Demand Response Application of Thermostatically Controlled Loads in Active Power Balancing Services

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The integration of Thermostatically Controlled Loads (TCLs) into the active power regulation framework of power systems provides a variety of benefits and multifarious uses. The TCLs specifically heating, ventilation, and air-conditioning (HVAC) systems constitutes the majority of the power demands in modern power systems for centralized building structures. This study investigates the utilization of an aggregated HVAC/TCL resource as a supplementary demand side reserve in a single-area load frequency control system that features a 250 MW coal-fired thermal generating unit. A 40 MW step-load disturbance is used to evaluate the system response to frequency under primary control alone and synchronized primary and HVAC secondary control. Under primary control only, the system frequency falls from the nominal 60 Hz to around 59.725 Hz, producing a steady-state frequency error of roughly 0.275 Hz. The HVAC resource is used as secondary control, delivering an estimated aggregate response of 40 MW. The resulting frequency deviation is corrected, and the system's frequency is returned to about 60 Hz within about 60 seconds. During the restoration procedure, the demand side resource response achieves a transient peak of about 70 MW, while the entire system frequency has a maximum transient excursion of around 60.20 Hz. The results show that the modeled aggregated resource may offer sufficient secondary frequency support while eliminating the residual steady-state frequency error that remains after the initial thermal generating response. A comprehensive simulation model is developed using MATLAB to validate the efficiency of the proposed strategy. The simulation integrates a coal-based thermal power plant with a robust HVAC model within the framework of load frequency control (LFC). This collective approach improves the active power balance and the operational stability of the grid.

Keywords: Load Frequency Control, Thermostatically Controlled Loads, Active power balancing, Frequency governance, Secondary control mechanism

Introduction:

Thermostatically controlled loads (TCLs) are proving to be transformative sources for the power grid. They perform multiple functions ranging from comfort management to ensuring the stability of the grid. Traditionally, the power production relied almost exclusively on conventional fuels like coal, oil and natural gas that degraded the environment through the emissions of greenhouse gases. Resultantly, the global energy dynamics have shifted towards more sustainable options, such as wind power, hydropower, and demand side technologies like TCLs.

The commercial HVACs offer frequency regulation services due to their considerable energy consumption and thermal inertia. [1]A variety of control strategies have been developed to improve this process while minimizing its detrimental effect on the system's efficiency[2]. Additionally, the variable-speed systems can deliver high quality services of the grid's frequency control, maintaining power balance and dependability. These systems can quickly regulate their energy usage in response to the frequency variations, resulting in a constant supply of power [3]. The flexibility of these systems improves grid resilience and also ensures cost-effectiveness and a more environmentally friendly power system.

The integration of flexible load, in power systems provides critical demand-response capabilities, allowing optimum peak hour governance and regulation of power flow inside power grids. Resultantly, it minimizes the requirement of reserve resources and improves the consistent operation of the system in a cost-effective manner[4].For instance, the centralized buildings equipped with HVACs offer ancillary services to the grid that includes frequency regulation and secondary reserves, which aids in grid management and reduces the demand for extra investments in energy infrastructure[5][6]. The domestic air conditioners which are part of the flexible loads, can be adjusted to provide demand side management and stability in order to minimize the variations in renewable power production [4][7].

Recent research has focused on sophisticated control, optimization, distributed interaction, extensive TCL modeling, and occupant comfort limitations, which are critical for practical deployment but can add modeling and control complexity. As a result, a very simple system-level evaluation of an aggregate HVAC resource acting as a supplementary demand side reserve in addition to the primary response of a typical thermal producing unit is still useful. In this case, specifically assessing the frequency response achieved using main thermal control alone to the response produced after including secondary support gives a straightforward method of evaluating flexible demand's frequency restoration capabilities.

As a result, this work uses MATLAB/Simulink to create a single-area LFC model that includes a 250 MW coal-fired thermal power unit and an aggregated demand side resource. The system is initially run at a standard frequency of 60 Hz, with demand and generation balance at 250 MW, followed by a 40 MW step increase in demand to generate a generation demand imbalance. The primary frequency response is provided by a coal-fired thermal generating unit, with the HVAC resource serving as a supplementary demand side reserves with an intended cumulative response of 40 MW.

Problem Statement:

Traditional thermal generating units can rectify frequency deviations after a load disturbance, but the primary control alone typically leads to residual steady-state frequency error. The utilization of flexible demands as a secondary control allows you to account for this residual error without having to depend only on additional generation reserves. However, the efficiency of an aggregated HVAC resource must be assessed within an integrated LFC framework that includes traditional thermal generation. As a result, this study tackles the challenge of restoring system frequency after a specific load disruption by combining demand response functions as a secondary reserve with the initial response of a coal-fired thermal generator unit, to ensure the balance between power supply and demand.

Novelty and Research Contributions:

This study presents a system-level contribution by integrating aggregate demand side resources as a secondary reserve with a traditional coal-fired thermal power unit in a single area LFC framework. Rather than providing a new optimization layer, the study emphasizes proving the frequency restoration capacity of HVAC demand response if combined with traditional primary control. A 40 MW step-load disturbance is utilized to assess system response with primary control alone versus combined primary and HVAC secondary controls. The resulting frequency and power outputs are quantified using frequency deviation, transient oscillation, steady-state frequency error, and recovery time. This gives a simple simulation-based evaluation of demand response as an alternative secondary frequency control source.

Research Objectives:

The research's key aims are as follows:

Develop a single-area 250 MW coal-fired thermal generating-unit model integrated with an aggregated HVAC/TCL demand side resource in Simulink, MATLAB.

Assess the frequency response of the system following a 40 MW step-load disturbance under primary thermal control.

Evaluate the use of HVAC as a supplemental demand side reserve and its effect on frequency recovery.

Quantify the frequency response using minimum frequency, maximum transient excursion, steady-state frequency error, and restoration time.

Compare system performance under primary control alone with that obtained using coordinated primary and HVAC secondary control.

Literature Survey:

Thermostatically Controlled Loads (TCLs) have been shown to be effective demand-side resources for frequency control in recent studies. The researchers looked at how aggregated TCLs might provide frequency regulation services and showed how they might assist with primary frequency regulation and synthetic inertia through integrated control [8]. The work emphasized the significance of appropriate aggregated load modeling for system-level management by creating a single state space model to facilitate the coordination and aggregation of large-scale TCLs and electric cars for frequency regulation[9]. The interactions and synchronization of aggregated sources were further investigated by the researchers in [10] demonstrating that when large TCL populations engage in frequency management, their behavior must be correctly taken into account. In [11] the study used experimental data to confirm the suggested modeling technique and created a physical model of central air conditioning load for emergency frequency regulation.

