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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