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A hybrid control approach for regulating frequency through demand response

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HIGHLIGHTS

- Simulation set up with both diesel and wind generation to study frequency regulation by demand response.
- Domestic refrigerators used as control loads along with automatic generation control for regulating frequency.
- Proposed architecture with Cooperative Home Energy Management systems (CoHEM) at distribution transformers.
- Results with proposed controller validated against no control and centralized control case.

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ABSTRACT

Many countries worldwide have set ambitious targets for integrating renewable energy in their power network. Where renewable energy reduces carbon footprint, its reduced inertia makes the system susceptible to frequency deviation after disturbance. This paper presents a novel hybrid frequency regulation strategy by using domestic refrigerators as control loads. The proposed strategy uses the idea of Cooperative Home Energy Management system (CoHEM) at distribution transformers and exploits the best of both centralized and decentralized control systems. A hybrid power network setup with both diesel and wind generation is designed in Simulink so as to study the frequency profile of the system after disturbance. The effectiveness of the strategy is validated without control and with centralized control under four different scenarios. Results when compared to without controller, suggest that the proposed controller exhibits less frequency error and is able to regulate frequency faster. The results were in par with the centralized controller; however, the proposed architecture is anticipated to save time, technical cost and computational burden over a centralized controller.

1. Introduction

Perfect supply-demand balance should be maintained at all times so as to ensure proper working of a power system. Power mismatch between supply and demand results in frequency drift from nominal value that jeopardize the reliability of the system. Traditionally, generation side control was used to regulate frequency. However, the increased penetration of renewable energy sources such as wind turbine and solar PV with reduced inertia and variable output, not only make the system vulnerable to disturbance but also reduce the controllability of generators [1]. Notable work in the past mentions the situation where the conventional Automatic generation control (AGC) is able to regulate frequency within a narrow band of the nominal frequency without renewables. However, with about 50% penetration of renewables the same system inertia reduces to half of its nominal value, which makes the AGC incapable of maintaining the frequency within acceptable limits [1]. The use of conventional generator-side frequency regulation in the presence of intermittent renewables in power system will urge additional capital investment in new power plants as well as the use of expensive, less efficient plants running partly loaded. On the other hand, demand side participation could provide spinning reserves, in turn increasing the ability of the power system to accommodate more renewables [2,3].

In the past, demand response has shown a great potential in regulating frequency. Essentially, Demand Response (DR) is the phenomenon where customers change their normal energy consumption pattern in response to price-signals or incentives offered to them. The main aim of this technique is to reduce peak [4]. DR not only reduces the reliance on conventional, green-house gas emitting generators but also maintains an evenly distributed load profile and reduces the likeliness of curtailing load involuntarily [5]. The following is worth quoting from Ref. [5]: “Owing to the results, even if only 10% of consumers become

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Nomenclature

Abbreviations

AGC	automatic generation control
TCLs	thermostatically controlled loads
DR	demand response
EWH	electric water heater
HVAC	heating, ventilation and air-conditioning
CoHEM	cooperative home energy management system
EV	electric vehicles
BESS	battery energy storage system
HEM	home energy management system
CL-OFF	critical load OFF
CL-ON	critical load ON

Symbols

Tc	compartment temperature
Te	evaporator temperature
Ta	ambient temperature
Tcond	condenser temperature
Tcomp	compressor temperature
Cc	heat storage capacity
Rec	thermal resistance of wall between cabinet and the evaporator
Ri	thermal resistance of insulation
Rcap	resistance of capillary tube
Ccond	capacity of condenser
Rcond	resistance of narrow tube supplying refrigerant from compressor to condenser
Total_on_1	total number of ON refrigerators in CoHEM 1
Total_Off_1	total number of OFF refrigerators in CoHEM 1
Total_CL_off_1	total number of Critical load OFF refrigerators in CoHEM 1
Total_CL_on_1	total number of Critical load ON refrigerators in CoHEM 1
Total_Power	total power being consumed by refrigerators in a particular CoHEM
P_comp	compressor power of refrigerators
f_ref	nominal frequency of power system
M	scaling parameter
load_o	total number of ON refrigerator units at previous iteration
df	frequency error
load_c	new number of refrigerator units that need to be ON/OFF
Total_Units_OFF	total number of OFF refrigerators in all 3 CoHEMs
New_load	new refrigerator load
Control_Total	number of refrigerator units whose compressor cycle needs to be manipulated
Total_off_1	total number of OFF refrigerators in CoHEM 1
Total_off_2	total number of OFF refrigerators in CoHEM 2
Total_off_3	total number of OFF refrigerators in CoHEM 3
Control_1	total refrigerators in CoHEM 1 whose compressor cycle needs to be changed
Control_2	total refrigerators in CoHEM 2 whose compressor cycle needs to be changed
Control_3	total refrigerators in CoHEM 3 whose compressor cycle needs to be changed
Total_Units_ON	total number of OFF refrigerators in all 3 CoHEMs
Total_On_1	total number of ON refrigerators in CoHEM 1
Total_On_2	total number of ON refrigerators in CoHEM 1
Total_On_2	total number of ON refrigerators in CoHEM 1
f_act	actual/measured frequency

active, nearly 5.6% peak reduction, 5.3% increment in the valley, and 6% increment in the load factor are achieved. The improvements would be 35.7%, 15.8%, and 55.8%, respectively, if DR potentials of all consumers are activated. It can be seen that the total network losses are reduced by 2.6% when 25% of consumers are active."

Many different control loads are used for DR. References [6–8] make use of Electric water heaters (EWHs). In [6], a central DR strategy has been proposed for eliminating frequency offset. Here, the number of loads required to be manipulated are calculated based on the value of frequency error. The simulation results validate the performance of the system in eliminating frequency error, however, it fails to consider the operating cycle of EWHs. The other drawback is considering aggregated loads and switching the active devices in the aggregated load ON or OFF at the same time which may lead to synchronization. In [7], the same authors refined their previously proposed frequency regulation technique by carrying out simulations both with and without wind generation and introducing a Step-By-Step (SBS) controller. The SBS reduced the number of manipulated EWH loads required to keep frequency within acceptable limits, hence improving the quality of service to customers. Another frequency regulation strategy using EWHs is proposed in [8]. The proposed controller treated EWHs as deferred loads at times of high power demand and as dispatchable loads at times of low demand. Monte Carlo simulations on a large population of EWHs validated the performance of the proposed controller. However, the water was allowed to cool to any temperature without considering customers' preferred temperature. Thus, this work did not account for customer satisfaction.

The concept of DR using heating, ventilation and air-conditioning (HVAC) units is presented in [9,10]. In [9], a decentralized demand control technique was suggested for frequency regulation. The temperature set point of HVAC units was changed in response to frequency deviation. Simulations with 1000 HVAC units were carried out validating the performance of proposed controller. In [10] a second order aggregated control model for heterogeneous HVAC loads was proposed. In the event of frequency offset from nominal value a centralized aggregated control was sent to all flexible loads that respond based on their individual temperature and power state. Results validated effective frequency regulation by aggregated HVAC units in addition to reducing the peak demand by 30%.

Various research studies have verified the potential of domestic refrigerators in regulating frequency [11–13]. In [11], the thermostat control system was modified such that the switching temperature would vary proportionally with frequency deviation. Simulations verified that refrigerators could provide services similar to spinning reserves. However, the proposed scheme tends to synchronize the thermostatically controlled loads (TCLs) leading to overshoots in energy demand. Another decentralized approach for DR of domestic refrigerators was proposed in [12]. The operating temperatures and thus the power consumption of refrigerators were varied in response to mains frequency deviation from nominal value. Simulations confirmed the ability of the proposed random controller in regulating frequency while ensuring the stability of the power system. Ref. [13], suggested a decentralized stochastic approach for manipulating power consumption of a large number of refrigerators in response to frequency deviation. The paper showed promising results in regulating frequency but the time between switching events of appliances was not minimized. This may result in appliances switching more than once in a short interval.

The possibility of reducing back and forth communication between utility and end-users is explored in [14,15]. These papers propose a frequency regulation strategy where refrigerators for load manipulation are chosen based on their ability to stay off for longer times. This would not only prevent refrigerators from pulsating between states but will also save utility from sending excessive control commands to refrigerators. Slopes of thermostatic curves from previous thermostatic cycles were used to predict the present cycle's OFF time. However, prediction errors can lead to refrigerators changing state frequently resulting in increased communication burden on utility.

Notable literature in the past has also explored the potential of Electric Vehicles (EVs) in providing primary frequency reserve. Electric vehicles not only reduce carbon emission on roads by transitioning from fossil fuels to cleaner, renewable energy but EV charging can also act as flexible demand and play a vital role in frequency regulation. A study of how various EV charging techniques could advantage EVs in supplying frequency reserve was carried out in [16,17]. In [18], frequency regulation challenges arising from power system with low inertia were studied. Additionally, the benefits of EVs in providing frequency reserve were explored. However, recent research [19] has highlighted the low performance of Li-ion batteries used in electric vehicles in cold temperatures, posing greater issues for cold- climate countries. Extensive research and high penetration of EVs is required without which EVs cannot deem their potential in providing frequency reserve.

A couple of papers have considered the idea of having Battery Energy Storage System (BESS) for supporting system frequency. In [20] wind diesel power system was considered along with BESS with potential-integral-derivative (PID) controller. BESS was successful in supporting frequency and shaving peaks. Another work [21] studied the optimal BESS sizing and profit maximizing strategies for BESS customers taking part in primary frequency control. Ref. [22] presented the idea of a bi-directional convertor that could be controlled with the objective of facilitating connection between LV grid and the RES based generators coupled with BESS. The basic idea was to use convertors to inject excess energy from batteries to grid as well as to charge batteries from the grid, in turn providing ancillary services and reducing customer bills.

