Distributed Compensation of a Large Intermittent Energy Resource in a Distribution Feeder

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***Abstract*--In a smart grid demonstration project in New Mexico, a combination of a 500kW PV farm and a 1MWh utility scale storage system which consists of a 500kW ultra fast smoothing battery and a 250kW shifting battery are installed. At a nearby location, a micro grid demonstration which incorporates a 240kW natural gas-powered generator, a 80kW fuel cell, a 50kW PV generator, a lead-acid battery storage system, and hot and cold thermal storage is installed.**

With the current configuration, the storage system associated with the 500kW PV is able to smooth PV output, to shift the peak generation to the time of peak consumption and also to firm the PV resource as a fixed amount of power. The problem is how the system would be managed in presence of several distributed resources with different ramp rates and capacities and different operation costs, which would reduce the stress placed on the battery.

In this paper, the results of the different studies on the system model are discussed. A complete feeder model in GridLAB-D is used to demonstrate several control algorithms. In one scenario, all other available generations are planned to compensate the PV generation ramp rate based on their individual capacity. Each agent will compensate the ramp rate of the total generation of the higher priority agents based on its own capacity. In another scenario, individual agents try to compensate the deficit in power generation scheduled for the whole system. Every particular agent is responsible for compensating the difference between the scheduled and the total generation of the higher priority agents.

***Index Terms*— distributed energy resources(DER), microgrid, Demand-Response(DR), State of Charge(SoC)**

I. Introduction

Recent advances in small scale power generation, increasing concerns about CO2 emissions, uncertainties about foreign oil supplies, high start-up costs coupled with growing public opposition over safety in nuclear reactor construction[1] and electricity business restructuring are the main factors responsible for the growing interest in the use of DER. It is argued that the connection of small generation units to low voltage networks has the potential to increase the reliability of the delivered power to final consumers. On the other hand, it can bring additional benefits for global system operation and planning[2]. The concept of integration of DER into the power grid includes small generators, energy storage, load control and -for certain classes of systems- advanced power electronic interfaces between the generators and the bulk power provider[3]. The capability of incorporating small scale local generators has urged the researchers, planners and designers in this field to pay more attention to microgrids.

From the utility perspective, a smart microgrid can be regarded as a controlled entity within the power system that can be operated as a single aggregate load[4]. Existing studies have investigated many microgrid architecture designs and control strategies. P. Piagi and R. Lasseter have proposed methods for autonomous control of each microsource contributing to keeping the feeder health factors in the required range while maintaining feeder operation even during islanded periods[5]. Shuai Lu *et. al.* have considered a DR method along with other DER to achieve the required control over the microgrid to maintain its operation in islanded situations[6].

Grid tied power systems currently have storage in the form of generators' inertia, which maintains the system's frequency during sudden changes in the total system load or supply. According to [7], a microgrid can not rely on its own generators' inertia and must provide some form of storage to ensure initial energy balance. There must be adequate total storage in the system to decouple voltage and frequency characteristics of the system from the load variations.

On the other hand the induced fluctuations due to the intermittent nature of the renewable energy resources like solar and wind, implies incorporating some type of storage system to decouple voltage and frequency characteristics of the system from sudden changes in the supply, when the penetration level of the renewable sources becomes large.

The most promising energy storage systems which have been appearing quickly are flywheel, battery energy storage technologies. They are also installed in smart grid demonstration projects [8] [9]. There are few hydraulic storage systems in use, but they require a geography that enables such systems[10].

A power distribution feeder which is traditionally a tree of conductors, transformers, switches and other distribution level equipments, has delivers electricity from the substation -the connection point of the distribution system to the transmission system- to the customers. Feeders are normally designed to operate in a one-way energy transfer direction. Energy is delivered from source (substation) to the customers where are distributed spatially along the feeder.

Increasing the penetration level of DER into the distribution feeders is considered an opportunity and a challenge. By integrating necessary communication and

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control infrastructure into the distribution feeders, controllable load/generation centers will be developed which provide substantial flexibility for the business and operation of the distribution system. On the other hand, such complex distributed system is prone to instability and black outs due to lack of a major “infinite” supply and other unpredicted variations in load and generation.

