure 2(b).

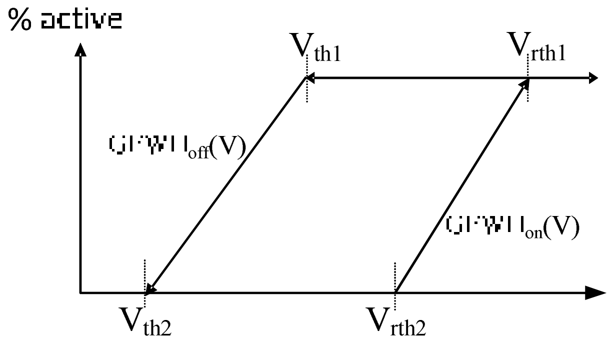


Figure 1. GFA Water Heater Load Hysteresis Response showing Fraction of Load Affected as a Function of Voltage

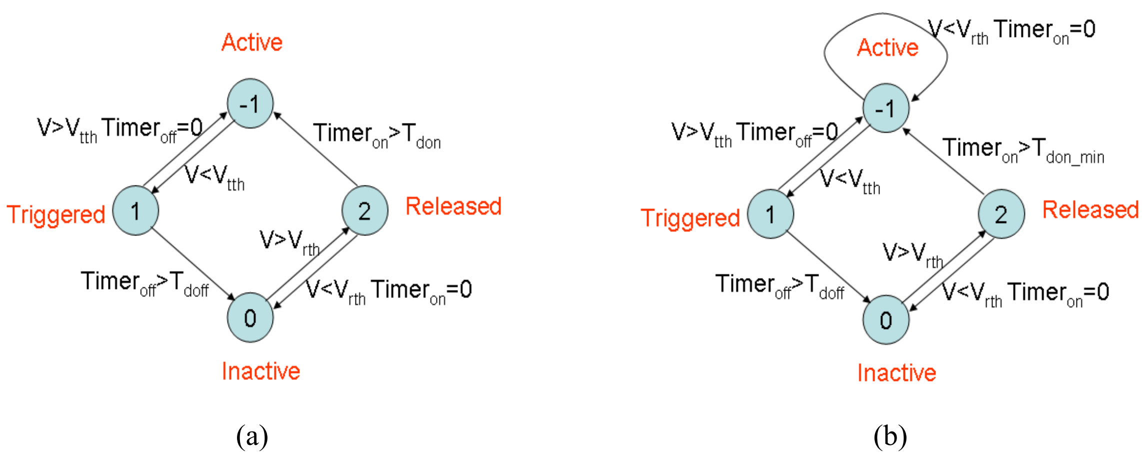


Figure 2. (a) The Voltage Control Logic of an Individual GFA Water Heater Device; (b) The Voltage Control Logic of the Aggregated GFA Water Heater Model

To prove the concept, a MATLAB model was built. The voltage responses were simulated with the individual water heater model following the control logic shown in Figure 2(a). Then, following the control logic shown in Figure 2(b), voltage responses were again simulated with the aggregate water heater model. The two sets of results were compared so that the modeling errors of the aggregated model could be evaluated. The advantage of this approach was that a virtually unlimited number of aggregation bins could be simulated in the MATLAB environment to create a dependable, *detailed* model.

After the aggregated control logic was tested using the MATLAB code, the EPCL coded EPCGEN model was developed for use in the PSLF simulation environment. The simulation results of a real test event are to be presented later using this PSLF dynamic model to evaluate the effectiveness of the water heater voltage control scheme in a realistic dynamic transmission system model.

2.1 Simulation of Aggregated Controller Behaviors

The dynamic model parameters are presented in Table 1. A description of the EPCL code is given below:

1. This following logic calculates the fraction of GFA water heaters that should remain un-triggered or active at the present voltage (i.e., $GFWHr_{off}(V)$):

   If $V(t_0) \geq V_{th1}$, Then Set $GFWH_{off}(V) = 1$
   Else if $V(t_0) \leq V_{th2}$, Then Set $GFWH_{off}(V) = 0$
   Else Set $GFWH_{off}(V) = (V(t_0) - V_{th2}) / (V_{th1} - V_{th2})$
   End If

2. This logic calculates the fraction of GFA water heaters that should again become released or become active at the present voltage (i.e., $GFWH_{on}(V)$):

   If $V(t_0) \geq V_{rth1}$, Then Set $GFWH_{on}(V) = 1$
   Else if $V(t_0) \leq V_{rth2}$, Then Set $GFWH_{on}(V) = 0$
   Else Set $GFWH_{on}(V) = (V(t_0) - V_{rth2}) / (V_{rth1} - V_{rth2})$
   End If

3. This logic calculates the number of GFA water heaters that should remain untriggered as voltage decreases and schedules future changes to the fraction of active loads $GFWH_{active}$ to account for the delay $t_{d\text{-}off}$:

   If $GFWH_{off}(V) < GFWH_{untriggered}$, Then
   Set $\Delta GFWH(t_0+t_{d\text{-}off}) = GFWH_{off}(V) - GFWH_{untriggered}$
   Set $GFWH_{untriggered} = GFWH_{off}(V)$
   Else if $GFWH_{off}(V) > GFWH_{active}$, Then
   Set $GFWH_{untriggered} = GFWH_{active}$
   For $t = t_0$ to ∞
   If $\Delta GFWH(t) < 0$, Then Set $\Delta GFWH(t) = 0$
   End For
   Else if $GFWH_{off}(V) > GFWH_{untriggered}$, Then
   Set $GFWH_{untriggered} = GFWH_{off}(V)$
   Set $Y = GFWH_{active}$
   For $t = t_0$ to ∞
   If $\Delta GFWH(t) < 0$, Then
   Set $Y = Y + \Delta GFWH(t)$
   If $Y < GFWH_{untriggered}$ Then Set $\Delta GFWH(t) = 0$
   End If
   End For
   End If

4. This next logic calculates the number of GFA water heaters that should become released as voltage increases and schedules future changes to the fraction of active loads $GFWH_{active}$ to account for the delay $t_{d\text{-}on}$. This logic will work for constant $t_{d\text{-}on}$. Additional complexity will result if a distribution of $t_{d\text{-}on}$ is imposed to re-establish load diversity after an event.

```
If GFWH_on (V) > GFWH_released, Then
    Set ΔGFWH(t_0+t_d-on) = (GFWH_on(V) – GFWH_released)
    Set GFWH_released = GFWH_on(V)
Else if GFWH_on(V) < GFWH_active, Then
    Set GFWH_released = GFWH_active
    For t = t_0 to ∞
        If ΔGFWH(t) > 0, Then Set ΔGFWH(t) = 0
        End For
Else if GFWH_on(V) < GFWH_released, Then
    Set GFWH_released = GFWH_on(V)
    Set Y = GFWH_active
    For t = t_0 to ∞
        If ΔGFWH(t) > 0, Then
                Set Y = Y + ΔGFWH(t)
                If Y > GFWH_released, Then Set ΔGFWH(t) = 0
        End If
    End For
End If
```

5. Check that $GFWH_{active}$ remains meaningful at each simulated time step:

If $GFWH_{active} > 1$, Then Set $GFWH_{active} = 1$
If $GFWH_{active} < 0$, Then Set $GFWH_{active} = 0$

Table 1. Parameters Defined for the Simulation Model.

t	Time
t_0	Present time
DeltaT	Time step
$t_{d\text{-}off}$	Time delay before a GFA water heater load is turned off —A GFA water heater will trigger but will not inactivate its load until after this delay period. If voltage recovers greater than the recover voltage of this GFA water heater device within this delay period, the GFA water heater will un-trigger itself and will not inactivate the load.
$T_{d\text{-}onmin}$	Minimum time delay before a GFA water heater load is released—A GFA water heater will not re-activate its load during this delay. If voltage again falls below the GFA water heater triggering voltage, $V_{GFWHoff}$, within this delay period, the GFA water heater will un-release its load and will leave the load inactive.
$T_{d\text{-}onmax}$	Maximum time delay before a GFA water heater load is released—A GFA water heater will not re-activate its load during this delay. If voltage again falls below the GFA water heater triggering voltage, $V_{GFWHoff}$, within this delay period, the GFA water heater will un-release its load and will leave the load inactive.
TimerTdoff	A GFA water heater timer is designed to record this delay. Once the timer is triggered, unless the voltage recovers over the V_{GFWHon}, the timer will not be reset.
TimerTdon	A GFA water heater timer is designed to record this delay. Once the timer is triggered, unless the voltage recovers over the V_{GFWHon}, the timer will not be reset.
N_timer	Number of timer sets for the aggregated GFA water heater load model
GFWHST	GFA water heater states
GFWH State (-1)	GFA water heater untriggered and not activated
GFWH State (0)	GFA water heater triggered and activated
GFWH State (1)	GFA water heater triggered but not yet activated
GFWH State (2)	GFA water heater partially released
Vtth1	1*N_timer matrix; Votlage tripping thresholds upper limits
Vtth2	1*N_timer matrix; Votlage tripping thresholds lower limits
Vrth1	1*N_timer matrix; Recover votlage thresholds upper limits
Vrth2	1*N_timer matrix; Recover votlage thresholds lower limits
GFWHoutput	1*N_timer matrix;GFA water heater outputs. 0 – 1/N_timer
$GFWH_{off}(V)$	Fraction of GFA water heater loads that should be active as voltage decreases.
$GFWH_{on}(V)$	Fraction of GFA water heater loads that should be active as voltage increases.
$GFWH_{untriggered}$	$GFWH_{active}$ less those loads that might have been triggered but not yet inactivated.
$GFWH_{released}$	$GFWH_{active}$ plus those loads that might have been released but not yet re-activated.
$GFWH_{active}$	GFA water heater loads that have not been inactivated. Active loads are those that remain free to draw electric load.

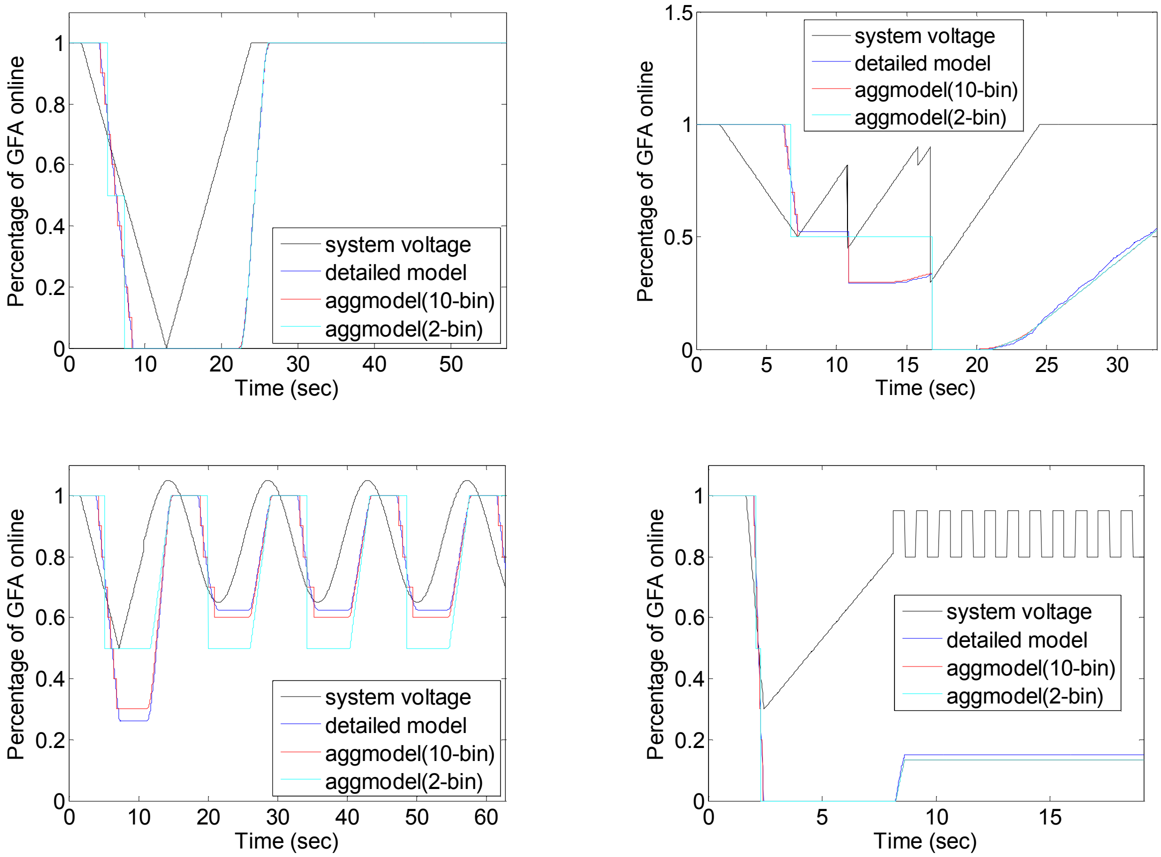


Figure 3. The Responses of the GFA Water Heater Devices under Different Test Voltage Signals for Model Representations that use Different Numbers of Aggregation Bins

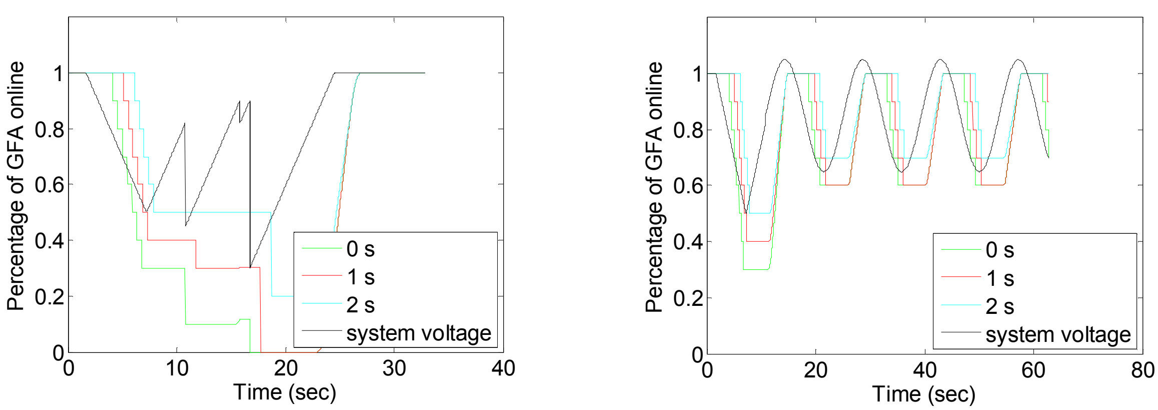


Figure 4. The Responses of the GFA Water Heater Devices under Different Test Voltage Signals for Controllers that Delay before Turning Off their GFA Water Heater Load