Thus, it is evident that the control loads most frequently used for DR include refrigerators, freezers, EWHs, HVAC. Although several studies have used the ability of EVs and BESSs in providing frequency regulation reserve, batteries are still expensive to be deployed in large capacities. In this paper, domestic refrigerators are used as control loads primarily because these are commonly available in all households, in all seasons and at all times of the day, unlike EWH and HVAC which are seasonal. EWH and HVAC may be commonly available in households in developed countries, but, they are still considered as luxury in developing countries and are cost-intensive for a common man. Thus, domestic refrigerators become a good fit for DR programs. The total cold storage load is anticipated to account for 11% of total domestic load by 2020 [11]. Refrigerators also have a large inertia and can mimic the behaviour of energy storage systems [23], offering the same advantages as a conventional battery storage system while providing higher capacity and at a lower cost [24].

While considering the different strategies for frequency regulation using DR, there exists three distinct classes of control algorithms namely, centralized, decentralized and hybrid control algorithms. As mentioned above [6,7,14], consider a central demand response strategy where a single controller is responsible for carrying out communication with all end-users. While the centralized control approach reduces the possibility of errors, it has the drawback of increasing communication cost and data processing burden on utility [25]. Refs. [9,11–13] present a decentralized approach which deploys more than one controller resulting in less computational burden and communication cost. However, the decentralized control approach has limitations such as greater possibility of erroneous measurements and high cost associated with setting up frequency measurement units in every household [25].

A hybrid of above mentioned control strategies is recommended for optimal performance of smart grid [26]. That said, a few studies [27–30] introduced the idea of an aggregator acting as a link between customer and utility. The aggregator carried out DR activities on behalf of utility. It was responsible for paying incentives to customers for manipulating their device operation in response to frequency deviation. Thus the use of an aggregator reduces profits for the utility, as now the utility had to pay aggregators for carrying out DR services for them.

To overcome the above issue, this paper proposes a frequency regulation strategy that uses the idea of CoHEM as a link between customers and utility. The authors have already introduced this idea to test the potential of refrigerators in changing their compressor cycle in response to supply-demand imbalance [31]. However, frequency regulation was not tested in their previous work. In this paper, the same idea of CoHEM at distribution transformers is implemented in a network model that is rich in renewable sources and the use of refrigerators in frequency regulation is tested.

Overall, the main contributions of this research study are outlined below:

A hybrid control approach is proposed for DR in a power system with flexible loads and both diesel generation and renewable wind energy. The hybrid architecture considers CoHEMs at distribution transformers. The CoHEMs act as a bridge between utility and end-users. The suggested architecture is expected to exploit the benefits of both centralized and decentralized control approaches without down turning utility revenues. Domestic refrigerators are used as control loads. The refrigerator compressor cycle is divided into four different states based on compartment temperature. The critical states added precisely prevent refrigerators from pulsating between states, in turn making the controller robust and reducing the communication between utility and CoHEMs. Synchronization of TCLs is avoided by randomizing parameters. Additionally, customer privacy is maintained at all times. Simulation results for proposed controller are validated against both without control and with centralized control under four different scenarios. Effects of increase in load and intermittent wind generation are studied in detail. Frequency nadir and frequency restoration times are compared for no control and hybrid control cases. The study also highlights anticipated benefits of hybrid controller over centralized controller and brings forward practical tips that can be derived from this work.

2. Methodology

Refrigerator modelling and control strategy is explained herein. Increase in customer demand or loss of generation results in supply demand volatility. Elastic load can play a pivotal role in maintaining a perfect supply demand balance.

2.1. Refrigerator modelling

Refrigerator is a cooling device that maintains compartment temperature within a narrow dead band of the thermostat temperature set by the end-user. Fig. 1 shows the operation of a refrigerator. The thermostat is set at 5 C and the compartment temperature keeps on pulsating between 5 C ± 2 C, i.e. 3 C and 7 C. The compressor turns ON as soon as compartment temperature hits 7 C and turns OFF as soon as the temperature hits 3 C. The different states are marked in Fig. 1. Maintaining temperature within bounds is crucial for the safety of food items in fridge.

The refrigerator for the simulation purpose is modelled in Simulink

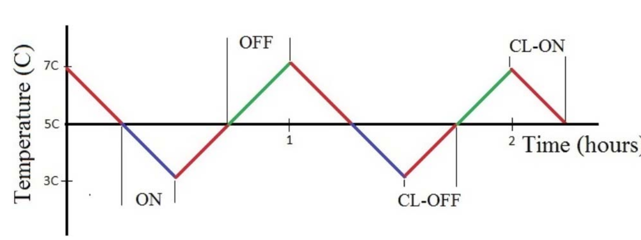

Fig. 1. Compressor cycle and refrigerator states.

using [32]. This looks into three different refrigerator models with varying complexity. one particular model that is closest in performance to real refrigerator is used in this paper. Fig. 2 shows the compressor cycle as well as states of refrigerator simulated in Simulink. As can be seen the refrigerator operation mimics the behaviour of a real refrigerator. Equations for both cool-down and warm-up phase of refrigerator are given below [32]:

Cool down:

$$\frac{dTc}{dt} = \frac{Te(t)-Tc(t)}{Cc*Rec} + \frac{Ta(t)-Tc(t)}{Cc*Ri} \quad (1)$$

$$\frac{dTe}{dt} = \frac{Tc(t)-Te(t)}{Ce*Rec} - \frac{Tcond(t)-Te(t)}{Ce*Rcap} \quad (2)$$

$$\frac{dTcond}{dt} = \frac{Tcomp-Tcond(t)}{Ccond*Rcond} + \frac{Tcond(t)-Te(t)}{Ccond*Rcap} \quad (3)$$

Warm up:

$$\frac{dTc}{dt} = \frac{Te(t)-Tc(t)}{Cc*Rec} + \frac{Ta(t)-Tc(t)}{Cc*Ri} \quad (4)$$

$$\frac{dTe}{dt} = \frac{Tc(t)-Te(t)}{Cc*Rec} \quad (5)$$

$$\frac{dTcond}{dt} = \frac{Tcomp-Tcond(t)}{Ccond*Rcond} \quad (6)$$

For the sake of frequency regulation the refrigerator operation is divided into four different states. Refrigerators can be in one of the four states at any given time.

1. State 0, OFF – when compartment temperature is greater than thermostat and compressor is OFF. State 0 suggests that refrigerator compressor is currently OFF and available to be switched ON.
2. State 1, ON – when compartment temperature is less than thermostat and compressor is ON. State 1 suggests that refrigerator compressor is currently ON and available to be switched OFF.
3. State 2, Critical Load OFF (CL-OFF) – when compartment temperature is less than thermostat and compressor is OFF. State 2 suggests that refrigerator is not available for load manipulation.
4. State 3, Critical Load ON (CL-ON) – when compartment temperature is greater than thermostat and compressor is ON. State 3 suggests that refrigerator is not available for load manipulation.

The critical load states have been added so as to prevent the refrigerators from pulsating between states. In the absence of Critical load state, if the refrigerator compressor just turned ON and it received OFF command it would turn OFF and then quickly turn ON again in order to maintain compartment temperature within bounds [31]. The presence of critical state will make the controller more robust.

All refrigerators for the simulation purpose are modelled such that their thermostat, ambient temperature, compressor temperature and temperature dead band are different from each other. Randomization in parameters help prevent the compressor cycle of refrigerators from getting locked up as oscillators, hence avoiding the phenomena of synchronization.

2.2. Controller description

Full deployment of smart grids will necessitate the installation of home energy management system (HEM) in every household. HEM will be a display screen installed in customer premises that will measure energy consumption of customers in a given time interval [33]. It will also be capable of carrying out bi-directional communication between end-users and utility and will be used for scheduling customer load based on customer priorities [33]. It is now well established by a number of studies [34,35] that HEMs will increase customer welfare by scheduling load during low electricity price periods, however, they may cause volatility in demand and reduce utility revenues. Rebound peaks is the phenomena where all customer schedule loads at low electricity price periods resulting in peak demand at times of low peak. Therefore, there is a need for Cooperative home energy management system (CoHEM) that will coordinate the operation of different HEMs such that it would benefit not only the end-users but also the utility [36].

This paper proposes a frequency regulation technique that will utilize the idea of CoHEMs. CoHEMs will be installed at distribution transformers and will be responsible for communicating with the utility as well as the house holds that are connected to that particular distribution transformer. Fig. 3 shows the proposed design with CoHEMs [31].

Refrigerators will be the control loads that will be used for regulating frequency in case of frequency drift outside acceptable limits. They will send their compartment temperature to HEM continuously. Based on the current temperature, thermostat settings and compressor state the HEM will update the state of refrigerator to CoHEM.

All CoHEMs will follow the steps listed in Fig. 4 and send the total number of ON and OFF refrigerators to utility as well as the Total_Power at that instant. Based on the values from CoHEMs, the Total_Power at the utility will be calculated.

$$\begin{aligned} \text{TotalPower at Utility} = &(\text{TotalPower at CoHEM 1}) \\ &+ (\text{TotalPower at CoHEM 2}) \\ &+ (\text{TotalPower at CoHEM 3}) \end{aligned} \quad (7)$$

The utility will compare nominal frequency and measured

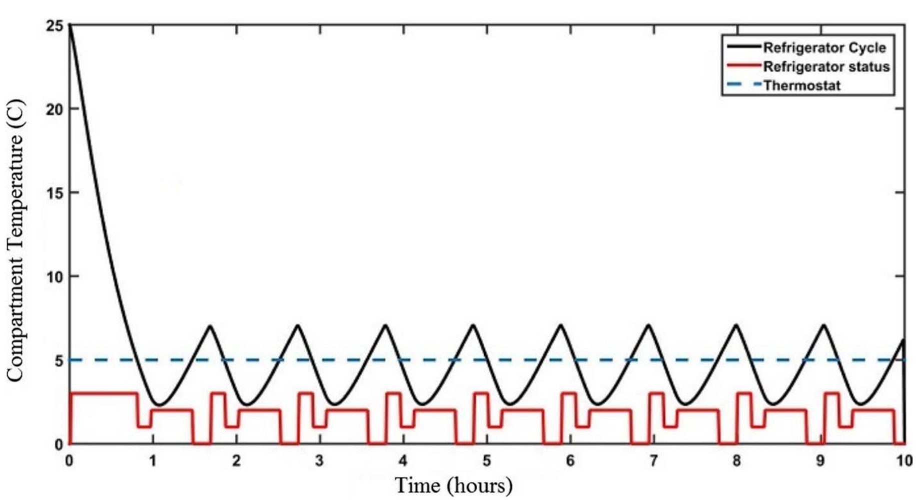

Fig. 2. Refrigerator compartment temperature for 10 h and the various refrigerator states.

