An Interactive Multi-agent Based Real Time Control Framework for the Interconnected Power Grid

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Abstract: The high penetration of renewable generation raises great concerns in grid operation on whether system will have sufficient flexibility for balancing the intermittent variation of renewable generation. With the development of smart grid, technologies like demand response, distribution generation , electric vehicle and energy storage become more popular. It is foreseen that with the increasing participation of these flexible load resources and high penetration of renewable generation, the system operations of the future interconnected power grid will become more complicated.

This paper discusses the system operational challenges, analyzes the potentials of load flexibility, then proposes a multi-agent system control framework to support the interactive operations of "Source-Grid-Load". An interactive leading control process is introduced to lead the flexible resources ramping with a sequence of advisory dispatches, reduce the balancing needs from the frequency control generators.

1 INTRODUCTION

With significant levels of renewable generation to be integrated in the future electric power systems, new balancing techniques and better forecasting are needed for System Operators to maintain power system security. The impact of renewable generation's uncertainty and variability motivate the introduction of new control technologies such that system operations can make better use of system flexibility to maintain system reliability and improve economic performance.

Power system uncertainties arise dramatically from conventional and emerging technologies with the development of smart grid. Such technologies include intermittent generation, controllable and price-sensitive loads, energy storage, and plug-in hybrid electric vehicles. Most of the resources with new technologies are connected to the distribution network, and usually are invisible to the transmission control centre except showing up aggregately at the transmission bus with large load variation.

Impact of uncertainty associated with renewable integration has drawn a great concerns in system operations. In order to tackle the uncertainty issues, utilities has made great efforts in improving renewable generation forecasting, preserving the ramping capability, increasing reserve procurement, and performing more frequent dispatches etc. However, experiments imply that traditional operating approaches cannot capture the full spectrum of system variability and uncertainties, which can cause more severe transmission overloading and congestion problems.

The MIT report (2011) on the future electric grid pointed out that it is increasingly important to devise and deploy mechanisms to provide incentives for investment in flexible generation and for operating flexibly within the system, also to remove the obstacles for boundary-crossing transmission to facilitate the efficient integration of renewable generation.

Hence, it is necessary to review the existing system operating practices and look for new control sources, new control strategies such that the system operations can break the barriers in the current practices of system operations, exploit the flexibility of all resources sufficiently and encourage cross-regional resource optimization.

Foreseen the needs of changing in system control, Wu et al (2005) suggested that the future control center shall be decentralized, integrated, flexible, and open to support the distributed control, and stipulated a grid service-based future control center. Yao et al.(2012) proposed "Source-Grid-Load" interactive operation and control to exploit the flexibility of load in system operations. Zhang (2013) discussed the autonomy and synergy of Source-Grid-Demand in smart grid operations and proposed smart grid EMS (Energy Management System) that implements the philosophy of "distributed autonomy and centralized coordination" in EMS.

This paper is intended to discuss a new real time system operation and control framework to fulfil the needs of system flexibility for balancing the increasing penetration of renewable generation, and encourage autonomous operation of system resources. Section 2 discusses the evolving changes of electric grid with emerging smart grid technologies, analyzes the impact of increasing uncertainties on system operations, and summarizes the anticipated operational challenges briefly. Then, this paper proposes an interactive multi-agent based grid control framework to support the interactive operation of "Source-Grid-Load" in Section 3 and describes an interactive leading control process that coordinates system flexible resources in a 2-stage decision process: a real time leading control dispatch and an automatic generation control in Section 4. At the end, this paper concludes with our vision of future grid interactive control.

2 OPERATIONAL CHALLENGES FOR FUTURE ELECTRIC GRID

The electric power systems are transforming with increasing penetration of renewable generation and emerging smart grid technologies. Such technologies include intermittent generation, controllable and price-sensitive loads, energy storage, distributed generation, and plug-in hybrid electric vehicles. System operations face big challenges with uncertainties arising from these emerging technologies. New balancing technologies and better control strategies are needed for System Operators to maintain power system security.

2.1 Emerging Smart Grid Technologies

With the development of smart grid, a wide array of new supply-side and demand-side technologies will be integrated into the grid in the coming decade as part of efficiency and smart-grid initiatives. As their use grows, their impact will complicate both load and generation forecasting by introducing higher levels of variability in supply, new kinds of uncertainty in demand, and non-traditional participants in grid operations.