The study in [12] investigated how to include HVAC demand response into the LFC framework and showed how it may enhance frequency regulation in micro-grid systems. In order to handle the coordination of numerous flexible loads while lowering dependency on centralized control, the researchers in [13] suggested a decentralized control technique for air conditioning loads taking part in main frequency regulation.

Proposed Methodology:

The proposed study investigates the use of an aggregated HVAC/TCL demand-side resource as a secondary frequency control reserve. The system is developed as a single area LFC model in Simulink, MATLAB. The thermal generation unit provides 250 MW at a nominal frequency of 60 Hz to a 250 MW demand under initial operational conditions. The generation and demand mismatch is then created by introducing a 40 MW step increase in load. The coal-fired generating unit's primary reaction is triggered by the resultant frequency deviation, and the HVAC secondary control response handles any remaining frequency inaccuracy. Frequency deviation, minimum frequency, transient frequency deviation, steady-state frequency error, and frequency recovery time are then used to assess the system response.

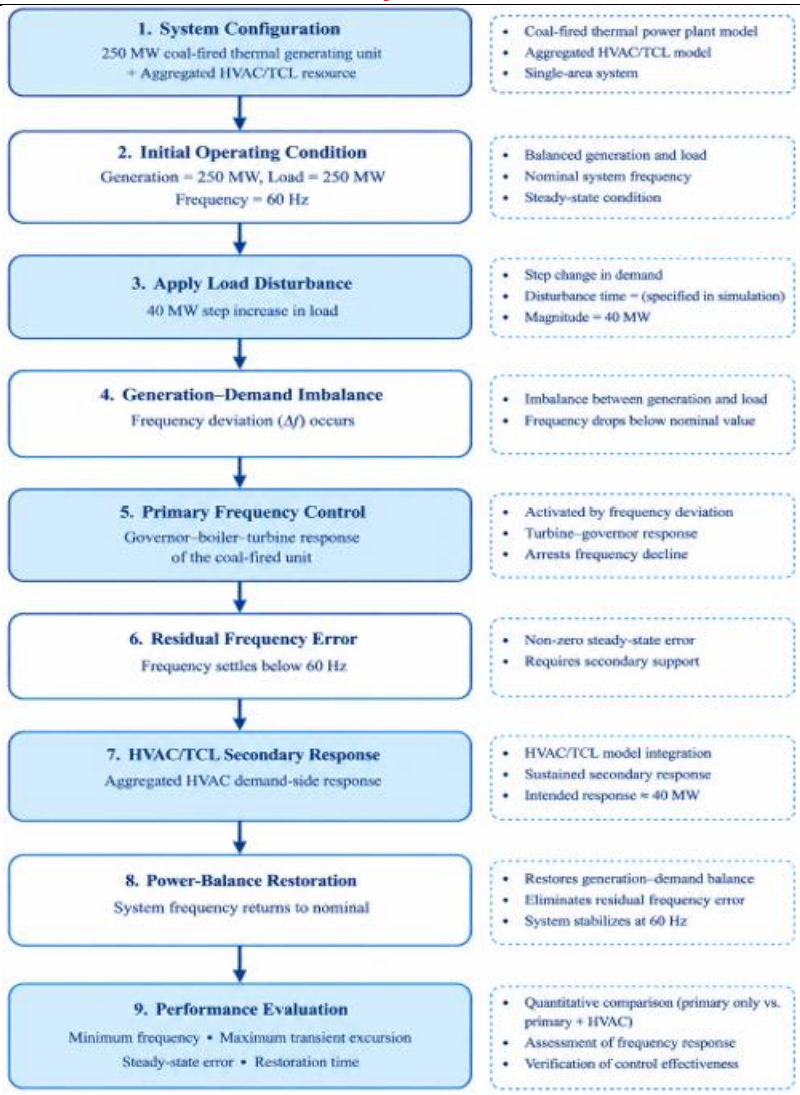


Figure 1. TCL in Load Frequency Control

Modeling of the Load Frequency Control (LFC) System:

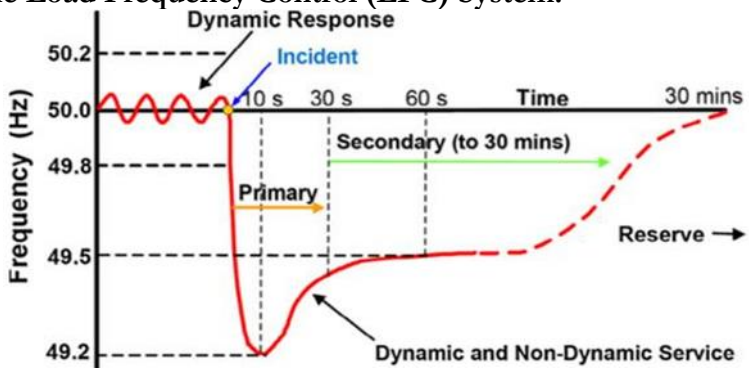


Figure 2. Frequency Governance Spectrum

The power grid must maintain a balance between the user demand and the energy output to ensure a seamless and efficient operation [14]. However, throughout real operation, the load requirement frequently fluctuates, affecting the load power production balance. These fluctuations can have adverse effects on the frequency and stability of system [15]. There are two control loops to govern the system's frequency: the primary and the secondary control loops. The basic control loop, seen in Figure 2, operates swiftly to prevent abrupt frequency shifts by activating frequency safety devices. It may, however, produce a minor inaccuracy in

the state of stability. The secondary control is utilized for maintaining a constant and stable frequency in the power system. It is referred to as Load frequency Control (LFC) [16]. This control maintains a power balance during the grid operation. It is achieved through the regulation of user demand and power supply.