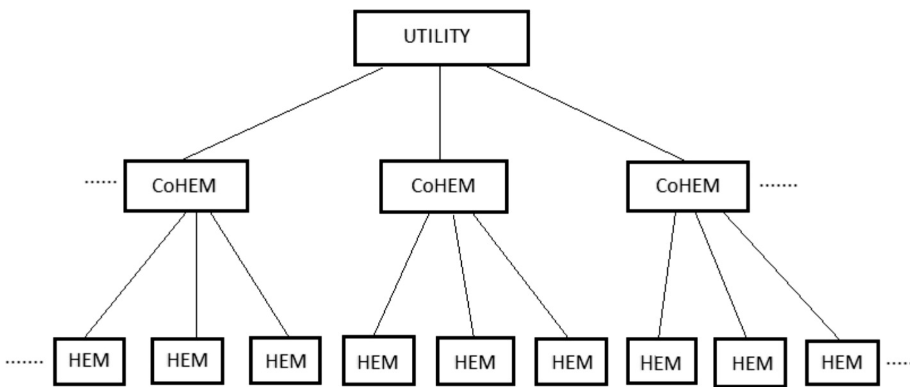

Fig. 3. Recommended architecture with CoHEMs acting as link between utility and end-users [31].

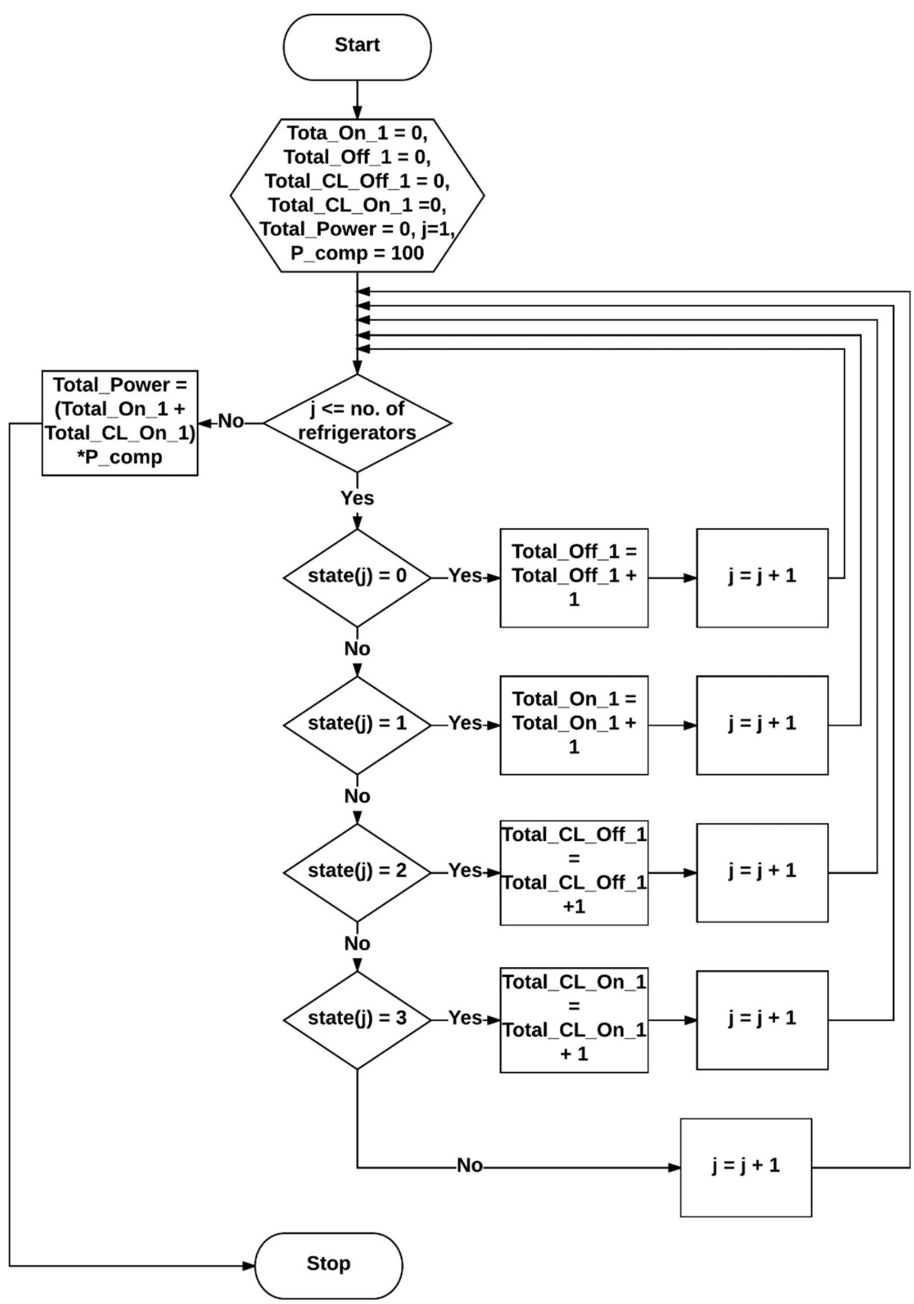

Fig. 4. Steps involved in computing total refrigerator load at a particular CoHEM.

frequency at all times. A frequency deviation within ± 0.05 Hz of the nominal value will be considered acceptable. However, if the frequency drifts out of acceptable bounds it will need to be regulated. The proposed controller will use Hill Climbing Method to calculate the total number of refrigerators whose compressor cycle will need to be altered so as to eliminate frequency error. Once the number has been computed control commands will be sent in a round robin approach. The control command will be sent to CoHEM 1 first. CoHEM 1 will instruct the available refrigerators via HEM to alter operation of compressor cycle. In the event where CoHEM 1 does not have any refrigerators available for manipulation, command will be send to CoHEM 2. Likewise, if no refrigerators are available it will be sent to CoHEM 3 and so on. Frequency error will be calculated at all times and control commands sent until the frequency is maintained within bounds.

2.3. Hill climbing method

In a decentralized control approach as discussed before all appliances monitor frequency in a distributed manner and respond to frequency deviation independently. However, improper design of decentralized control approaches can result in more loads being manipulated then required leading to a frequency drift in opposite direction [25]. In order to avoid over-activation of flexible loads, [37] proposed randomized frequency set points to be applied to a group of appliances to trigger control action. Another work in [14] considered the idea of reducing load in steps in response to under-frequency. Ref. [23] discussed the idea of using prediction so as to calculate the reserve power at every instant that would be used for regulating frequency in the event of frequency offset from nominal value. On the other hand, Hill

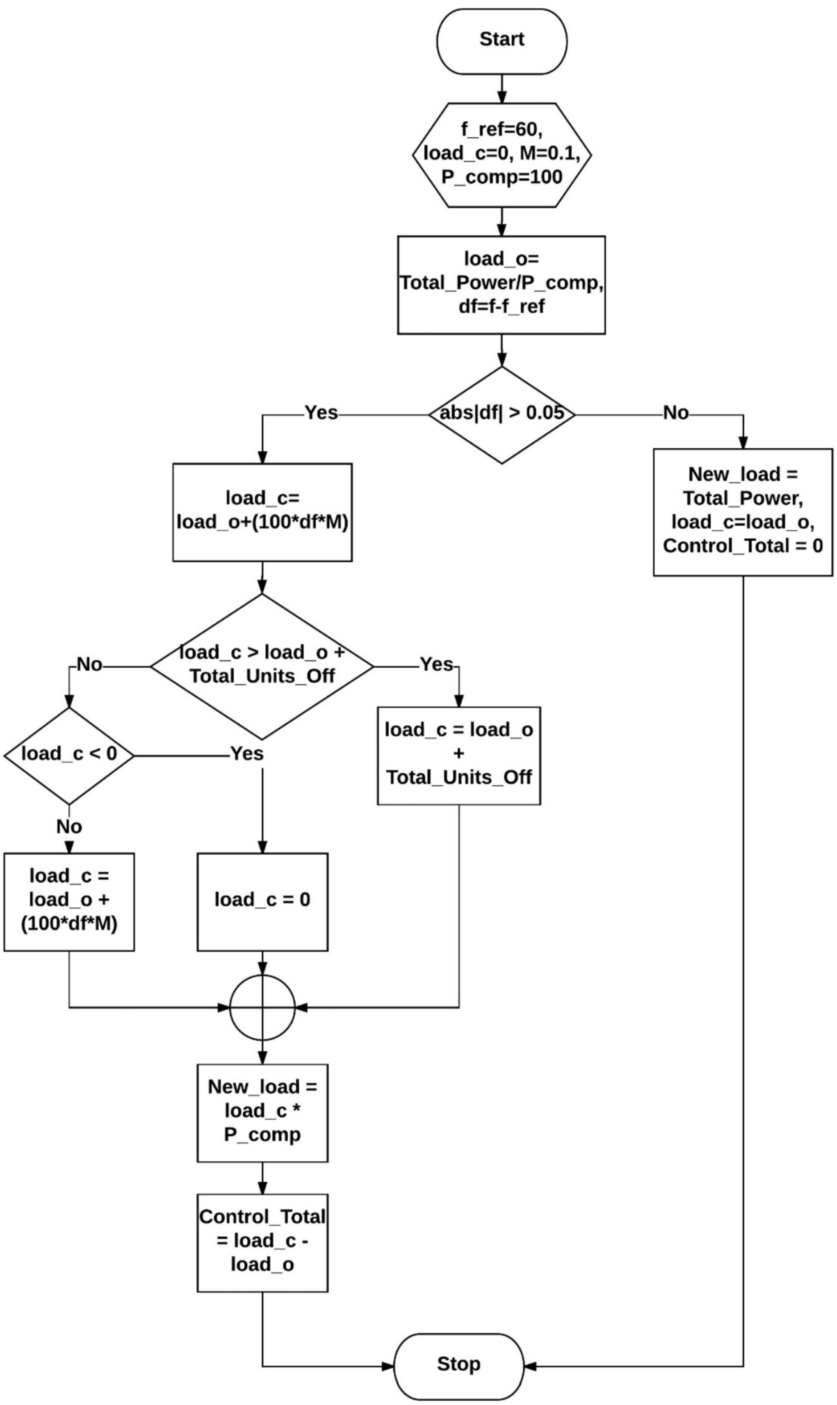

Fig. 5. Hill Climbing Method.

