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Voltage control in a distribution system using active power loads

Mounika Chava

VOLTAGE CONTROL IN A DISTRIBUTION SYSTEM USING ACTIVE POWER LOADS

by

MOUNIKA CHAVA

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Approved by

Jhi-Young Joo, Advisor
Mariesa L. Crow
Pourya Shamsi

ABSTRACT

High penetration of renewable energy resources such as rooftop solar photovoltaic (PV) systems is exacerbating violations of the voltage limits in power distribution networks. Existing solutions to these over-/under-voltage issues include tap-changing transformers and shunt capacitors. However, tap changers only allow voltage changes in discrete steps and shunt capacitors cannot handle over-voltage situations. To overcome these problems, this thesis proposes voltage control in a distribution system by adjusting active power loads. The proposed solution can be used for both under- and over-voltage cases at any levels of voltage adjustment. First, the active power that needs to be adjusted at selected nodes to bring the voltages within acceptable limits is calculated for under and over-voltage cases using alternating current optimal power flow (ACOPF). ACOPF is solved for three different cases by varying the cost of active power adjustment and the marginal cost from the feeder supply, which is assumed to be the market price. Secondly, demand response on electric water heaters is implemented to achieve active power adjustments at selected nodes obtained from the ACOPF results. The problem is formulated over multiple time steps to minimize the energy costs of water heaters at a specific node subject to the dynamics of the water temperature, the energy consumption, the temperature constraints, and the voltage limits at the node. The IEEE 34-bus radial distribution system is used as a case study. By solving the same problem for different price settings, it is observed that the price structure affects the energy demand only in the under-voltage system, but not in the over-voltage system. The main contribution of this thesis is to show that by adjusting active power loads, voltages in a distribution system can be maintained within the permissible limits.

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1. INTRODUCTION

1.1 BACKGROUND

In power systems, the voltage at each node is maintained between above and below 5% of the rated value. An electric power distribution system is generally designed as a radial system, which is arranged in a tree like structure with usually only one power supply source at the beginning of the feeder. Due to this structure, distribution systems are more prone to voltage issues than the transmission system.

Under-voltages may be the result of 1) faults on the power system 2) capacitor bank switching off 3) high load on the system 4) loss of renewable distributed generation. Over voltages can occur because of 1) switching off high load 2) energizing a capacitor bank [2] 3) high penetration of distributed generation renewable sources particularly solar [3].

The voltage issues in a distribution system have become worse with increase in uncontrollable renewable distributed generation especially solar photovoltaic (PV). In the last few years, there has been a dramatic increase in renewable distributed generation. With the increasing PV, high PV penetration and low demand together can lead to over-voltage problems [18]. On the other hand, when there is peak load and low PV generation, voltage can drop below lower limit causing under-voltage issues [12].

There have been various studies on mitigating voltage violation problems in distribution system considering DG renewable energy resources. Reference [24] presents impact of distributed generation on voltages especially voltage sag problems. Reference [26] addressed effect of PV power variability on voltage regulation in distribution system considering 20% of PV penetration. The typical approach is to provide reactive power support from inverter units to tackle the voltage rise caused by high penetration of PV [8], [9], [10], [11] and [21]. References [19] and [21] proposed PV generation curtailment to prevent over voltages. Reference [20] suggested use of shunt reactors, shunt capacitors and transformer tap changer to prevent voltage instability. However, the tap changers only allow voltage change at discrete steps. Reactive power is adjusted at the point of PV installation to mitigate voltage rise problems [23]. The authors of [25] suggested use of onsite battery energy storage that is integrated with PV inverter to reduce the effects of

PV output variability. Reference [27] proposed use of PV over production in the LV feeder by shifting the peak loads i.e. demand side management and compared it against the PV energy curtailment.

In this thesis, maintaining the bus voltages (under-voltages and over-voltages) within the acceptable limits is achieved using demand response (DR) with active power loads. The proposed solution can be used for both under and over-voltage issues and any level of voltage adjustment can be achieved.

Demand response is defined as “changes in electric usage by end use customers from their normal consumption patterns in response to changes in the price of electricity over time or incentive payments” [5]. In this thesis, electric water heaters are used as controllable loads for demand response (DR). Water heaters contribute a large portion of household loads in the U.S. and have following advantages to implement demand response [6]

- Water heaters have relatively high consumption, which is up to 30% of household load compared to other home appliances [6]
- The heating element in an electric water heater is a resistor, which does not require reactive power support. Main aim is to adjust only active power but not reactive power

1.2 PROBLEM STATEMENT

This section describes the objective of the thesis problem and steps involved in it. The main goal is to control the voltage in a distribution system by adjusting active power loads. The first step is to determine the active power adjustments needed to bring the voltages within limits. Over-voltage and under-voltage cases were setup by increasing and decreasing the system load respectively. These under-voltage and over-voltage systems are used for the rest of study and analysis. Few nodes has been selected to adjust the active power and assumed that the active power at those nodes can be adjusted. ACOPF problem (as shown in Section 2) is then formulated by modeling the load buses where the active power can be adjusted as generation buses. The ACOPF problem is modeled and solved over one time step in MATPOWER. The ACOPF results provide information on the optimal feeder source generation and active power adjustment needed at the selected nodes to maintain voltages within acceptable limits.

The second step is to achieve the active power adjustments at selected nodes obtained in step one using demand response on electric water heaters. A demand response model for electric water heaters is designed (as given in Section 2) over multiple time steps minimizing the energy costs subject to the dynamics of the water temperature, energy and the temperature limits. The DR model is solved over multiple time steps since the electric water heater cannot be on/off throughout the time and the water temperature has to be maintained within the temperature limits. The limits on energy consumption are derived from the active power adjustments obtained in the first step. DR model is formulated as a mixed integer linear programming and solved in MATLAB.

2. FORMULATION AND METHODOLOGY

In this section, first ACOPF problem is formulated that determines the active power adjustments needed to bring the voltages within permissible limits. Next, a demand response model on electric water heaters is formulated to achieve the active power adjustments obtained from the ACOPF solution.

2.1 ACOPF FORMULATION

The objective of ACOPF problem is to optimize active and reactive power dispatch subject to demand, transmission network, voltage constraints and active and reactive power generation output limits [7]. Active power adjustment by the loads in this work is equated as active power adjustment as generator. If the load decreases its consumption, it is equivalent as a generator producing active power at the node, and vice versa. Therefore, the load buses in the distribution system where the active power can be adjusted are treated as generation buses in the ACOPF problem. The formulation is given by

$$\underset{P_{gi}, Q_{gi}, V_i, \theta_i}{minimize} \sum_{i=1}^{N_g} C_{gi} P_{gi}$$

Subject to

$$P_{gi} - P_{di} = \sum_{k=1}^{n} |V_i| |V_k| (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) \quad (1)$$

$$Q_{gi} - Q_{di} = \sum_{k=1}^{n} |V_i| |V_k| (G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}) \quad (2)$$

$$S_{ik,min} \leq S_{ik} \leq S_{ik,max} \quad (3)$$

$$P_{gi,min} \leq P_{gi} \leq P_{gi,max} \; for \; i = 1, \dots, N_g \quad (4)$$

$$Q_{gi,min} \leq Q_{gi} \leq Q_{gi,max} \; for \; i = 1, \dots, N_g \quad (5)$$

$$V_{i,min} \leq V_i \leq V_{i,max} \quad (6)$$

Where

P_{gi} – Active power generation at bus i

P_{di} – Active power demand at bus i

Q_{gi} – Reactive power injection of generator at bus i

Q_{di} – Reactive power demand at bus i

S_{ik} - MVA flow on line ik

V_i – Voltage magnitude at bus i

C_{gi} – Cost function of generator at bus i

G_{ik} – Conductance of line ik

B_{ik} – Susceptance of line ik

$S_{ik,min}$, $S_{ik,max}$ – Lower and upper MVA flow limits on line ik

$P_{gi,min}$, $P_{gi,max}$ - Lower and upper active power generation limits on line ik

$Q_{gi,min}$, $Q_{gi,max}$ - Lower and upper reactive power generation limits on line ik

$V_{i,min}$, $V_{i,max}$ – Lower and upper limit of voltage magnitude at bus i

Equations (1) and (2) are the power flow equations. (3) is related with the lower and upper flow on the lines. Equation 4 and 5 define active and reactive power limits of each generating unit. Equation 6 limits voltage at each bus. P_{gi} limits for the load buses are obtained from the original P_{di} at those nodes. ACOPF problem is modeled and solved in MATPOWER.

2.2 DEMAND RESPONSE PROBLEM FORMULATION

To develop the demand response model, the electric water heater load model is first derived. Then an optimization problem is formulated for controlling water heaters with the water temperature dynamics as a constraint.

2.2.1 Electric Water Heater Model. This section presents electric water heater load model. Figure 2.1 shows the block diagram of the water heater model [14]. The water heater model parameters are classified into three parts:

1. The temperature profile that includes the ambient temperature, the inlet water temperature and the hot water temperature set points
2. The water heater characteristics including the heat resistance of the tank (R), the surface area of the tank (SA_{tank}) and the rated power
3. Hot water usage profile by the user