The stability and dependability of a balanced energy system in delivering seamless supply of power largely depends upon the mechanism of Load Frequency Control (LFC). The variations in frequency and tie line power dispatch are especially critical factors. The efficient regulation of these variables guarantees stable frequency and organized exchange of power across integrated energy systems. These metrics are the foundation of the Area Control Error (ACE) equation, an important element of LFC that assures a reliable and seamless supply of power for the customers. The equation for the ACE is following:

$$\sum_{j \epsilon A_n} \quad \beta_i \Delta f + (P_{ij}^{Sch} - P_{ij}^{Act}) \tag{1}$$

In equation (1), the overall fluctuations inside the ith control area are represented byP_(ACE,i). The factors P_ij^Sch and 〖P〗_ij^Act denotes the preset exchange of power and the actual exchange. The frequency bias constant is denoted by β_i and is described asβ_i=D_i+1/R_i , where D_i and R_i are correspondingly the damping and droop constants.

$$\Delta P_{Sec} = K.\Delta P_{ACE} + KT \int \quad \Delta P_{ACE} dt \tag{2}$$

As mentioned in the equation 2, the parameters K and T are regulated in accordance with a set of rules that are necessary for system administration. The variable T is usually selected within the range of 50-200 seconds, and K is chosen between 0 and 0.5. The time constant possesses vital significance as it demonstrates the system's response swiftness to the variations in power supply and demand. Upon calculating the requisite adjustment in power output (ΔP_Sec), the LFC controller allocates it throughout the active power generating units and HVAC resource as an integral component of the LFC management process.

Single Area Network:

The block diagram for the single area network is given in Figure 3 as:

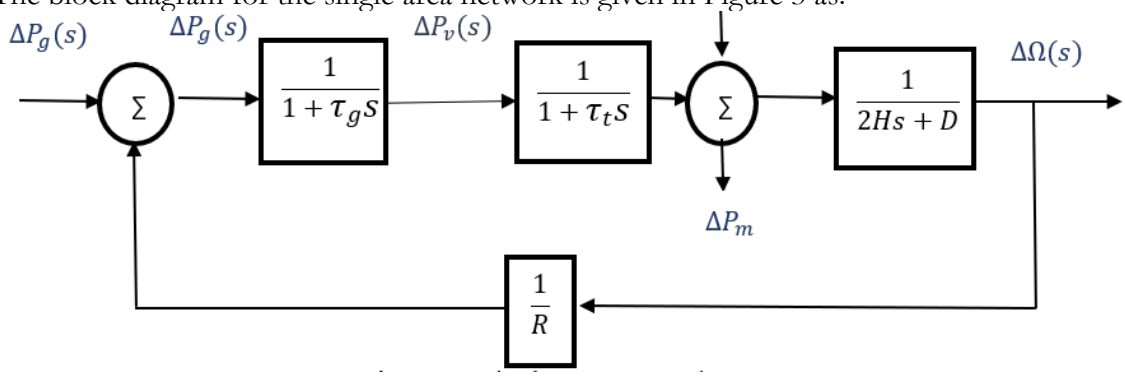


Figure 3. Single area network.

Modeling of Energy Systems:

This section comprises comprehensive details regarding the modeling of various power plant units, encompassing coal-fired thermal energy system (TES) based on coal turbines and HVAC system.

Thermal Energy System:

The integrated Thermal Power Plant (TPP) model consists of a number of modules that are interconnected with each other, namely the boiler system, the turbine-governor assembly, the generator itself and the control systems, which include the Automatic Voltage Regulator (AVR) and speed governor. Each module can be described mathematically as the algebraic representation of a differential equation and control logic that mimics the dynamic behavior of the module in response to a change in input, such as in load demand or control

signals of a higher-level grid coordination system. The turbine mechanism shown in Figure 4 is modeled to describe the conversion of thermal energy into mechanical power output, P_mech driven by the interaction of the governor section's output signal (CV) and the steam pressure P_t.

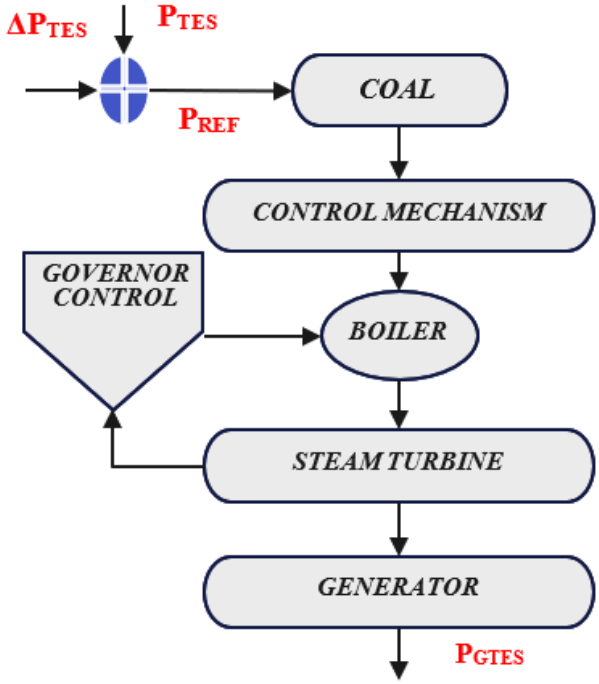


Figure 4. Coal-fired Thermal Energy System

The operating efficiency of a TPP unit is dictated by the kind of plant, the boiler control system parameters, and functional mode, all of which affect the steam turbine reaction during flexible operations. This project model simplifies the framework for long term dynamical modeling research.

Boiler Turbine Control:

The steam boiler turbine controller framework, laid out in Figure 5, has been designed to generate LR. The Load Regulator (LR) varies the opening of the turbine valve to match the actual power output with the planned generation and also sends a feedforward control signal to the boiler system to signal coordinated operation and stable overall system performance.

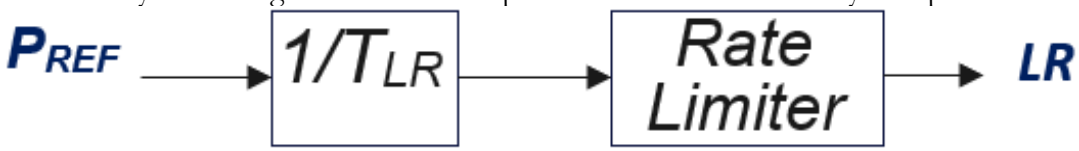


Figure 5. Control Mechanism of Boiler

The LR signal functions as a boiler speed control parameter, providing precise modulation of the turbine valve to achieve synchronized operation between actual and reference generation.