Climbing method as proposed in [6,7] used a simple formula based on the value of frequency error to calculate exact number of TCLs that need to be manipulated in order to eliminate frequency error, hence eliminating any chances of frequency drift in the other direction. Owing to the simplicity and accuracy offered by Hill Climbing method this paper uses this approach in the work. Fig. 5 below shows the various steps involved in Hill Climbing method.

Step 1: At the start of every iteration, variables are initialized. f_ref is the nominal frequency of power system, M is the scaling parameter that is set equal to 0.1 [7] and P_comp is the refrigerator compressor power. M is a constant and is used to curtail the frequency error [7].

Step 2: Load_o is the total number of ON refrigerator units at the previous iteration. Whereas, Total_Power is the total power being consumed by refrigerators at preceding iteration and is calculated using (7). df is the frequency error between measured and nominal frequency. A frequency deviation up to $\pm$ 0.05 Hz is considered acceptable. However, if frequency drifts out of acceptable limits the Hill Climbing formula is used.

Step 3: Hill Climbing formula calculates load_c, that is the new number of refrigerator units that need to be in ON/OFF state so as to eliminate frequency error. A positive frequency error will result in load_c greater than load_o, which means that more refrigerator units will need to be turned ON and vice versa. Load_c cannot be a negative number; also it cannot be greater than the maximum number of refrigerator units that can be in ON state.

$$\text{Maximum refrigerator units that can be in ON state} \\ = \text{load o+ TotalUnitsOFF} \tag{8}$$

In the above equation, Total_Units_OFF is equal to the number of refrigerator units in OFF state in CoHEM 1, CoHEM 2 and CoHEM 3.

$$\text{TotalUnitsOFF} = \text{TotalOff1} + \text{TotalOff}_2 + \text{TotalOff3} \tag{9}$$

Step 4: Once load_c value is computed, the new refrigerator load, New_load can be found by multiplying load_c by refrigerator compressor power, P_comp. Control_Total gives the number of refrigerator units whose compressor cycle needs to be manipulated so as to eliminate frequency error. In the case where frequency is within bounds New_load is set equal to load at previous iteration and Control_Total is

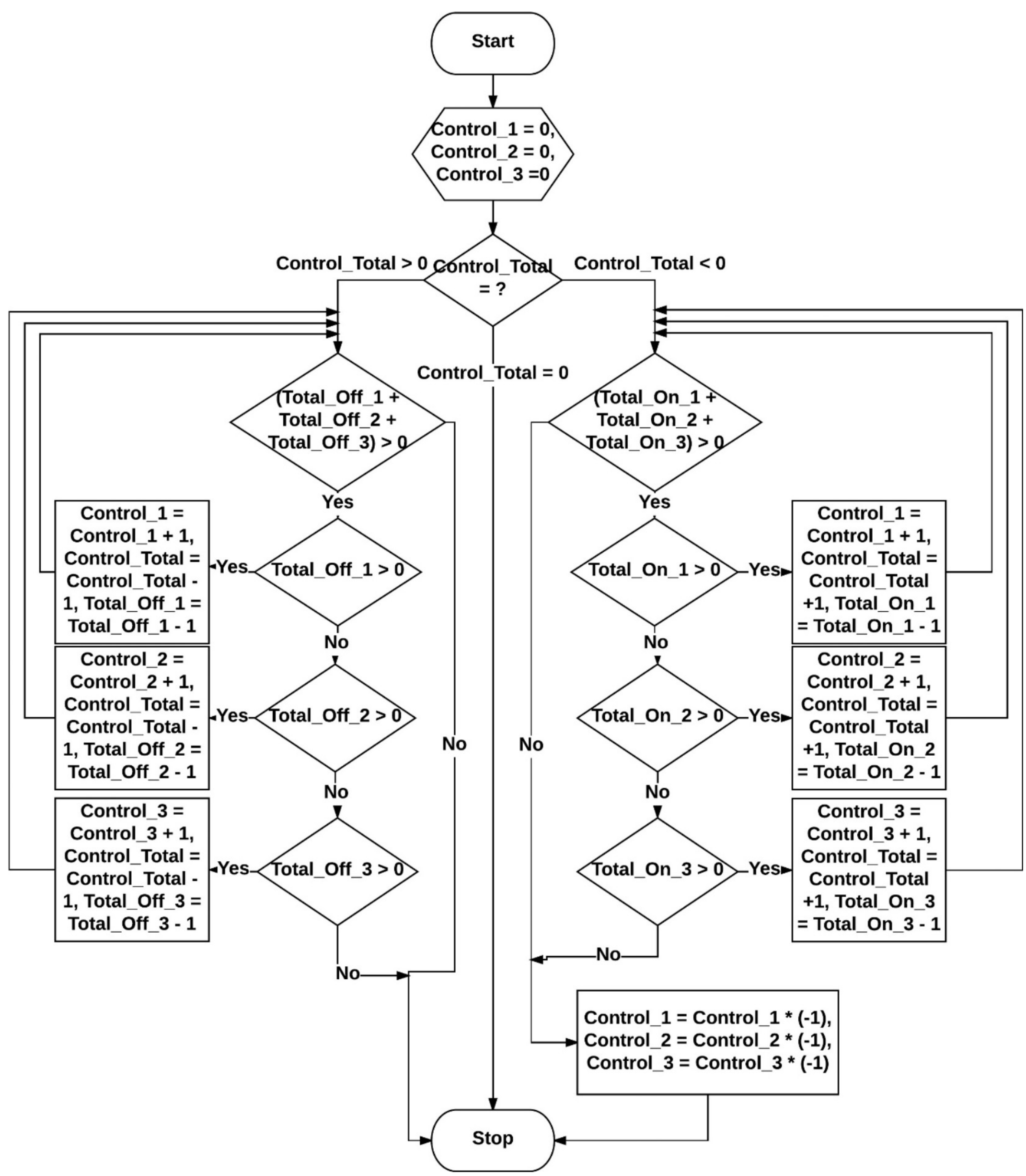

Fig. 6. Steps involved in calculating number of control signals sent to each CoHEM.

set equal to zero

2.4. Utility controller

Once Control_Total is enumerated, the utility needs to compute the number of refrigerators in each CoHEM needed to manipulate their operation. Fig. 6 shows the different steps involved in calculating the number of control signals sent to every CoHEM.

Step 1: At the start of every iteration, variables are initialized. The control signals to all CoHEMs are set equal to zero, which implies that none of the refrigerators are requested to change operation of compressor cycle.

Control_Total = 0 implies that all refrigerators carry on with their normal operation.

Control_Total > 0 denotes that refrigerators need to be turned ON.

Control_Total < 0 denotes that refrigerators need to be turned OFF.

Step 2: If Control_Total > 0 and refrigerators are available to be turned ON, that is Total_Units_OFF > 0 then control command will be send in a round robin approach to CoHEM 1 first.

In case CoHEM 1 has refrigerators in OFF state it will follow the command by incrementing Control_1 by 1. Control_Total will be decremented by 1 indicating that one control command has been received by the CoHEM. Total_Off_1 will also be reduced by 1 denoting that one refrigerator is going to change its compressor cycle from OFF to ON. However, in the event where CoHEM 1 has no refrigerator in OFF state (Total_Off_1 = 0), control command will be send to CoHEM 2 and same steps will be repeated. In the case where CoHEM 2 is also unavailable command will be send to CoHEM 3. The loop will be repeated until Control_Total = 0 or Total_Units_OFF = 0. Once one of the two conditions or both conditions are achieved the process will terminate.

On the other hand, if Control_Total < 0 and refrigerators are available to be turned OFF, i.e., Total_Units_ON > 0 than control command will be send to CoHEM 1 first. In Fig. 6, Total_On_1, Total_On_2 and Total_On_3 denote total ON refrigerator units in CoHEM 1, CoHEM 2 and CoHEM 3 respectively.

$$\text{TotalUnitsON} = \text{TotalOn1} + \text{TotalOn}_2 + \text{TotalOn3} \tag{10}$$

In case CoHEM 1 has refrigerators in ON state it will follow the command by incrementing Control_1 by 1. Control_Total will be incremented by 1 indicating that one control command has been received by the CoHEM. Total_On_1 will be reduced by 1 denoting that one refrigerator is going to change its compressor cycle from ON to OFF. However, in the event where CoHEM 1 has no refrigerator in ON state, control command will be send to CoHEM 2 and same steps will be repeated. In the case where CoHEM 2 is also unavailable command will be send to CoHEM 3. The loop will be repeated until Control_Total = 0 or Total_Units_ON = 0. Once one of the two conditions or both conditions are reached Control_1, Control_2 and Control_3 will be multiplied by -1. A negative Control_1, Control_2 and Control_3 when sent to CoHEMs will indicate that refrigerators need to be turned OFF.

3. System description

The proposed system is modelled in Simulink using the SimPowerSystems toolbox. It is essentially a hybrid of conventional diesel generation and renewable wind energy. The system configuration is shown in Fig. 7. It is a modified system from [6] and includes a renewable energy source.