Demand Response

Demand Response is designed primarily to shave peak demand, have accelerated in many countries. In the United States, FERC (Federal Energy Regulatory Commission) 2012 DR and AMI Survey(FERC 2012) indicated that advanced metering penetration reached 22.9% of total meters in 2012, up from less than 8.7% in 2010. The survey estimates the peak load reduction from demand response to be over 31 GW in 2010, representing approximately 7.0 percent of the 2010 peak ISO/RTO electricity demand. The United States FERC 2009 demand response potential study (FERC 2009) estimated that demand response under full participation, can help to reduce the peak load by almost 20% or 188GW in 2019. The China EPRI (Electric Power Research Institute) also performed a similar assessment for the demand response potentials in North China region and projected about 13% reduction on peak load when the demand response markets are fully developed in 2022.

The Lawrence Berkeley National Laboratory investigation (Watson et al, 2012) on fast automated demand response for renewable generation integration showed that the fast demand response, that can response in less than 2 hours, will be about 20% of the total demand response potentials if the automated demand response technologies are fully implemented. That tells us, the fast response capability from demand response can reduce the peak load by 4% if it is fully utilized. This is big compensation for the real time load following.

Renewable Generation

To maintain sustainable economic development and energy security, many countries have ambitions plan in developing renewable energy. US is targeting 20% of electricity provided by the renewable energy in 2020 . China is trying to reduce the coal generation from almost 70% now to 34% in 2050 by increasing investment in wind and solar power.

Recently, large scale of renewable generation from Solar power and wind power have been developed and integrated into the transmission grids. In China, several 10,000MW wind farms have been developed in the West and North China. In the US, a large amounts of wind power have been injected into the Midwest and Texas grids and large arrays of solar panels have been installed in the Nevada and California deserts. Besides, with the technology improvement and cost reduction, Solar Photovoltaic(PV) is becoming popular to serve local area needs at distribution voltages, reducing daily demand moderately during the solar peak (generally a few hours before load peak). Other distributed generation technologies, like micro turbine generator, diesel generator, integrated PV and energy storage units also are deployed in many places.

Electric Vehicles

Electric Vehicles use electricity instead of gas to drive vehicles with zero-emission. It is becoming promising for wide promotion with the improvement in battery technologies. The charging and discharging property makes the battery a two-way electricity load. With the vehicle-to-grid technology, the electric vehicles can receive and send power to the grid.

Energy Storage

Energy storage technologies enable the decoupling of the instantaneous supply of energy from the variable nature of demand and variable supplies. With the initiatives of smart grid, a variety of energy storage technologies are developed, such as lithium-based battery, flying-wheel, compressed air etc. The deployment of energy storage enhances the integration of variable renewable resources into the grid and the provision of ancillary services.

2.2 Incremental Resource Scheduling and Dispatch

The electric power system operation is a consecutive decision process to schedule and dispatch sufficient generation to meet the system demand. Electrical systems include a range of different generating resources, including fossil-fuel units, hydro-power units, nuclear units, and renewable-resource units such as solar and wind. Different units can have significantly different operational characteristics, even among similar resource types. For example, some thermal units take hours or more to start up, while other units (e.g., quick start gas turbines) can start up and shut down quickly, in a few minutes. Some generating units have to run stably at a certain level, like nuclear units, geothermal units, and some hydro power units, particularly where frequent changes of the prime power are undesirable for safety or efficient energy use.

Generating units such as solar-power and wind-power units have output which highly variable and may have limited control facilities.

Hence, in normal system operations, system operators commit long-start units, ramp slow-ramp units early to meet the projected load change, and procure sufficient reserves for the real time imbalance and contingencies in one day or more time ahead. When real time gets closer, the pre-dispatcher commits the quick-start units, schedule interchange between control areas, and procure additional reserves if necessary. In real time, the system dispatchers adjust fast-moving units to balance load and respond to conditions not anticipated earlier in the process. The day-ahead, pre-dispatch and real-time decision cycles repeat daily, hourly, and every 5 to 10 minutes to continually match supply and demand.

2.3 Operational Challenges

With increasing integration of renewable generation, demand response, electric vehicle load, and energy storage facilities, bringing new and challenging operational characteristics, traditional approaches present an inaccurate picture of impacts and costs associated with new resources and changing business processes. Along with the application of smart grid technologies, the operational challenges emerge in three aspects below:

First, the interconnected transmission grids will connect much closely to support the wide area energy transmission and renewable integration. In China, State Grid Company of China planned to build multiple ultra-high voltage (above 500KV) transmission corridors (*Fig. 1*) to transfer the electricity from West and North China to the load centres in East and South China. In the US, a super station is being built to connect the East Interconnect Grid, the Texas Grid and the West Interconnect Grid together such that the large amount of wind generation in the ERCOT area and SPP the area can be transferred to California (Tres Amigas 2013).