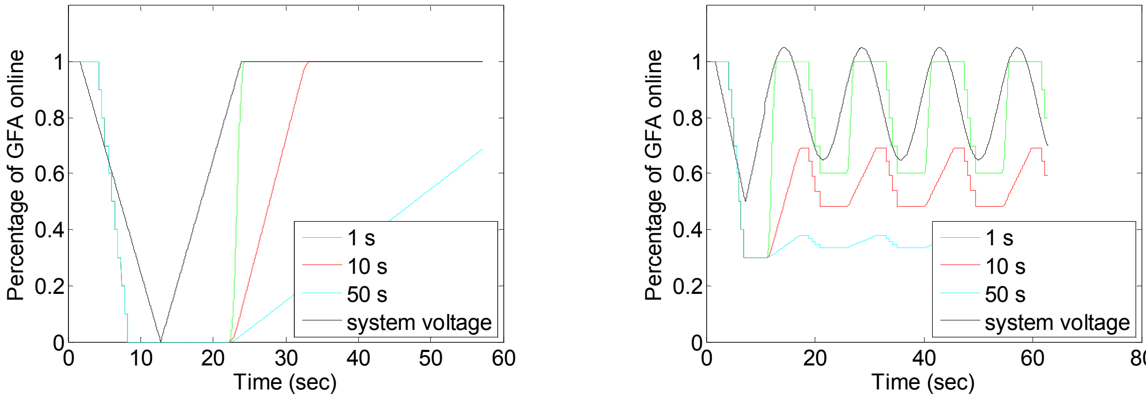


Figure 5. The Responses of the GFA Water Heaters under Different Test Voltage Signals when Different Delays are Imposed Prior to the Release of the GFA Water Heater Curtailments

The modeling results are shown in

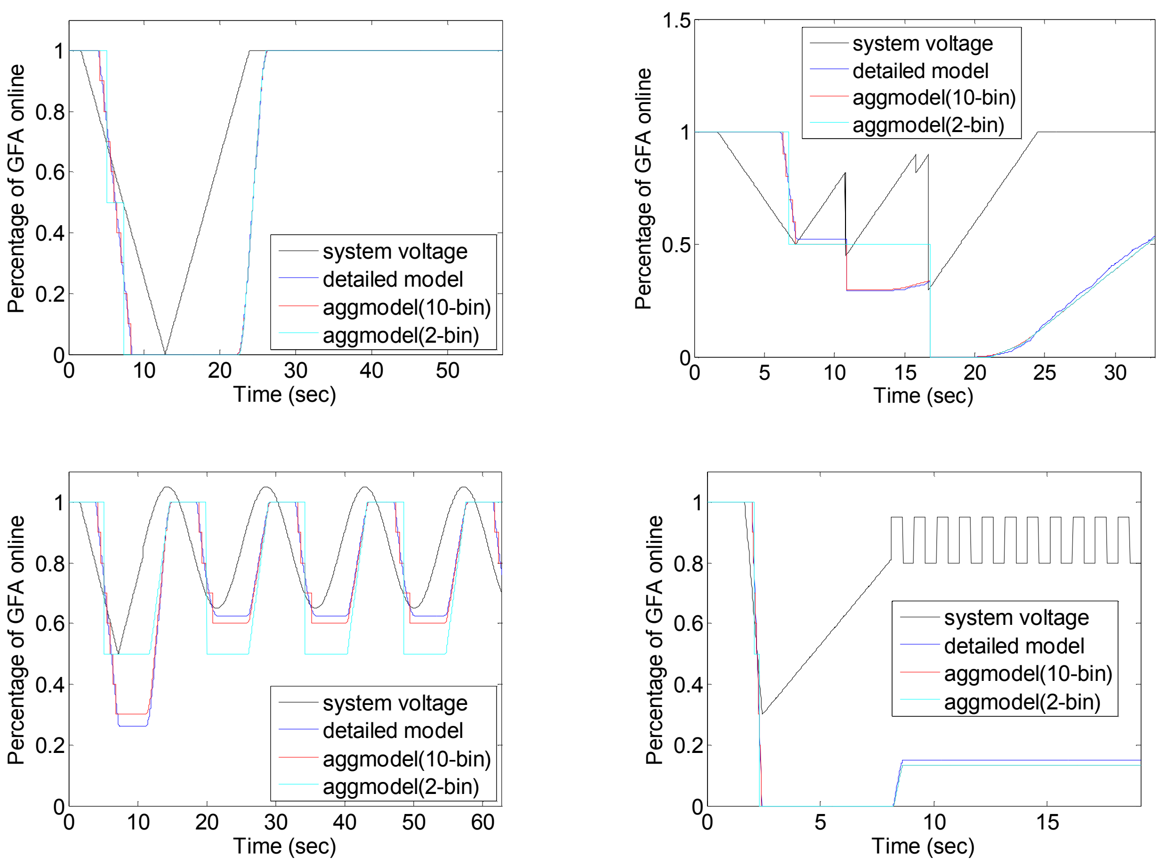


Figure 3 and Figure 4.

Observed for following:

- The simulation results become more accurate when more aggregation bins are used (Figure 3)
- Because of discretization, there are inaccuracies in the simulated fraction of active GFA water heaters when comparing the aggregated model against the ideal model that does not use aggregation bins (Figure 3)
- With different turn-off delays, the GFA water heaters will be taken offline at different times (Figure 4)
- With different distributions of turn-on delays, the GFA water heaters will again become active at different times and rates (Figure 5). A longer distribution of turn-on delays avoids frequent reaction of the GFA water heater controller during a single event. The GFA water heaters will be then cycled on and off less frequently.

Therefore, we conclude that

- The aggregated model is based on statistic performance of individual models. If properly designed, the modeling of GFA water heater populations using aggregation bins matches the detailed model well.
- The more bins in the aggregated model, the better the results agree with the detailed model. 5-10 bins are recommended to balance the conflicting needs for computational speed and model accuracy.

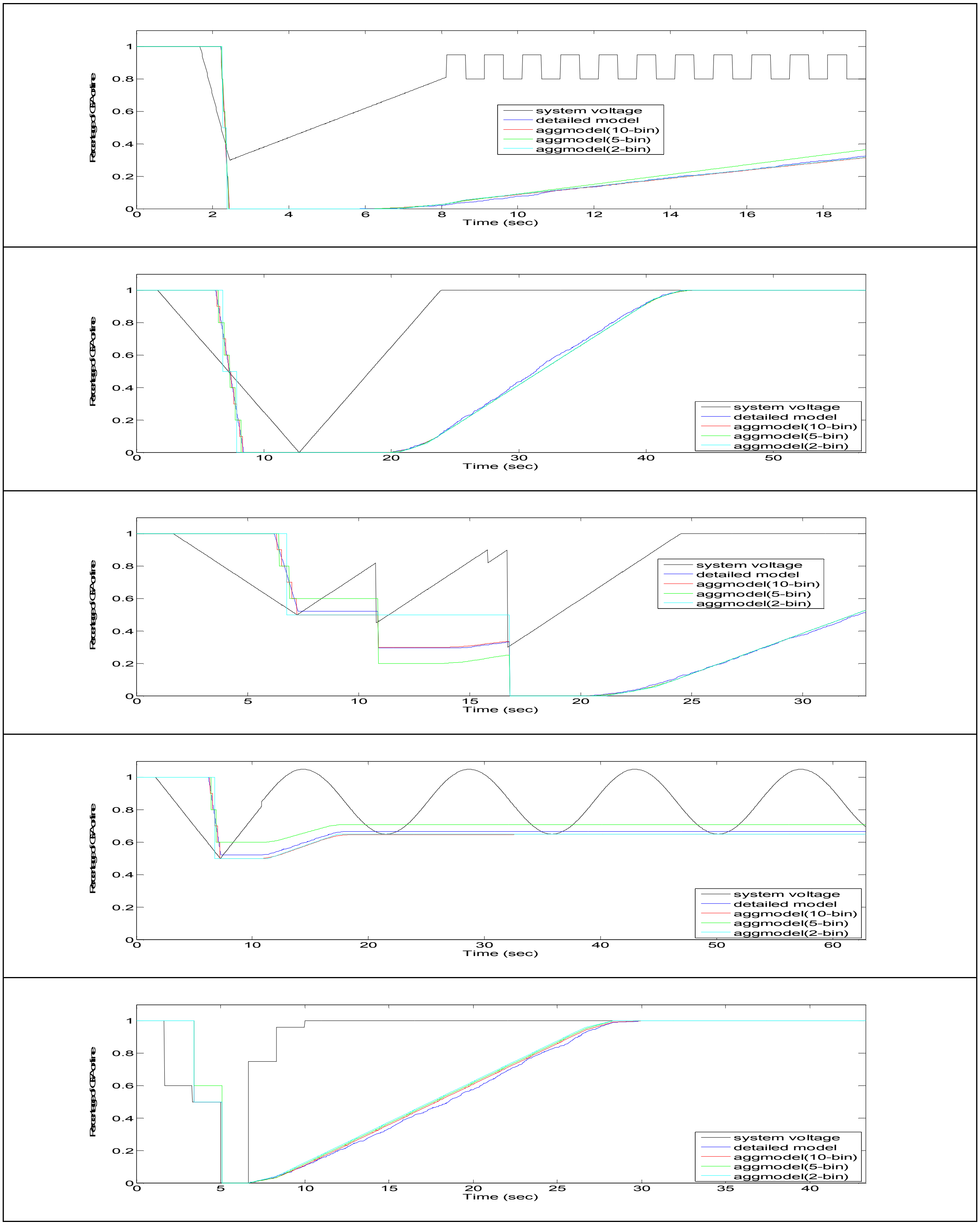


Figure 6. The Influence of the Number of Bins on GFA Water Heater Under-Voltage Responses

2.2 PSLF simulation

The control logic having been tested by MATLAB code, it was then implemented using an EPCGEN model coded in EPCL. The EPCGEN model descriptions are shown in Figure 7. By inputting the same voltage signals, a comparison between the EPCGEN and the MATLAB modeling results was performed. Some of the results of this comparison are shown in Figure 8. The results show that the EPCGEN model produces the same results as in MATLAB simulation.

```
/************** Model comments and data description follow *******************

Sample input data record:

Input Data:
    Iterface:
        .rsrc     Armature resistance (p.u.)
        .xsrc     Subtransient reactance (p.u.)
        .tv       Voltage Input time constant                                   (default = 0.0)
        .tf       Frequency Input time constant                                 (default = 0.0)
    GFA Waterheater Model:
        .GFALF    GFA loading factor, per unit of rated current                 (default = 1.0)
                  If ".GFALF" is zero, it is computed during the initalization
                  If ".GFALF" is greater than zero, generator MVA base is adjusted
        .GFAPF    GFA power factor at 1.0 per unit voltage                      (default = 1.0)
        .Vtth1    GFA tripping voltage max                                      (0.85 pu)
        .Vtth2    GFA tripping voltage min (Below which all GFA will be tripped) (0.70 pu)
        .Vrth1    GFA restore voltage max                                       (0.95 pu)
        .Vrth2    GFA restore voltage min                                       (0.86 pu)
        .Tdonmin  GFA minimum reclose delay                                     (0 sec  )
        .Tdonmax  GFA maximum reclose delay                                     (60 sec )
        .Tdoff    GFA tripping delay                                            (1 sec  )
        .nBins    Number of Control Groups                                      (10     )
.

        Internal Parameters:
                epcgen[@mx].v0  - utility voltage, per unit
                epcgen[@mx].v1  - utility frequency, per unit
                epcgen[@mx].v2  - GFA real power, MW
                epcgen[@mx].v3  - GFA reactive power, MVAR
                epcgen[@mx].v4  - GFA current, per unit on machine MVA
                epcgen[@mx].v5  - GFA real power, per unit on GFA MVA
                epcgen[@mx].v6  - GFA reactive power, per unit on GFA MVA
                epcgen[@mx].v7  - GFA current, per unit on GFA MVA
                epcgen[@mx].v8  - Under voltage relay output total, per unit
                epcgen[@mx].v9  - time at which the model was called previous time
                epcgen[@mx].v10 - shunt reactive power, per unit on ac unit MVA
                epcgen[@mx].v61 - shunt value in per unit, computed during the initalization
                epcgen[@mx].v71 - real component of voltage at pervious step
                epcgen[@mx].v72 - reactive component of voltage at previous step

                epcgen[@mx].v11 - Bin 1: Under voltage relay status
                                  (Active (-1);Inactive (0);Triggered (1);Released(2))
                epcgen[@mx].v12 - Bin 1: Output, per unit
                epcgen[@mx].v13 - Bin 1: GFATTdoff  triggering timer
                epcgen[@mx].v14 - Bin 1: GFATTdon  release timer
                epcgen[@mx].v15 - Bin 1: TTdonmin  release timer minimum
                ....
                epcgen[@mx].v16 - Bin 2: Under voltage relay status
                ....
                epcgen[@mx].v21 - Bin 3: Under voltage relay status
                ....
                epcgen[@mx].v26 - Bin 4: Under voltage relay status
                ...
                epcgen[@mx].v31 - Bin 5: Under voltage relay status
                ...
                epcgen[@mx].v36 - Bin 6: Under voltage relay status
                ....
                epcgen[@mx].v41 - Bin 7: Under voltage relay status
                ....
                epcgen[@mx].v46 - Bin 8: Under voltage relay status
                ...
                epcgen[@mx].v51 - Bin 9: Under voltage relay status
                ...
                epcgen[@mx].v56 - Bin 10: Under voltage relay status


                 States:
                        epcgen[@mx].s0  - utility voltage, per unit
                        epcgen[@mx].s1  - utility frequency, per unit
```

Figure 7. The Inputs, Internal Parameters, and the States of EPCGEN Model for the Water Heater Controller