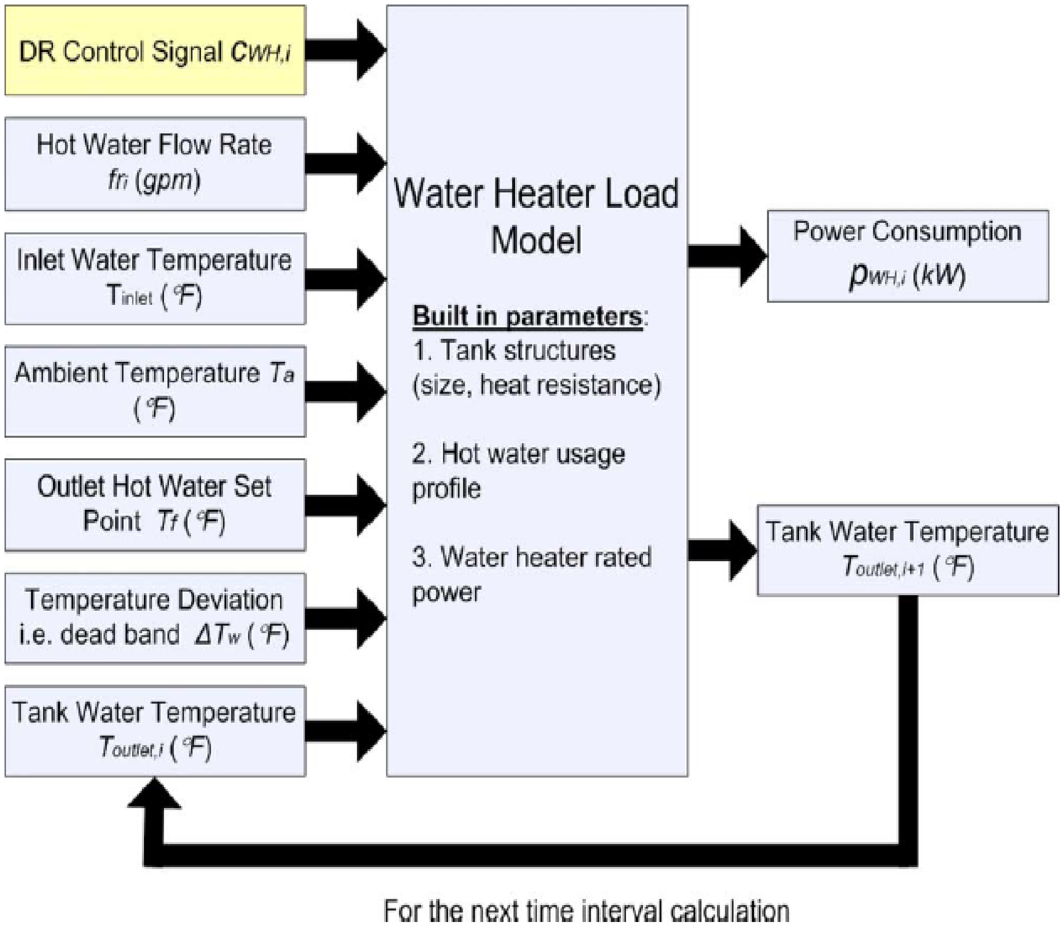

Figure 2.1. Block diagram of water heater model

The water temperature in the tank is calculated as [14]

$$T_{t+1} = \frac{T_t(V_{tank} - V_{wd}.\Delta t)}{V_{tank}} + \frac{T_{in}.V_{wd}.\Delta t}{V_{tank}} + \frac{1gal}{8.34lb}.\left[P_t\,.\eta.\frac{3412\;Btu}{kWh} - \frac{SA_{tank}.(T_t - T_{amb})}{R}\right].\frac{\Delta t}{60\frac{min}{h}}.\frac{1}{V_{tank}} \tag{7}$$

where

T_t	Water temperature in the tank (°F) in time slot t
V_{tank}	Volume of tank (gallons)
V_{wd}	Volume of hot water withdrawn (gallons per minute)
Δt	Duration of each time slot (minutes)
T_{in}	Inlet water temperature (°F)
P_t	Electricity demand of water heating unit in time slot t (KW)
SA_{tank}	Surface area of the tank (ft^2)
T_{amb}	Ambient temperature (°F)
R	Heat resistance of tank (°F. ft^2. h/Btu)
η	Efficiency factor

2.2.2 DR Problem Formulation. The objective of demand response model is to minimize the total energy consumption subject to temperature dynamics of electric water heater, set point temperature and energy limits. As water temperature has to be maintained within bounds, the water heater cannot be on or off for the whole hour, hence the demand response problem has been solved for each 5-minute interval over an hour. It can be formulated as

$$minimize \sum_{i=1}^{n} \sum_{t=1}^{12} C_t E_t$$

Subject to

$$T_{t+1} = \frac{T_t(V_{tank} - V_{wd}.\Delta t)}{V_{tank}} + \frac{T_{in}.V_{wd}.\Delta t}{V_{tank}} + \frac{1gal}{8.34lb}.\left[P_t\,.\eta.\frac{3412\ Btu}{kWh} - \frac{SA_{tank}.(T_t - T_{amb})}{R}\right].\frac{\Delta t}{60\,\frac{min}{h}}.\frac{1}{V_{tank}} \tag{8}$$

$$T_{t,min} \leq\ T_t \leq\ T_{t,max}\ \ \forall t \tag{9}$$

$$\sum_{i=1}^{n} E_t \leq E_{t,max} \ \forall t \tag{10}$$

$$\sum_{i=1}^{n} E_t \geq E_{t,min} \ \forall t \tag{11}$$

Where n is number of electric water heaters and t is the time interval. C_t is electricity market price at each time step t. E_t $(P_t/12)$ is energy consumption of electric water heater at each time step. At each time step t, demand for electricity of the water heater unit is calculated as

$$P_t = p_r \,.\, W_s \tag{12}$$

where

p_r Rated power of water heater (EWH)

W_s Water heater status, 0=OFF, 1=ON

Equation 9 represents lower ($T_{t,min}$) and upper ($T_{t,max}$) bounds of water temperature. Equation 10 and 11 are Energy consumption limits ($E_{t,min}$ and $E_{t,max}$) which are determined based on the active power adjustments obtained in Section 3. Equation 12 defines the water heater status during the given interval, p_r is the rated input power of electric water heater, which is constant and Ws is the solving variable that tells the status of water heater.

High load and low generation together causes under-voltages in the system. Hence, the energy consumption in under-voltage system has to be decreased and in over-voltage system, energy consumption has to be increased. Maximum limit on energy consumption for under-voltage system and minimum energy consumption for over-voltage system has been imposed in problem (8)-(12). In under voltage case, maximum limit on energy consumption at each time step t is given as difference between energy consumption before DR and amount of energy consumption reduction that needs to be achieved at each node. In over voltage case, energy consumption lower bound is obtained by adding the energy consumption before DR and the amount of energy consumption that has to be increased.

For the DR optimization problem, expected hot water usage for each house and the electricity market price are given in 5-minute time intervals, with the initial water temperature known. The optimization problem is solved using a mixed integer linear programming with an equality constraint and minimum and maximum bounds. Energy consumption and water temperature at each time step *t* are the results of the optimization problem. To observe the price sensitivity of the loads, the same optimization problem is solved for different price settings.

3. SIMULATION RESULTS

3.1 ACTIVE POWER ADJUSTMENT

The IEEE 34-node radial distribution network with generation at node 800 (slack bus) is used for the study as shown in Figure 3.1[13]. The test system is modeled after an actual feeder located in Arizona. The feeder's nominal voltage is 24.9 kV [13]. The single-phase balanced test system was modeled in MATPOWER ignoring voltage regulators between 814 and 850 and between 852 and 832 nodes.

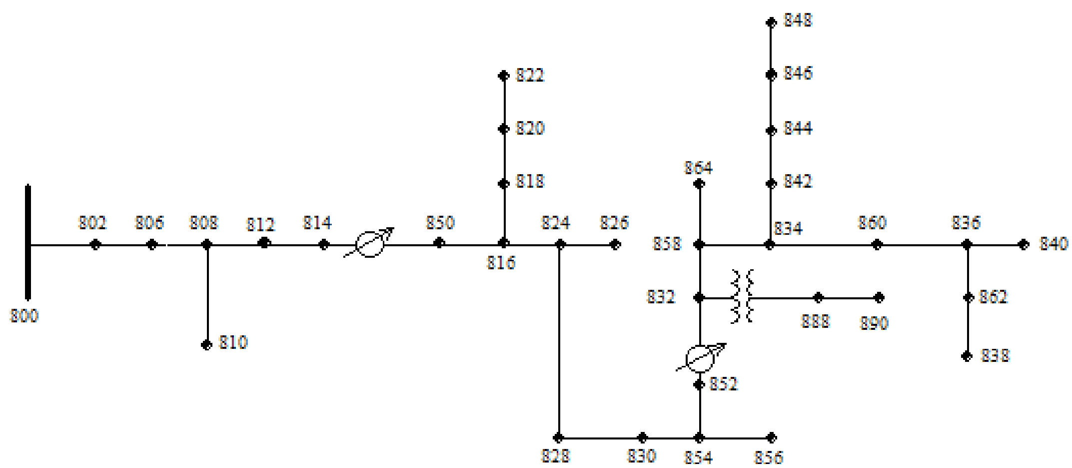

Figure 3.1. IEEE 34 bus system

To study the test system further, the total load was adjusted (as shown in Table 3.1) randomly to setup a system with over voltages and under voltages. Over-voltage and under-voltage cases were derived by decreasing 13% of the load at each node and by increasing 16% of the load at each bus respectively.

Table 3.1. Total load of the system

Initial system load		Under -voltage system load		Over-voltage system load	
P (MW)	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**	**P (MW)**	**Q (Mvar)**
3.062	1.898	3.55	2.2	2.66	1.65

Figure 3.2 shows the voltage profile of the initial, under-voltage and over-voltage test system. From the graph, the voltage profile of the initial test system is within limits (0.95 p.u.-1.05 p.u.). In the under-voltage system, voltages at a few (16) nodes especially the nodes that are far from the source are below the lower limit (0.95 p.u.). In the over-voltage system, some of the node voltages are above (1.05 p.u.). After setting up the under-voltage and over voltage systems, next how much active power needs to be adjusted is determined to bring the voltages within acceptable limits of 0.95 p.u. to 1.05 p.u. The nodes that have lateral branches (nodes 824, 834, and 836) has been selected and assumed the active power at those nodes can be adjusted.

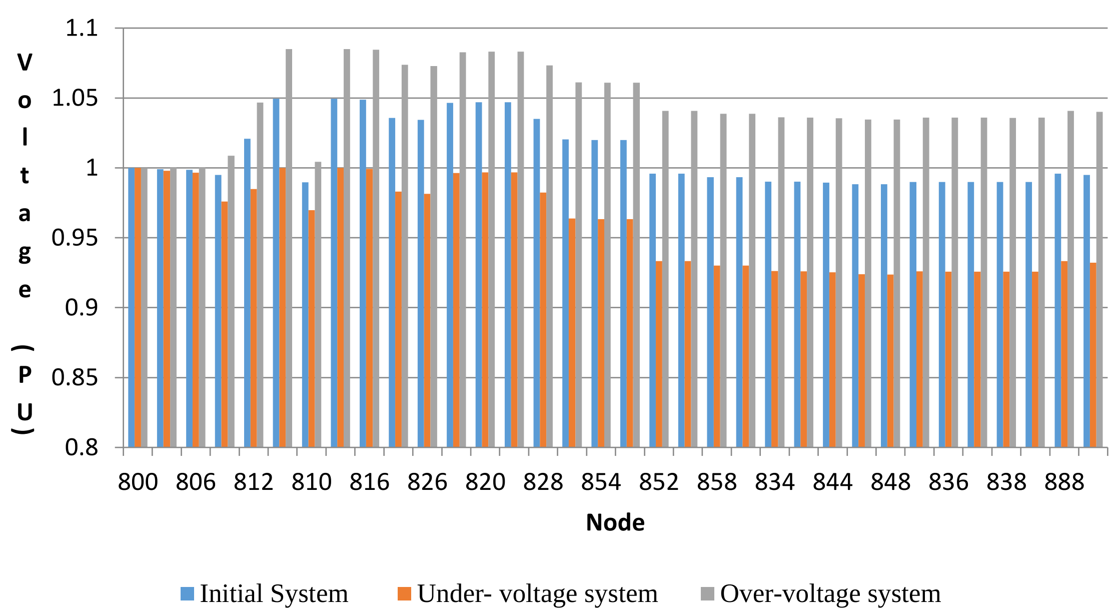

Figure 3.2. Voltage profile of initial, under-voltage and over-voltage test system

The ACOPF problem is solved for both under-voltage and over-voltage test systems, to calculate the active power adjustment to bring the voltages within limits. The problem is formulated in Section 2. Active power adjustment at nodes 824, 834 and 836 nodes is modeled as generation for solving ACOPF. The solution of the ACOPF problem gives the optimal slack bus generation and the active power that needs to be adjusted at nodes 824, 834 and 836.