The diesel engine model is equipped with governor as well as excitation system so as to regulate rotor speed and voltage of synchronous generator within acceptable narrow band. The synchronous generator has a nominal power of 6200 W.

The simulation model of wind turbine generator is composed of asynchronous generator, wind turbine and a signal builder block. The wind turbine block has two inputs wherein wind speed is provided by signal builder block and rotor speed is supplied by the wind turbine. The output of wind turbine is mechanical torque Tm, which is given to asynchronous generator. The asynchronous generator has a nominal power of 5000 W.

Two different types of loads are considered, namely responsive and non-responsive load. Refrigerators are considered as responsive loads, whose operation can be manipulated in response to frequency error. However, non-responsive loads will not have any role in regulating frequency. A total of 24 refrigerators are considered with a compressor power of 100 W each. The system consists of 3 CoHEMs. Each CoHEM has 8 refrigerators and reports to the utility. Percentage of refrigerators available for load manipulation varies all the time. In the case where all refrigerators are available for load manipulation, flexible load will be equal to 38% of fixed load. On the other hand, if only half of the refrigerators are available the flexible load will be 16% of fixed load.

Addition of renewables reduce the capability of Automatic generation control (AGC) to regulate frequency. Therefore, a controller has been added to the system. The controller helps maintain frequency within a narrow dead band of nominal frequency.

4. Simulation results

To establish whether the proposed hybrid strategy was able to regulate frequency within acceptable limits, simulations were conducted with four scenarios. In each scenario either the wind generation or the customer load was changed so as to study the designed system under heavy loading conditions. In each case both diesel and wind generation supply customer load. The diesel engine has both governor and excitation system and is connected to a synchronous machine that supplies 6200 W. For each scenario comparisons between no control case and cases with proposed controller were made in order to validate the performance of the proposed controller.

4.1. Scenario 1: Wind speed dropped from 9.5 m/s to 8 m/s at 15 sec

In this case, a fixed load of 6800 W was considered. 24 refrigerators were considered with a compressor power of 100 W each. Refrigerator compressors turned ON and OFF maintaining the compartment temperature within bounds. The wind speed suddenly changed from 9.5 m/s to 8 m/s at 15 sec reducing the wind power generation from almost 3000 W to 1700 W, resulting in a supply-demand mismatch. Fig. 8 shows the frequency deviations caused by sudden change in wind speed for the cases without controller and with proposed controller. The controller was applied at 14 sec just before the event was introduced. In

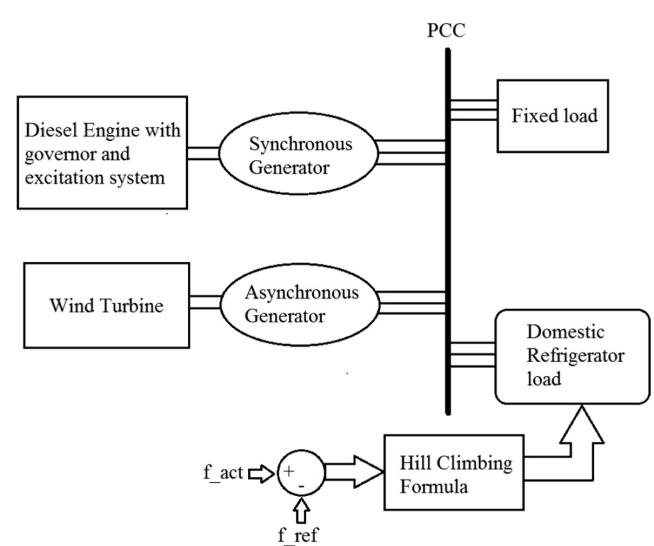

Fig. 7. Configuration of the proposed system [6].

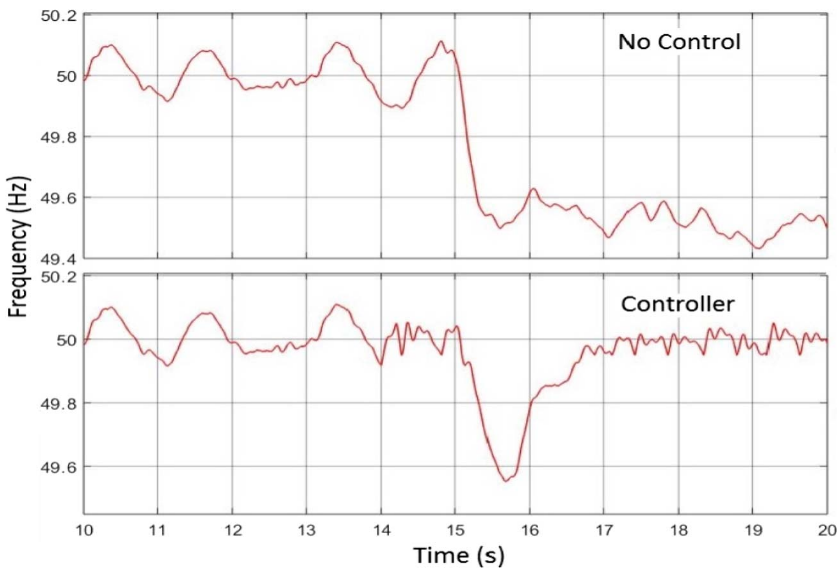

Fig. 8. System frequency graph for No Control and Controller Case.

a practical case the controller would be applied at all times so as to respond to any frequency deviation out of acceptable bounds. However, in simulations controller was applied just before event for comparison purposes, in order to show same frequency profile with both controller and no control case before the event.

Is it apparent from Fig. 8 that the no control case was unable to regulate frequency. After the wind speed changed, the frequency continuously dropped to below 49.6 Hz and kept oscillating around this value. On the other hand, the control case restored frequency to acceptable limits in around 1.5 sec and maintained the frequency within a narrow dead band of 49.95–50.05 Hz afterwards.

Fig. 9 shows the control commands sent by the controller to the three CoHEMs. A signal of +1 indicates that refrigerator needs to be turned ON, whereas, −1 implies that refrigerator needs to be turned OFF so as to regulate frequency. It is apparent that signals to turn refrigerators OFF were rapidly send to CoHEMs from 15 to 17 sec. However, once the frequency was regulated at around 17 sec the frequency of control commands reduced. Fig. 10 shows the number of ON refrigerators in each CoHEM. The number of ON refrigerators was lowest between 15 and 17 sec owing to the control commands sent to turn the refrigerators OFF in order to regulate frequency.

Fig. 11 shows the refrigerator load in no control and control case. At 15 sec the no control case had a refrigerator load of 1500 W which increased further just after the event. Whereas, the control case had a load of 1100 W at 15 sec and the controller drastically reduced the load from 1100 to 100 W so as to eliminate frequency error.

4.2. Scenario 2: Wind speed reduced from 9.5 m/s to 7.5 m/s at 15 sec

In this scenario, fixed load of 6800 W was considered. Wind speed was reduced from 9.5 m/s to 7.5 m/s at 15 sec, in turn curtailing wind power generation from almost 3000 W to below 1500 W. The decrease in generation resulted in excess demand, leading to frequency deviation. Fig. 12 shows frequency deviation graphs for no control and control case. Controller was applied at 14 sec just before the event was introduced.

It is interesting to note that neither case was able to regulate frequency. However, there were still significant differences between the two results. Just for this scenario simulation time was set to 24 sec instead of 20 sec so as to study detailed difference in frequency deviation between the two systems. At 20 sec, the frequency dropped to around 45.5 Hz without the controller and to 48.7 Hz with controller. The difference in frequency was much more significant at 24 sec. The controller was able to restrict the frequency to around 47.5 Hz in

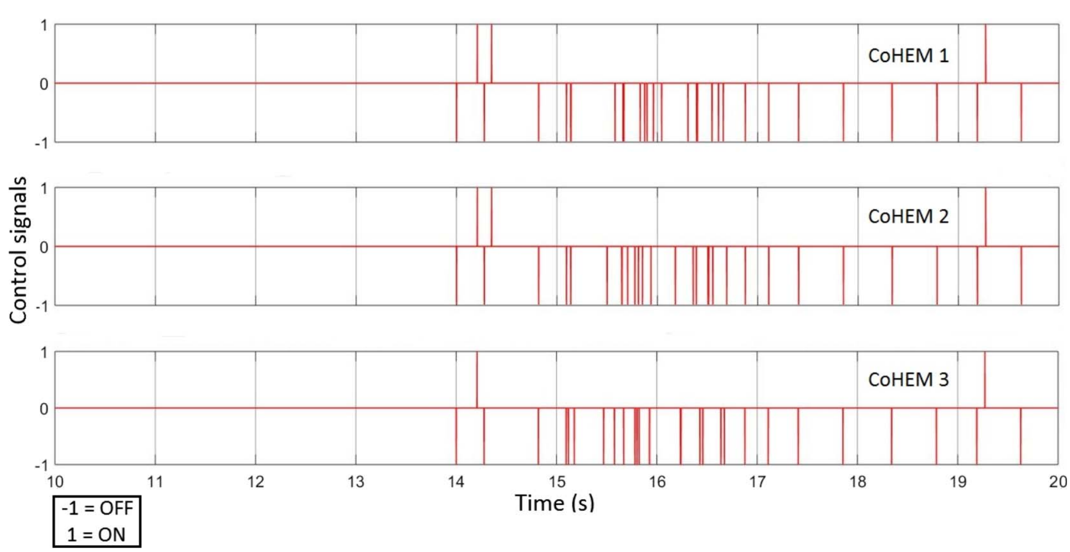

Fig. 9. Control signals sent by utility to CoHEM 1, CoHEM 2 and CoHEM 3.