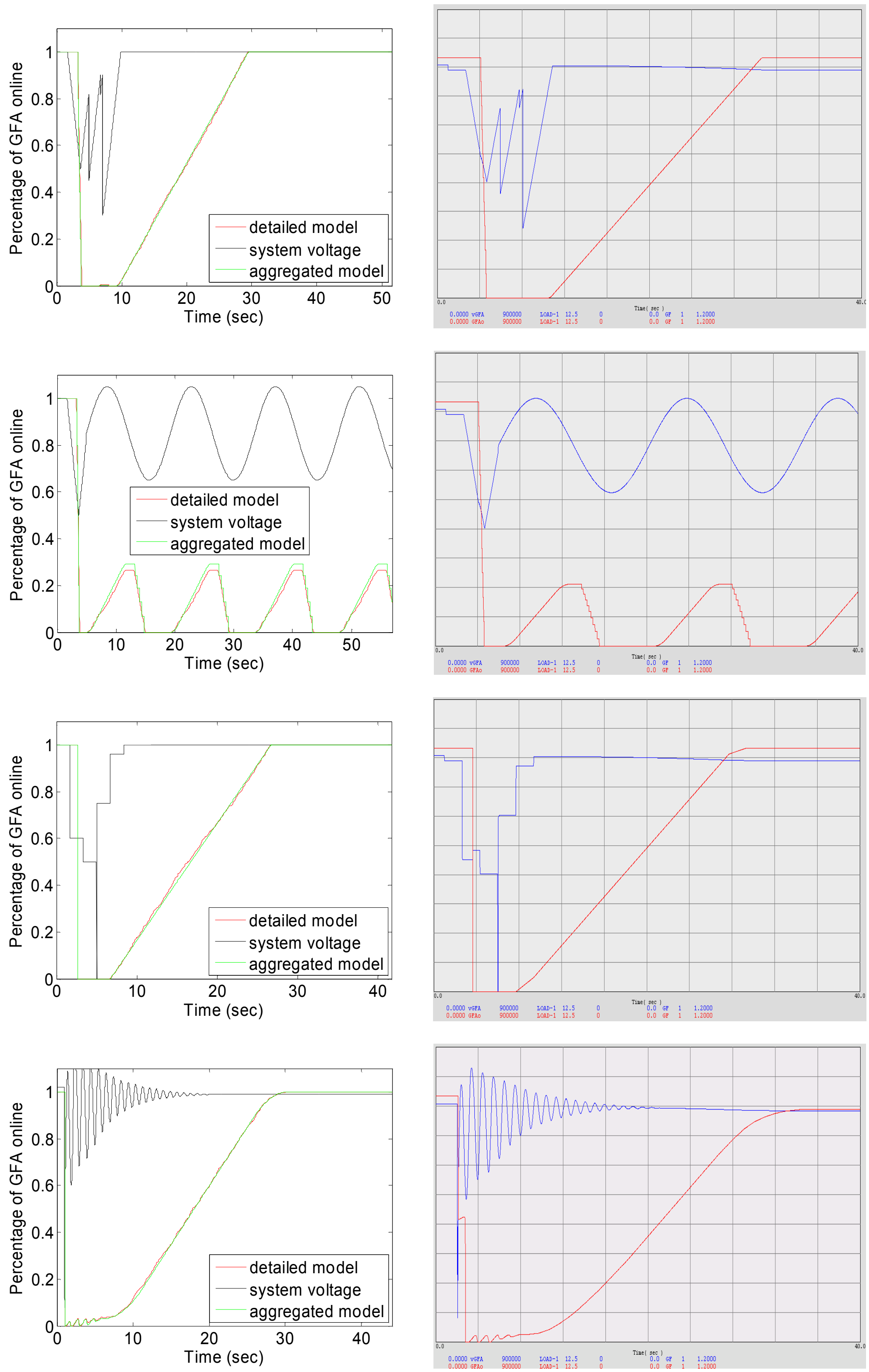


Figure 8. A Comparison of the Modeling Results between the MATLAB Model (Left) and the EPCGEN Model (Right)

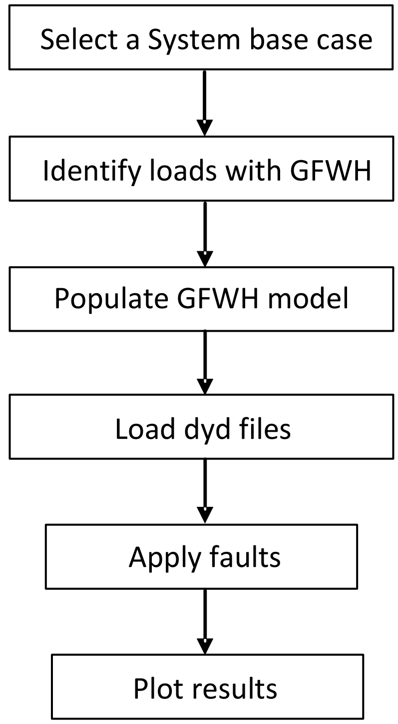


Figure 9. A Flow Chart of the PSLF Modeling Process

2.3 A Three-feeder Test Case

A three-feeder test bed of Figure 10 was used to examine the basic characteristics of the water heater under-voltage response. The generator plays back voltage signals, and the distribution feeders supply four types of loads: the motor load, air conditioner motor load, water heater load and other ZIP loads.

2.3.1 Voltage Sags

In the first case, we tested the GFA water heater response to the voltage sags. The voltage response when there are 30% 3-phase motor, 10% 1-phase a/c motor, 0~20% water heater load are shown in Figure 11. The rest of the loads are represented by ZIP load. The results show that 10% water heater load can only influence the voltage on the magnitude of 0.05 p.u.. Another simulation is done for the case of 10% 3-phase motor and 0~30% water heater load. The results are shown in Figure 16. The rest of the loads are represented by ZIP loads.

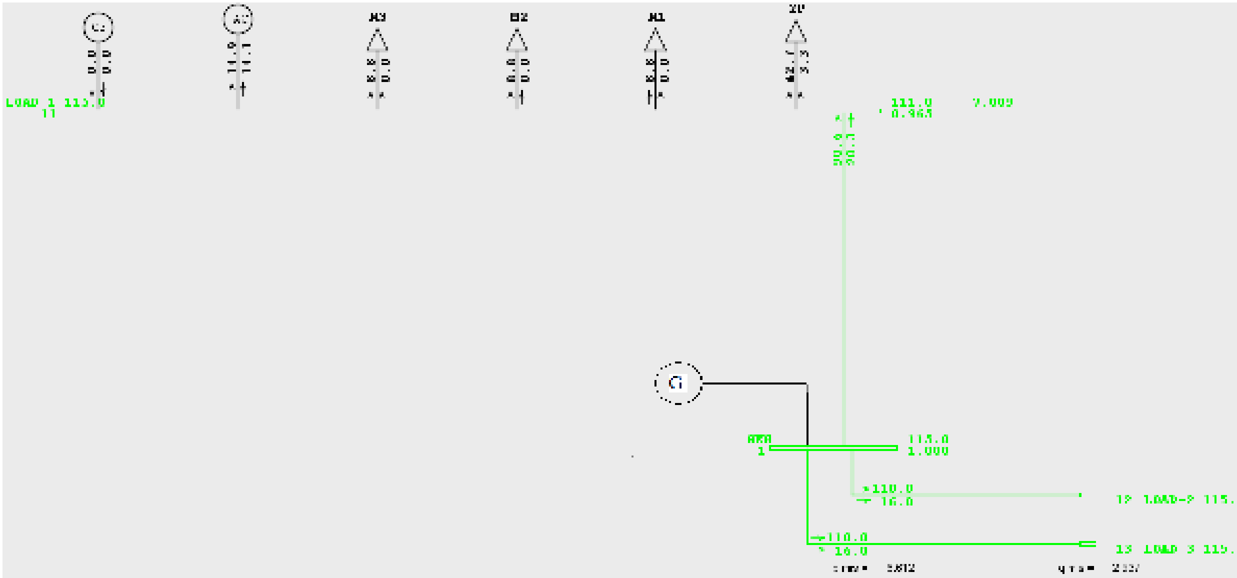


Figure 10. A Three-Feeder Test Bed

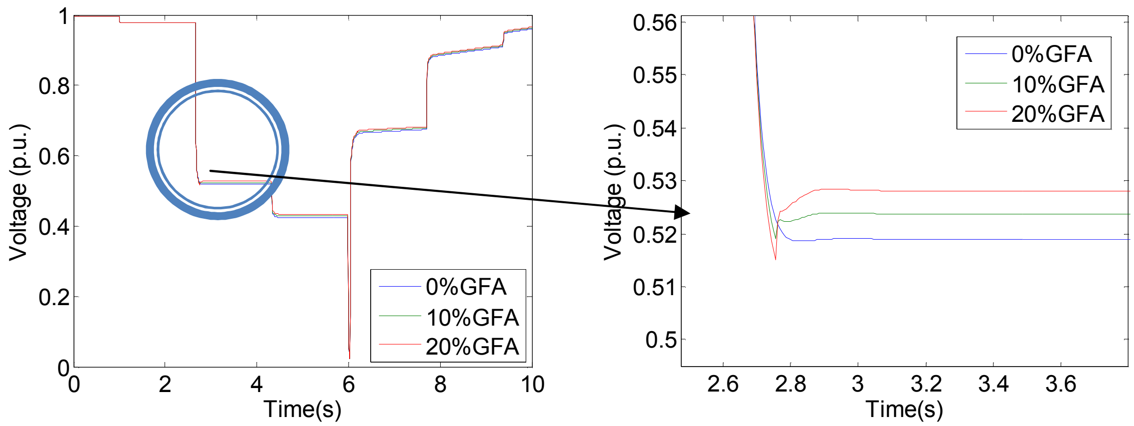


Figure 11. Voltage Response the GFA Water Heater Load

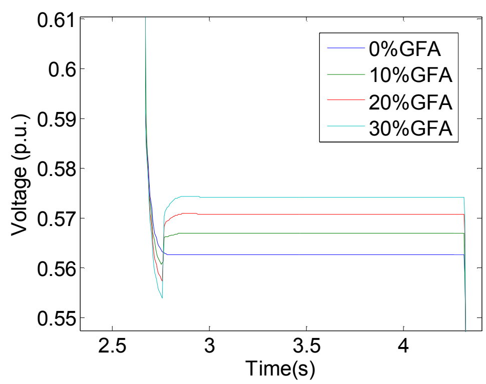


Figure 12. Voltage Response of the GFA Water Heater Load on a System having 10% 3-Phase Motor Load

2.3.2 Slow Voltage Recovery Phenomena

Assume that 40% of the feeder loads are single-phase a/c loads and 20% are 3-phase motor loads that can restart when voltage recovers. As shown in Figure 13, assuming GFA water heater loads consist of 10% to 30% of the feeder load, the slow voltage recovery process has not been improved much. This is because a/c motors stall, at which time they draw much greater current than water heater loads. Therefore, taking water heater loads offline will only slightly reduce the feeder current. As a result, the voltage only recovers 0.4% higher when there is 10% reduction of the GFA water heater load.

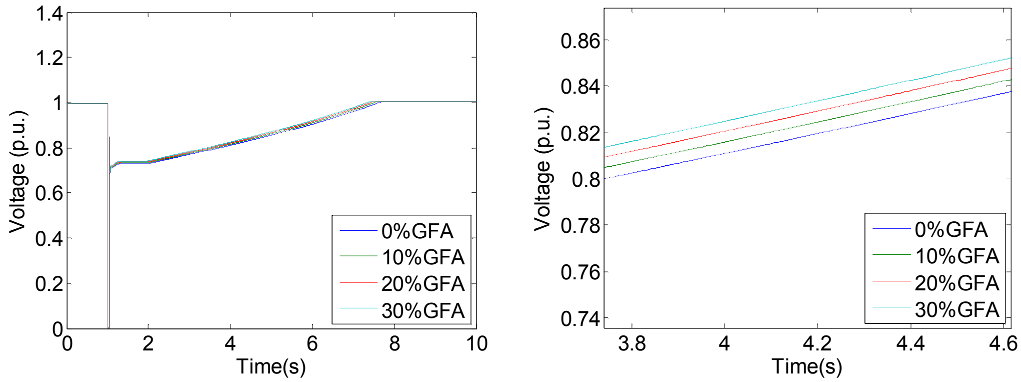


Figure 13. Voltages at Bus 11 with 40% A/C Load and Different Penetrations of GFA Water Heaters

2.4 The Fairview Event

Fairview test case was then used to model the impact of using the Grid Friendly^{TM} controller for water heater under-voltage load shed. The following types of loads are not considered:

"DC" "SS" "CO" "F " "FS" "I " "S " "SS" "W " "F1" "F2" "F3" "F4" "F5" "P "

Only loads that are in Zone 40 (Zone 402, owner 55), greater than 2.5 MW, and above 30 kV, are considered. Change the report level from #9 to #2 so that there is enough memory to record the output reports. Seven loads in the Fairview transmission grid can be modified to test the influence of the different GFA water heater penetration levels, as shown in the system diagram of the Fairview area in Figure 14. The simulation results are shown in Figure 15 and Figure 16.