Maximum active power output limits for the active power adjustment at nodes 824, 834 and 836 is given as 10% of the load at those buses respectively (as shown in Table 3.2). Reactive power limits are given as zero since the objective is to adjust active power only.

Table 3.2. Active and Reactive power limits for under and over-voltage system

	Under-voltage system				**Over-voltage system**			
Bus	**Active Power (MW)**		**Reactive Power (Mvar)**		**Active Power (MW)**		**Reactive Power (Mvar)**	
	P_{Max}	P_{Min}	Q_{Max}	Q_{Min}	P_{Max}	P_{Min}	Q_{Max}	Q_{Min}
800	100	0	5	−5	100	0	5	−5
824	0.0026	0	0	0	0	−0.0019	0	0
834	0.0020	0	0	0	0	−0.0015	0	0
836	0.0018	0	0	0	0	−0.0013	0	0

3.1.1 Under-voltage System. Figure 3.3 represents the under-voltage test system and highlighted nodes represent the nodes whose voltages were below 0.95 p.u.

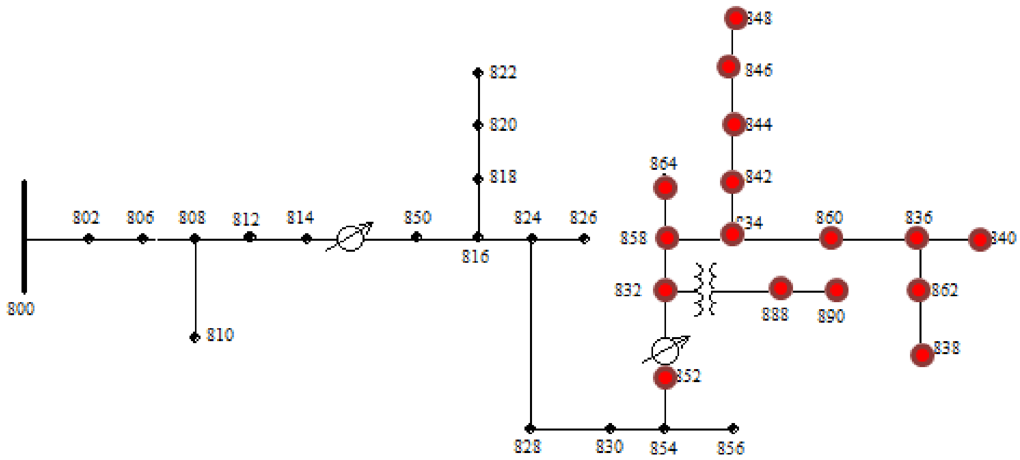

Figure 3.3. Under-voltage test system

ACOPF problem is solved for the under-voltage system having only feeder supply, to obtain the optimal “generation”, or net active power production satisfying the voltage limits at each node. ACOPF results with adjusting active power only at the slack bus is given in the Table 3.3.

Table 3.3. ACOPF with adjusting active power only at the slack bus

Bus	**Slack bus Generation**	
	Active power (MW)	**Reactive power (Mvar)**
800	4.7482	2.8016

ACOPF problem is solved for the under-voltage system for below cases, to evaluate the economy of adjusting active power at the nodes (i.e., demand response), compared with the cost of adjusting active power from the feeder supply.

Case 1: Cost of feeder supply ($10/MWh) < cost of active power adjustment ($50/MWh)

Case 2: Cost of feeder supply ($50/MWh) > cost of active power adjustment ($10/MWh)

Case 3: Cost of feeder supply ($10/MWh) = cost of active power adjustment ($10/MWh)

Table 3.4 shows the ACOPF results for all three cases. From the results, it is clear that in Case 1, slack bus is generating the total active and reactive power required by the system while the active power adjustment at nodes 824, 834 and 836 nodes is zero. This is because the cost for adjusting active power is higher than the cost of the slack bus generation.

Table 3.4. ACOPF with slack bus and active power adjustment for Cases 1, 2 and 3

Under voltage test system						
Bus	Case 1 cost of (feeder supply < adjusting P)		Case 2 cost of (feeder supply > adjusting P)		Case 3 cost of (feeder supply = adjusting P)	
	Active power (MW)	Reactive Power (Mvar)	Active power (MW)	Reactive Power (Mvar)	Active power (MW)	Reactive Power (Mvar)
800	4.7477	2.8016	4.7390	2.8016	4.7391	2.8016
824	0	0	0.0025	0	0.0025	0
834	0	0	0.0020	0	0.0020	0
836	0	0	0.0018	0	0.0018	0

In Case 2, active power adjustment at nodes 824, 834, and 836 is using almost its full capacity (2,500 W at 824, 2,000 W at 834, and 1,800 W at 836). In total, 6,628 W needs to be adjusted to bring the voltage profile within the limits.

Case 3 is similar to case 2 where active power adjustment needed at 824, 834 and 836 is its maximum active power limit (2500 W at 824, 2000 W at 834 and 1800 W at 836). To maintain voltage conditions in the under-voltage system, it requires 6,578 W active power adjustments at nodes 824, 834, and 836.

In all three cases, reactive power supplied by the slack (2.801 Mvar) is same. In Cases 2 and 3 active power adjustment needed is its maximum active power limit where as in Case 1 it is zero. This is because the cost for active power adjustment is less than or equal to slack bus generation in Cases 2 and 3.

Figure 3.4. Voltage Profile of under-voltage test system shows voltage profile of initial system and improved voltage profile before adjusting and after adjusting active power at selected nodes. Voltage profile before and after adjusting active power is same.

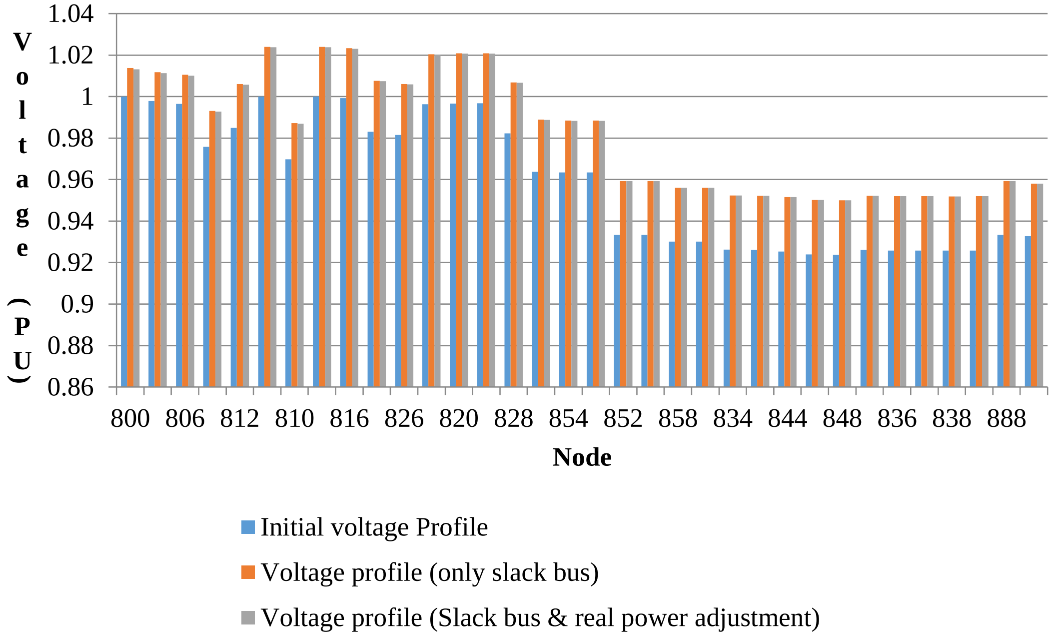

Figure 3.4. Voltage Profile of under-voltage test system

From Table 3.5, the total cost of generation remains the same before and after adjusting active power when the cost of slack bus generation is less than the cost of adjusting active power. However, in Cases 2 and 3 total cost of generation is low after adjusting active power compared to the total cost of generation before adjusting active power. The total optimal cost of generation in Case 2 is much higher than Cases 1 and 3. It is because most of the total generation is coming from slack bus and it is costly (five times the cost of active power adjustment) in Case 2. It is economical to adjust active power to maintain the voltage condition of the system within permissible limits only if the cost of adjusting active power is less than or equal to the cost of slack bus generation.

Table 3.5. Cost analysis of correcting voltages in the under-voltage system

	The total cost of generation ($/hr)	
	Before adjusting active power	**After adjusting active power**
Case 1 **(cost for slack < P adjustment)**	47.48203	47.48209
Case 2 **(cost for slack > P adjustment)**	237.41	237.02
Case 3 **(cost for slack = P adjustment)**	47.48	47.46

3.1.2. Over-voltage System. Figure 3.5 represents the over-voltage test system. The voltages at the highlighted nodes are above 1.05 p.u. The optimal generation of slack bus without any active power adjustment is given in Table 3.8. In an over-voltage system, voltage profile of the system can be improved by increasing the load. Producing negative active power is equivalent to increasing active power. Hence the selected load nodes are modeled as negative generation for solving ACOPF for the over voltage system in the study. Negative per-MWh cost with negative power production is a positive cost, which is adding to generation cost. Hence, it involves more cost to adjust active power using demand response compared to cost of active power adjustment at the slack bus. Table 3.6 show the ACOPF results with only feeder supply and feeder supply along with adjusting active power.