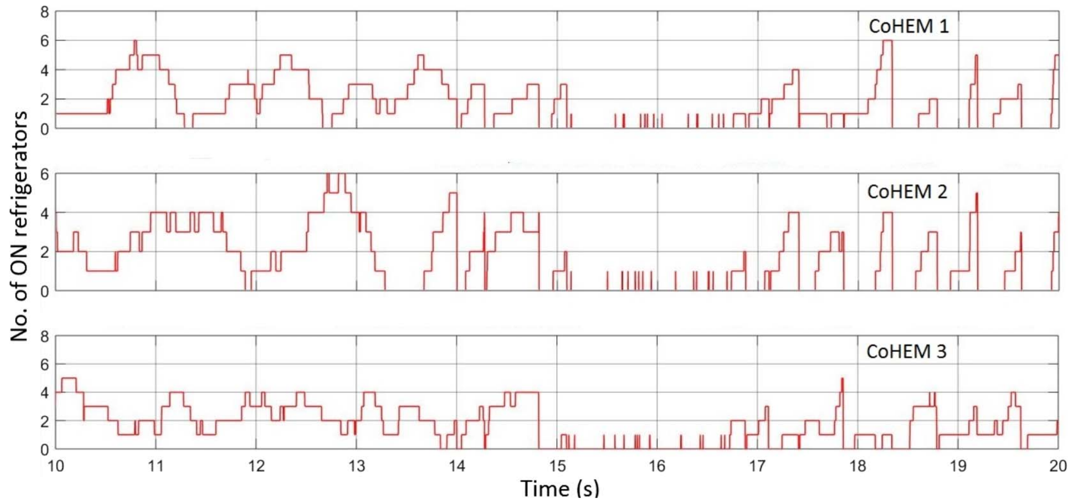

Fig. 10. Number of ON refrigerators in each CoHEM.

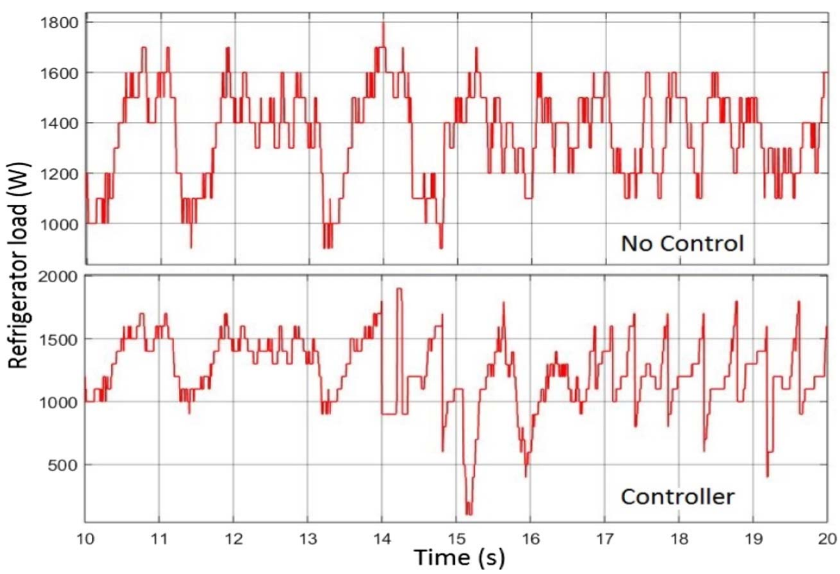

Fig. 11. Refrigerator load for No Control and Controller case.

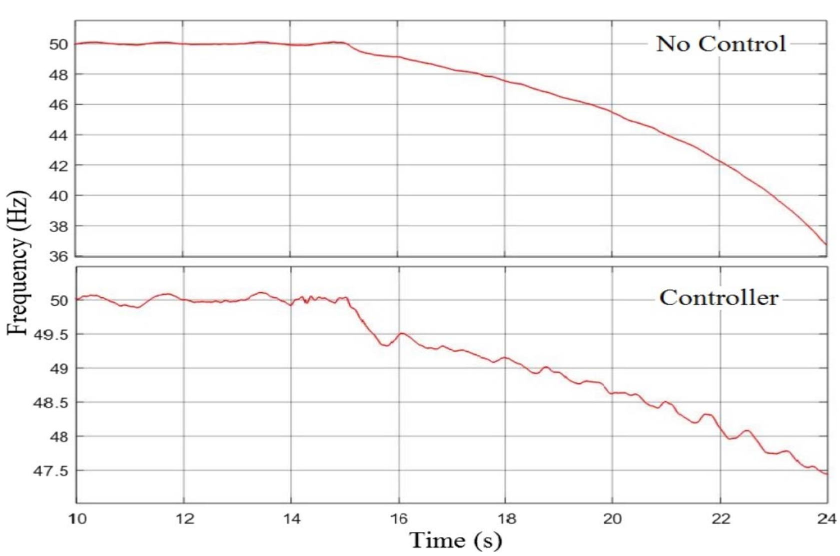

Fig. 12. System frequency graph for No Control and Controller Case.

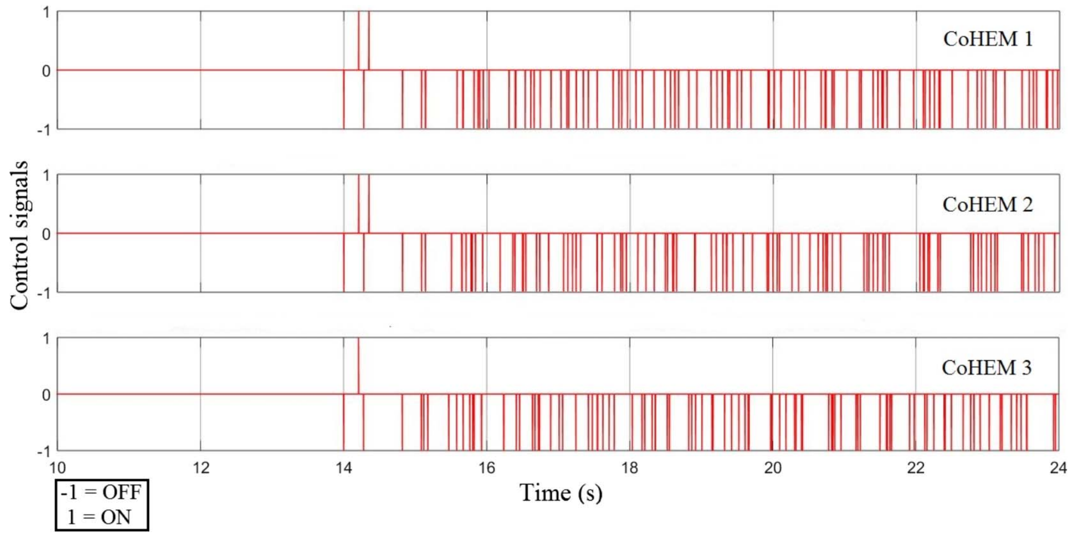

Fig. 13. Control signals sent by utility to CoHEM 1, CoHEM 2 and CoHEM 3.

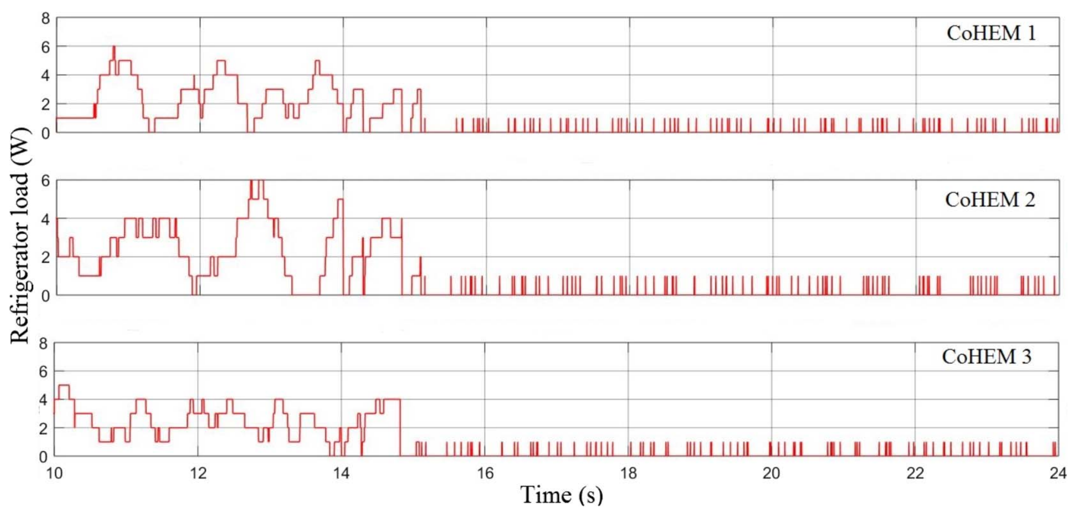

Fig. 14. Number of ON refrigerators in each CoHEM.

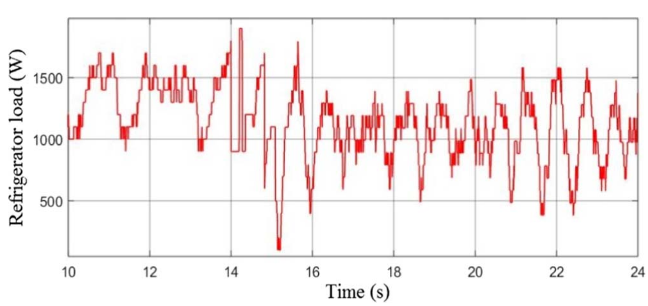

Fig. 15. Refrigerator load in Controller Case.

24 sec. With the no control case, frequency dropped to a value of about 37 Hz at the same time. Frequency drop with controller was less rapid providing time for generation reserves to rebalance supply and demand.

What stands out in Fig. 13 is that the control commands were continuously sent at a high rate from 15 to 24 sec so as to turn refrigerators OFF, aiming to eliminate frequency error. However, the supply-demand mismatch was significant and the refrigerators alone were unable to regulate frequency. Further analysis in Fig. 14 reveals that the control commands restricted the number of ON refrigerators to a minimum in each CoHEM after the event so as to maintain power balance. Fig. 15 shows that the refrigerator load in controller case dropped from 1500 W to 100 W right after the event. Refrigerator load for no control case is the same as in Fig. 11.