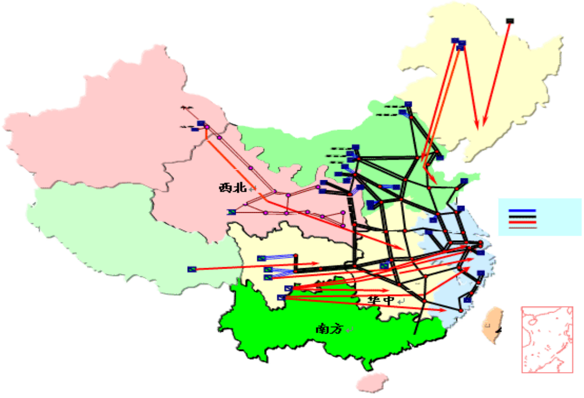

Fig. 1 SGCC Ultra-High Voltage Transmission in 2020

The high volume transmission facilities can achieve cross-regional, large amount of electricity delivery and a wide range of resource optimization, but they also make the connections between regions more closer, that increase the mutual impacts of system disturbances and power imbalances. A cross regional coordination is becoming necessary.

Second, the intermittency of renewable generation requires additional load following reserves. Due to high uncertainty, it is very difficult to make accurate forecast of renewable generation, like wind power and solar power. For example, statistics of the California ISO production data in 2012 (as shown in Fig. 2) shows that the average forecast errors of wind generation in northern California area were about 20% in one day ahead forecast, and about 10% in two hours ahead forecast. In real time, when renewable generation differs from its forecast level, other generating capacity is needed to make up the difference to keep the power balance of the system.

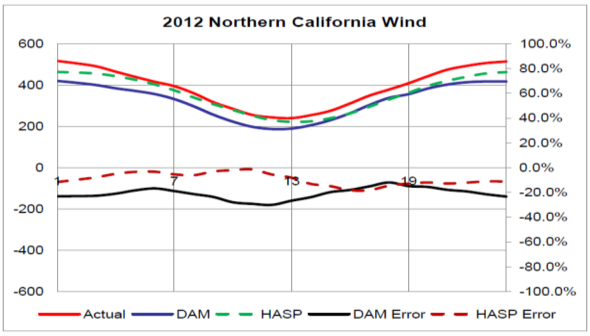

Fig. 2 Northern California Wind Forecast Error in 2012

The impact of renewable generation also showed that additional system ramping capability is needed. *Fig. 3* shows a one-day California ISO actual load vs. wind and solar generation. During the morning load ramp period between 06:30 and 10:00, wind generation dropped fast while the load was ramping up. In this period, system generating resources had to provide additional ramping capability to match the wind generation drop.

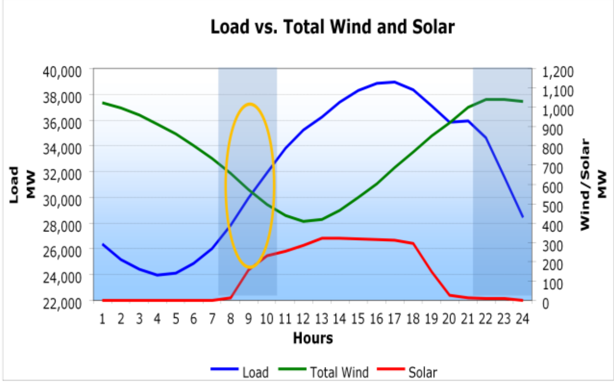

Fig. 3 One Day Load vs. Wind and Solar Generation

Third, with the increasing application of smart grid technologies, such as demand response, distributed generation, energy storage and electric vehicle charging facilities, system load become flexible in some degree because these facilities can respond to system dispatch information and move correspondently. Traditionally load is treated as uncontrollable. Generators are dispatched to follow the load change. In one aspect, when load becomes responsive, it becomes difficult to forecast. In the other aspect, the load can provide partial flexibility for the system to balance the variation of renewable generation.

The operational challenges motivate us to look for better mechanism and control strategies to utilize the system from other resources besides controllable generators, to encourage cross region resource optimization and to improve resource autonomy in operation such that the system operation can be more reliable and economical.

