**Sequential Set-Point Control of Thermostatic Loads Using Extended Markov Chain Abstraction to Improve Future Renewable Energy Integration**

**By Ashraf Radaideh**

Additional flexible resources are required to achieve resilience and sustainable power systems. Challenges emerged due to the increasing amounts of renewable generation penetrations at both the bulk power system and the distribution sides. System operators are required to deal with higher levels of variable and uncertain power outputs for various time-scales. Moreover, replacing existing thermal units with other inertial-less technologies, make the system sensitive to even small contingencies. Demand side control is becoming an ingredient part of our future power system operation. Effective utilization of demand side resources can make the system more elastic to integrate the future renewable plans. To help resolving these challenges, this work develop a demand side control framework on the Thermostatically Controlled Loads (TCLs) to support the grid with minimal impacts on customers' comfort and devices' integrity.

The Markov chain abstraction method is used to aggregate the TCLs and describe their collective dynamics. Statistical learning techniques of hidden Markov chain analysis is used to identify the parameters of the resulting Markov chains at fixed temperature set-points. Various sensitivity analysis are conducted to reveal the optimal Markov chain representation. To allow extracting or storing additional thermal energy. The work in this thesis develop an Extended Markov Model(EMM) which describes devices transition when a new set-point is instructed. The results have shown that the EMM is able to capture both devices’ transient and steady-state behaviors under small and large set-point adjustments.

 Parameters heterogeneity affects the accuracy of the EMM model. In contrast to what proposed in literature, more comprehensive heterogeneous parameters are defined and considered. The K-mean clustering approach is proposed in our analysis to minimize the heterogeneity error. Devices are divided into multiple clusters based on the power ratings and cycling characteristics. The results have shown that clustering highly improves the EMM performance and minimize the heterogeneity errors.

 Under temperature set-point control the TCLs' aggregated power experience two main challenges before it converges to the new steady-state value, the abrupt load change, and the power oscillations. This is due to devices' synchronous operations once a new operating set-point is ordered. Such power profiles may cause serious stability issues. Therefore, Model Predictive Control (MPC) with direct ON/OFF switching capability is proposed to apply the set-point control sequentially and prevent any possible power oscillations. The MPC can determine the optimal devices' flow toward the new operating set-point. The results have shown that the proposed modeling and control approaches highly minimize the required switching actions. Control actions are required only during the transition between the set-points and finally converges to zero when all devices reach the new set-point setting. In contrast, the models proposed in literature require very high switching rates which can cause damage or reducing devices' life expectancy.

The last part of this thesis proposes a dispatching framework to utilize the TCLs' flexibility. The developed modeling and control techniques are used to support the grid with three demand response ancillary services. Namely, spinning reserves, load reduction, and load shifting. The three ancillary services are designed as demand response programs and integrated to the Security Constrained Unit Commitment (SCUC) Problem. Three participation scenarios are considered to evaluate the benefits of aggregating the TCLs in the day-ahead markets.