Speed Governor:

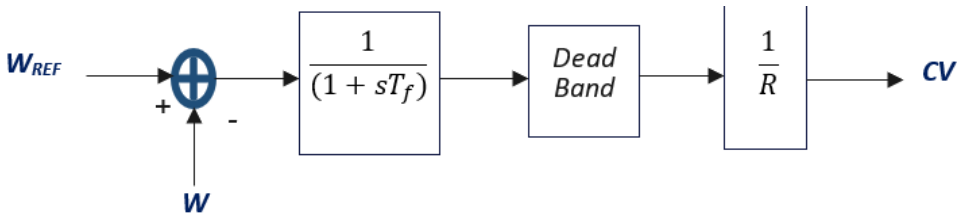


Figure 6. Speed Governance

Any speed variability triggered by a power disparity converts to power deviation employing a closed loop system relying on the droop feature. The turbine governor obtains

the generator speed as input as well as output to the steam entering the valve flow area as shown in Figure 6.

Boiler Model:

Key parameters includeB_1, B_2 and P_t, which represent moderate boiler pressure levels, along withT_B1, T_B2 and T_B3, which signify the inherent time delays within the boiler system. These delays which are innate in coal combustion because of slower ignition and combustion rates compared to other fossil fuels cause a significant impact on the responsiveness of the system. It is depicted in Figure 7.

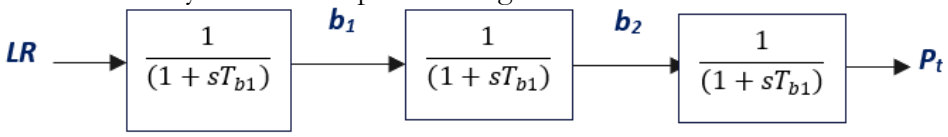


Figure 7. Block Diagram of Boiler

The response time of the boiler becomes an important factor determining the operational efficiency and the ability of the system to adapt to abrupt changes in energy supply and demand. The boiler model includes time constants representing the slower dynamic response of the boiler section. It has a profound effect on the operation and the overall dynamic behavior of the thermal power plant.

Turbine Model:

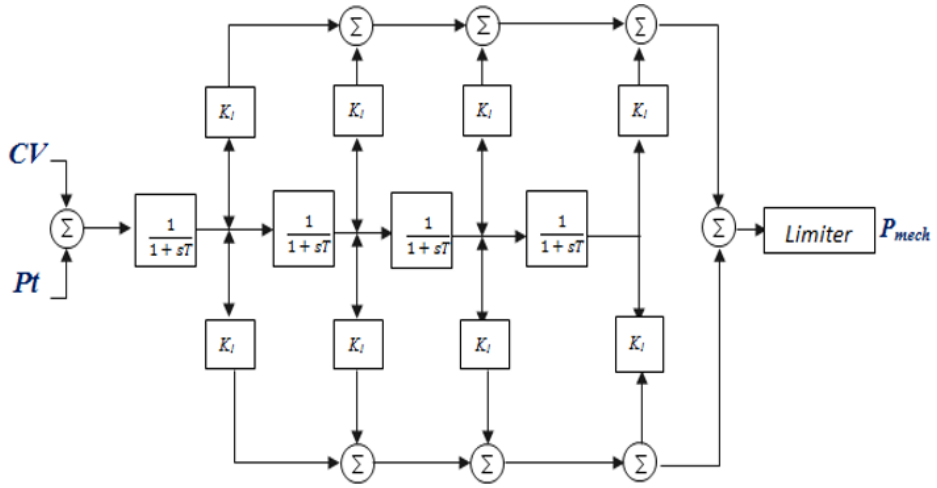


Figure 8. Steam Turbine Model

The steam turbine responsiveness can be estimated by the four-time variables illustrated in Figure 8. These time constants—T1 for the extreme pressure turbine bowl, T2 for the reheater, T3 for the crossover, and T4 for the two simultaneous re heat units—represent the charging process of various volumes. The impact that comes generated by various turbine sections, including high pressure, extremely high pressure, mild pressure, and very little pressure, is represented by the coefficients K1 through K8. The coefficients mentioned above show how distinct turbine sections add to the overall mechanical power. High pressure turbine constants are K3 and K4, medium pressure turbine coefficients are K5 and K6, moderate pressure turbine coefficients are K7 and K8, and extremely extreme pressure turbine coefficients are K1 and K2.

Modeling of HVAC System:

Heating, Ventilation, and Air Conditioning (HVAC), apart from their elemental function of maintaining the interior environmental conditions, have become a critical asset for the system's frequency regulation. The demand-side management capability is provided by three principal parts; the Variable Speed Heat Pump (VSHP), the Thermostat, and the Equivalent Thermal Activated Building Model (ETABM). These components facilitate secondary frequency regulation, which adjusts supply and demand. Each of the elements plays

a vital role in the proper functioning of the overall system.

Variable Speed Heat Pump (VSHP):

The VSHP adjusts room temperature by dynamically modifying its power input in response to load frequency variations. The transfer function is represented as follows:

$$G_{VSHP}(s) = \frac{K_{comp} \cdot K_{shaft} \cdot K_{motor}}{T_{m1}s^2 + T_{m2}s + T_{m3}} \quad (3)$$

Where K_{comp}, K_{shaft}, K_{motor} represent the compressor, shaft, and motor constants and the damping and mechanical inertia of the system is reflected in the parameters T_m1,T_m2,T_m3 that regulate the heat pump's dynamic response. The values of these parameters used in the simulation are provided in Tables 1 and 2. The VSHP collaborates with the thermostat to alter heating or cooling power, maintaining temperature control while also resulting in load frequency regulation. The VSHP model represents the dynamic response of the heat pump unit to changes in the control input and forms the **demand-side component** of the HVAC demand response model.

Thermostat:

As a feedback mechanism, the thermostat monitors changes in temperature and regulates the power output accordingly. Its transfer function is:

$$G_{Th}(s) = \frac{K_{Th}}{s} \quad (4)$$

Where K_Th is the thermostat's gain, which indicates its responsiveness to temperature fluctuations. The thermostat maintains the indoor temperature aligned by directly regulating the operation of the heat pump.