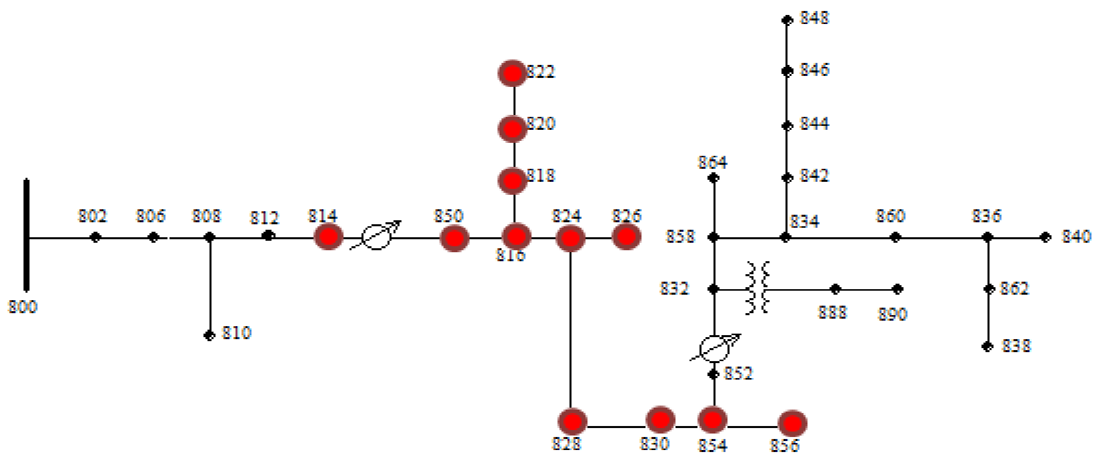

Figure 3.5. Over-voltage test system

Table 3.6. Active power adjustment at feeder and selected nodes

Node	**Only feeder adjustment (MW)**	**Adjustment at slack and nodes (MW)**
800	3.808	3.8142
824	0	−0.0019
834	0	−0.0015
836	0	−0.0013

ACOPF is solved for three different cases

Case 1-

Cost of feeder supply (10 $/MWh) < cost for active power adjustment (-50 $/MWh)

Case 2-

Cost of feeder supply (50 $/MWh) > cost for active power adjustment (-10 $/MWh)

Case 3-

Cost of feeder supply (10 $/MWh) = cost for active power adjustment (-10 $/MWh)

From the Table 3.7, for all the three cases, cost of active power adjustment at the slack bus is cheaper than the active power adjustment at the nodes 824, 834 and 836. From simulations, assuming a positive per-Wh cost for active power consumption (or negative active power production) did not turn out to be an economical option. Therefore, in the over-voltage case, demand response can be economically used only when a negative cost is assigned to active power consumption (or negative active power production). In other words, a per-Wh net benefit for active power consumption, which is equivalent to a negative cost of producing active power is considered. Net benefit of adjusting active power is defined as revenue minus costs. The costs include maintenance, losses and costs for implementing demand response, such as meter/controller installation. Hence, cases 1, 2 and 3 are redefined as

Case 1 –

Cost of feeder supply (10 $/MWh) < net benefit of adjusting active power (50 $/MWh)

Case 2 –

Cost of feeder supply (50 $/MWh) > net benefit of adjusting active power (10 $/MWh)

Case 3 –

Cost of feeder supply (10 $/MWh) = net benefit of adjusting active power (10 $/MWh)

Table 3.7. Comparison between cost for feeder adjustment and cost for adjustment at nodes 824, 834 and 836 for 3 cases

	Cost for only feeder adjustment	Cost for adjustment at nodes 824,834 and 836
Case 1: (cost of feeder supply (10 $/MWh) < cost for active power adjustment (-50 $/MWh)	38.08	38.38
Case 2: (cost of feeder supply (50 $/MWh) > cost for active power adjustment (-10 $/MWh)	190.40	190.76
Case 3: (cost of feeder supply (10 $/MWh) = cost for active power adjustment (-10 $/MWh)	38.08	38.19

The ACOPF results for the over-voltage case with only slack bus generation are shown in Table 3.9. From Table 3.9, Case 2 is same as system without any active power adjustment. In Cases 1 and 3, active power adjustments needed at nodes 824, 834 and 836 are equal to its minimum active power limits .In total, 5,046 W needs to be adjusted in Cases 1 and 3 respectively, to bring the voltage profile within the limits.

Table 3.8. ACOPF with only slack bus generation

Bus	**Optimal slack bus Generation**	
	Active power (MW)	**Reactive power (Mvar)**
800	3.8086	-3.2742

Table 3.9. ACOPF with slack bus and active power adjustment for cases 1, 2 and 3

Over -voltage test system						
Bus	**Case 1 (cost of feeder supply < net benefit of adjusting P)**		**Case 2 (cost of feeder supply > net benefit of adjusting P)**		**Case 3 (cost of feeder supply = net benefit of adjusting P)**	
	Active power (MW)	**Reactive Power (Mvar)**	**Active power (MW)**	**Reactive Power (Mvar)**	**Active power (MW)**	**Reactive Power (Mvar)**
800	3.8141	−3.271	3.8087	−3.274	3.8141	−3.271
824	−0.0019	0	0	0	−0.0019	0
834	−0.0015	0	0	0	−0.0015	0
836	−0.0013	0	0	0	−0.0013	0

Figure 3.6 shows the voltage profile of initial system, which has voltage violations, and improved voltage profile after adjusting active power. The total cost of generation in cases 2 and 3 before and after adjusting active power remains same. In case 1, the total cost of generation after adjusting active power is less than the cost before adjusting active power (as shown in Table 3.10).

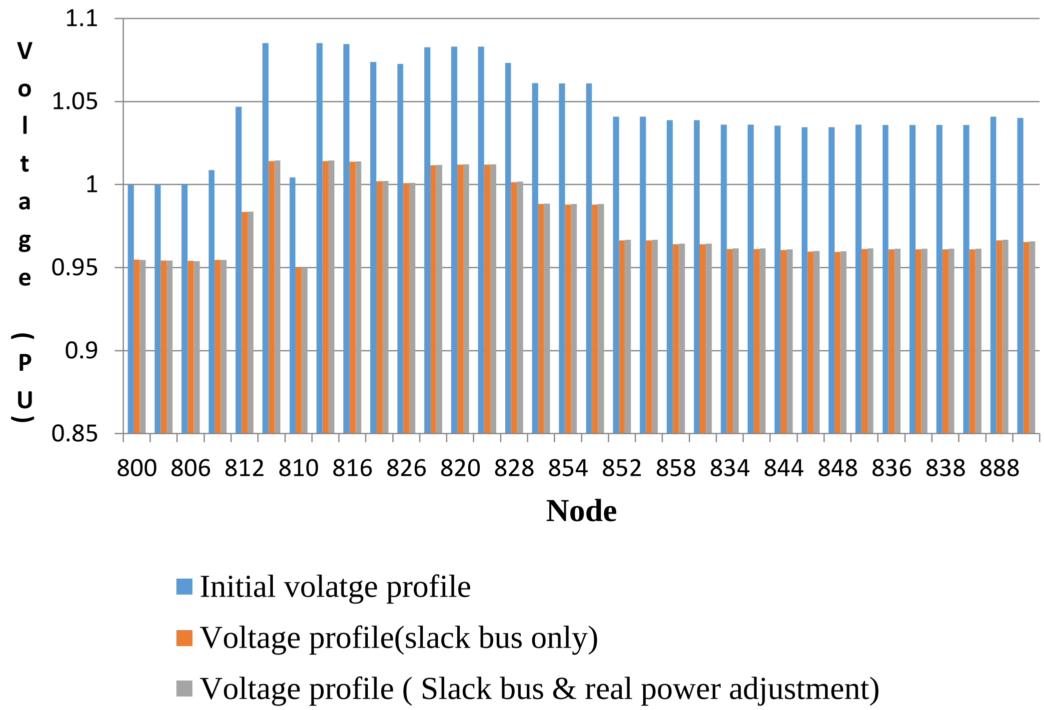

Figure 3.6. Voltage Profile of over-voltage test system

Table 3.11 shows the active power adjustments needed at the nodes 824, 834 and 836 to bring the voltages within limits (0.95 p.u. – 1.05 p.u.). In the under-voltage system, the load by the amount of active power is decreased as shown in Table 3.11 at each node whereas the active power at each node is increased in the over-voltage system.

Table 3.10. Cost analysis of correcting voltages in the over-voltage system

	The total cost of generation ($/hr)	
	Before adjusting P	**After adjusting P**
Case 1 (cost for slack < net benefit of adjusting P)	38.09	37.90
Case 2 (cost for slack > net benefit of adjusting P)	190.43	190.43
Case 3 (cost for slack = net benefit of adjusting P)	38.09	38.09

Table 3.11. Active power adjustments in under & over-voltage system

Node	Active power adjustment needed(W)	
	Under-voltage system	**Over-voltage system**
824	2500	−1900
834	2000	−1500
836	1800	−1300

3.2 DEMAND RESPONSE MODEL

In this section, demand response (DR) on electric water heater is implemented to achieve the active power adjustments at nodes 824, 834 and 836 as calculated in Section 3.1. First, the number of water heaters that needs to be controlled is determined. Typical individual household peak load is 6 kW [15]. Considering the household peak load and total load at nodes 824, 834 and 836, 3 houses are assigned at node 824, 2 houses at node 834 and 836. It is assumed that each household has an electric water heater. Demand response problem is simulated in MATLAB over an hour in 5-minute intervals.

The lower ($T_{t,min}$) and upper ($T_{t,max}$) bounds of the hot water temperature are considered as 110°F and 130°F [17]. Energy consumption limits ($E_{t,min}$ and $E_{t,max}$) is determined based on the active power adjustments needed at nodes 824, 834 and 836 (as shown in Table 3.11. Active power adjustments in under & over-voltage system).

Table 3.12 shows the parameters setup [14] needed to run the DR optimization problem.

Table 3.12. Simulation parameter setup

Attribute	**Value**
Inlet water temperature (T_{in})	60 (°F)
Ambient temperature (T_{amb})	60 (°F)
Tank volume (V_{tank})	40 (gallons)
Heat resistance of tank (R)	20 (°F. ft^2. h/Btu)
Surface area of tank (SA_{tank})	30.8 (ft^2)
Rated power (P)	4.5 KW

In order to obtain the price sensitivity of the electric water heater load, the same optimization problem is solved for three different electricity price profiles (as shown in Figure 3.7 [16].

3.2.1 Under-voltage System. It is assumed that all the houses at nodes at 824, 834 and 836 are at their peak during the hour. Each house at a node has different water usage profiles and the initial water temperature is assumed 118°F. Three different water usage profiles are used for the analysis and are given as Figure 3.8.

First the default case is simulated i.e., before DR when there are no constraints on the energy consumption of water heaters. The water heater status is determined according to the following rules: the water heater status is OFF when the tank water temperature is within the limits. If the tank temperature drops below the lower temperature bound, the heating coils start working at its rated power until it reaches the upper limit.