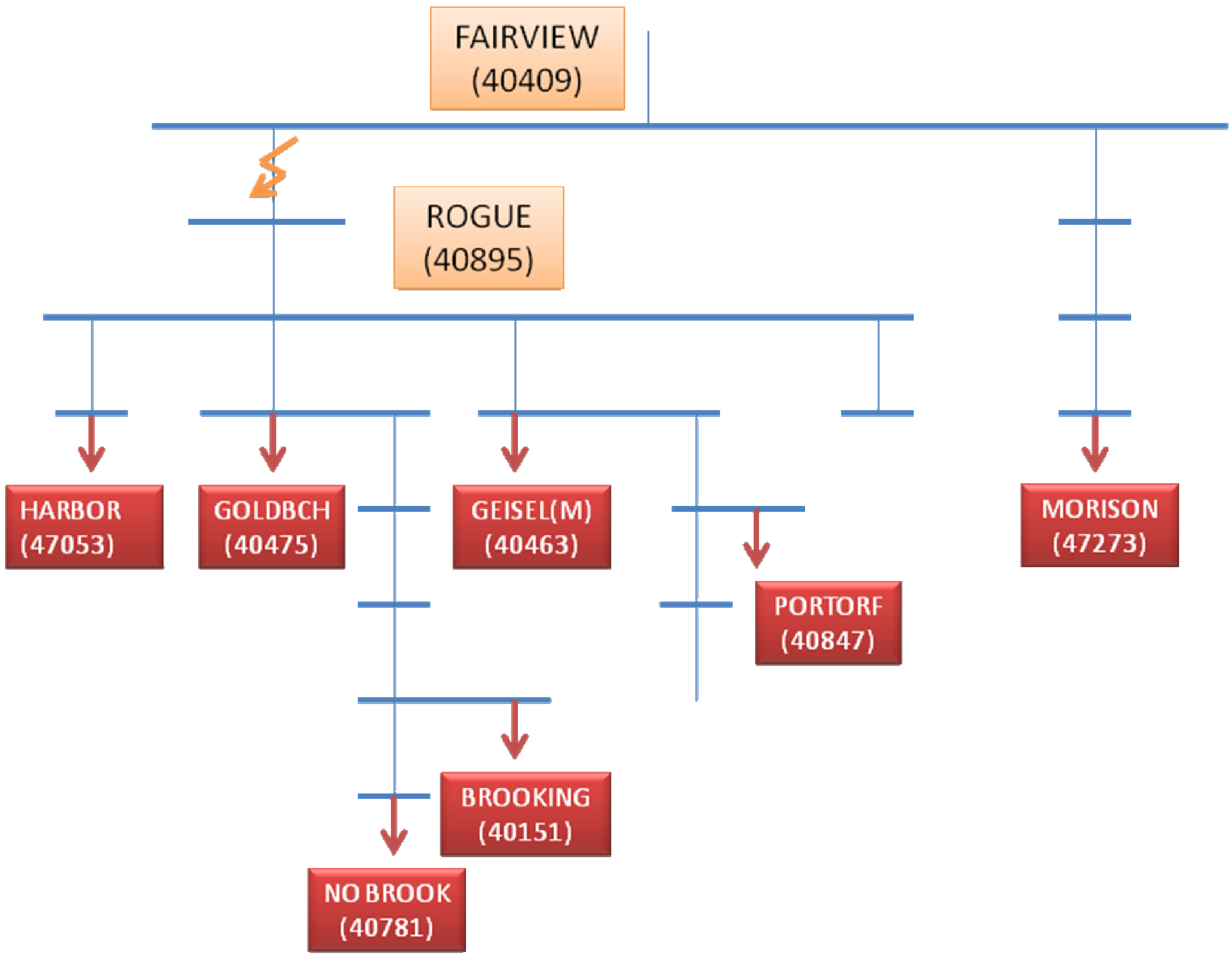


Figure 14. The One-Line Diagram of the Fairview Area

2.4.1 Modify Load on Bus 40151

In the first case, only the load on Bus 40151 was modified so that 10% and 30% of the total load was the GFA water heater load respectively. As shown in Figure 15 and Figure 16, the GFA water heater can help the recovery of the system voltage and frequency to some extent. However, as shown in Figure 17, if the system contains many 1-phase air conditioners (a/c), which will stall during voltage sag, then the curtailment of the GFA water heater load is not going to accelerate the voltage recovery process. The voltage simply recovers to a slightly higher voltage at the feeder head. This is because when an a/c motor stalls, it draws a huge amount of current, which causes the voltage to drop. Unless the stalled motors are taken off line, the slow voltage recovery process will not be shortened.

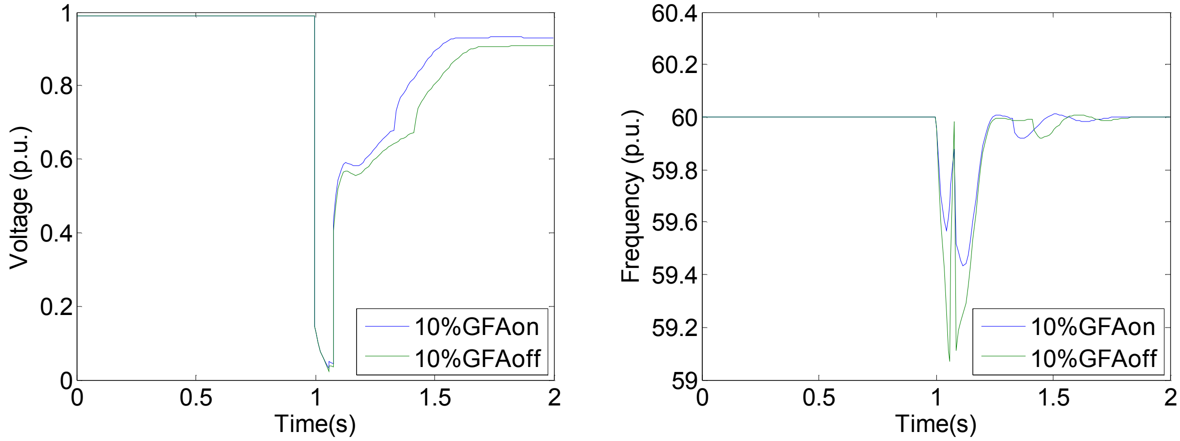


Figure 15. The Voltage and Frequency Profiles on Bus 40895 for 10% GFA Water Heater Penetration and 18% 3-Phase Motor Case. (On: GFA Load is Active; Off: GFA Load is Inactive)

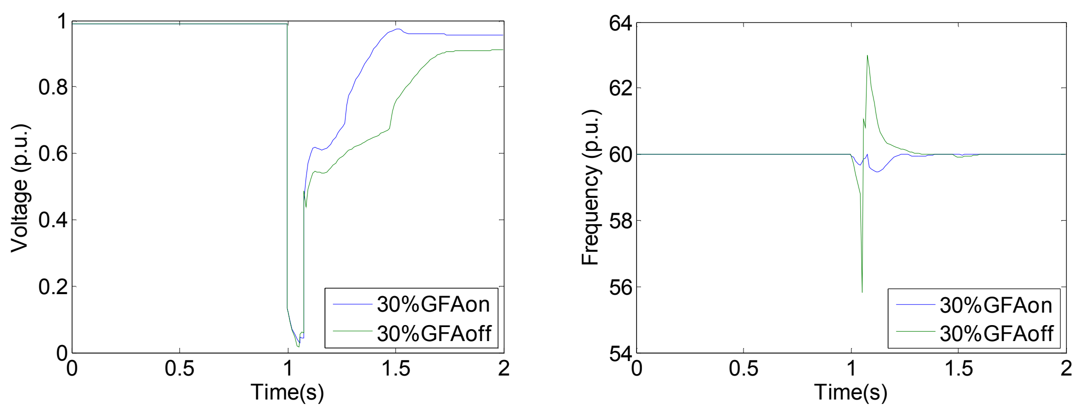


Figure 16. The Voltage and Frequency on Bus 40895 for 30% GFA Water Heater Penetration and 18% 3-Phase Motor Case. (On: GFA Load is Active; Off: GFA Load is Inactive)

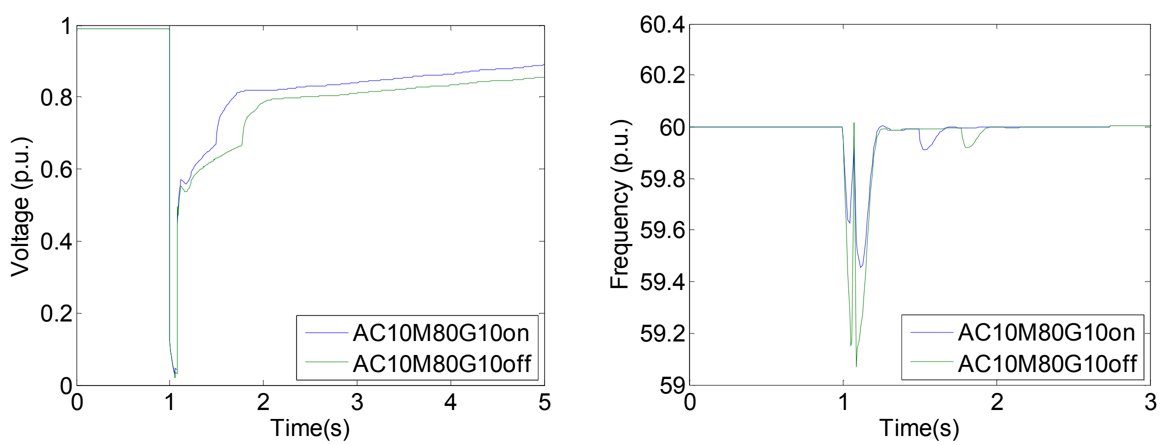


Figure 17. The Voltage and Frequency on Bus 40895 for 10% GFA Water Heater Penetration, 10% 1-Phase Air Conditioner, and 16% 3-Phase Motor. (On: GFA Load is Active; Off: GFA Load is Inactive)

2.4.2 Modify Load on all Seven Buses

In the second case, all the seven bus loads in the area were modified. As shown in Figure 18, the voltage will sag lower than when only one bus load contains a/c motor load. Again, the GFA water heater load, though improving the voltage up a little, is not able to make the voltage recover to the nominal value. Figure 19 shows the voltage and frequency plot when under-voltage relays are implemented to take the a/c motors offline when they stall. As seen in the plots, the voltage recovered rapidly once the stalled a/c motors were taken offline. However, the frequency plots show that the GFA water heater load, because of its rapid response, can result in a faster recovery of the system frequency.

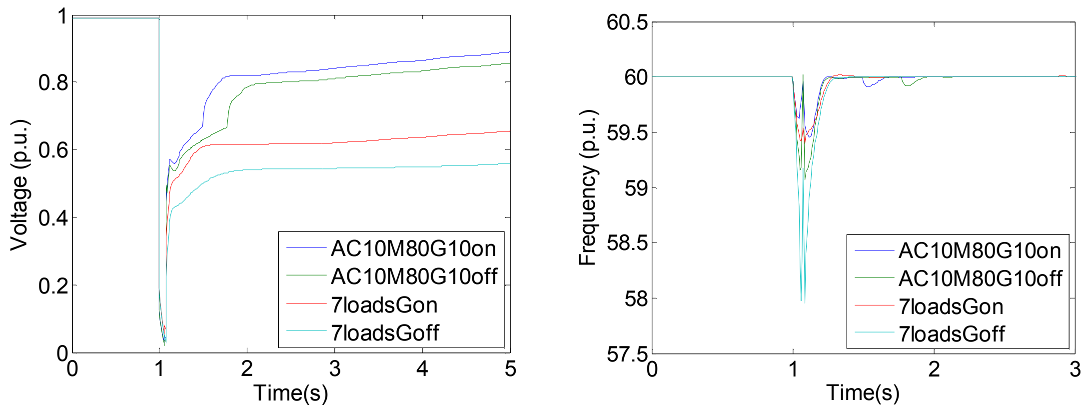


Figure 18.The Votage and Fequency Pofiles on Bus 40895 for 10% GFA Wter Heater Penetration, 10% 1-Phase Air Conditioner, and 16% 3-Phase Motor when all the 7 Bus Loads are Modified. (AC10M80G10on/off: Only Load at Bus 40151 has been Modified; 7loadsGon/off: All the 7 Bus Loads in the FAIRVIEW System have been Modified)

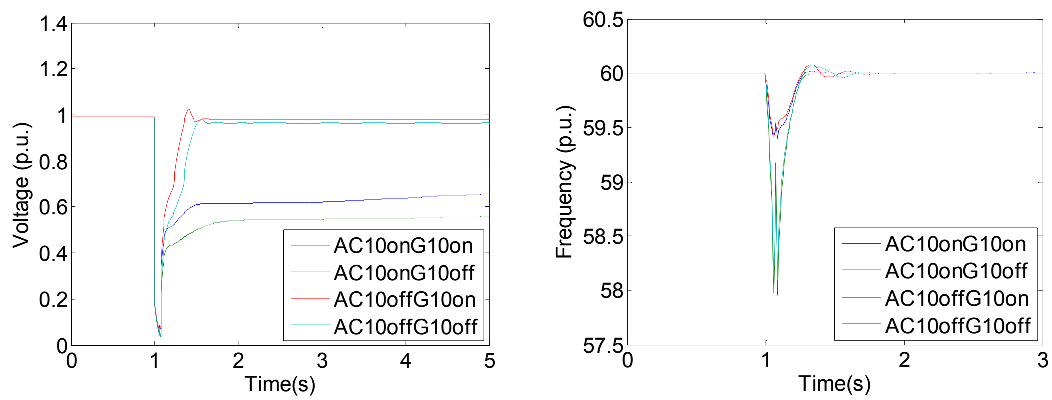


Figure 19. The Voltage and Frequency on Bus 40895 for 10% GFA Water Heater Penetration, 10% 1-Phase Air Conditioner, and 16% 3-Phase Motor when All the 7 Bus Loads have been Modified and A/C Protection scheme has been Implemented. (AC10on: A/C Load with Under-Voltage Protection. AC10off: the A/C Load without Under-Voltage Protection.)

2.4.3 Conclusions Concerning the System Benefits of Under-Voltage-Responsive GFA Water Heaters

From the above discussion, we conclude that

- The GFA water heater load can help the system voltage to recover depending on the penetration of the a/c motor load. If a/c motors stall, then the best way to recover the system voltage is to take the stalled motors offline rapidly.

- GFA water heater load can help the system frequency recover if it is set to be tripped to respond to voltage sags.

2.4.4 EPCL Code Set Description

These parameters are set in the *ini files.

1) 0_motor.ini: Define the load composition and the GFA model parameters, as shown in Figure 20.

```
#Case 1
#MAcomp MBcomp  MCcomp  MDcomp  MGFA    *.CHF       Vtth1   Vtth2   Vrth1   Vrth2   Tdonmin Tdonmax Tdoff   nBins   a/cTtr1 a/cFtr1
0.9     0.      0.      0.      0.1     AM9G1on     0.85    0.7     0.95    0.86    60      300     0.1     10      0.2     1.0
0.9     0.      0.      0.      0.1     AM9G1of     0.001   0.0001  0.95    0.86    60      300     0.1     10      0.2     1.0
0.7     0.      0.      0.      0.3     AM7G3on     0.85    0.7     0.95    0.86    60      300     0.1     10      0.2     1.0
0.7     0.      0.      0.      0.3     AM7G3of     0.001   0.0001  0.95    0.86    60      300     0.1     10      0.2     1.0
0.8     0.      0.      0.1     0.1     AG1onAC1on  0.85    0.7     0.95    0.86    60      300     0.01    10      0.2     1.0
0.8     0.      0.      0.1     0.1     AG1ofAC1on  0.85    0.7     0.95    0.86    60      300     5       10      0.2     1.0
0.8     0.      0.      0.1     0.1     AG1onAC1of  0.85    0.7     0.95    0.86    60      300     0.01    10      999     1.0
0.8     0.      0.      0.1     0.1     AG1ofAC1of  0.85    0.7     0.95    0.86    60      300     5       10      999     1.0
```

MAcomp	MBcomp	MCcomp	MDcomp	MGFA	*.CHF	Vtth1	Vtth2	Vrth1	Vrth2	Tdonmin	Tdonmax	Tdoff	nBins	a/cTtr1	a/cFtr1
0.9	0	0	0	0.1	AM9G1on	0.85	0.7	0.95	0.86	60	300	0.1	10	0.2	1
0.9	0	0	0	0.1	AM9G1of	0.001	0.0001	0.95	0.86	60	300	0.1	10	0.2	1
0.7	0	0	0	0.3	AM7G3on	0.85	0.7	0.95	0.86	60	300	0.1	10	0.2	1
0.7	0	0	0	0.3	AM7G3of	0.001	0.0001	0.95	0.86	60	300	0.1	10	0.2	1
0.8	0	0	0.1	0.1	AG1onAC1on	0.85	0.7	0.95	0.86	60	300	0.01	10	0.2	1
0.8	0	0	0.1	0.1	AG1ofAC1on	0.85	0.7	0.95	0.86	60	300	5	10	0.2	1
0.8	0	0	0.1	0.1	AG1onAC1of	0.85	0.7	0.95	0.86	60	300	0.01	10	999	1
0.8	0	0	0.1	0.1	AG1ofAC1of	0.85	0.7	0.95	0.86	60	300	5	10	999	1

Figure 20. An Example of the **0_motor.ini** File

2) **ExtractAreaLoad.ini**: The extract buses information are defined in this file. An example is shown as follows:

```
OUTPUT FILE
"Model Database.csv"
ZONE
402
AREA
40
BUS
ALL
OWNER
55
EXCLUDE ID'S
"DC" "SS" "CO" "F " "FS" "I " "S " "SS" "W " "F1" "F2" "F3" "F4" "F5" "P "
MW THRESHOLD
4
KV THRESHOLD
30.0
```

MIN KV FOR TRANSFORMER
40.0
DEFAULT DATA FILE
"Default Data.ini"

3) Output0_plot.ini: define the output file names and channel names, as shown in Figure 21.

