Applied Energy 205 (2017) 304–315

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

$\mathscr{H}_2$-optimal transactive control of electric power regulation from fast-acting demand response in the presence of high renewables

David P. Chassin[a,b,*], Sahand Behboodi[b], Yang Shi[b], Ned Djilali[b,c]

[a] SLAC National Accelerator Laboratory, Menlo Park, CA, USA
[b] Inst. for Integrated Energy Systems, and Dept. of Mechanical Engineering, University of Victoria, Victoria, British Columbia Canada
[c] Renewable Energy Research Group, King Abdulaziz University, Jeddah Saudi Arabia

HIGHLIGHTS

- A transactive scheme that minimizes real-time operation deviations from schedule.
- A model of fast acting demand response that provides frequency regulation service.
- A robust control method that provides an economically-efficient use of load resources.
- An $\mathscr{H}_2$-optimal control framework that outperforms the conventional ACE control policy.

ARTICLE INFO

Keywords:
Transactive control
Power system control
Frequency regulation
Renewable intermittency
Demand response

ABSTRACT

This paper presents an $\mathscr{H}_2$-optimal power regulation scheme for balancing authorities to provide regulation services using both generation and load resources in the presence of a significant amount of intermittent renewable generation. The optimal controller is designed to minimize the loss of total economic surplus due to deviations from the schedule because of generation contingencies. The results show that the optimal controller outperforms the conventional ACE control policy by (1) providing faster return to the schedule under varying demand response levels, (2) reducing the cost of using reserve units for regulation services, and (3) minimizing deviations from the global surplus-maximizing schedule.

1. Introduction

Demand response is widely regarded as an important option for utilities to mitigate the intermittency of renewable generation resources [1]. System operator control of distributed loads is an emerging challenge in systems where demand response is expected to play a significant role in mitigating the adverse effects of renewable intermittency [2]. Transactive control has been proposed and demonstrated as an efficient approach to integrate demand response [3,4]. Transactive control is a multi-scale and multi-temporal paradigm that can integrate wholesale energy, capacity, and regulation markets at the bulk system level with distribution operations, where demand response resource are aggregated and dispatched [5]. Under the transactive control paradigm, retail markets for energy, capacity, and regulation services are deployed to provide an analogous realization of wholesale markets at the distribution level. In spite of the conceptual similarity, the behavior of retail markets differs significantly from that of wholesale markets and remains an active area of research [6]. In particular, load behavior usually dominates the behavior of retail systems, which contrasts with wholesale systems where generation is dominant. In addition, there are a number of important processes in bulk power interconnection operations that have yet to be integrated fully into the transactive paradigm. Two very important such processes are system frequency regulation and control area import/export schedule tracking.

Frequency regulation and schedule tracking are jointly regulated using a tracking signal called "area control error" (ACE). The standard mechanism is based on a computation performed in time-domain independently in each control area by evaluating

$$[e(t)-e_s] + B[f(t)-f_s], \tag{1}$$

where e is the actual net exports from the control area, e_s is the scheduled net exports, B is the frequency bias, f is the interconnection frequency, and f_s is the nominal or scheduled frequency. In most realizations the ACE signal is updated by the SCADA system about every 4 s and further passed through a smoothing filter so that it changes with a time-constant well in excess of the generating units' fastest response, e.g., 30–90 s, with the purpose of reducing wear and tear on generating unit governor motors and turbine valves [7]. Generators equipped with

* Corresponding author at: SLAC National Accelerator Laboratory, Menlo Park, CA, USA.
E-mail addresses: dchassin@slac.stanford.edu (D.P. Chassin), behboodi@uvic.ca (S. Behboodi), yshi@uvic.ca (Y. Shi), ndjilali@uvic.ca (N. Djilali).

http://dx.doi.org/10.1016/j.apenergy.2017.07.099
Received 11 January 2017; Received in revised form 19 May 2017; Accepted 23 July 2017

Nomenclature

$\Delta_e(t)$	area net power exports deviation in MW
$\Delta_f(t)$	system frequency deviation in Hz
$\hat{f}(s)$	interconnection frequency response in s-domain
$\hat{f}(s)$	system frequency in s-domain
$G_d(s)$	droop-controlled generation response transfer function
$\hat{g}_r(s)$	ACE-controlled generation response response in s-domain
$\hat{l}(s)$	load response in s-domain
$\hat{p}(s)$	interconnection power response in s-domain
$\hat{s}_s(s)$	filtered ACE signal in s-domain
$\varkappa_g(kt_d)$	slope of the generation supply curve at the dispatch point in $/MW^{2}h
$\varkappa_l(kt_d)$	slope of the load demand curve at the dispatch point in $/MW^{2}h
$\psi(t)$	regulation energy price in $/MWh
$a(t)$	raw ACE signal in MW
B	frequency control bias in MW/Hz
D	interconnection damping constant
$d_p(t)$	disturbance magnitude in MW
$e(t)$	actual net exports from a control area in MW
e_s	scheduled net exports from a control area in MW
$F(s)$	low-pass ACE control signal filter transfer function
$f(t)$	system frequency in Hz
F_d	fraction of total load that can be responsive to frequency
F_r	fraction of generating units that are ACE-controlled
f_s	nominal or scheduled system frequency in Hz
$\hat{g}_d(s)$	droop-controlled generation response in s-domain
$G_r(s)$	ACE-controlled generation resource transfer function
$H(s)$	interconnection overall transfer function
K_d	fraction of total load that is armed by 5-min dispatch
K_l	load control recovery time constant in seconds
K_p	load quasi-steady rebound response time constant in seconds
$L(s)$	load transfer function
M	interconnection inertial constant
R	droop control constant
s	complex frequency variable
t	real time variable in seconds
T_f	ACE control signal filter time constant in seconds
T_g	generation resource governor time constant in seconds
T_{ch}	generation resource steam chest time constant in seconds
T_l	load control derivative response gain
d	disturbance magnitude in MW