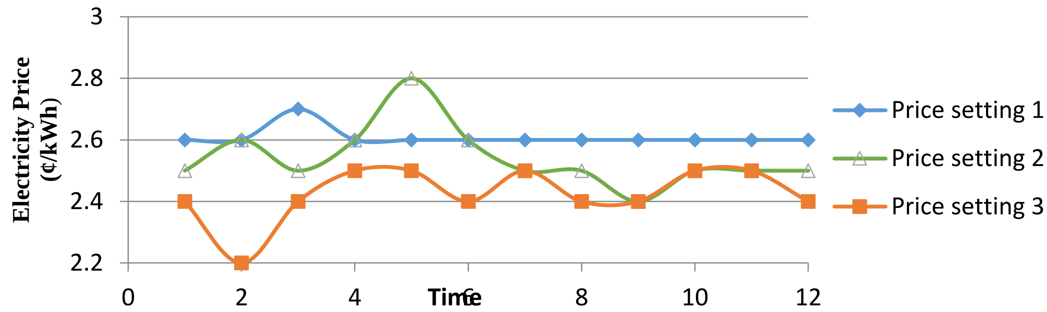

Figure 3.7. Electricity price settings 1, 2 and 3

To solve the DR model (formulated in Section 2), $E_{t,max}$ has to be determined at each node as they vary with the active power adjustment needed at each node.

$$\mathrm{E_{t,max}} = \text{ consumption before DR} - \frac{\text{active adjustment needed at the node}}{12} \tag{13}$$

Hence, $E_{t,max}$ at each node is given as in Table 3.13. The inputs to DR model and simulated results before and after DR at each node are arranged in following order

1. Hot water usage [17]
2. Total energy consumption
3. Water temperature profile of each electric water heater

Table 3.13. Maximum energy consumption limit for under-voltage system

Node	**$E_{t,max}$ (kWh)**
824	0.911583
834	0.957583
836	0.970833

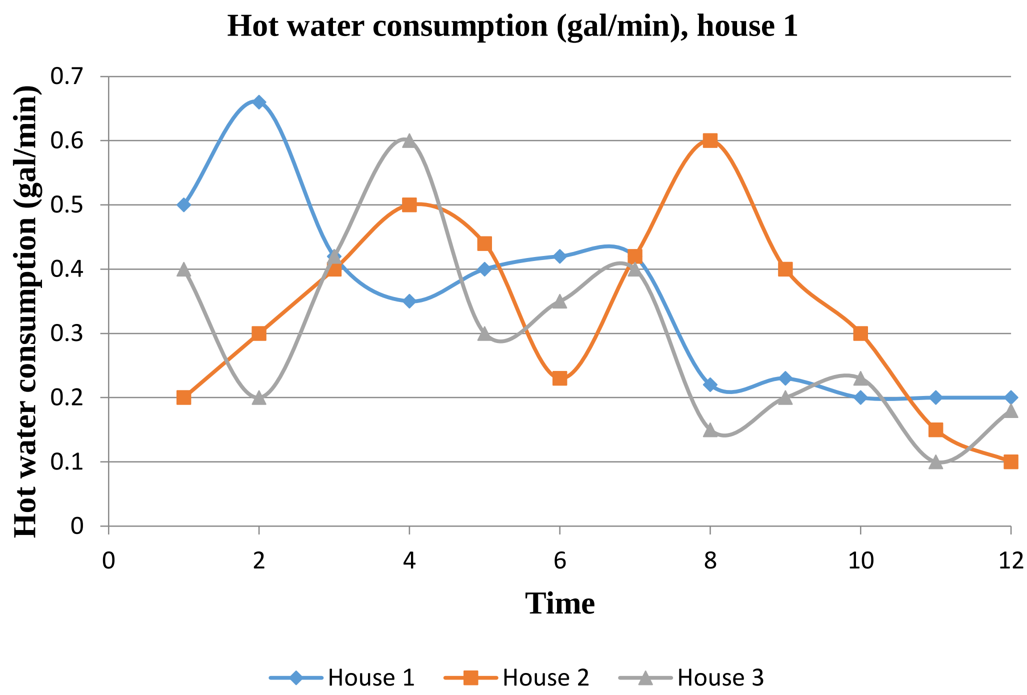

Figure 3.8. Hot water usage profiles of houses 1, 2 and 3 at node 824

Figures 3.9, 3.10 and 3.11 are the DR results at node 824. From Figure 3.9, total energy consumption over an hour at node 824 before and after DR is 10.125kWh and 6.375 kWh respectively.

At node 824, as the upper limit on energy consumption is 0.911583kWh, during any interval, maximum number of water heaters that are allowed to operate is two. From Figure 3.9, before DR three water heaters are ON during 6^{th},7^{th},8^{th},9^{th},10^{th},11^{th} and 12^{th} intervals but after DR, maximum number of water heaters ON in any of the intervals is two.

Before DR when water temperature drops below the lower bound (110°F), the heating element starts working and tries to reach the upper bound (130°F). The demand response model does not require the water temperature to reach its maximum but it maintains the temperature between 110°F and 130°F minimizing the energy consumption. From Figure 3.10 and 3.11 before DR, water temperature dropped below 110°F before and during the fifth interval. From then, the water heater is ON until the last interval to reach the maximum temperature limit.

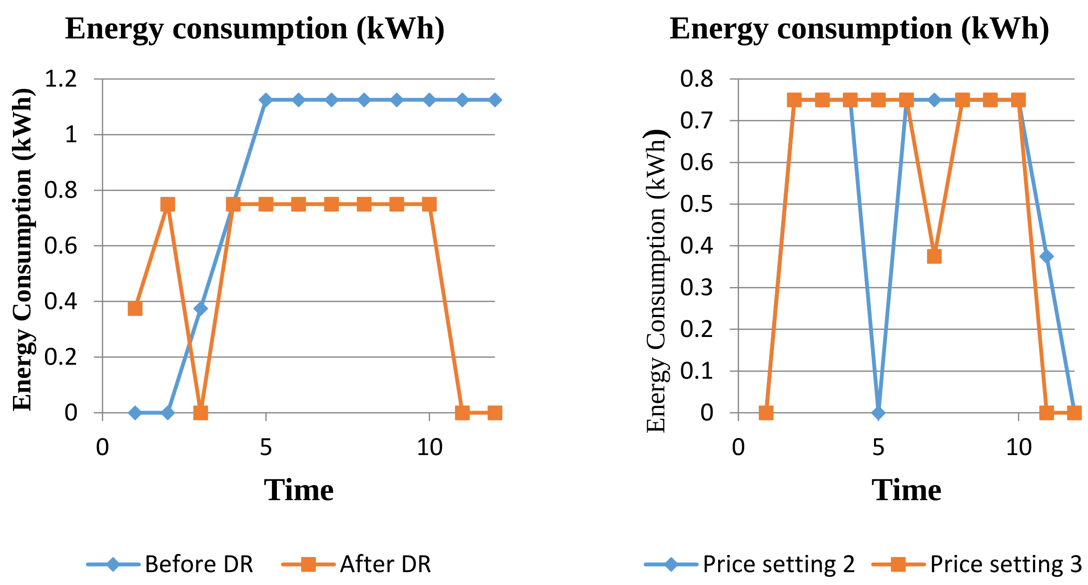

Figure 3.9. Energy consumption at node 824 a) price setting 1 b) price settings 2 and 3

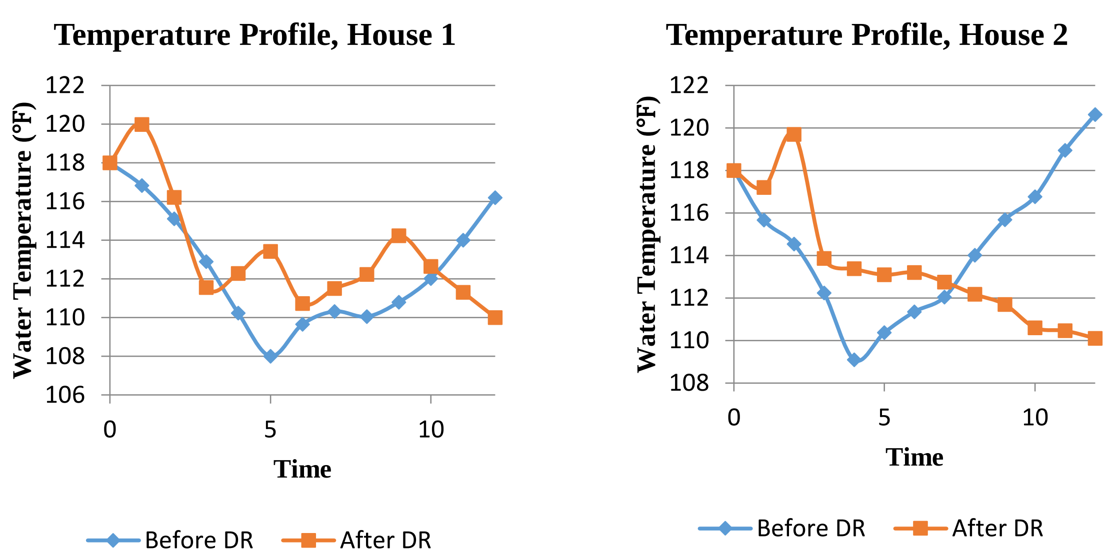

Figure 3.10. Temperature profile at node 824 a) house 1 b) house 2

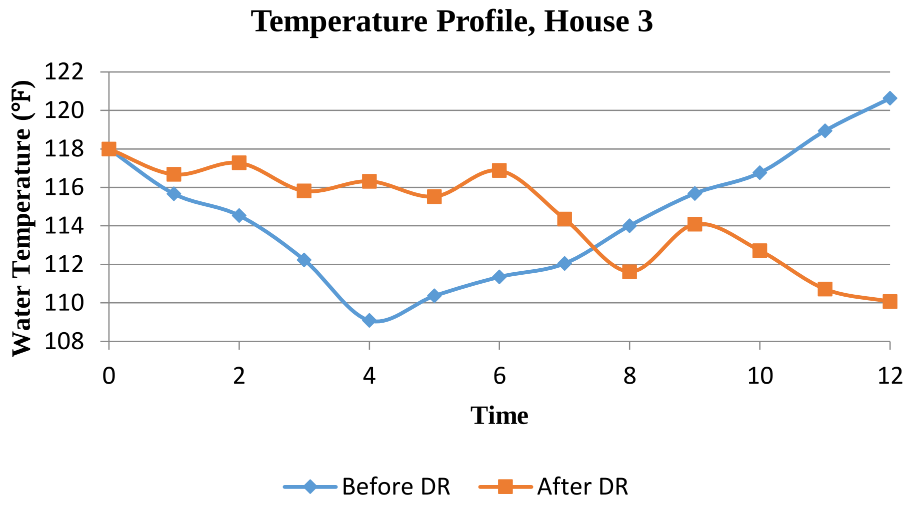

Figure 3.11. Temperature profile of house 3 at node 824

By solving the same optimization problem for different price settings, obtained different energy usage at each time step are obtained. Energy consumption for price settings 2 and 3 is obtained and shown in Figure 3.9. From Figure 3.9, total energy consumption is same for all price settings but the energy usage over a particular time interval is different. Figure 3.12 shows the hot water usage profile of house 1 and 2 at node 834.