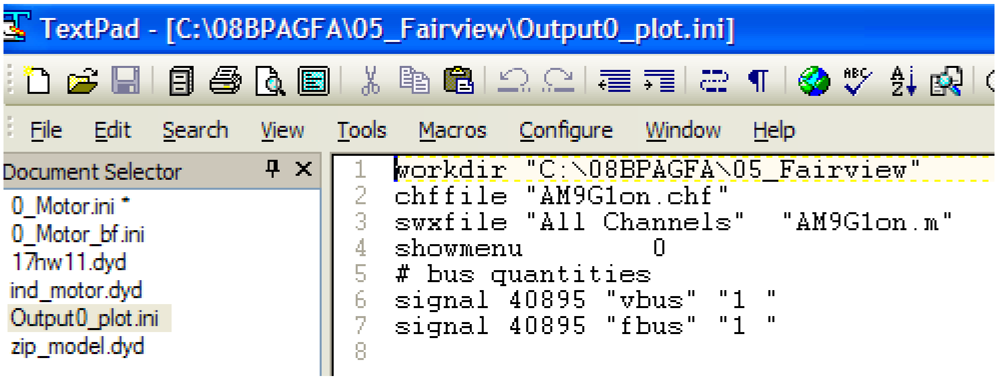


Figure 21: An Example of Output0_plot.ini

The EPCL codes used to populate the model are:

ST1_ExtractAreaLoad.p
ST0_LoadComposition.p

A batch file **BATCH_multicase.p** is created to run the scenarios, as shown in Figure 22.

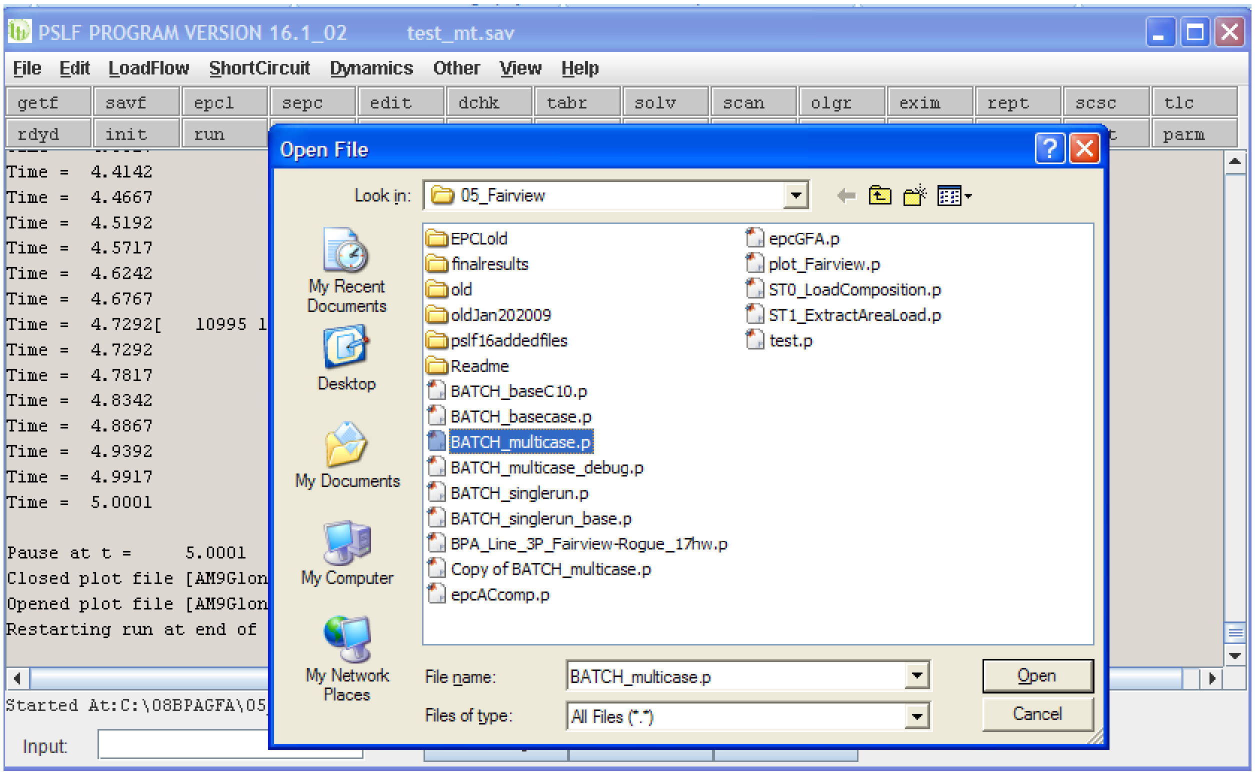


Figure 22. An Example of Running the **BATCH_multicase.p** File

4) A EPCL batch file **plot_Fairview.p** is created to output the data out to *.mat files. It needs to be run in PSLF POLT, as shown in Figure 23.

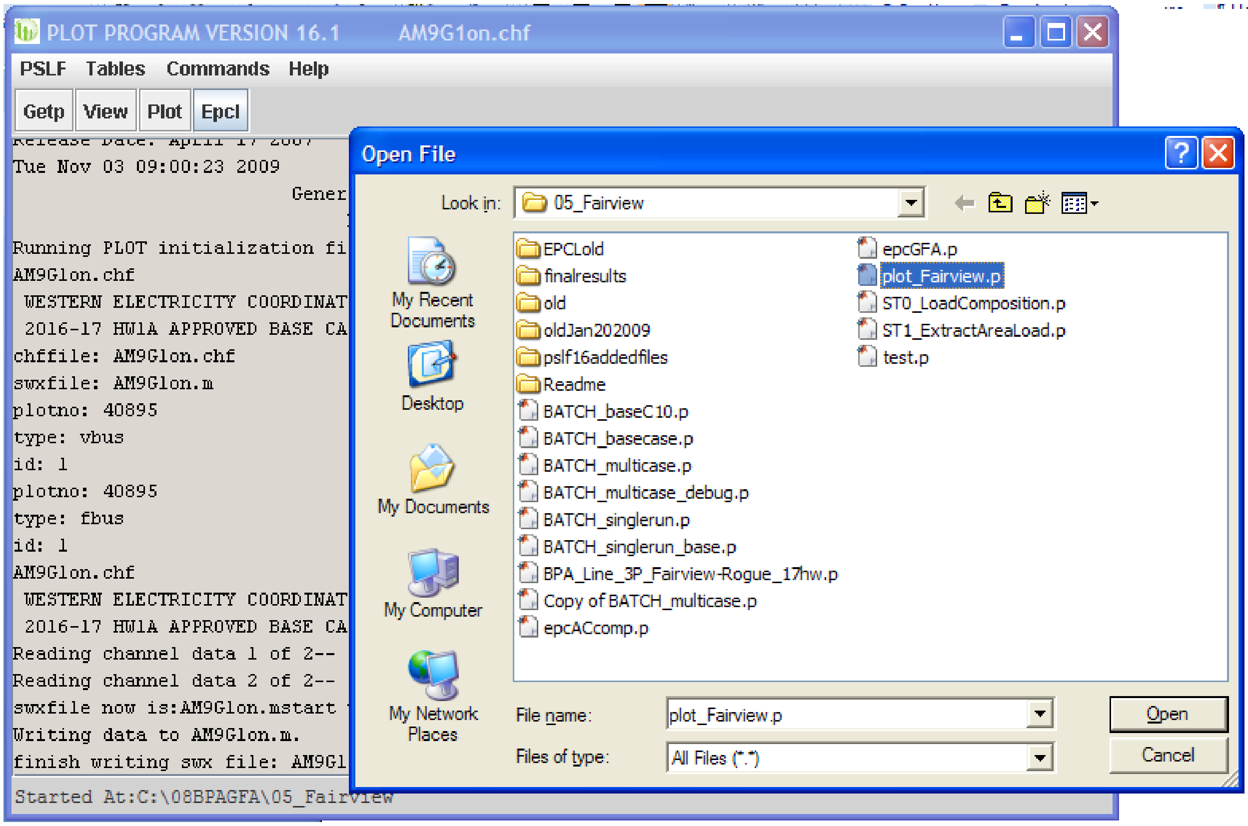


Figure 23: An Example of Running the File **plot_Fairview.p**

3.0 Underfrequency-Responsive GFA Water Heaters

Two models were created in MATLAB, to simulate the likely response of a collection of GFA water heaters to underfrequency events on the power grid. One model has a higher degree of accuracy, modeling the behaviors of many independent controllers, while the second model can be simulated more quickly, modeling a large population's behaviors by using a limited number or representative bins. In this study, the two models' responses to an array of different system frequency signals are compared. The result is that the performance of the more quickly simulated GFA response model closely follows the performance of the highly realistic model.

GFA water heaters can turn off in order to decrease the demand on the power grid, and thus are a possible means of keeping the frequency of the grid from declining. When the demand on the grid is decreased, the frequency of the grid recovers or increases. The goal of underfrequency-responsive GFA water heaters is to keep the power grid's frequency near 60 Hz when events threaten system frequency. In addition to keeping the power grid's frequency at a reasonable value, minimal inconvenience to the user is also a primary goal.

3.1 Introduction to the Underfrequency-Responsive GFA Water Heater

Two models were created in MATLAB, to simulate the likely response of a collection of GFA water heaters to underfrequency events on the power grid. The logic in these models almost identical to the logic used to simulate GFA water heater responses to under-voltage events. The detailed model is the baseline experimental model, which the aggregate model is tuned to match. The detailed model is more accurate than the aggregate model, but the aggregate model takes less time to compute simulations.

Each model receives as input a pre-specified, realistic frequency signal, as well as the following pre-specified parameters:

- numbers of GFA water heaters
- number of bins to be used in the aggregate model
- upper frequency threshold for triggering active GFA water heaters to stop operation
- lower frequency threshold for triggering active GFA water heaters to stop operation
- upper frequency threshold for releasing inactive GFA water heaters to resume operation
- lower frequency threshold for releasing inactive GFA water heaters to resume operation
- time delay between when active GFA water heaters are triggered (by low frequency) to stop operation and when the GFA water heater actually turns off
- minimum time delay between when inactive GFA water heaters are released (by high enough frequency) to resume normal, uncurtailed operation and when they actually turn on
- maximum time delay between when inactive GFA water heaters are released (by high enough frequency) to resume operation and when they actually turn on

Nine different types of system frequency signal events were formulated to test the model's responses. These signals were intended to be realistic in both duration and magnitude of underfrequency events that could occur on the power grid. The time duration of each simulation varies, but each is approximately one minute long. The system frequency signals were fed into MATLAB subroutines, one subroutine for each of the two GFA water heater behavior model types – detailed and aggregated.

The structure of the MATLAB program files and their names are as follows:

- GFA_response_to_frequency_events.m
    - subroutine_plot_detailed_GFA_models.m
        - subroutine_generate_detailed_GFA_models.m
    - subroutine_plot_aggregate_GFA_models.m
        - subroutine_generate_aggregate_GFA_models.m

Both the aggregate and detailed GFA model subroutines allow GFA water heaters to be in one of the following four states: active, inactive, triggered, and released.

- Active—all GFA water heaters in the bin are active (fully on)
- Inactive—all GFA water heaters in the bin are inactive (fully off)
- Triggered—at least one GFA water heater in the bin has been triggered, although others may remain inactive; all GFA water heaters in the bin will turn off after the bin's turn-off timer reaches its threshold
- Released—at least one GFA in the bin has been released to resume normal operation, although others may be active; all GFA water heaters in the bin will turn on after the bin's turn-on timer reaches its threshold.

The frequency thresholds were selected so that, when viewing the percent of active GFA water heaters as a function of power grid frequency, a quadrilateral-shaped hysteresis loop is formed. Therefore, the difference between the upper and lower frequency thresholds to trigger active GFA water heaters to stop operation is the same as the difference between the upper and lower frequency thresholds for releasing inactive GFA water heaters to resume operation.

Because there are not yet standards for the assignment of underfrequency thresholds for demand-side devices, engineering judgment is allowed. The thresholds are assignable variables for the purposes of simulation. The efforts here were focused on the model response, regardless of the specific thresholds. In the authors' opinions, the underfrequency curtailment thresholds should be distributed throughout a range above a region's highest remedial action scheme (RAS) threshold and the bottom of the normal frequency distribution, say 59.94 Hz. Because GFA water heaters often may be curtailed without causing any discomfort to any utility customer, there is little harm done if some of the GFA water heaters recognize and respond to shallow, non-emergency, frequency excursions. The GFA water heaters should be considered the first resource called upon in a RAS scheme.

3.2 The Detailed Underfrequency-Responsive Model

The detailed GFA behavior model has a few key differences from the aggregate model, which differences will be described below.

All GFA water heaters are initially set to the active state, and the turn-off and turn-on delay timers are set to zero for each GFA. The curtailment trigger frequency for each individual GFA water heater is set to a unique number between the upper frequency threshold and lower frequency threshold. (If there were to be 1,000 GFA water heaters in the model, then there would be 1,000 different trigger frequencies, one for each GFA.) All GFA trigger frequencies are evenly distributed between these upper and lower limits.