In this research, a unique distribution feeder is studied as a bench mark for the future smart grid. The feeder Studio14(ST14) is located in Mesa del Sol, Albuquerque. A 500kW PV farm and a 1MWh utility scale storage system which consists of a 500kW ultra fast smoothing battery and a 250kW shifting battery are connected close to the feeder source. At a nearby location, a micro grid demonstration(NEDO)[11] which incorporates a 240kW natural gas-powered generator(NGPG), a 80kW fuel cell, a 50kW PV generator, a lead-acid battery storage system, and hot and cold thermal storage is also installed and connected to the feeder through a 1000kVA transformer. A complete model of the feeder is developed in GridLAB-D[12]. The generators are defined as negative loads and the storage system is assumed to have constant SoC to energy ratio. More accurate models could be develped in GridLAB. A detailed report about the modeling process could be found in [13]. The storage system has been under several test cases to demonstrate its capabilities for smoothing the PV output in cloudy days, to shift the off-peak generated power of the PV system to peak consumption times and to firm the total PV/BESS system as a dispatchable resource for the utility. The purpose of the current study is to devise and simulate some techniques which enable the system operator to take advantage of other available DER connected to the feeder and reduce the storage battery cycling. If financially and operationally plausible, implementation of such methods could substantially increase the expected life time of the battery energy storage system (BESS) and the associated power converters. Two algorithms are introduced and simulated.

II. System Description

The system configuration is shown in Fig. 1. Feeder ST14 is supplying power to a number of commercial customers, NEDO microgrid and to the developing residential community of Mesa del Sol[14]. The PV farm and the BESS are located 2 miles away from the NEDO microgrid. In the current configuration all those subsystems are operating independently. The customers get their required energy from the feeder. The BESS system is smoothing the PV output based on the adjustments done by the utility and each individual resource in the microgrid generates power according to the operator’s adjusted settings.

Non of the energy resources that are studied here contribute to Volt/Var or frequency control. Net real power is exchanged with the grid and also the energy exchange efficiency is assumed to be 100%. Practical efficiency of the system could be considered for further studies.

In a partially cloudy day - based on the amount of smoothing required by the utility- the BESS could be under severe stress to compensate the intermittency of the solar generation. A 24-hour PV generation in a partially cloudy day is shown in Fig. 2. Drastic variations in the order of 100kW/Sec is recorded.

The idea behind this study is first to demonstrate how the BESS can contribute to smoothing out the fluctuant output power of the PV system. Then, to show how the NGPG could be controlled in order to contribute to the smoothing process based on its capacity and dynamic capabilities. As a matter of fact the BESS system can operate in charge mode and in discharge mode. It means the BESS can sink energy from the grid when the batteries have to be charged and can inject energy to the grid and discherge. During BESS operation, the SoC of the batteries has to be maintained within allowable range. On the other hand, the NGPG can just operate in generation mode and can not sink energy from the grid.

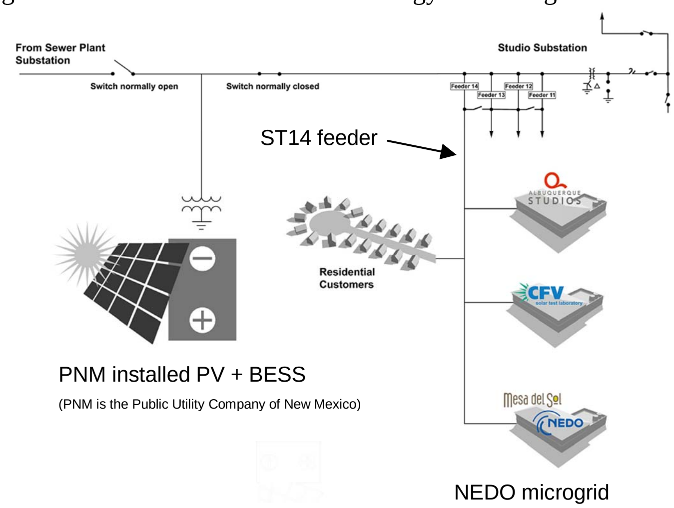

Fig. 1. Feeder ST14 configuration diagram showing the connections to the PV+BESS, the NEDO microgrid, commercial and residential customers.

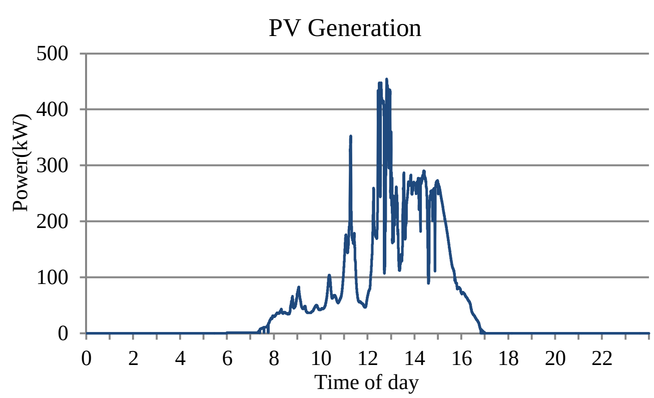

Fig. 2. PV generation power in a cloudy day

The smoothing resource, must be capable of bidirectional energy exchange because the instantaneous rate of change in the PV generation (Ramp Rate) can be positive and negative (Fig.3). To adapt the NGPG to operate in both positive and negative rate regions, its normal operation power is set at 180kW and the control system is allowed to ramp it up to ±60kW by 0.3 kW/Sec rate[4]. Therefore, the NGPG behaves like a storage system ramping up and down, while its net