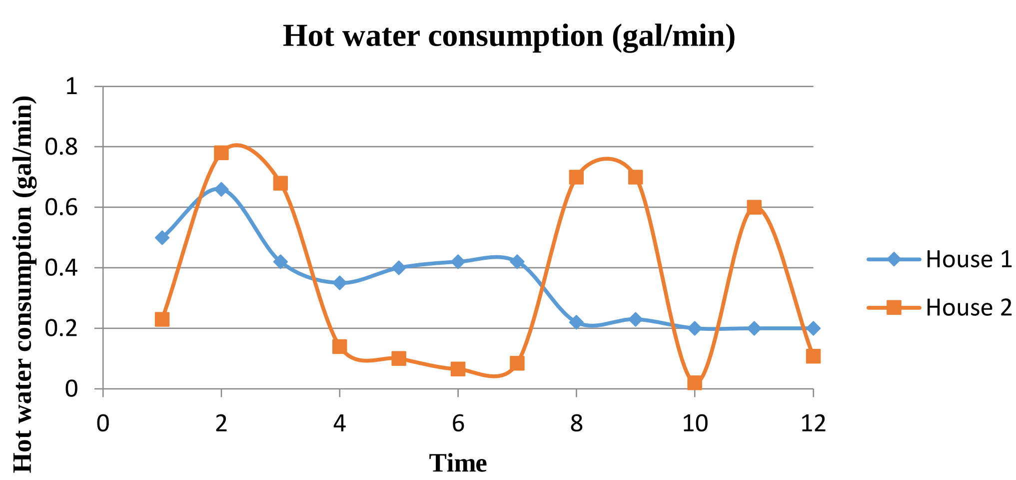

Figure 3.12. Hot water usage profiles of house 1 and 2 at node 834

By solving the DR model at node 834, obtained results as shown in Figure 3.13 and 3.14. From Figure 3.13, total energy consumption at node 834 for price setting 1 before and after DR is 6.75 kWh and 4.125 kWh respectively.

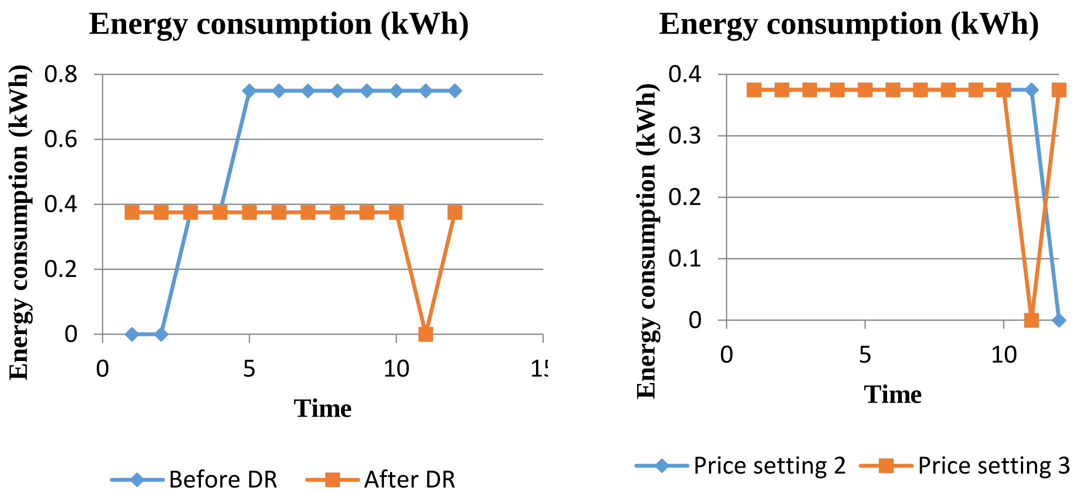

Figure 3.13. Energy consumption at node 834 a) price setting 1 b) price settings 2 and 3

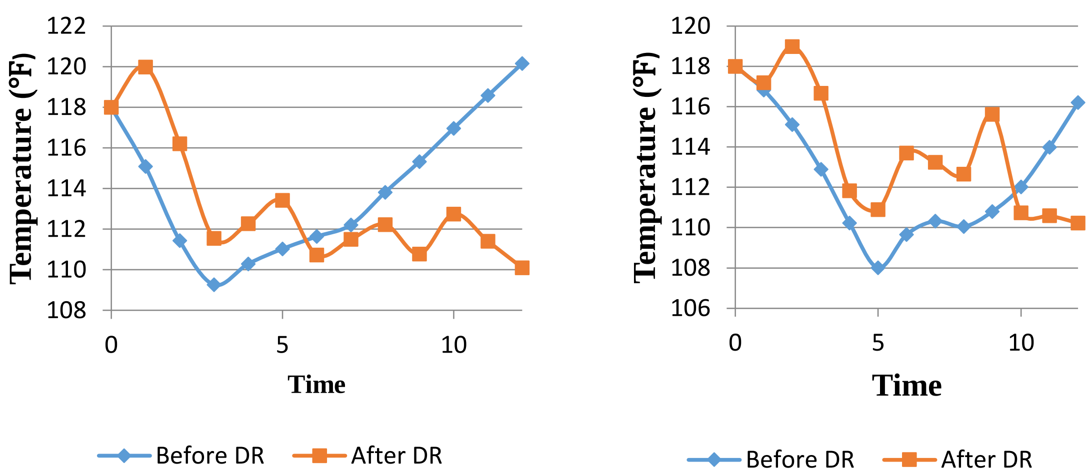

Figure 3.14. Temperature profile at node 834 a) house 1 b) house 2

Before DR, both the water heaters are ON from 5th interval to 12th interval but after DR due to limit on energy consumption, any one of the water heaters is allowed to operate at time step t. From Figure 3.13, it is clear that only one water heater is on while the other water heaters are off at a given time interval.

Figure 3.14 represents water temperature profile for each house at node 834 before and after DR. From Figure 3.14, before DR water temperature dropped below 110°F at second and fifth intervals for electric water heater one and two respectively. From then until the last interval, water heater is ON to bring the water temperature to its maximum. After DR, the water temperatures are maintained between 110°F and 130°F.

By solving the same DR model at node 834 for different price settings 2 and 3, energy consumption of water heater is obtained as shown in Figure 3.13. Total energy consumption over an hour is same for price setting one, two and three but energy usage in a specific time interval varies with the price structure. Hot water usage at node 834 is given as in Figure 3.15.

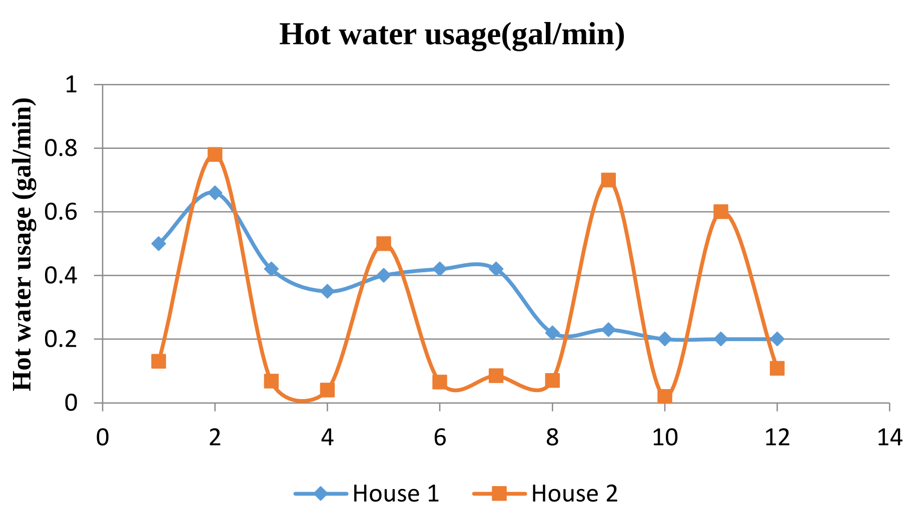

Figure 3.15. Hot water usage profiles of houses 1 and 2 at node 836

Similar to the results at nodes 824 and 834, energy consumption and temperature profile of water heaters 1 anad 2 at node 836 is given in Figures 3.16 and 3.17. From

Figure 3.16, total energy consumption at node 836 before and after DR for price setting 1 is 6.375kWH and 3.37 kWh respectively. Energy consumption at node 836 for price settings 2 and 3 is as in Figure 3.16.

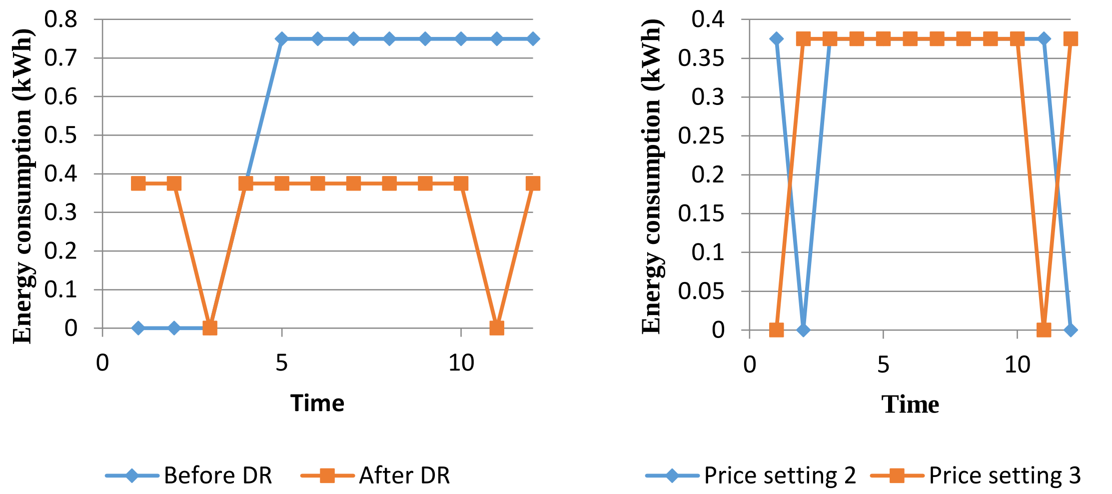

Figure 3.16. Energy consumption at node 836 a) price setting 1 b) price settings 2 and 3