In the same manner, the release frequency for each GFA water heater is set to a unique number between the upper frequency threshold and lower frequency threshold for releasing curtailed GFA water heaters to resume their operation. All GFA release frequencies are evenly distributed between these pre-specified upper and lower limits.

There are three different situations simulated for each of the detailed models. As were the test cases for the aggregate model, each of these three situations has a different maximum GFA turn-on time delay of 1, 10, and 50 seconds.

Unlike the aggregate model, each GFA water heater in the detailed model is assigned its own bin, which corresponds to its unique turn-on time delay. A random number generator is employed, in order to set the time delay for turning on each GFA. This random number generator is how each individual GFA gets fully turned on at a slightly different time from all the others. The turn-on time delays for the GFA water heaters are evenly distributed between a 0 seconds and the maximum turn-on time delay for the particular simulation (1, 10, or 50 seconds). Even longer time delay periods should be considered in future studies.

After a GFA water heater's trigger (turn-off) or release (turn-on) threshold is reached, that GFA water heater's turn-off or turn-on delay timer begins to run. Once the turn-off (or turn-on) timer reaches the maximum pre-specified threshold, the GFA water heater's status is set to inactive (or active).

The flow diagram of the appendix Figure 27 illustrates the logic used in the detailed GFA model's MATLAB code.

3.3 The Aggregate Underfrequency-Responsive Model

All GFA water heaters in the aggregate model are equally divided into a pre-specified number of bins (e.g., ten). Each bin corresponds to a specific frequency threshold range at which inactive GFA water heaters in that bin are triggered to stop operation, as well as released to resume normal operation.

The frequency range between the upper and the lower frequency thresholds for triggering to stop operation, or releasing inactive GFA water heaters to resume operation, is equally divided into the selected number of bins. The GFA water heaters are equally distributed among the frequency threshold bins. The set of bins necessarily span the entire distribution over which the GFA water heaters curtail or resume their operation. Each bin's threshold frequency is set to be halfway between that bin's upper and lower frequency limits. All bins are initially set to the active state, and the turn-off and turn-on delay timers are set to zero for each bin.

The flow diagram of appendix Figure 28 illustrates the logic used in the aggregate GFA model's MATLAB code.

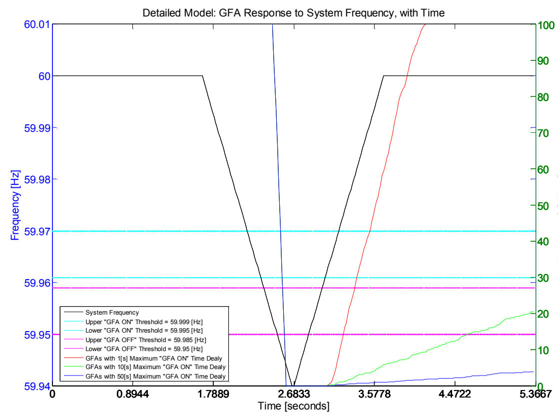
3.4 Results and Analyses from the MAT LAB Simulation of the Underfrequency-Responsive Algorithm

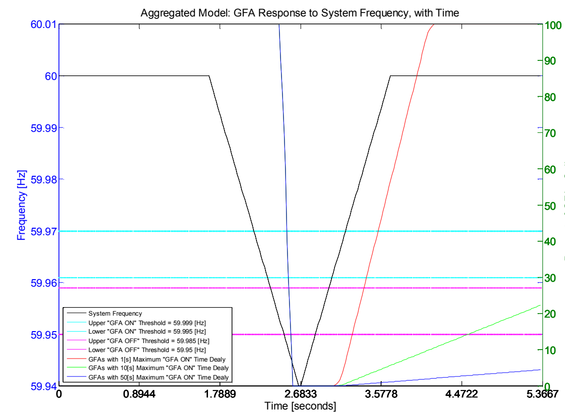
The detailed and aggregate MAT LAB models were subjected to batteries of tests, the results of which will be presented and compared in this section. The legend key in Table 2 has been provided to help the reader interpret the various lines in the figures of this section. Note that the exemplary thresholds shown in these figures are too high, but the questionable values will not greatly diminish the demonstration of model behaviors in this section.

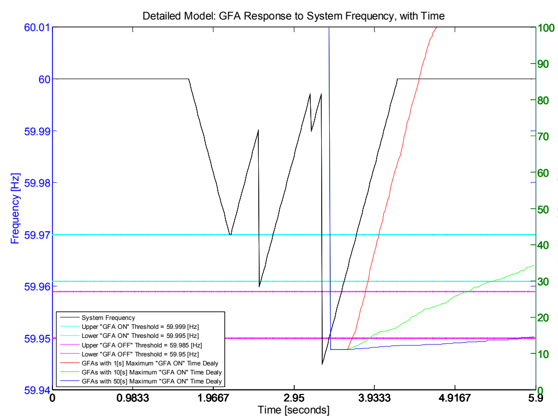
Table 2. Legend for Figures in this Section

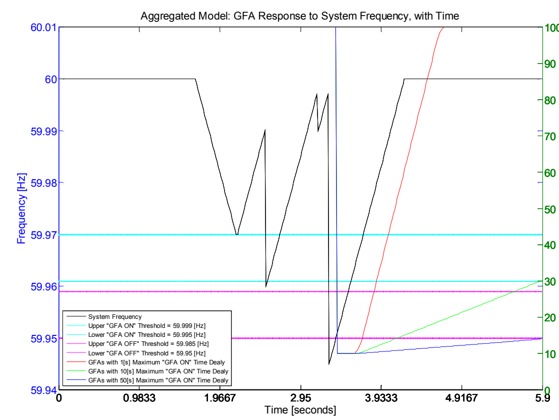
Variable	Meaning	Color key
Frequency	System grid frequency	Black
Upper and lower GFA_ON (59.999 and 59.995 Hz)	Range over which GFA water heaters release after a curtailment	Lt. blue
Upper and lower GFA_OFF (59.985 and 59.95 Hz)	Range over which GFA water heaters curtail	Pink
1-s restart delay case	Case where GFA water heaters are release curtailment from 0 to 1 second after frequency surpasses GFA_ON	Orange
10-s restart delay case	Case where GFA water heaters are release curtailment from 0 to 1 second after frequency surpasses GFA_ON	Green
50-2 restart delay case	Case where GFA water heaters are release curtailment from 0 to 1 second after frequency surpasses GFA_ON	Dk. blue

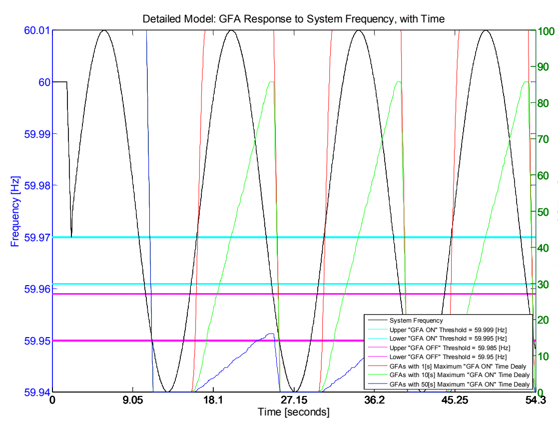
Figure 24 represents the behaviors of the detailed (left) and aggregated (right) MAT LAB models of underfrequency-responsive GFA water heaters in response to five prototypical frequency events that include a short, symmetrical v-shaped dip in frequency; a short event that exhibits successive excursions until it enters the range of curtailment frequency thresholds; a short oscillatory event; a short, step-wise event; and longer event that has multiple successive underfrequency periods. The point of this exercise is that the results of the detailed and aggregated models are very similar.

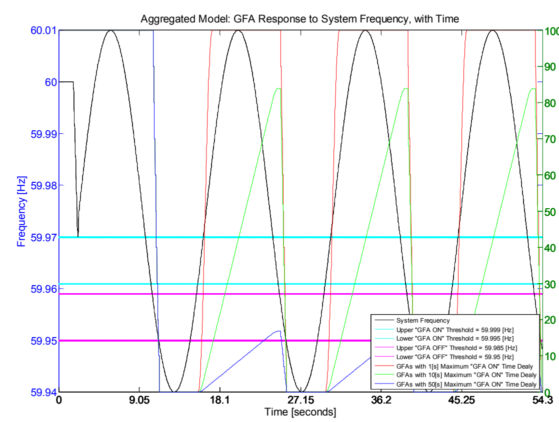

Detailed Model: GFA Response to System Frequency, with Time
Frequency [Hz]
60.01
60
59.99
59.98
59.97
59.96
59.95
59.94
Percent of GFAs Online
100
90
80
70
60
50
40
30
20
10
0
0
0.8944
1.7889
2.6833
3.5778
4.4722
5.3667
Time [seconds]
System Frequency
Upper "GFA ON" Threshold = 59.999 [Hz]
Lower "GFA ON" Threshold = 59.995 [Hz]
Upper "GFA OFF" Threshold = 59.985 [Hz]
Lower "GFA OFF" Threshold = 59.95 [Hz]
GFAs with 1[s] Maximum "GFA ON" Time Dealy
GFAs with 10[s] Maximum "GFA ON" Time Dealy
GFAs with 50[s] Maximum "GFA ON" Time Dealy


Aggregated Model: GFA Response to System Frequency, with Time
Frequency [Hz]
60.01
60
59.99
59.98
59.97
59.96
59.95
59.94
Percent of GFAs Online
100
90
80
70
60
50
40
30
20
10
0
0
0.8944
1.7889
2.6833
3.5778
4.4722
5.3667
Time [seconds]
System Frequency
Upper "GFA ON" Threshold = 59.999 [Hz]
Lower "GFA ON" Threshold = 59.995 [Hz]
Upper "GFA OFF" Threshold = 59.985 [Hz]
Lower "GFA OFF" Threshold = 59.95 [Hz]
GFAs with 1[s] Maximum "GFA ON" Time Dealy
GFAs with 10[s] Maximum "GFA ON" Time Dealy
GFAs with 50[s] Maximum "GFA ON" Time Dealy


Detailed Model: GFA Response to System Frequency, with Time
Frequency [Hz]
60.01
60
59.99
59.98
59.97
59.96
59.95
59.94
Percent of GFAs Online
100
90
80
70
60
50
40
30
20
10
0
0
0.9833
1.9667
2.95
3.9333
4.9167
5.9
Time [seconds]
System Frequency
Upper "GFA ON" Threshold = 59.999 [Hz]
Lower "GFA ON" Threshold = 59.995 [Hz]
Upper "GFA OFF" Threshold = 59.985 [Hz]
Lower "GFA OFF" Threshold = 59.95 [Hz]
GFAs with 1[s] Maximum "GFA ON" Time Dealy
GFAs with 10[s] Maximum "GFA ON" Time Dealy
GFAs with 50[s] Maximum "GFA ON" Time Dealy


Aggregated Model: GFA Response to System Frequency, with Time
Frequency [Hz]
60.01
60
59.99
59.98
59.97
59.96
59.95
59.94
Percent of GFAs Online
100
90
80
70
60
50
40
30
20
10
0
0
0.9833
1.9667
2.95
3.9333
4.9167
5.9
Time [seconds]
System Frequency
Upper "GFA ON" Threshold = 59.999 [Hz]
Lower "GFA ON" Threshold = 59.995 [Hz]
Upper "GFA OFF" Threshold = 59.985 [Hz]
Lower "GFA OFF" Threshold = 59.95 [Hz]
GFAs with 1[s] Maximum "GFA ON" Time Dealy
GFAs with 10[s] Maximum "GFA ON" Time Dealy
GFAs with 50[s] Maximum "GFA ON" Time Dealy


Detailed Model: GFA Response to System Frequency, with Time
Frequency [Hz]
60.01
60
59.99
59.98
59.97
59.96
59.95
59.94
Percent of GFAs Online
100
90
80
70
60
50
40
30
20
10
0
0
9.05
18.1
27.15
36.2
45.25
54.3
Time [seconds]
System Frequency
Upper "GFA ON" Threshold = 59.999 [Hz]
Lower "GFA ON" Threshold = 59.995 [Hz]
Upper "GFA OFF" Threshold = 59.985 [Hz]
Lower "GFA OFF" Threshold = 59.95 [Hz]
GFAs with 1[s] Maximum "GFA ON" Time Dealy
GFAs with 10[s] Maximum "GFA ON" Time Dealy
GFAs with 50[s] Maximum "GFA ON" Time Dealy


Aggregated Model: GFA Response to System Frequency, with Time
Frequency [Hz]
60.01
60
59.99
59.98
59.97
59.96
59.95
59.94
Percent of GFAs Online
100
90
80
70
60
50
40
30
20
10
0
0
9.05
18.1
27.15
36.2
45.25
54.3
Time [seconds]
System Frequency
Upper "GFA ON" Threshold = 59.999 [Hz]
Lower "GFA ON" Threshold = 59.995 [Hz]
Upper "GFA OFF" Threshold = 59.985 [Hz]
Lower "GFA OFF" Threshold = 59.95 [Hz]
GFAs with 1[s] Maximum "GFA ON" Time Dealy
GFAs with 10[s] Maximum "GFA ON" Time Dealy
GFAs with 50[s] Maximum "GFA ON" Time Dealy