Equivalent Thermal Activated Building Model (ETABM):

The ETABM depicts the building's thermal dynamics by taking into consideration heat flow and accumulation within its structure. The combined transfer function is:

$$G_{ETABM}(s) = \frac{a_2s^2 + a_1s + a_0}{b_2s^2 + b_1s + b_0} \cdot \frac{K_E}{\tau\varepsilon s + 1} \quad (5)$$

The parameters for regulating heat gain are represented by a_2, a_1, a_0 and b_2, b_1, b_0 indicate the thermal resistance and capacitance properties of the building. In addition to this, K_E and τε denote the heat dissipation dynamics. The values of these parameters are provided in Tables 1 and 2. The ETABM provides an extensive description of the thermal behavior of the building, modeling how the HVACs respond to external fluctuations in temperature. Figure 9 shows the schematic Transfer Function model.

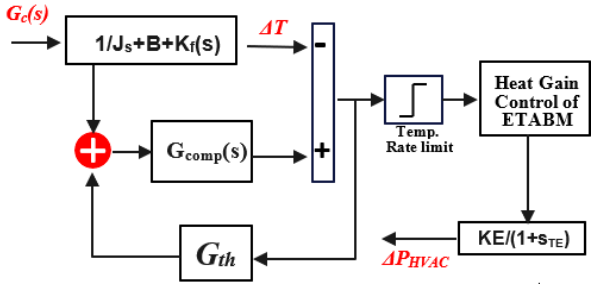


Figure 9. Structural diagram of the proposed HVAC for simulation.

Simulink Model:

The proposed system model depicted in Figure 10, is specifically selected to determine the frequency regulation capabilities of a hybrid power grid that is composed of a coal-fired thermal power plant, and Thermostatically Controlled Load (TCL) network, of which HVACs are the main representation. The model has attempted to examine the dynamic characteristics, responsiveness, and effectiveness of this type of a hybrid system in terms of the LFC within a collaborative operational structure of traditional generation and demand- side control assets. Realized in MATLAB/Simulink, the simulation platform offers a flexible and strong tool to investigate the time-responses of variables in the system in different working conditions. The

model which is developed captures the basic nonlinearity and dynamics features of HVACs and thermal generator. It integrates realistic parameters in the system such as the generation time constants, governor and turbine dynamics to the thermal plant, thermal inertia and hysteresis behaviors in the TCLs. This simulation platform is based on the simplified power system with one area, which allows studying the frequency control separately, without inter-area power flows. Adding primary control, normally performed by the speed governor in the coal plant, and secondary control gives a complete picture of how the system behaves. The secondary reserves will be connected at the secondary control level to help counter frequency deviations by varying their power use in relation to changes in frequency, and thus serve as responsive frequency regulators.

The major issues investigated using the model include the coordinated control dynamics between the generator and reserve, the degree to which secondary control could offset the frequency variations and the overall enhancement of system performance and stability measures e.g. settling time and steady-state error.

Further, the model is used in various conditions to test reliability and flexibility. The paper presents the effects observed in terms of HVACs enhancing secondary capabilities of the overall system.

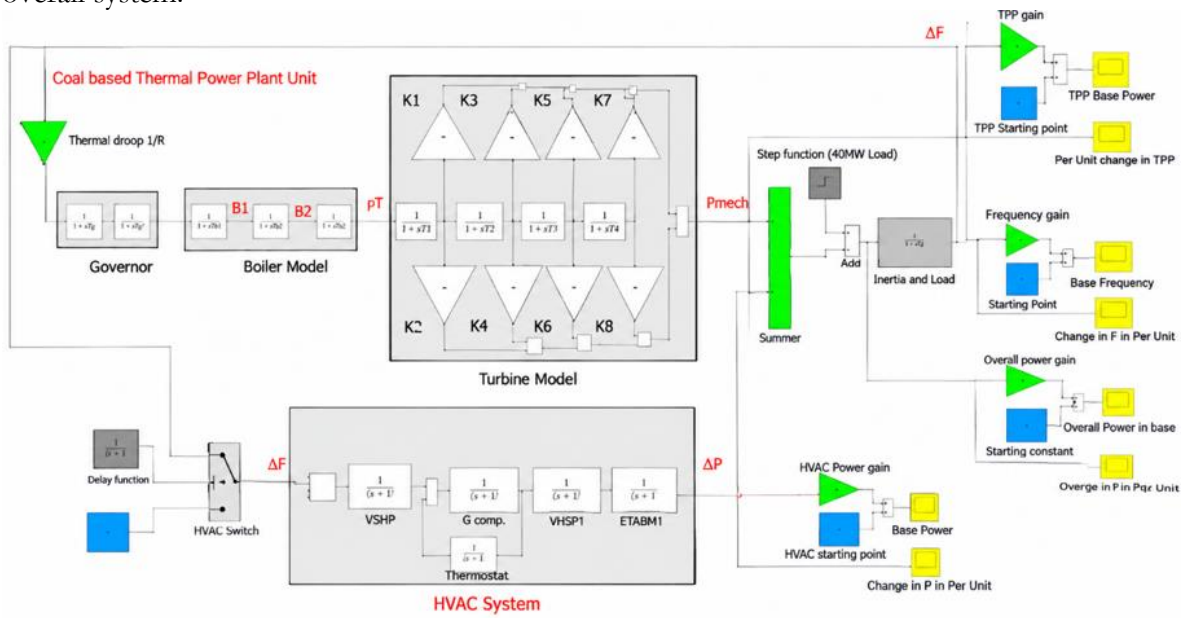


Figure 10. Simulink Model

Results and Discussion:

The principal energy source of the proposed power system is a coal-based thermal power plant with a consistent output of 250 megawatts (MW). Under typical operating conditions, the power supply of the plant perfectly corresponds with a load requirement of 250 MW, resulting in a constant system frequency of 60 Hz and uninterrupted grid operation.

Impact of Load Disturbance on Frequency Deviation:

When a supplementary 40 MW load is added, the equilibrium between the supply and demand is disrupted, resulting in a frequency variation from the standard 60 Hz.

The introduction of this load causes an instantaneous reduction of the overall frequency. The droop setting for this turbine is defined by:

$$\frac{1}{R_{actuall}} = \frac{1}{R_{pu}} * \frac{P_{base}}{F_{base}} \tag{6}$$

$$\frac{1}{R_{actuall}} = \frac{1}{0.0364} * \frac{250}{60} = 114.46\ MW/Hz$$

Where R is the droop characteristic of the turbine governor. The primary response of the coal

turbine was evaluated by introducing a sudden load increase of 40 MW in the system at 10 seconds. This sudden increase in demand caused a frequency drop due to the power imbalance.

