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Frequency prediction method considering demand response aggregate characteristics and control effects☆

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HIGHLIGHTS

- Frequency dynamics is analyzed based on aggregated demand response control effect.
- Response latency is firstly adopted for aggregate characteristics analysis.
- Proposed aggregate model effectively addresses actual dynamics of demand response.
- Adaptive control strategy helps realize effective use of demand response resources.
- Modified model with adaptive parameter improves frequency nadir prediction accuracy.

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ABSTRACT

Due to an increase in intermittent renewable energy penetration, the mechanical inertia of power systems has gradually decreased, threatening system frequency stability. As one effective solution to this problem, demand response (DR) technologies, which enable large-scale residential loads to regulate system frequencies via load aggregators, have been widely used. Aggregated loads, while treated as a whole from the perspective of the system operator, present some aggregate characteristics related to the specificities of individual loads within each aggregator. To construct such a relationship, DR aggregate characteristics based on load heterogeneity in response latency and user comfort requirements are analysed in this paper. As a result, an aggregate model for available response capacity evaluation is constructed. To realize the effective utilization of DR resources, feasible control strategies based on aggregate characteristics are discussed and compared with an emphasis on frequency regulating effects. Furthermore, a two stage-based DR section related to control strategies is introduced into a conventional system frequency response model for post-disturbance frequency nadir prediction. Finally, simulations are performed to verify the validity and accuracy of the proposed method.

1. Introduction

With the ongoing integration of intermittent renewable generation (e.g., wind and solar energy), post-disturbance frequency stability has encountered challenges due to a lack of mechanical inertial support [1]. To mitigate potential risks of frequency instability, efficient and accurate frequency dynamic analysis methods must be applied when designing reasonable and effective control measures.

To realize frequency dynamic analysis, time-domain simulation, single machine equivalent model and artificial intelligence-based methods are adopted. Time-domain simulations are reliable and suited for processing power system transient problems, but they are too time-consuming to use to meet online application requirements. Artificial intelligence-based methods show promising potential in managing transient frequency problems [2]. However, effects of these methods are strongly dependent on developers' levels of experience, and data-source problems can also present an obstacle to actual application. Single machine equivalent model methods are the most widely applied for frequency dynamic analysis, including system frequency response (SFR) and average system response (ASF) methods [3,4]. While the SFR

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Nomenclature

Abbreviations

DR	demand response
LA	load aggregator
SFR	system frequency response
LFC	load frequency control
AC	air conditioner
WH	water heater
EV	electric vehicle
SOC	state of charge

Symbols

$P_{AC,i}$	response power level of the *i*-th AC
$P_{WH,j}$	response power level of the *j*-th WH
$P_{EV,k}$	response power level of the *k*-th EV
n_1	value of the AC load of the residential area
n_2	value of the WH load of the residential area
n_3	value of the EV load of the residential area
$S_i(t)$	responsive state of the *i*-th AC at time *t*
$S_j(t)$	responsive state of the *j*-th WH at time *t*
$S_k(t)$	responsive state of the *k*-th EV at time *t*
0	no response
1	response
Z_{AC}	user comfort zones of AC
Z_{WH}	user comfort zones of WH
Z_{EV}	user comfort zones of EV
$I_{AC,i}$	user comfort indices of the *i*th AC
$I_{WH,j}$	user comfort indices of the *j*th WH
$I_{EV,k}$	user comfort indices of the *k*th EV
$t_{AC,i}$	response latency of the *i*-th AC
$t_{WH,j}$	response latency of the *j*-th WH
$t_{EV,k}$	response latency of the *k*-th EV
Δf_1	first-round response threshold of frequency
Δf_2	second-round response threshold of frequency
Δf_n	*n*-round response threshold of frequency
$\Delta P_L(s)$	incremental load power per unit
$\Delta\omega(s)$	incremental speed per unit
H	inertia constant in seconds
D	damping factor
s	Laplace operator
$Gen(s)$	transfer function of the generator model
F_{HP}	fraction of total power generated by the HP turbine
T_g	governor time constant in seconds
T_l	turbine time constant in seconds
T_r	reheat time constant in seconds
$DR(s)$	transfer function of the DR control model
k_b	basic slope value of the DR control strategy
k	equivalent slope value of the DR control strategy
S_{Pdr}	area denoting the actual DR contribution measured in the ΔP-$\lvert\Delta f\rvert$ plane
S_{Ps}	area denoting the maximum DR contribution measured in the ΔP-$\lvert\Delta f\rvert$ plane
$\Delta P_L(s)$	disturbance power of power systems