3 AN INTERACTIVE MULTI-AGENT BASED GRID CONTROL FRAMEWORK

It is believed that the multiple level hierarchy of grid control won't change in the future, but the centralized control mode of grid operation will change with the changes of controllable resources in system. With the participation of demand response, distributed generation, electric vehicle load and energy storage facilities, there will be massive, small individual elements to be monitored and controlled. This scenario is very different from the current system control that only a limited number of large generating units are controlled to balance the demand of electricity. Hence, the centralized direct control becomes impossible. The system control shall follow the principle "distributed control, centralized coordination".

In addition, with the wide application of information technology, system elements (such as wind power cluster, flexible load, the local distribution etc.) can be highly intelligent, operate naturally like agents with capabilities of self-decision, autonomy, communication, learning and evolution etc. In another way, the system elements can perceive the changes of system condition, automatically adjust and improve their behaviour, collaborate with others, to achieve the operational goal of the grid.

Here a multi-layer multi-agent based grid control architecture is proposed (as shown in Fig. 4) to support distributed control of massive individual components. In includes three layers: A Coordination Layer, an Area Control Layer and an Interaction Layer.

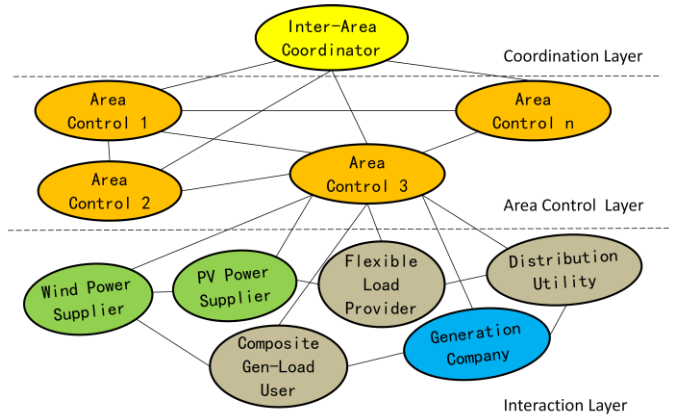

Fig. 4 The Multi-Agent Based Grid Control Framework

In this grid control framework, an inter-area coordinator is designated to perform cross region coordination at the Coordination Layer. Coordination in network scheduling is very important for a wide range resource optimization. It is expected the future electric grid control shall be coordinated in the regional level to support renewable integration in multiple regions.

For example, in China, with the fast growing renewable generation, and increasing demand of long distance electricity transmission, the State Grid Company of China planned to build several UHV AC and DC transmission lines across the country in 2020. By then, the whole state grid will be connected together closely. But to the scale of the grid, it is impossible to achieve centralized control, the electric grid will still be operated at the provincial level. It is expected that there will be a state grid level inter-area coordinator. The inter-area coordinator monitors the major changes of system in transmission, generation and demand and periodically sends target instructions to the area (provincial) control centres in every 5 minutes, but the inter-area coordinator will not directly control the resources.

Such coordination role actually exists in current grid operations. For example, in the United States, there are several reliability coordinators, such as the Western Electricity Coordinating Council, the Southern Power Pool, the Texas Reliability Entity, the Midwest Reliability Organization , the Southeast Reliability Corporation, the Florida Reliability Coordinating Council, the Reliability First Corporation and the Northeast Power Coordinating Council. Currently they perform reliability monitoring and coordinating, but not energy scheduling. In China, state grid company has one state grid dispatch center and four divisions. They perform regional reliability monitoring and limited frequency control. It is expected these coordinators can expand their role to system wide resource scheduling.

In fact, the real-time interactive coordination between regional control centres is somewhat realized in some grids,. For example, in the United States, PJM and NYISO are sharing the real-time electricity prices of imbalance market to attract the resources in the other control area to participate in its real time imbalance market.

The middle layer is Area Control Layer, where Each area (provincial) control centre will coordinate with the adjacent control areas interactively and control the internal resources to follow the inter-area coordinator's instructions. The area control centres serves much similar as their current roles, but can be more intelligently. They shall be able interact with other area control centres for more information, not only limited to some measured information like system frequency, tie line power flows.

The third layer includes the internal resources, represented by agents like Wind power suppliers, Solar power suppliers, Flexible load providers, Distribution utilities, Composite Gen/Load Customers, Conventional Power Suppliers etc. In the future, these resource shall act autonomously, follow the instructions from the area controller, work together to fulfil the balancing obligation of the area. The area control centre will control those direct control resources to balance the remaining power imbalance. With this approach, the uncontrollable resources, such as flexible loads, will contribute their flexibility to the system control, reduce the balancing needs from the frequency control generators.