The sensitivity of frequency deviation to changes in power demand is represented by the frequency bias factor β which is given by:

$$\beta = \frac{1}{R} + D = 114.46 + 31 \quad (7)$$

$$\beta = 145.46\ \text{MW/Hz}$$

where D represents the damping coefficient that accounts for load sensitivity to frequency changes. The frequency deviation resulting from the load disturbance can be expressed as

$$\Delta f = \frac{\Delta P_L}{\beta} = \frac{40\ \text{MW}}{145.46\ \text{MW/Hz}} = 0.275\text{Hz} \quad (8)$$

$$f_{actuall} = 60 - 0.275 = 59.725\text{Hz} \quad (9)$$

This imbalance causes the coal-fired thermal power plant to engage its major control mechanism which makes an effort to reduce the impact by raising the power output. While the primary control responds immediately to the disturbance, it is unable to completely restore the frequency to 60 Hz due to limits in the plant's ramp rate and ability to adjust to rapid and severe load fluctuations as shown in Figure 11(a).

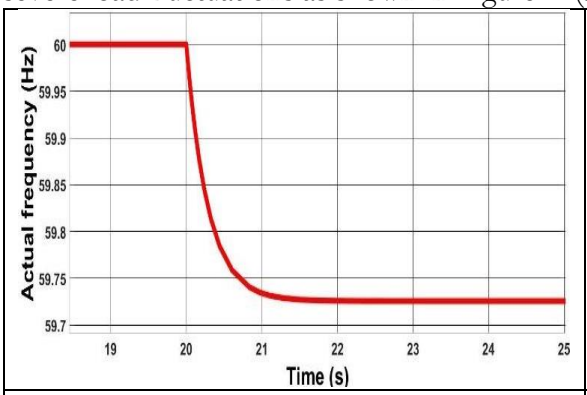


Figure 11(a). Primary response from Coal-fired Thermal Power Plant

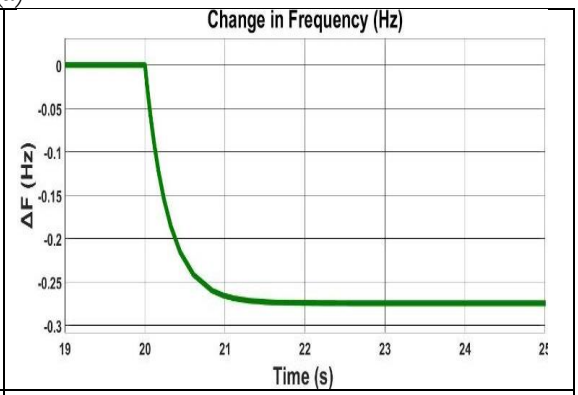


Figure 11(b). Frequency difference after primary response

The difference between the standard frequency of 60 Hz and the frequency attained after the primary response of thermal energy system is depicted in Figure 11(b).

Secondary Control Response: HVAC as a Frequency Regulator:

In this research, secondary reserves are used to solve the residual frequency instability and return the system to equilibrium. The HVAC functions as a backup reserve, offering 40 MW of demand side response capabilities as illustrated in Figure 12.

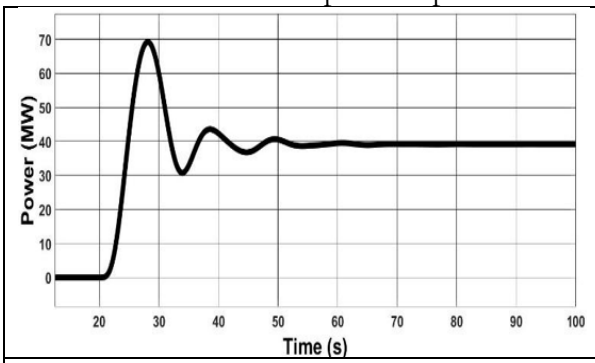


Figure 12. Power delivered by HVAC system

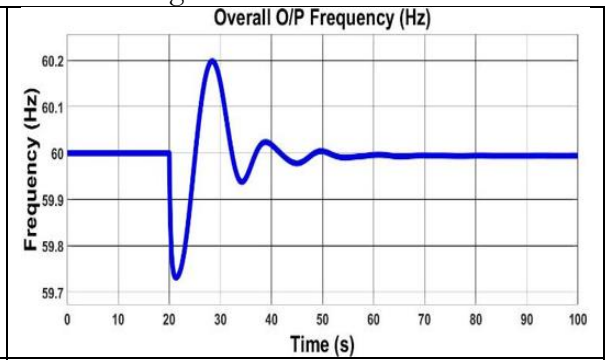


Figure 13. Secondary control mechanism

As part of secondary control mechanism of the LFC, the flexible demand resource dynamically changes its power usage to compensate for supply-demand imbalance. Unlike primary control, which is quick but restricted in its remedial scope, secondary control takes

advantage of the adaptability and agility of such systems to perform accurate and persistent modifications, restoring the frequency to the nominal value of 60 Hz as demonstrated in Figure 13. The frequency is restored and the supply and demand balance is maintained. This depicts the effectiveness of flexible loads in control strategies.

Table 1 illustrates a thorough summary of the time constants related to both the thermal energy system and the HVAC which are critical aspects of the transient responses and the operational dynamics of both the systems. This accurate representation of generation units is vital for efficient grid operation.

Table 1. Time constants used in the thermal generating unit and HVAC model

Block	Generating Units	Time Constant			
Steam turbine	Steam	T_1	1s	T_2	20s
		T_3	25s	T_4	0.5s
	Boiler	T_{b1}	10s	T_{b2}	80s
		T_{b3}	100s	-	-
	Governor	T_f	0.5s	-	-
HVAC	VSHP	T_{m1}	1s	T_{m2}	3s
		T_{m3}	1s	-	-
	ETABM	TE	0.8s	-	-

On the other hand, Table 2 depicts the gain values for both systems which evaluate the steady state effectiveness and the interdependence of both the input and output parameters. These parameters are useful in understanding the behavior of the system in LFC framework.