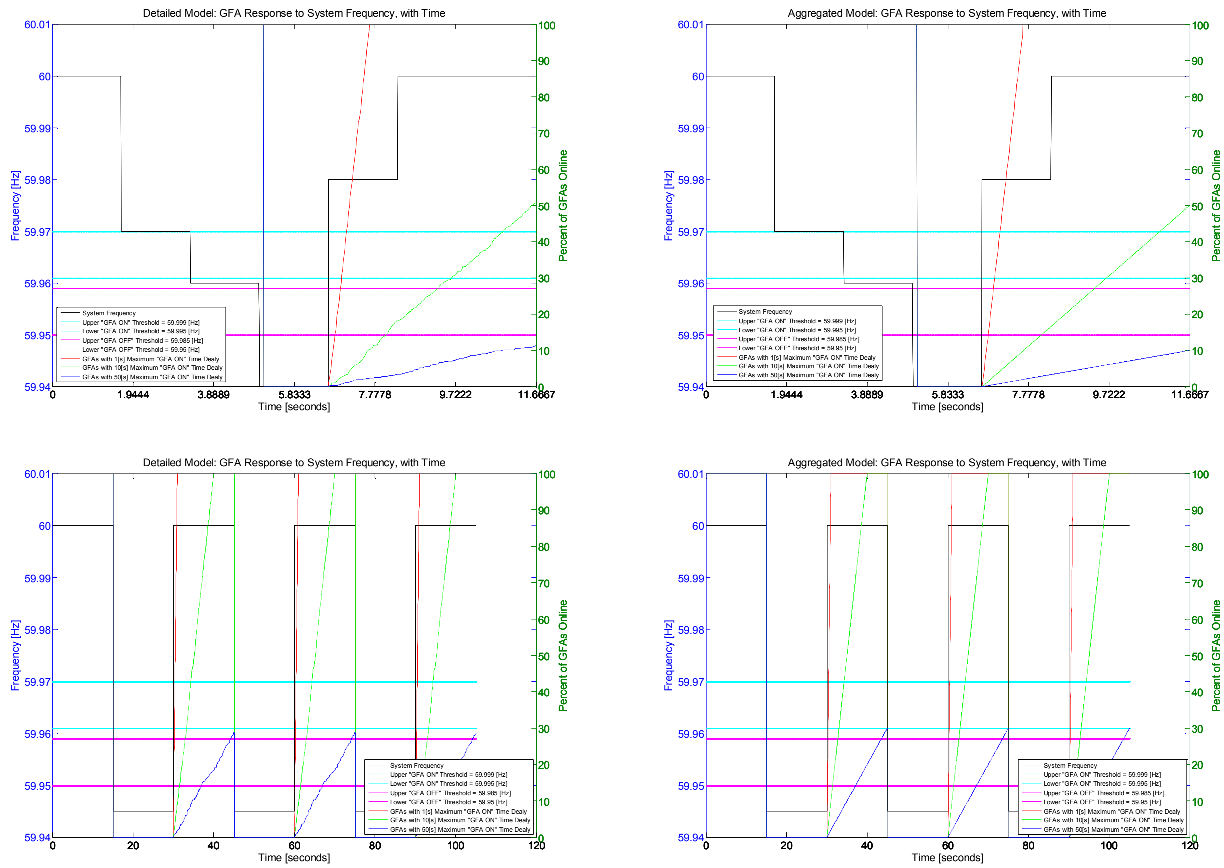


Figure 24. MAT LAB Simulations of the Detailed (Left) and Aggregated (Right) Model Behaviors are Very Similar against Various Test Cases

Figure 25 shows that some inaccuracy should be anticipated by using the aggregated bin approach due to the discretization itself. The discretization will be evident whenever system frequency traverses the distribution of curtailment (GFA_OFF) thresholds slowly. During recovery, the detailed model shows variability due to its use of randomized time delays among the many (1000) representative GFA water heater samples. The effect of bins is clearly evident in the aggregated model whenever system frequency traverses the distribution of recovery thresholds slowly compared to the GFA_ON time delay. Realistically, the GFA_ON time delay will almost always be long compared to the rate of frequency recovery, and the effects of discretized bins will not be very evident in a simulation.

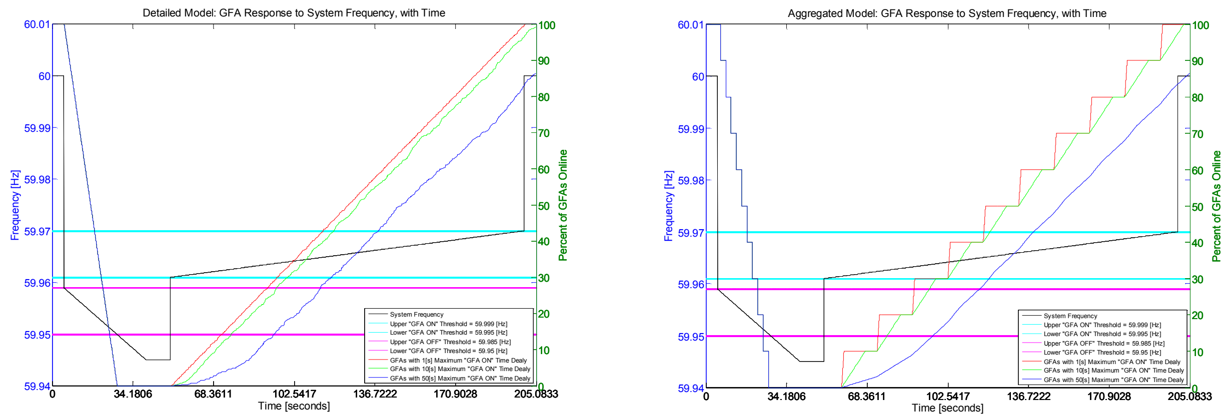


Figure 25. Potential Inaccuracies become Evident when Comparing Detailed (Left) and Aggregated (Right with Ten Bins) Model Responses to a Slowly Changing Underfrequency Event

3.5 PSLF EPCGEN Model of the Underfrequency-Responsive GFA Water Heater Response

As was done for the under-voltage-responsive GFA water heater model, an underfrequency-responsive GFA water heater EPCGEN model was prepared for the PSLF simulation environment. The model is similar in many respects to the one used for voltage responsiveness and is being made available to the client in electronic format.

Regrettably, a fundamental limitation of EPCGEN was determined to limit its use for simulation of events and responses that require knowledge of system frequency. System frequency is not made available by the PSLF simulation to EPSGEN, where the underfrequency-responsive model has been inserted. Efforts to calculate system frequency from available phasor information did not identify a representation of system frequency accurate or stable enough to use for this simulation.

It is our recommendation that General Electric should be requested by the client to develop and deliver a user-modifiable code module that incorporates the effects of frequency-responsive loads closely into the dynamic simulation.

3.6 Conclusions Concerning the System Benefits of Underfrequency-Responsive GFA Water Heaters

An underfrequency-responsive GFA water heater algorithm and model was constructed, but no system behaviors were modeled due to a fundamental limitation of the dynamic simulation environment. Consequently, the project failed to simulate any effect that our dynamic load could have on the provided test case. We recommend that General Electric be invited to provide users access to system frequency for simulating frequency-dependent dynamic loads like the underfrequency-responsive GFA water heater.

4.0 References

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APPENDIX

Table 3. GFA Water Heater Water Heater Model Input Data Sheet

Interface:		Default Values
.rsrc	Armature resistance (p.u.)	
.xsrc	Subtransient reactance (p.u.)	
.tv	Voltage Input time constant	0
.tf	Frequency Input time constant	0
Compressor Motor Model:		
GFWHLF	GFA water heater loading factor, per unit of rated current	1
GFWHPF	GFA water heater power factor at 1.0 per unit voltage	1
Vtth1	GFA water heater tripping voltage max	0.85
Vtth2	tripping voltage min	0.7
Vrth1	GFA water heater restore voltage max	0.95
Vrth2	GFA water heater restore voltage min	0.86
Tdonmin	GFA water heater minimum reclose delay	0
Tdonmax	GFA water heater maximum reclose delay	60
Tdoff	GFA water heater tripping delay	1
nBins	Number of Control Groups	10

```
epcgen  40151  "BROOKING"  115 "GF" : #2  "epcGFWH.p" 13 "rsrc" 0.0 "xsrc" 0.0 "tv" 0.016 "tf" 0.1  /
 "GFWHLF" 1 "GFWHPF" 1 "Vtth1" 0.85 "Vtth2" 0.7 "Vrth1" 0.95  "Vrth2" 0.86 "Tdonmin" 60 "Tdonmax" 300 /
"Tdoff" 5  "nBins" 10
```

Figure 26. An Example *.dyd File

Table 4. Air Conditioner Performance Model Input Data

Interface:	
.rsrc	Armature resistance (p.u.)
.xsrc	Subtransient reactance (p.u.)
.tv	Voltage Input time constant
.tf	Frequency Input time constant
Compressor Motor Model:	
.CompLF	compressor load factor, per unit of rated current
.CompPF	Compressor power factor at 1.0 per unit voltage
.Kps	Real power constant for stalled condition
.Nps	Real power exponent for stalled condition
.Kqs	Reactive power constant for stalled condition
.Nqs	Reactive power exponent for stalled condition
.Kp1	Real power constant for runing state 1
.Np1	Real power exponent for runing state 1
.Kq1	Reactive power constant for runing state 1
.Nq1	Reactive power exponent for runing state 1
.Kp2	Real power constant for runing state 2
.Np2	Real power exponent for runing state 2
.Kq2	Reactive power constant for runing state 2
.Nq2	Reactive power exponent for runing state 2
.Vbrk	Compressor motor "break-down" voltage
.Vstall	Compressor stall voltage at base condition
.LFadj	Adjustment to the stall voltage proportional to compressor load factor
.Vrest	Compressor re-start voltage
.Prest	Percent of compressor motors re-starting
.CmpKpf	Real power constant for frequency dependency pu W / pu frequency
.CmpKqf	Reactive power constant for frequency dependency pu VAR / pu frequency (default = -3.3)
Contactor Model:	
.vcoff	Voltage at which contactors open
.vcon	Voltage at which contractor re-close
.vvt	Reclose time-delay "voltage^2 * time" in (pu V)^2-cycle
.pcoff	Percent of air-conditioner units turned off by the thermostat/air handler controls (default=0.15)
Thermal Relay Model:	
.rth	Thermal relay resistance
.kth	Thermal relay rate
.ith	Current at which compressor temperature will be rasing
.tth1	Tempearture at which compressor motor begin tripping
.tth2	Temperature at which compressor all motors are tripped
.Vtr1	Voltage threshold trip #1
.Ttr1	Timer threshold #1
.Ftr1	Fraction trip #1
.Vtr2	Voltage threshold #2
.Ttr2	Timer threshold #2
.Ftr2	Fraction trip #2

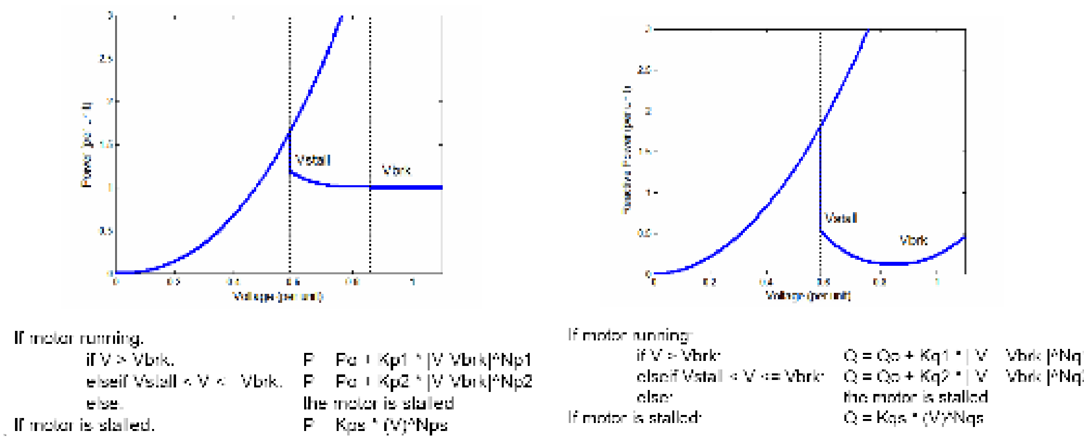

Figure 25. The Curve Fitting Plots of Motor Real and Reactive Power Versus Voltage

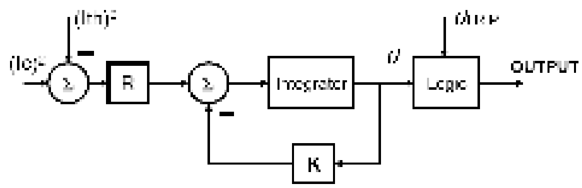

Figure 26. The Block Diagram of the Thermal Relay Model

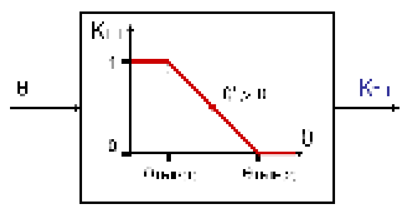

Figure 27. Thermal Relay Aggregation

Table 5. MATLAB Variable and Function Naming Scheme

- Variables beginning with “t_” have units of time, and are one-dimensional; “t” represents time
- Variables beginning with “f_” have units of Hertz, and are one-dimensional; “f” represents frequency
- Variables beginning with “frequency” have units of Hertz, are system frequency inputs to the simulations, and are two-dimensional vectors
- Variables beginning with “time” have units of time, and are two-dimensional vectors
- Variables beginning with “t_timer_” have units of time, and are used to measure elapsed time with reference to a frequency event in the simulation
- Variables beginning with “no_” are unitless, static variables; “no” stands for number
- Functions beginning with “subroutine_” are separate subroutine programs called within a main program
- “GFA_parameters” is a two-dimensional vector, which stores the following properties
- upper frequency threshold for triggering active GFA water heaters to stop operation [Hz]
- lower frequency threshold for triggering active GFA water heaters to stop operation [Hz]
- upper frequency threshold for releasing inactive GFA water heaters to resume operation [Hz]
- lower frequency threshold for releasing inactive GFA water heaters to resume operation [Hz]
- min delay and max delay? = 0, 1