4.3. Scenario 3: Load changed from 6200 W – 6800 W at a fixed wind speed of 8 m/s

Wind speed was fixed at 8 m/s, resulting in wind power generation of around 1700 W. Fixed load was changed from 6200 W to 6800 W at 15 sec for 1.5 sec and reduced afterwards to 6500 W for the rest of the simulation. Controller was applied at 14 sec just before the event was introduced. It is apparent from Fig. 16 that without any controller the system took around 3 sec to recover frequency within acceptable limits. On the other hand, with the controller frequency was regulated in a little over 1 sec.

Fig. 17 shows how the utility sent control commands between 15 and 17 sec to turn refrigerators OFF. Fig. 18 shows the reduced number of ON refrigerators between 15 and 16 sec as a result of commands from controller. It is interesting to see in Fig. 19 how the refrigerators load dropped from 1800 W to 300 W almost instantaneously after the event, aiming to eliminate frequency error. Refrigerator load for no control case is the same as in Fig. 11.

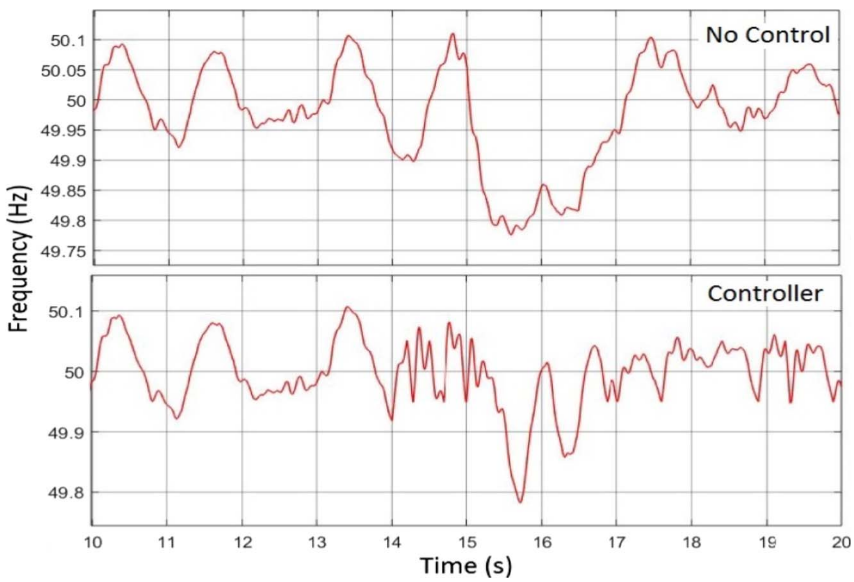

Fig. 16. System frequency graph for No Control and Controller Case.

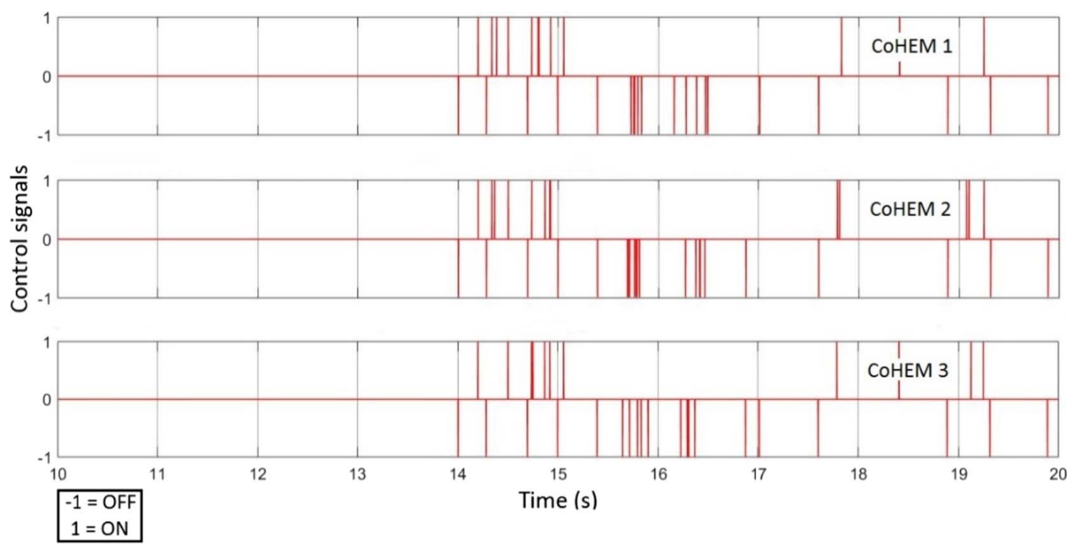

Fig. 17. Control signals sent by utility to CoHEM 1, CoHEM 2 and CoHEM 3.

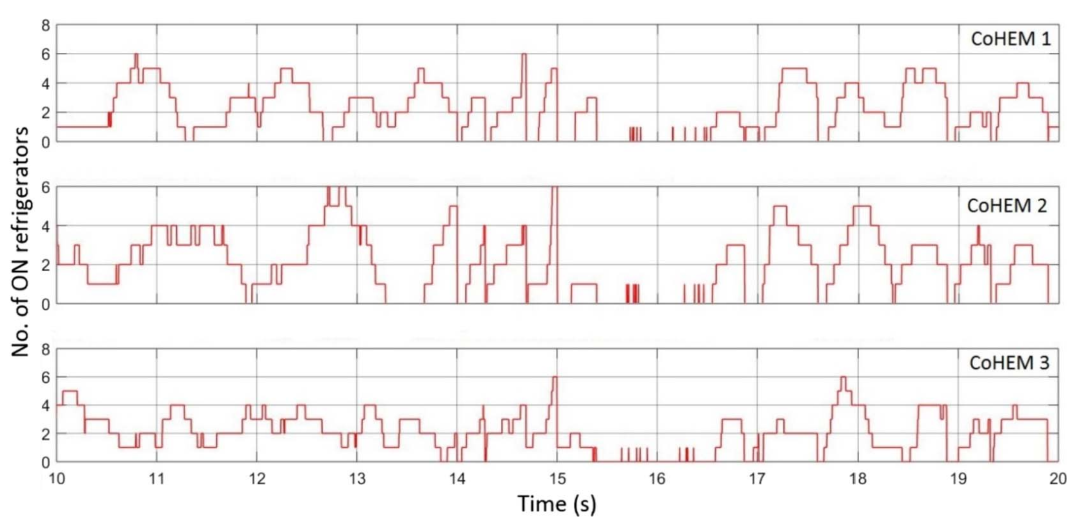

Fig. 18. Number of ON refrigerators in each CoHEM.

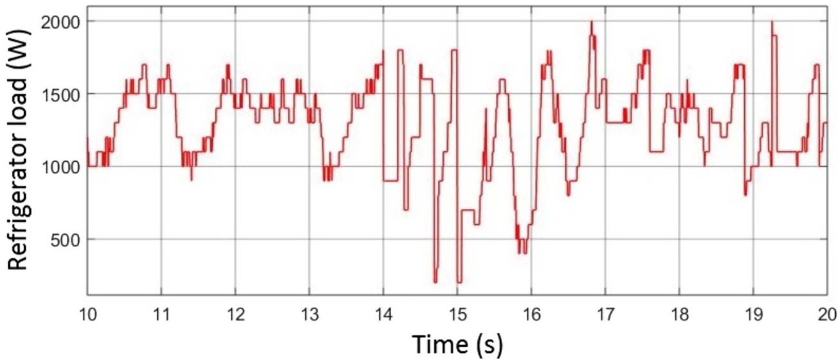

Fig. 19. Refrigerator load in Controller Case.

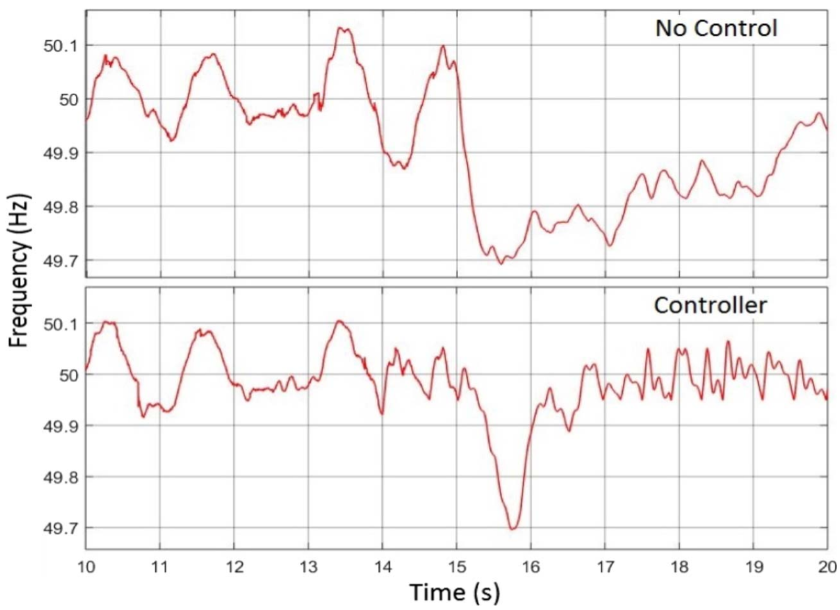

Fig. 20. System frequency graph for No Control and Controller Case.