Table 2. Gain parameters used in the thermal generating unit and HVAC model

Block	Generating Units	Gain			
Steam turbine	Steam	K_1	0.001	K_2	0
		K_3	0	K4	0.001
		K_5	0.0008	K6	0.0008
		K_7	0.0008	K8	0.002
		K_c	-30	Kb	0
HVAC	VSHP	K_{comp}	1	K_{shaft}	1
		K_{motor}	1	-	-
	Thermostat	K_{Th}	5	-	-
	ETABM	K_E	1	-	-

The incorporation of the HVAC technology into the LFC's secondary control enables more efficient use of demand-side resources. The system adjusts its operational energy consumption based on real-time grid demands, lowering the demand for power during frequency fluctuations and thereby assisting in grid stabilization.

This demand-side flexibility guarantees that corrective measures are dispersed across the grid, lowering reliance on generation resources and reducing operational stress on coal-fired thermal power plants. In addition to that, its ability to make necessary adjustments over time enhances the overall efficiency of the secondary control mechanism assuring frequency stability. It demonstrates its capability as a dependable and practical energy source that can be utilized as reserve for secondary control. Its responsiveness and adaptability make it the most suitable choice for frequency regulation.

Overall Frequency Response with HVAC Secondary Control:

The system frequency returns to its nominal value of 60 Hz when the HVAC secondary responses are synchronized with the coal-fired thermal generation unit's primary response. After the 40 MW disruption, the total frequency response first drops to about 59.73 Hz. The frequency shows a brief positive excursion to around 60.20 Hz during the ensuing HVAC reaction before progressively reverting to 60 Hz. The final frequency, which is around

60.00 Hz, shows that the residual steady-state frequency error has been successfully removed.

The transient response linked to the integrated primary and secondary control systems is demonstrated by the positive transient excursion of about 0.20 Hz above nominal frequency. On the other hand, because its maximum frequency stays below the nominal value, the primary-only response fails to demonstrate a similar positive excursion.

In the simulated response, the frequency restoration takes around 60 seconds. Therefore, the main benefit of the demand side resource is the removal of the residual steady-state frequency error and the restoration of the system to about 60 Hz rather than a significant decrease in the initial frequency nadir.

Quantitative Comparison:

To provide a direct comparison between the two control configurations, the principal frequency response characteristics are summarized in Table 3.

Table 3. Quantitative comparison of primary and secondary frequency-control responses

Performance parameter	Primary control only	Primary + HVAC secondary
Load disturbance	40 MW	40 MW
Nominal frequency	60 Hz	60 Hz
Minimum frequency	≈59.725 Hz	≈59.725 Hz
Maximum frequency	≈59.725 Hz	≈60.20 Hz
Maximum initial frequency deviation	≈0.275 Hz	≈0.27 Hz
Steady-state frequency error	≈0.275 Hz	≈0 Hz
Positive transient excursion	Not observed	≈0.20 Hz
Frequency restoration	Not achieved	Achieved
Settling time	—	60 s
Intended HVAC secondary response	—	40 MW
HVAC transient peak	—	≈70 MW

The comparison indicates that a steady-state frequency inaccuracy of around 0.275 Hz is left behind by the primary thermal effect alone. The maximum frequency approaches 60 Hz when the HVAC secondary response is added, and the steady-state error is reduced. As a result, the secondary response needed to make up for the imbalance created by the initial thermal reaction is provided by the modeled secondary resource.

The combined LFC mechanism of the coal powered thermal plant and the HVAC structure as depicted in Figure 14, emphasizes the importance of both the primary and secondary control mechanism in contemporary grid operation. While the thermal energy system quickly resolves the rapid variations in frequency, the overall system's frequency is restored to its nominal value of 60 Hz through the reserves. This helps in developing more robust and efficient power systems that have the ability to manage variations in the normal operating conditions.

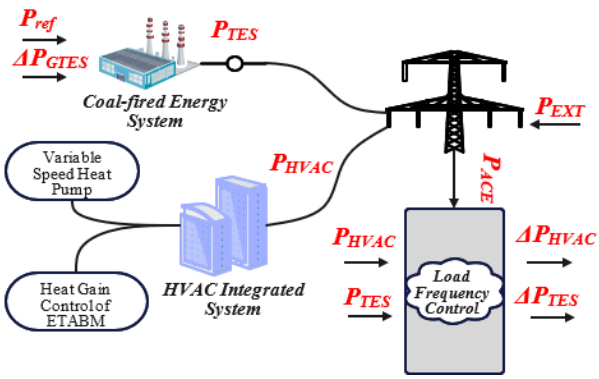


Figure 14. Proposed LFC model

The results of this study hold special significance in terms of the importance that

flexible loads may serve as auxiliary control mechanisms in frequency control in the domains of contemporary power systems. The simulation results of this study demonstrate the considerable potential of demand side flexibility options to increase the performance of the system.

The incorporation of the HVAC technology into the LFC's secondary control enables more efficient use of demand-side resources. The system adjusts its operational energy consumption based on real-time grid demands, lowering the demand for power during frequency fluctuations and thereby assisting in grid stabilization. This demand-side flexibility guarantees that corrective measures are dispersed across the grid, lowering reliance on generation resources and reducing operational stress on coal-fired thermal power plants.

Limitations and Future Work:

The purpose of this research is to evaluate HVAC demand response at the system level for secondary frequency management, not to provide a real-world demand response installation or a thorough depiction of particular buildings. Under a particular 40 MW step-load disturbance, the research focuses on coordinating a 250 MW coal-generated thermal power unit with an aggregate demand side resource. The findings show that while the projected 40 MW secondary response returns the system frequency to about its nominal value, primary control alone creates a residual steady-state frequency error. As a result, the model mainly evaluates the demand side frequency restoration capacity and system level contribution. Since the current analysis does not explicitly describe practical issues such as occupant comfort needs, temperature limits, availability, and aggregation size, these factors are acknowledged as scope limits rather than implications of practical deployment.

In an effort to give a clearer picture of aggregated HVAC contribution to grid services, future work will expand the proposed structure by incorporating these technical and consumer-related restrictions. Multiple HVAC systems with varied thermal properties and available capacities, particular comfort limitations, and variable operating conditions can all be taken into consideration by further developing the model. The scalability and robustness of the suggested approach may also be evaluated by extending it to multi-area power networks and combining it with renewable energy sources and other adaptable resources. Further investigation may also use sophisticated control or optimization methods to improve the HVAC response's transient effectiveness while preserving operational and comfort criteria.