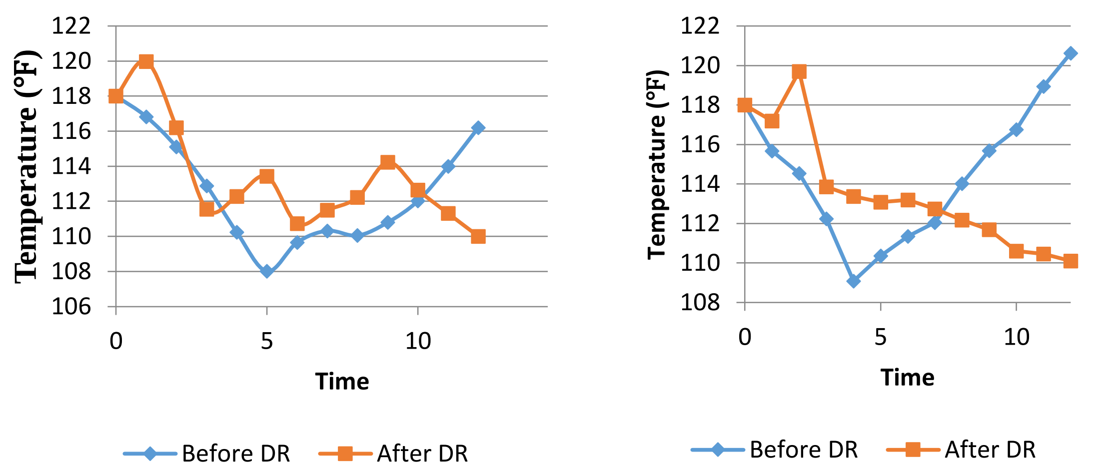

Figure 3.17. Temperature profile at node 836 a) house 1 b) house 2

Total energy consumption remains same for all price settings but the energy usage over a time step t varies with price structure.

Figure 3.17 represents water temperature profiles water heater 1 and 2. Before DR, water temperature dropped below 110°F during 5th and 4th time intervals. From then the water heaters are on until the the last time interval trying to reach the maximum limit. After DR, temperatures are maintained between limits (110°F 130°F).

3.2.2 Over-voltage System. Over-voltages are due to high generation or less load. The load is increased by the amount of active power as calculated in Section 3.1. In over-voltage case, limits on the minimum energy demand is imposed. The initial temperature is assumed 115°F. Hence, $\boldsymbol{E_{t,min}}$ at each node is calculated using below equation (given as in Table 3.14).

$$\mathrm{E_{t,min}} = \text{ consumption before DR} + \frac{\text{active adjustment needed at the node}}{12} \tag{14}$$

Table 3.14. Minimum energy consumption limits for over-voltage system

Node	$\mathbf{E_{t,min}}$ **(kWh)**
824	0.1628
834	0.1265
836	0.11571

The hot water usage demand is very low in the over-voltage system compared to the demand in the under-voltage system. Three different hot water usage profiles are defined as shown in Figure 3.18. As the hot water usage is very low, the energy consumption of water heaters at node 824 before DR is 0 and the water temperature is between 110°F and 130°F during all the intervals. In the DR model as limits on minimum energy consumption (0.1628 kWh) has been imposed throughout the whole period, this means that any one of the three water heaters has to be on at each interval. Figure 3.19 shows the energy consumption of water heaters at node 824 before and after DR. From the Figure 3.19, energy consumption before DR is zero because of low water usage. After

DR, energy consumption is set to its minimum limit i.e. any one of the three water heaters are on during any given interval.

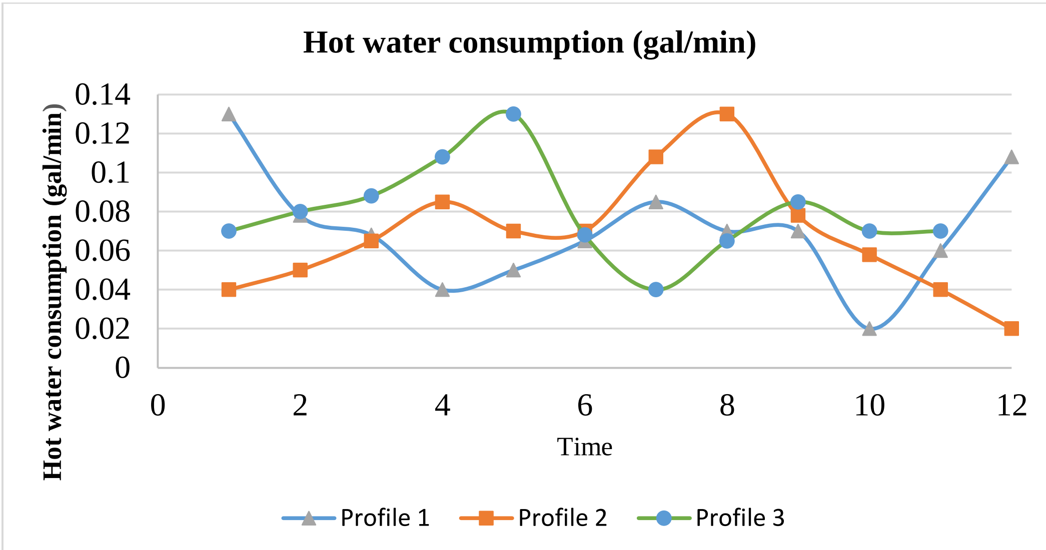

Figure 3.18. Hot water usage profiles 1, 2 and 3

The same optimization problem is solved for different price settings to observe the price sensitivity. Unlike the under-voltage system case, price does not have any effect on the energy consumption in the over-voltage system. This is because of the constraint on the minimum energy consumption of water heaters. The result of DR model is setting energy usage output at the minimum limit (shown in Figure 3.19).

From Figure 3.20 and 3.21 before DR, the water temperature profile during all the intervals is between 110°F and 130°F, it did not drop below 110°F hence water heater status is off and energy consumption is zero. After DR, since the water heaters, one and two are on for 15 minutes and water heater 3 is on for 30-minutes.Hnece, water temperature of each water heater raised gradually compared to the default case.

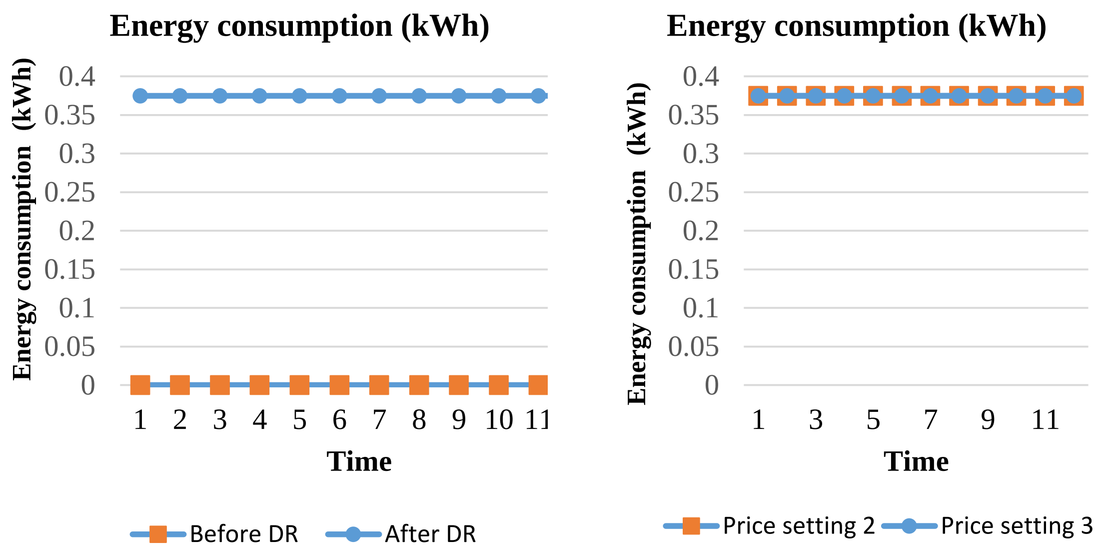

Figure 3.19. Energy consumption at node 824 a) price setting 1 b) price setting 2 and 3