4 AN INTERACTIVE LEADING CONTROL PROCESS

Within the multi-agent based grid control framework, the real time dispatch and the automatic generation control (AGC) will be integrated together for the area control. An interactive leading control process is designed as shown in the diagram in Fig. 5.

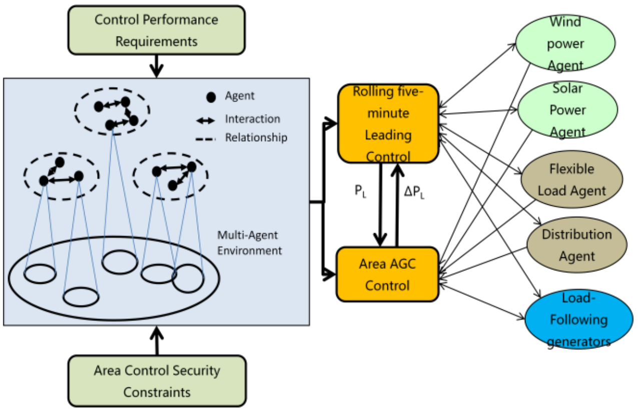

Fig. 5 The Leading Interactive Control Process

First, a multi-agent environment is created to model the grid operational constraints, the characteristics of grid components, and the area control strategies that are designed to meet the control performance requirements enforced by the grid reliability authorities. Mathematically, the steady state operational characteristics of the system can be described in two sets of constraints, one set of stochastic constraints that describe the operational behaviours with impact of uncertainty as shown below,

$$g(X(t), \mu(t), \omega) \le 0 \qquad (1)$$

The other set of constraints represent the system operational behaviours with no uncertainty as shown below:

$$h(X(t), \mu(t)) \le 0 \qquad (2)$$

Here t represents time; ω represents the uncertainty the constraints; X(t) is the states of system; μ(t) represents the controls applied to the system that maintain system stability and consensus of behaviours of system elements after disturbance, typically is a negative feedback control as below,

$$\mu(t) = -r(X(t)) \qquad (3)$$

Second, the real time operation is achieved in a nested 2-stage control, one stage is a leading control stage that sets the control target with a rolling multi-interval five-minute optimal dispatch the other is an automatic generation control stage. The rolling five-minute leading control solves the following optimization problem,

$$\min \textstyle\sum_t \|X(t, \omega)-X_L(t)\| \qquad (4)$$

S.T.:

Stochastic Constraints: $g(X(t, \omega), \mu(t), \omega) \le 0,$

Deterministic Constraints: $h(X(t, \omega), \mu(t)) \le 0$

Stability Constraints: $\mu(t) = -r(X_L(t)) \in U(t)$

Time Horizon: $t \in [1,2,...,T]$

The objective of the optimization problem is to minimize the variances of state variables over a given time period T. The constraints include the system operational constraints represented by a set of stochastic constraints and a set of deterministic constraints, the stability constraints derived from the system stability analysis that defines the set of controls U(t). In general, this is a stochastic optimization problem and can be solved with the solution techniques of stochastic programming.

The inactive leading control process can be illustrated below. As shown in Fig. 6, a sequence of control based on $X_L(t)$ $=\{X_L(t_0), X_L(t_1), X_L(t_2),..., X_L(T)\}$ can be obtained by solving the above optimization problem., represented in a red line in the plot. The black lines shows the possible trajectories of states X(t). It is expected the system to operate from the initial states at time t_0 evolves along with the trajectory of leading control to maintain the balance of system generation and demand. The control target based on $X_L(t)$ will be sent to the participating agents, such as the flexible load providers, the distribution companies, or the renewable power suppliers, to follow. The first target based on $X_L(t_1)$ will be a binding instructions and will be counted in energy settlement. The others based on the future states $X_L(t)$ will be advisory signals for the participating agents to respond in the future. By observing the possible trajectory of system movement, the non-load following resources can move ahead of time to meet the needs of incoming power imbalance partially. It reduces the burden on the frequency control resources.