Conclusion:

This study explored the use of an aggregated demand side resource, which is depicted by an HVAC-based demand side model, as a supplemental frequency-control reserve in conjunction with a traditional coal-fired thermal generating unit. A single-area 250 MW LFC simulation was generated in MATLAB/Simulink, with the system first running at 60 Hz with 250 MW of balanced generation and load. A 40 MW rise in the load was used to examine the frequency response. The findings demonstrated that the coal-fired generating unit's principal response was effective in preventing the frequency fall, although it produced a steady-state frequency error of around 0.275 Hz, with the frequency stabilizing at roughly 59.725 Hz. The residual steady-state frequency error was removed when the aggregated source was added as a secondary demand side response with a predicted sustained contribution of 40 MW, restoring the system frequency to about 60 Hz. The frequency restoration process took around 60 seconds, and the coordinated response showed a brief positive frequency fluctuation of about 0.20 Hz.

The results indicate that flexible HVAC/TCL demand, with provision of a secondary corrective action subsequent to a load disturbance, has the potential to provide supplemental generation. A key feature of this approach is the system-level depiction of typical demand response for frequency restoration services. Therefore, this study provides a framework to consider aggregated thermal loads as ancillary services for active power and frequency control.

References:

[1] I. Beil, I. Hiskens, and S. Backhaus, "Frequency Regulation from Commercial Building HVAC Demand Response," Proc. IEEE, vol. 104, no. 4, pp. 745–757, Apr. 2016, doi: 10.1109/JPROC.2016.2520640.

[2] J. Cai and J. E. Braun, "Laboratory-based assessment of HVAC equipment for power grid frequency regulation: Methods, regulation performance, economics, indoor comfort and energy efficiency," *Energy Build.*, vol. 185, pp. 148–161, Feb. 2019, doi: 10.1016/j.enbuild.2018.12.022.

[3] H. Wang, S. Wang, and K. Shan, "Experimental study on the dynamics, quality and impacts of using variable-speed pumps in buildings for frequency regulation of smart power grids," *Energy*, vol. 199, p. 117406, May 2020, doi: 10.1016/j.energy.2020.117406.

[4] A. Basit, T. Ahmad, A. Yar Ali, K. Ullah, G. Mufti, and A. D. Hansen, "Flexible Modern Power System: Real-Time Power Balancing through Load and Wind Power," *Energies*, vol. 12, no. 9, p. 1710, May 2019, doi: 10.3390/en12091710.

[5] H. Wang and S. Wang, "A hierarchical optimal control strategy for continuous demand response of building HVAC systems to provide frequency regulation service to smart power grids," *Energy*, vol. 230, p. 120741, Sep. 2021, doi: 10.1016/j.energy.2021.120741.

[6] H. Wang, S. Wang, and R. Tang, "Development of grid-responsive buildings: Opportunities, challenges, capabilities and applications of HVAC systems in non-residential buildings in providing ancillary services by fast demand responses to smart grids," *Appl. Energy*, vol. 250, pp. 697–712, Sep. 2019, doi: 10.1016/j.apenergy.2019.04.159.

[7] N. Mahdavi, J. H. Braslavsky, M. M. Seron, and S. R. West, "Model Predictive Control of Distributed Air-Conditioning Loads to Compensate Fluctuations in Solar Power," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 3055–3065, Nov. 2017, doi: 10.1109/TSG.2017.2717447.

[8] F. Conte, M. Crosa Di Vergagni, S. Massucco, F. Silvestro, E. Ciapessoni, and D. Cirio, "Performance analysis of frequency regulation services provided by aggregates of domestic thermostatically controlled loads," *Int. J. Electr. Power Energy Syst.*, vol. 131, p. 107050, Oct. 2021, doi: 10.1016/j.ijepes.2021.107050.

[9] S. Kiani, K. Sheshyekani, and H. Dagdougui, "A unified state space model for aggregation and coordination of large-scale TCLs and EVs for frequency regulation," *Electr. Power Syst. Res.*, vol. 195, p. 107181, Jun. 2021, doi: 10.1016/j.epsr.2021.107181.

[10] A. Kasis and I. Lestas, "Frequency regulation with thermostatically controlled loads: aggregation of dynamics and synchronization," Oct. 27, 2021, *arXiv*: arXiv:2002.06649. doi: 10.48550/arXiv.2002.06649.

[11] M. Liu, Y. Tian, D. Cheng, Y. Zhang, and L. Ding, "Modelling and control of central air-conditioning loads for power system emergency frequency control," *IET Gener. Transm. Distrib.*, vol. 16, no. 20, pp. 4054–4067, Oct. 2022, doi: 10.1049/gtd2.12571.

[12] T. Bal, S. Ray, N. Sinha, R. Devarapalli, and Ł. Knypiński, "Integrating Demand Response for Enhanced Load Frequency Control in Micro-Grids with Heating, Ventilation and Air-Conditioning Systems", *Energies*, vol. 16, no. 15, p. 5767, 2023, doi: 10.3390/en16155767".

[13] B. Jiang, Z. Yang, W. Xiong, L. Chen, P. Wang, and S. Liao, "Decentralized control strategy of air-conditioning loads for primary frequency regulation based on environment information," *Front. Energy Res.*, vol. 11, p. 1347789, Jan. 2024, doi: 10.3389/fenrg.2023.1347789.

[14] L. Li, H. Li, M.-L. Tseng, H. Feng, and A. S. F. Chiu, "Renewable Energy System on Frequency Stability Control Strategy Using Virtual Synchronous Generator," *Symmetry*, vol. 12, no. 10, p. 1697, Oct. 2020, doi: 10.3390/sym12101697.

[15] S. Wen, Y. Wang, Y. Tang, Y. Xu, P. Li, and T. Zhao, "Real-Time Identification of Power Fluctuations Based on LSTM Recurrent Neural Network: A Case Study on Singapore Power System," *IEEE Trans. Ind. Inform.*, vol. 15, no. 9, pp. 5266–5275, Sep. 2019, doi: 10.1109/TII.2019.2910416.

[16] C. Chen, K. Zhang, J. Geng, K. Yuan, Z. Yang, and L. Li, "Multiobjective-based optimal allocation scheme for load frequency control," *Int. Trans. Electr. Energy Syst.*, vol. 27, no. 7, p. e2334, Jul. 2017, doi: 10.1002/etep.2334.

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