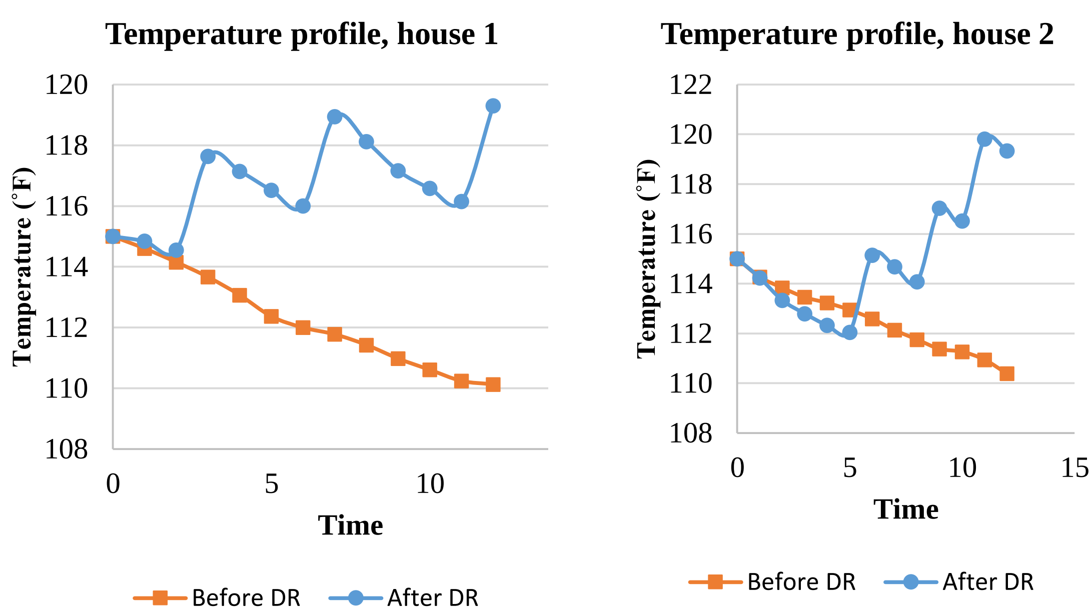

Figure 3.20. Temperature profiles at node 824 a) house 1 b) house 2

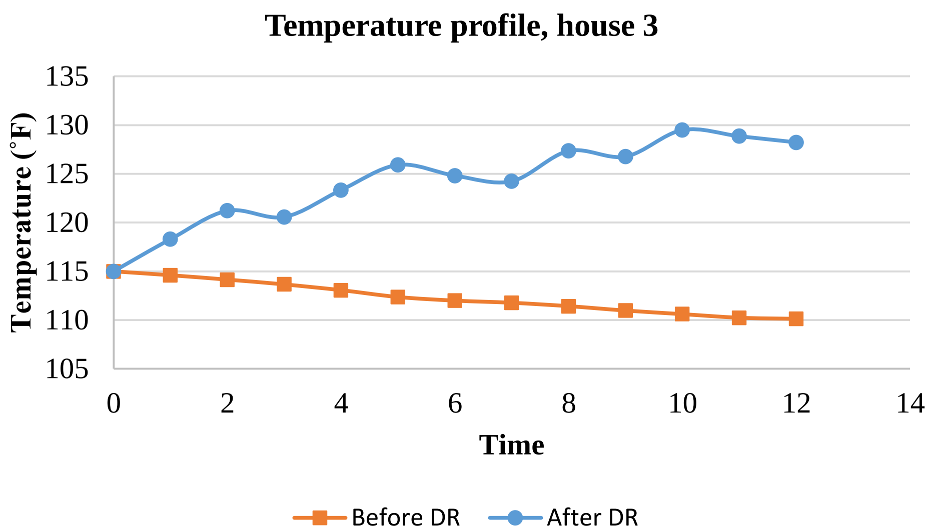

Figure 3.21. Temperature profile of house 3 at node 824

Figure 3.22 and 3.24 are the results of DR at node 834. Hot water usage profile 1 and 2, price settings 1 and 2 are given as inputs to DR model. From Figure 3.22, before DR the energy usage is zero. Since the water temperature did not drop below 110°F, water heater is off throughout the period. After DR, any one of the waters is on during all the intervals because of the limit on minimum energy consumption. Hence the water temperature of water heater 1 and 2 increased gradually (shown in Figure 3.23).

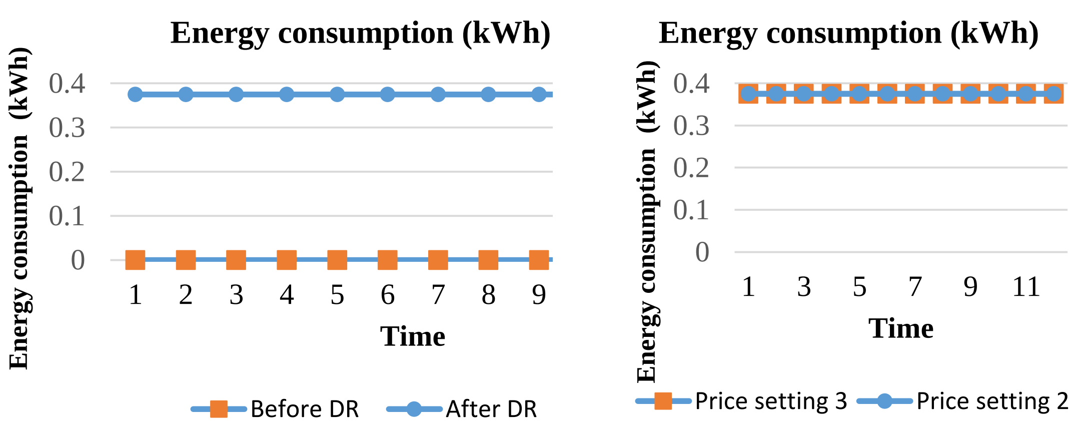

Figure 3.22. Energy consumption at node 834 a) price setting 1 b) price settings 2 and 3

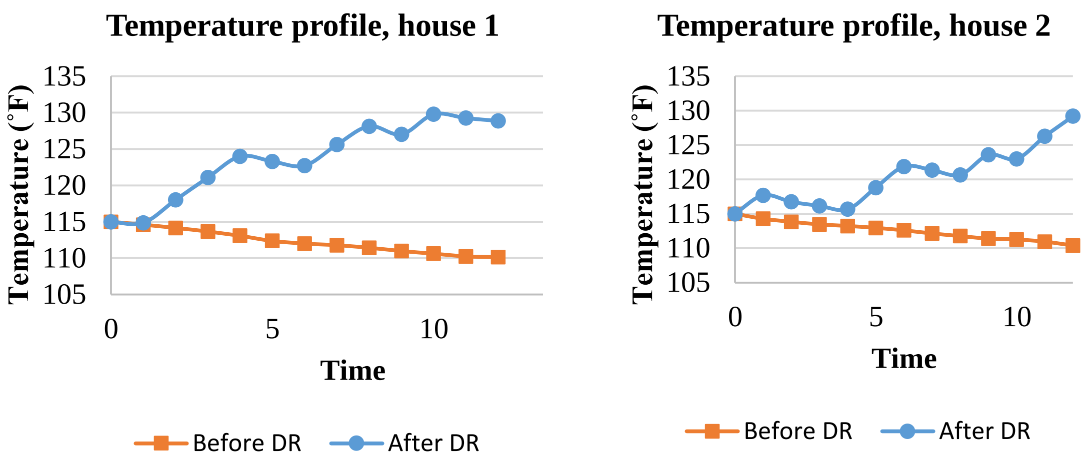

Figure 3.23. Temperature profiles at node 834 a) house 1 b) house 2

Water heater is not required to be on because for the given low water usage, water temperature is within limits. Since the objective of DR model is to minimize energy costs satisfying energy and the temperature constraints, it is setting the energy usage at its minimum limit. The DR results at node 836 are shown in Figure 3.24 and 3.25. Similar to the energy consumption at node 824 and 834, from Figure 3.24 energy usage at node 836 before DR is 0 and it is at its minimum limit after DR.

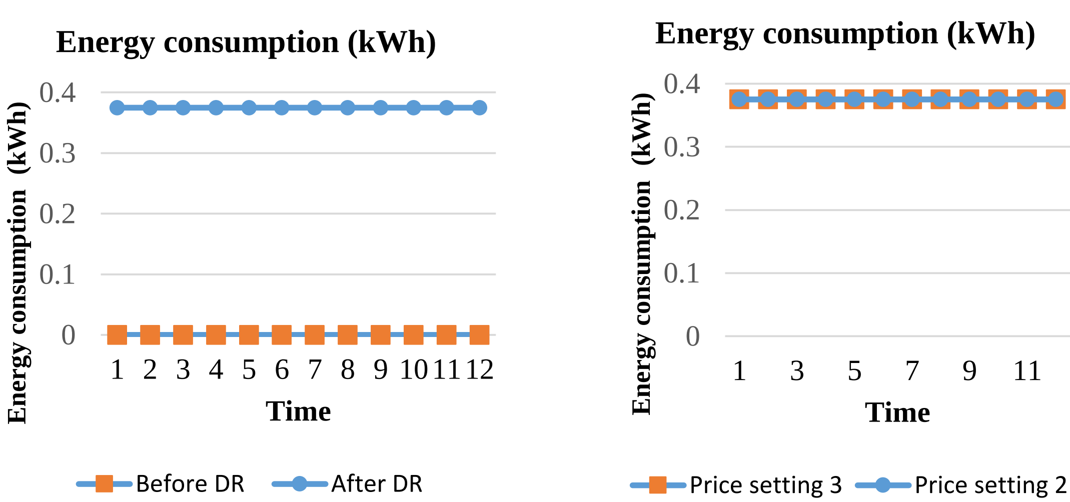

Figure 3.24. Energy consumption at node 836 a) price setting 1 b) price setting 2 and 3

Before DR, the water temperature is between the limits and it did not drop below 110°F . The water temperature rose gradually after DR. Energy usage for different price settings is same (shown in Figure 3.24)

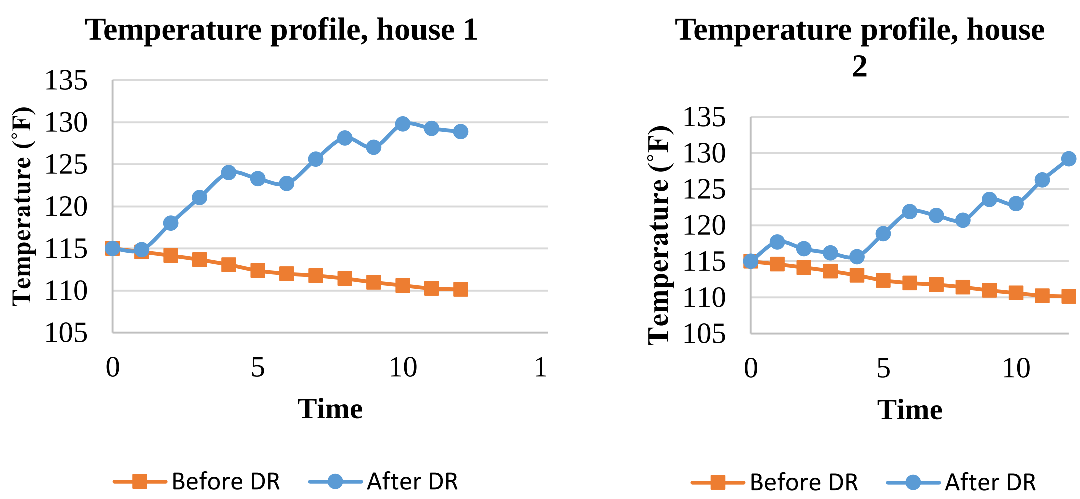

Figure 3.25. Temperature profiles at node 836 a) house 1 b) house 2

4. CONCLUSION

This thesis provides an approach to maintain voltages within the limits in a distribution system with active power adjustment. The ACOPF problem is solved to calculate the active power adjustments at each node to bring the violated voltages within the limits. The problem is solved for three different cases where the marginal cost of feeder supply and the cost of active power adjustment were varied. The solution to this problem i.e., the active power adjustments at eligible nodes was realized by adjusting energy consumption of electric water heaters. It can be concluded that voltages in a distribution system can be maintained within limits by adjusting active power using demand response. This is especially economical when the cost of adjusting active power with loads is lower than or equal to the cost form the feeder supply in under-voltage system. In over-voltage case, demand response is economical when cost of feeder supply is less than net benefit of adjusting P.

There is much future work ahead where the assumption on nodes that has the active power adjustment capability that were made to show the proof of concept can be relaxed and systematic approach can be defined. Assumptions that were made in solving demand response on electric water heater temperature such as the same initial temperature, inlet and ambient temperature for all the houses can be relaxed and more variability can be included.

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VITA

Mounika Chava was born in Andhra Pradesh, India. She earned her Bachelor's degree in Electrical and Electronics Engineering from VR Siddhartha Engineering College, India in 2012. She then worked as systems engineer for Tata Consultancy Services, India until 2014. She began her graduate study towards the master's degree in the department of Electrical and Computer Engineering at the Missouri University of Science and Technology, USA, in August 2014 and received degree in December 2016.