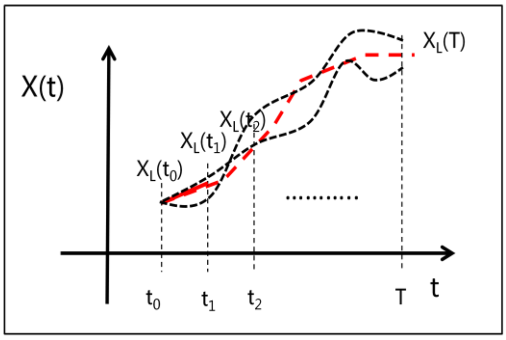

Fig. 6 The Sequence of Leading Control

Third,. the area AGC control will estimate the potential response from the non-AGC controllable resources, and control the AGC units to balance the load. Usually AGC control is in a few seconds, mostly responds to system frequency change and the Area Control Error (ACE).

Currently, the ACE is calculated as below,

$$ACE = B\Delta f + \Delta P_T \qquad (5)$$

Here, Δf is the frequency difference to the system nominal frequency. B is the system frequency response coefficient, ΔP_T is the deviation of actual flows on the tie lines from the scheduled tie line flows. Typically the North America

Electric Reliability Council(NERC) Control Performance Standard is adopted by most area control centres to monitor its control performance.

Under the interactive multi-agent based grid control framework, the area control target is set by the inter-area coordinator. the inter-area power exchange will become more frequently. The ACE calculation shall be adjusted to count the leading control effects.

5 CONCLUSIONS

A future grid control structure shall be able to fully utilize the system resources to accommodate the needs of integration of renewable generation and maintain system security. The technology improvement and policy evolvement enable the load facilities to be more responsive, flexible and intelligent. The massive individual load facilities can be aggregated and represented by agents to participate the system operation. Similarly, the massive distributed generating resources, or electric vehicle and energy storage facilities, can participate the system operation in the same fashion. With increasing applications of information technologies, all the electric system elements can naturally be represented in forms of agent, the electric system will be a multi-agent based system where system elements can act autonomously, interactively and responsibly with coordination.

For the purpose of real time grid control, an interactive multi-layer multi-agent based grid control framework for the future system control is provided to set the coordinative structure of the future grid operation, defining the roles of the inter-area coordinator, the area control centres and the system elements. An interactive leading control process is designed to lead the system elements to respond to the system operating needs correspondingly and contribute their flexibility for system balance.

In this paper, we anticipate the evolving changes of the electric grid, attempt conceptually to build a grid control structure and introduce an interactive control process such that the future grid can be operated more efficiently and reliably, even with high uncertainty arising with integration of renewable generation, distributed generation, demand response, energy storage and electric vehicles. A lot of works are still remaining in the future research. In our vision, the following aspects need to be studied further.

- When massive individual loads participate the grid control, how to stimulate and assess their flexible capability and model their aggregated responsive characteristics is a complicated and difficult work. It is crucial for the grid control center to make reasonable judgment in energy scheduling and dispatch. Existing experiences in designing and implementing demand response programs can provide us valuable references.
- System security is always the highest concern in system operation. Traditional operational process may be obsolete under the circumstance of high uncertainty. New power system analysis techniques are needed to better represent the system security constraints.
- The presented interactive multi-layer multi-agent based grid control structure involves policy or regulatory changes. New policy or regulations shall be established to support the interactive coordination and control, for example, the control performance standard, the settlement mechanism for energy transactions etc.

Surely, we bring more questions in this paper than solutions. However, changes to the future grid control are inevitable because of the unstopping evolvement of technology. Here present our vision for the future grid control. Further research is continuing.

6 REFERENCES

FERC Staff Report (2009). *A National Assessment of Demand Response Potential.*

FERC Staff Report (2012). *Assessment of Demand Response and Advanced Metering.*

MIT (2011). *MIT Study on The Future of The Electric Grid*, ISBN: 978-0-9828008-6-7

Tres Amigas (2013), *The Tres Amigas SuperStation*, Presented in Transmission Summit 2013, February 28,2103, http://tresamigasllc.com/, accessed on November 11,2013

Watson, D. S., N. Matson and others (2012). Fast Automated Demand Response to Enable the Integration of Renewable Resources. A Lawrence Berkeley National Laboratory Study Report for California Energy Commission.

Wu, Felix F., M. Khosrow, A. Bose (2005). Power System Control Centers: Past, Present, and Future", *Proc. of the IEEE,* **vol.93, no.11**, pp. 1890-1908

Yao, J., S. Yang and other (2012). Concept and Research Framework of Smart Grid "Source-Grid-Load" Interactive Operation and Control. *Automation of Electric Power Systems*，**36(21)**,pp. 1-5.

Zhang, B. (2013). Smart Grid EMS with Source-Grid-Demand Synergy. Proceedings of 12th EPCC Workshop, Bedford Springs, PA USA