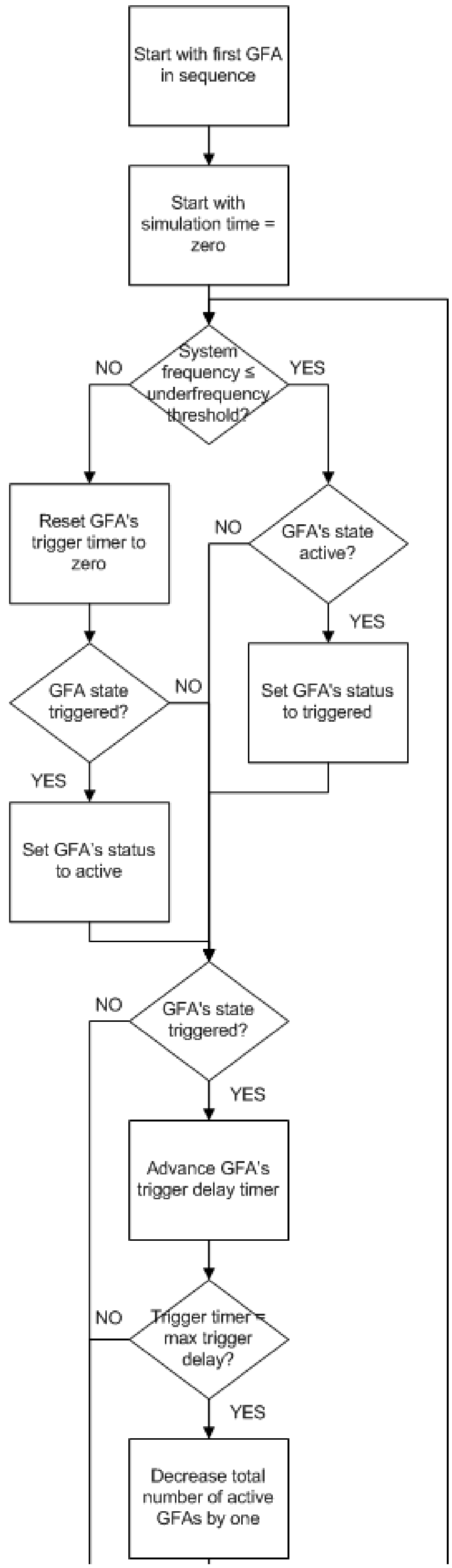

Figure 27. Flow Diagram for Detailed Model MAT LAB Code

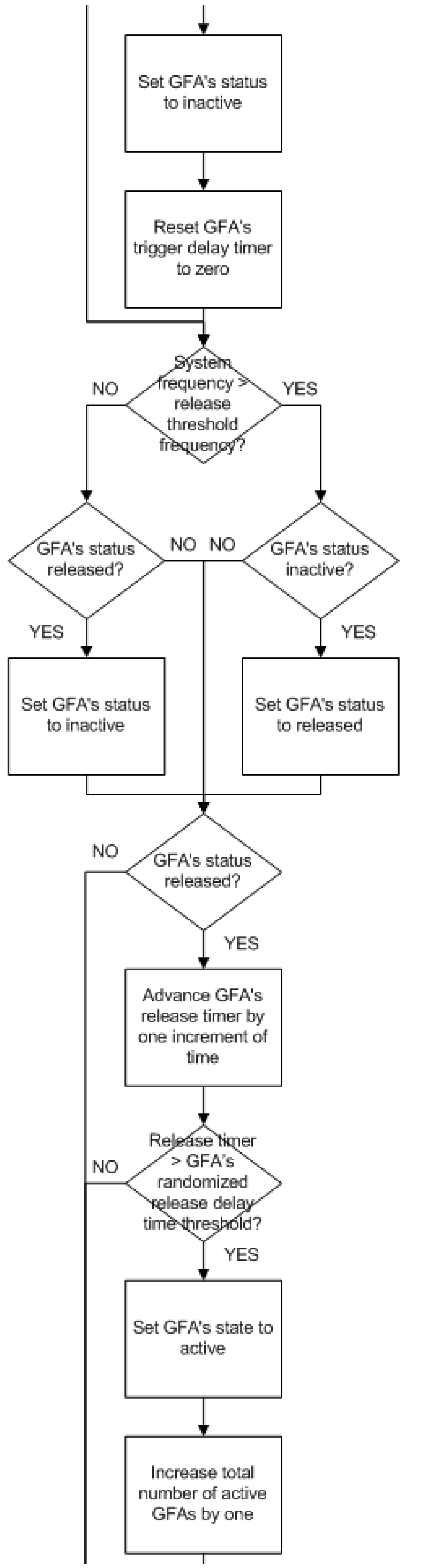

Figure 27. Flow Diagram for Detailed Model MAT LAB Code (Continued)

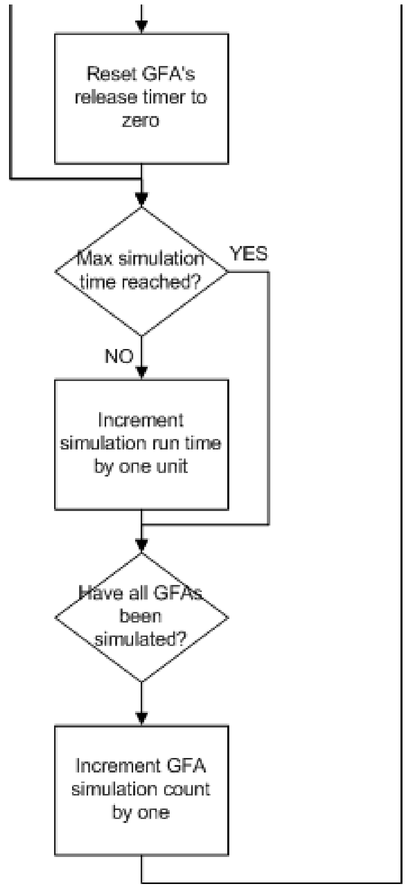

Figure 27. Flow Diagram for Detailed Model MAT LAB Code (Continued)

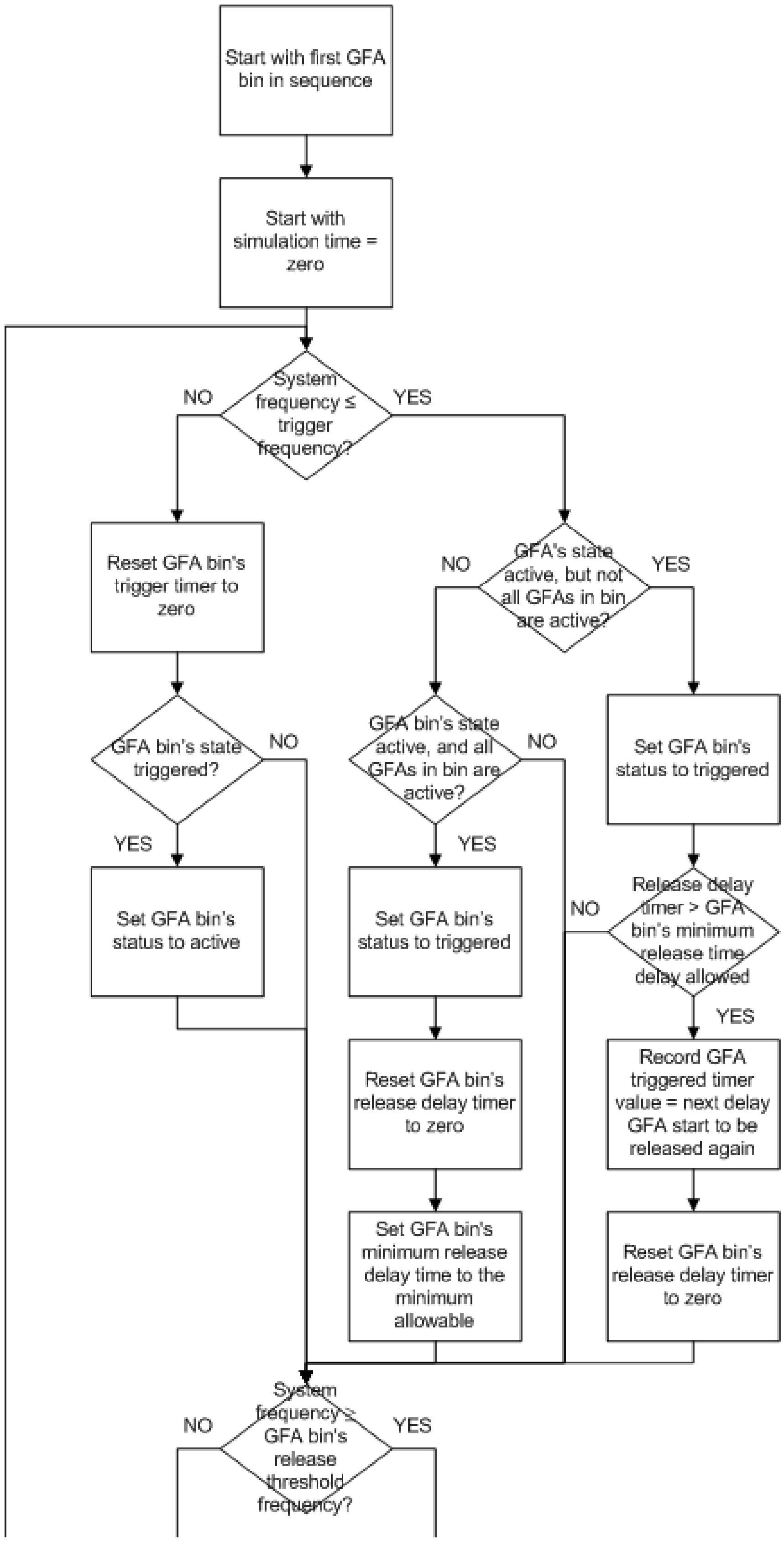

Figure 28. Flow Diagram for MAT LAB Underfrequency-Responsive Aggregate Model

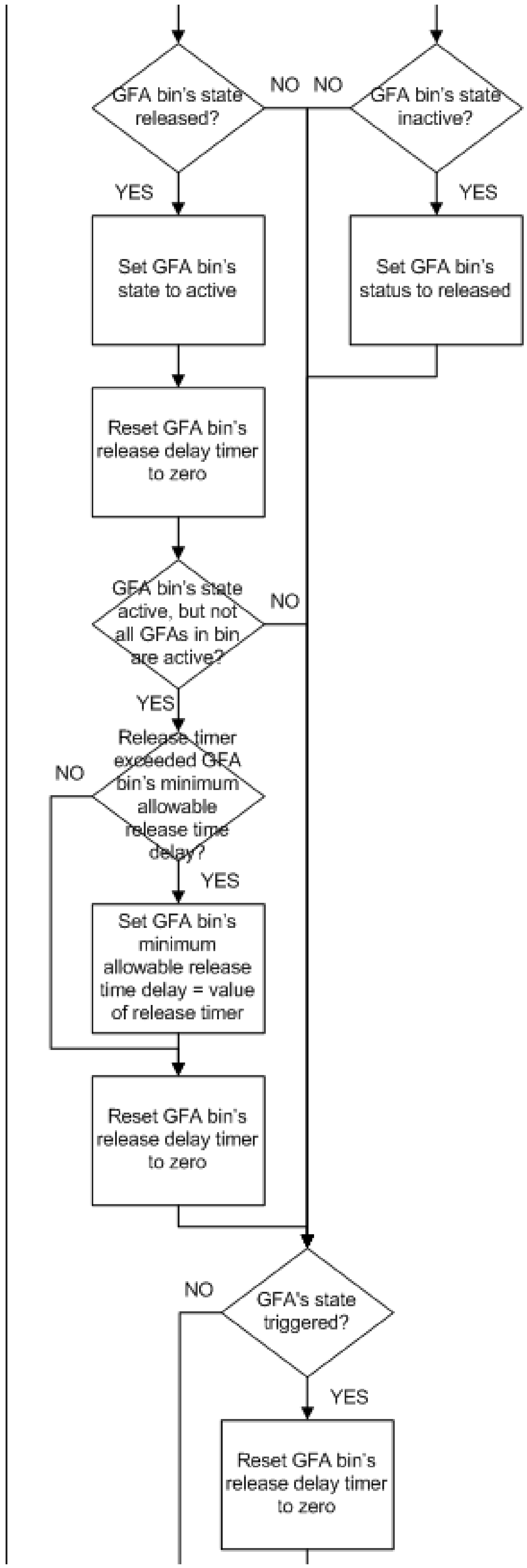

Figure 28. Flow Diagram for MAT LAB Underfrequency-Responsive Aggregate Model (Continued)

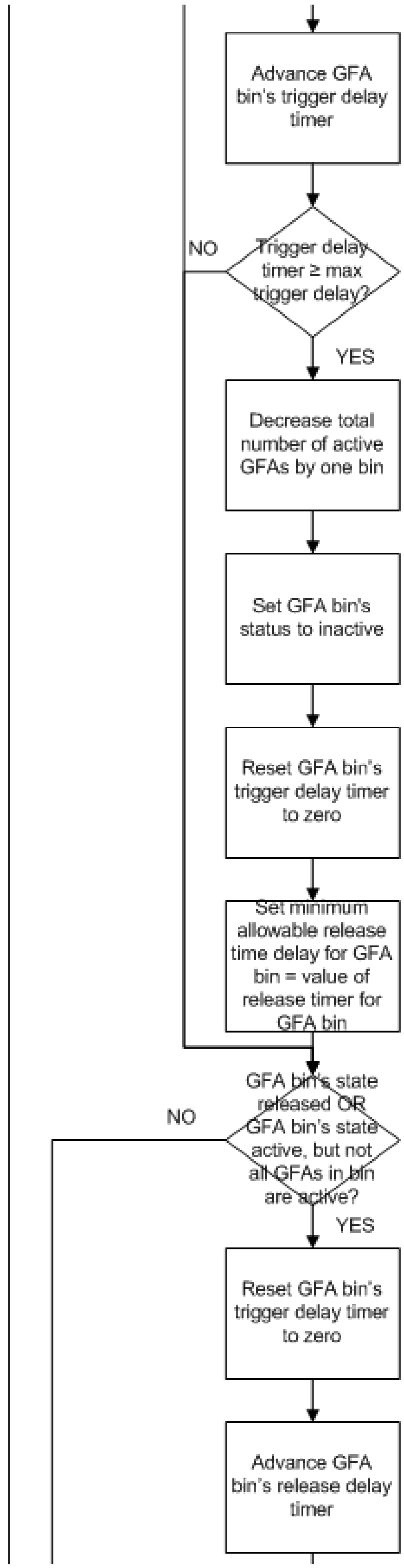

Figure 28. Flow Diagram for MAT LAB Underfrequency-Responsive Aggregate Model (Continued)

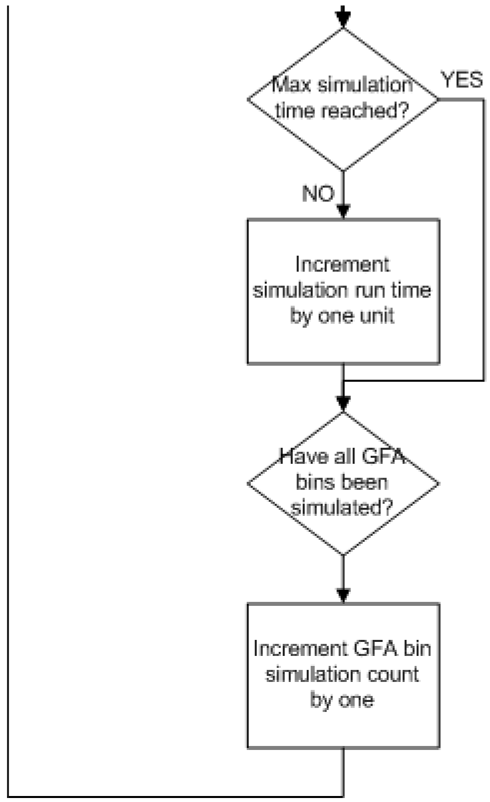

Figure 28. Flow Diagram for MAT LAB Underfrequency-Responsive Aggregate Model (Continued)