model directs all generator turbine governors to one machine, the ASF model maintains all generator turbine governors.

The conventional single machine equivalent model method focuses on approximating system frequency dynamics by considering frequency regulation effects of the generation side. With the use of smart devices (e.g., smart controllers, smart meters, smart appliances, etc.) and with the improvement of commutation technologies on the demand side [5–7], demand responses (DRs) have become useful tools for system frequency regulation [8,9]. In integrating DR frequency regulation effects with the system frequency analysis model, researchers have further developed DR resources and DR control strategy modelling methods.

DR resource modelling is mostly used for DR capacity evaluation and dynamic characteristic analysis. It can be classified into the following three types according to the spatial scale of the participants involved: the individual energy consumer model, the aggregator-based model and the virtual power plant [10,11]. For the individual energy consumer model, Shao et al. developed appliance-level physical-based load models for space cooling/space heating, water heaters and electric vehicles with physical and operational characteristics considered [12]. DR resources aggregated via load aggregators (LAs) enable small-capacity users to use DR programmes. General characteristics and potentials of numerous DR resources are aggregated with agents. Zhang et al. developed a model for aggregated air conditioning loading that considers load heterogeneity and load second-order dynamics [13]. Cheng et al. applied a decentralized control to the aggregated power consumption of melting pots in proportion to changes in grid frequencies [14]. Further, Good et al. took user comfort into consideration to realize on-time statistical calculations of 1000 electric water heaters (EWH) with a physical-based model [15]. Nevertheless, response latency in DR aggregation has always been ignored, affecting aggregate model transient dynamics of the collective response.

When implementing the DR programme, DR control strategies and their effects on frequency dynamics are also considered during power system scheduling and operating. These strategies are used to realize load regulation over seconds [16], minutes [17], 24 h [18] and even longer periods. Second-level load regulation for primary frequency control during transient processes is the focus of this paper. Vardakas et al. described centralized, decentralized and distributed DR control strategies [19]. Pacific Northwest National Laboratory (PNNL) reported a novel hierarchical framework for frequency control from the demand side and designed a decentralized load controller based on DR effects on overall system frequency dynamics [16]. Mallada et al. proposed a distributed optimal DR method that considers both frequency regulation and power system operation constraints [20]. Malik et al. exploited a hybrid control approach used for domestic refrigerators by combining centralized with decentralized control [21]. In these studies, DR aggregate characteristics are considered during control implementation while actual states of DR resources should also be considered during strategy formulation to realize expected effects of control strategies.

In evaluating DR control effects on frequency dynamics, frequency domain analysis methods are typically applied. Pourmousavi et al. introduced a DR control loop into the traditional load frequency control (LFC) model for single-area and multi-area power systems [22,23]. It is presumed that DR resources can be changed instantaneously at the moment a command signal is received. Therefore, DR resources present no ramp up or ramp down limitations when taking part in frequency control processes. Based on this, Devi et al. described how a LQR-Fuzzy controller can stabilize the frequency of a micro grid under normal and emergency conditions [24]. Furthermore, Zhu et al. investigated the modelling and controller design of an LFC together with dynamic demand control based on the impact of multiple delays on control loops [25].

Though significant efforts have been made to adapt the conventional frequency domain response model with DR participation effects considered, studies have barely considered the influence of DR aggregate characteristics and control strategies on frequency dynamics. More specifically, three key points need further examination.

- First, response processes of aggregated DR resources are regarded as