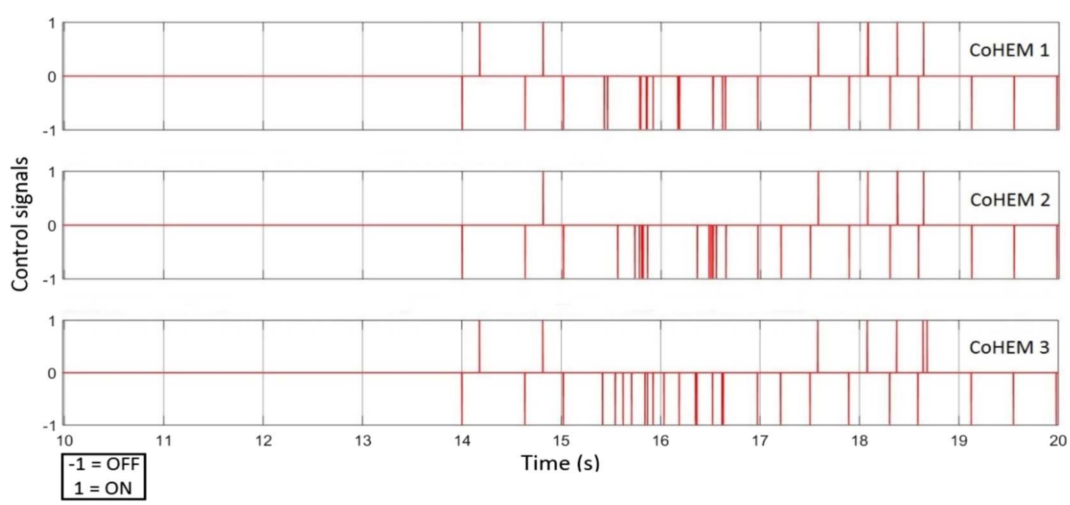

Fig. 21. Control signals sent by utility to CoHEM 1, CoHEM 2 and CoHEM 3.

4.4. Scenario 4: Load changed from 6800 W – 7700 W at a fixed wind speed of 9 m/s

Wind speed was fixed at 9 m/s generating wind power of around 2500 W. The load was changed from 6800 W to 7700 W at 15 sec, resulting in the demand becoming higher than supply. Controller was applied at 14 sec just before the event was introduced. As can be seen in Fig. 20 the power mismatch resulted in a frequency deviation of −0.3 Hz with the no control case. The frequency error reduced as the simulation progressed, however, the frequency could not be regulated in 20 sec. With control case frequency dipped to the same value as the no control case but the frequency offset was eliminated in about 1.5 sec after which frequency was maintained within a narrow band of 49.5–50.5 Hz.

Fig. 21 shows that control commands were continuously sent after the event. The control commands were sent even after the frequency

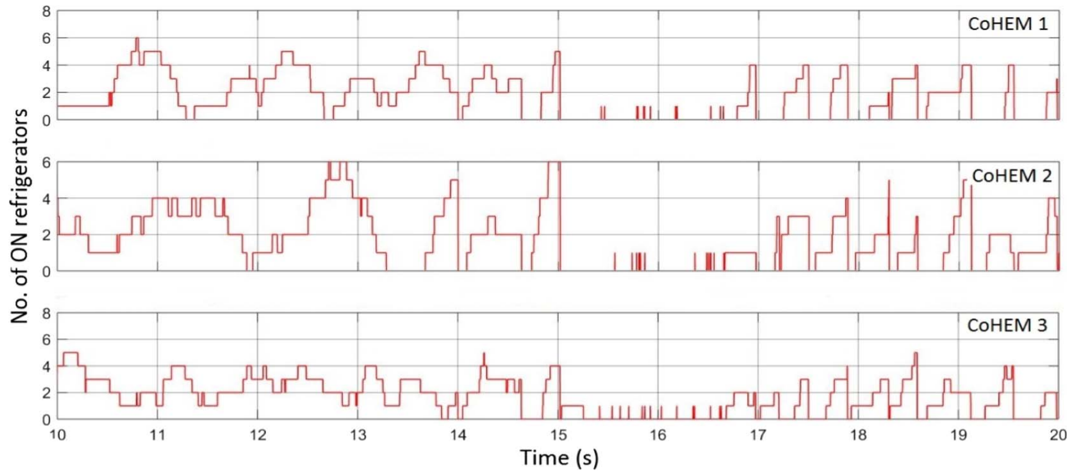

Fig. 22. Number of ON refrigerators in each CoHEM.

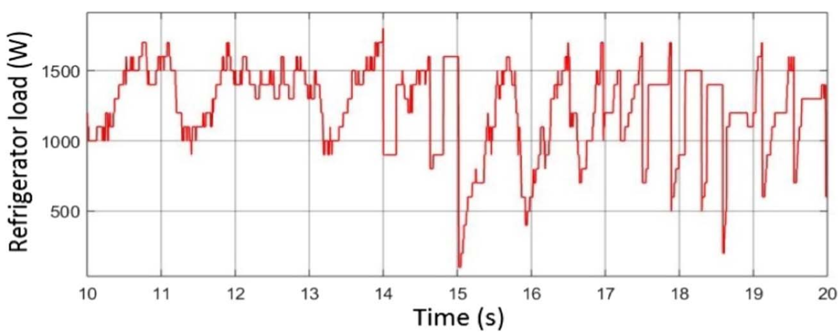

Fig. 23. Refrigerator load in Controller Case.

Table 1
Comparison of centralized and hybrid controller.

Centralized controller	Hybrid controller
Centralized control model will result in more computational burden on the single controller	Presence of multiple controllers will result in less computational burden on any single controller
High technical and maintenance cost will be associated with establishing secure communication link between a single controller and all end-users	Comparatively less cost will be required for providing communication link between utility and CoHEMs at distribution transformers, and between CoHEMs and end-users connected to the particular distribution transformer
More time will be required for frequency regulation as a single controller will have to communicate with every end-user	Less time will be required for frequency regulation owing to the presence of multiple controllers

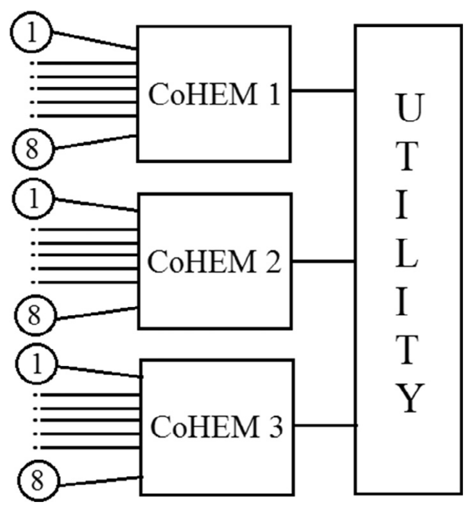

Fig. 24. Configuration with hybrid controller.

was regulated so as to keep maintaining frequency within acceptable limits. Further analysis in Fig. 22 shows that the number of ON refrigerators was the minimum between 15 and 17 sec. According to Fig. 23 the refrigerator load was reduced from 1600 W to 100 W in order to bring the frequency back to nominal value. Refrigerator load for no control case is the same as in Fig. 11.

5. Discussion

The simulation results suggest that all four scenarios with controller revealed superior performance over scenarios without controller. The results were also validated against a centralized controller which produced exactly same results as a hybrid controller. Practically, the hybrid controller should take less time for frequency regulation. As opposed to centralized controller, the presence of multiple controllers in hybrid control case reduces the computational burden and time required to communicate with end-users. However, due to limitations of Simulink software the difference could not be seen in simulations. The hybrid controller is anticipated to offer the following benefits over centralized controller (see Table 1).

Fig. 24 below shows the configuration with the proposed hybrid

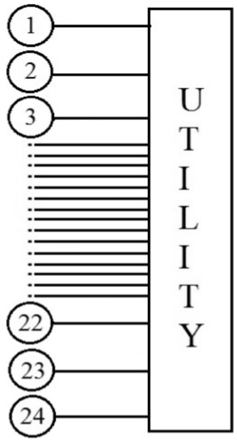

Fig. 25. Configuration with centralized controller.

controller. With the hybrid controller the connections appear to be neat and simplistic. However, as can be seen in Fig. 25 the centralized controller complicates the network by adding so many links to a single controller. Even by looking at the two figures it can be easily concluded that the centralized controller will increase the computational burden on the controller.

The proposed control approach is expected to offer a number of environmental and economic benefits when implemented in the real world. In the network setup proposed, domestic refrigerators are considered as control loads and act as spinning reserves. Having refrigerators as spinning reserves will defer the requirement for reinforcing of existing network. This will not only save huge sums of money to utility but will also eventually reduce cost of network charges offered to customers as part of electricity tariff. Practically, for any refrigerator to act as a control load no changes are required in the refrigerator hardware, only a temperature sensor and relay unit are required to be installed [15]. Therefore, just with minor additions any domestic refrigerator can play its role in frequency regulation. The proposed frequency regulation approach with flexible load is expected to allow the penetration of more renewable energy resources, at the same time reducing the green-house gas emission.

In the future, there is a need to consider load scheduling and frequency regulation in a single model. The integration of renewables with reduced inertia makes the system susceptible to instability after disturbance. However, load scheduling can play a vital role in reducing power mismatch by maintaining a fairly uniform load profile and matching demand closely with supply, in turn leading to smaller frequency offset. Any frequency error that exists can then be eliminated by the frequency regulation controller.

Many countries worldwide have aggressive targets of integrating renewable generation in their electricity network. Huge deployment of renewables, with reduced inertia results in an insurmountable obstacle of restricting frequency within bounds. The concept of synthetic inertia, where the renewable generator can mimic the behaviour of a synchronous generator by use of proper controllers can play a vital role in curtailing frequency offset. There is a need to analyse the effects of synthetic inertia on the frequency profile of a power system.

6. Conclusion

A hybrid control model using the concept of CoHEM and exploiting the advantages of both centralized and decentralized controllers is proposed, aiming at regulating frequency. A power network set up with both diesel generation and renewable wind generation is considered. The proposed system with 24 refrigerators as control loads is validated against system with no controller as well as centralized controller. Four different scenarios for heavy loading condition are simulated in Simulink. All four scenarios display superior performance of hybrid control model over no control model. The performance is in par with the case of centralized control. As opposed to centralized controller in real world the proposed hybrid system is expected to reduce the computational burden on the controllers. Additionally, the designed architecture is anticipated to save on time and cost required for frequency regulation.

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