University of Victoria | Graduate Studies

Notice of the Final Oral Examination for the Degree of Doctor of Philosophy

of

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"Modeling and Control of Controllable Electric Loads in Smart Grid"

Department of Mechanical Engineering

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Engineering Office Wing
Room 430

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Abstract

Renewable and green energy development is vigorously supported by most countries to suppress the continuously increasing greenhouse gas (GHG) emissions. However, as the total renewable capacity expands, the growth rate of emissions is not effectively restrained. An unforeseen factor contributing to this growth is the regulation service, which aims to mitigate power frequency deviations caused by the intermittent renewable power generation and unbalanced power supply and demand. Regulation services, normally issued by supply-side balancing authorities, leads to inefficient operations of regulating generators, thus directly contributing to the emissions growth. Therefore, it is urged to find solutions that can stabilize the power frequency with an increased energy using efficiency.

Demand response (DR) is an ideal candidate to solve this problem. The current smart grid infrastructure enables a high penetration of smart residential electric loads, including heating, ventilation, and air conditioning systems (HVACs), air conditioners (A/Cs), electric water heaters (EWHs), and plug-in hybrid electric vehicles (PHEVs). Beyond simply drawing power from the grid for local electric demand, those loads can also adjust their power consumption patterns by responding to the control signals sent to them. It has been proved that, if appropriately aggregated and controlled, power consumption of demand-side residential loads possesses a huge potential for providing regulation services without operating regulating generators. The research of DR is pivotal from the the application perspective due to the efficient usage of renewable energy generation and the high power quality. However, many problems remain open in this area due to the load heterogeneity, device physical constraints, and computational and communication restrictions. In order to move one step further toward industry applications, this PhD thesis is concerned with two cruces in DR program design: Aggregation Modeling and Control; it deals with two main types of terminal loads: Thermostatically Controlled Appliances (TCAs) (Chapters 2-4) and PHEVs (Chapter 5).

This thesis proceeds with Chapter 1 by reviewing the state-of-the-art of DR. Then in Chapter 2, the focus is put on modeling and control of TCAs for secondary frequency control. In order to explicitly describe local TCA dynamics and to provide the aggregator a clear global view, TCAs are aggregated by directly stacking their individual dynamics. Terminal TCAs are assumed in a general case that an arbitrary number of TCAs are equipped with varying frequency drives (VFDs). A centralized model predictive control (MPC) scheme is firstly constructed. In the design, to tackle the TCA lockout effect and to facilitate the MPC scheme, a novel approach for converting time-integrated interdependent logic constraints into inequality constraints are

proposed. Since a centralized MPC scheme may introduce non-trivial computational load by using this aggregation model, especially when the number of TCAs increases, a distributed MPC (DMPC) scheme is proposed. This DMPC scheme is validated through a more practical case study that all TCAs are subject to pure ON/OFF control.

Chapter 3 targets on aggregation modeling and control of TCAs for the provision of primary frequency control. To efficiently reduce the computational load to facilitate the primary frequency control, the explicit monitoring of terminal TCAs must be compromised. To this end, a 2-D population-based model is proposed, in which TCAs are clustered into state bins according to their temperature information and running status. Within the proposed aggregation framework, individual TCA dynamics' evolutions develop into TCA population migration probabilities, thus the computational load of the centralized controller is dramatically reduced. Based on this model, a centralized MPC scheme is proposed for the primary frequency control. The previously proposed population-based model provides a promising direction for the centralized control. However, in traditional population-based model, TCA lockout effect can only be considered when implementing the control signals. This will cause a mismatch between the nominal control signals and the actually implemented ones. To conquer this, in Chapter 4, an improved population-based model is studied to explicitly formulate the TCA lockout effect in the aggregation model. A DMPC scheme is firstly constructed based on this model. Furthermore, since the predictions of regulation signals may not be available or they may include severe disturbances, a control scheme that does not require future regulation signals is urged. To this end, an optimal control scheme, in which a novel penalty is included to maximize the regulation capability, is proposed to facilitate the most practical scenario.

Another type of terminal loads that has a huge potential in providing grid services is PHEV. At this point, Chapter 5 presents the aggregation and charging control of heterogeneous PHEVs for the provision of DR. In contrast to using battery state-of- charge (SOC) solely as the system state, a new aggregation model is proposed by introducing a novel concept, i.e., charging requirement index. This index combines the SOC with drivers' specified charging requirements, thus inherently providing the aggregation model with richer information. A centralized MPC scheme is proposed based on this novel model. Both of the model and controller are validated through an overnight valley-filling case study. Finally, the conclusions of the thesis are summarized and future research topics are presented.