"automatic generation control" (AGC) respond proportionally to this ACE signal and adjust their output to compensate for both local and global under or over production. In parallel, load resources can also contribute to the power balancing, in particular considering their inherent capability for fast response to frequency deviations. Related to this we present a modification to control area balancing policy so that the grid operator can consider the load's response when dispatching generation assets and do so in a more economically efficient manner.

Numerous studies examining frequency regulation resource performance using diverse loads have been conducted in recent years. Lakshmanan et al. [8] studied the provision of secondary frequency control in electric power systems based on demand response activation on thermostatically controlled loads in domestic refrigerators in an islanded power system. Observations of household refrigerator response time, ramp rate, and consumer impact showed that they provide sufficient fast-acting demand response (FADR) resources for grid services, with a typical response time of 24 s and a p.u. ramp down rate of 0.63 per minute, which can satisfy the requirements for primary frequency control.

Zhong et al. [9] developed a coordinated control strategy for large-scale electric vehicles, battery storage and traditional frequency regulation resources for automatic generation control. Recognizing that response priorities and control strategies for these resources vary with different operating states they showed that a coordinated control approach not only fully utilizes each resource's advantages but also improves the frequency stability and facilitates the integration of renewable energy.

Falahati et al. [10] examined a model of storage using electric vehicles as moving batteries in deregulated power systems as one way to deal with the frequency regulation problem in a deregulated system with a growing share of intermittent generation resources. They enabled a vehicle-to-grid option for the control of the frequency using an optimized fuzzy controller to manage electric vehicle charging and discharging based on system frequency. The results illustrated satisfactory performance for frequency control of the grid system and verified the effectiveness of the approach at reducing the need for under-frequency load shedding to protect the system against large frequency excursions.

Teng et al. [11] proposed a framework to quantify and evaluate the impact of electric vehicles on island systems like Great Britain. This framework used a simplified power system model to analyze the effect of declining system inertia on primary frequency control and the ability of electric vehicle chargers and batteries to provide resources to mitigate that impact. Using this model they proposed an advanced stochastic system scheduling tool that explicitly models the loss of inertia and assesses the costs and emissions arising from primary frequency control as well as the benefits of having electric vehicles provide primary frequency response. In an analysis for Great Britain they showed that integrating electric vehicles in the primary frequency control system can significantly reduce anticipated cost and emissions growth.

Biel et al. [12] examined the frequency response of commercial HVAC systems by comparing different control strategies for providing frequency regulation demand response. Aside from significant impacts from intra-facility communications delay and control latencies, the authors did observe reductions in energy efficiency when the frequency regulation controls are more active, pointing to the necessity that the combined long-term energy cost and short-term regulation response revenue to be considered jointly. In a concurrent study, Khan et al. [13] followed up on studies by Hao [14] and Sanandaji [15] of the storage-like behavior of thermostatic loads by proposing a stochastic battery model. This model provides parameters of the battery model and considers changes to the hysteretic thermostatic control in response to frequency. This provides a relatively simple solution to load model aggregation. However the approach does not facilitate, or integrate easily with, transactive approaches, and does not properly account for the long-term endogenous energy integral error feedback that is intrinsic to thermostatic control in general.

A number of studies of optimal generation control designs have been previously reported. Bevrani and Bevrani [16] studied the general frequency control tuning problem for multiple objectives and proposed three methods for tuning PID controllers to improve the performance of closed-loop system, including a mixed $\mathscr{H}_2/\mathscr{H}_\infty$ optimal design method. This approach is easily transferable to a static output feedback control implementation, as is the case with ACE and any generalized extension where export schedule tracking is desired. The $\mathscr{H}_2$-optimal design method is particularly interesting when there are significant robustness issues to consider, although the authors did not present a solution to the synthesis of an optimal ACE controller.

The optimal ACE control design problem in the presence of significant demand response resources that autonomously respond to frequency deviations caused by intermittent generation has yet to be carefully examined. Autonomous frequency control using responsive