[4] This rate is the maximum possible value achieved during the tests.

generated energy is positive.

The internal controller characteristics of the BESS and the NGPG were not studied in this research. They are assumed to be able to follow the power commands issued by the virtual controller which is introduced in the next section.

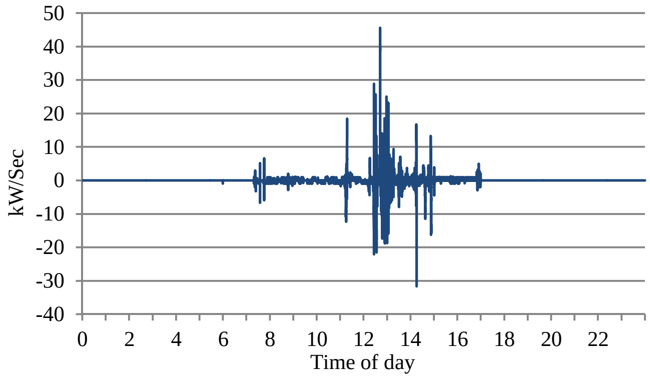

Fig. 3. PV generation power variation in the same cloudy day

III. Smoothing Methods

The ultimate goal of this study is to design a decentralized control method for each agent (every separate DER) to be able to contribute to an optimum smoothing scenario. Those optimum scenarios won't be necessarily unique because the optimizing parameters are not unique and may vary based on the associated cost functions.

Two different approaches are introduced for smoothing. One is based on compensating the ramp rate (RR) and the other is based on compensating the deficit or abundance in PV generation. In this study, it is assumed that the instantaneous generation power data for every DER is available to all agents with no delays. Future work will cover the effects of delay or error and transparency of data for every agent.

A. Ramp Rate Compensation (RRC)

In this method, each DER receives the aggregate RR of the higher ranked contributing resources as input signal and tries to change its power proportional to RR and in the opposite direction with regard to its maximum RR and capacity characteristics. Output power control signal is equal to the integral of the RR signal plus the initial operating value. Two internal loops try to maintain the smoothing energy and the output power close to their preset values.

Every DER is ranked based on the total operational costs and/or other priorities. For this study, the NGPG is given rank1 and the BESS is given rank2. Therefore, the NGPG has a higher priority than the BESS to compensate the aggregate RR.

Internal control loops oppose the compensation procedure because the compensation RR tries to keep the output RR as close to the reference RR as possible which pushes the DER to sink/source more energy, while the average smoothing power and energy is desired to be as lower as possible. Accordingly, there is a trade-off between smoothness and average exchanged energy and power.

Conceptually, producing smoother output requires instantaneous RR calculation. Hence, 1-Sec RRC, which produces smoother aggregate output compared to 20-Sec RRC necessitates faster response devices to be installed and used. Nevertheless, delay in power measurement and transmission may cause significant error which may not only generate a less smooth output but also may act in reverse direction and add even more fluctuation to the aggregate output.

A simplified block diagram of the controller implementing RRC method for adjusting the smoothing DER power set point is illustrated in Fig.4. As it was mentioned previously, BESS has a lower rank than NGPG. Therefore it has to compensate the aggregated RR of the PV and the NGPG.

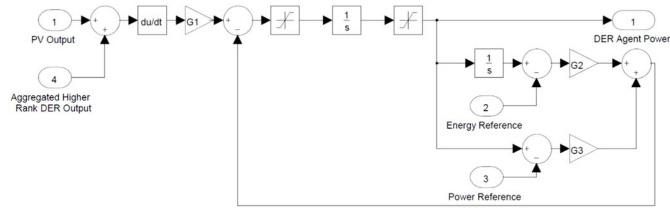

Fig. 4. Smoothing agent power reference controller block diagram implementing RRC method

B. Sliding Window Moving Average Compensation (SWMAC)

In this method, each DER receives the difference between the aggregate power and its sliding window moving average of the higher ranked contributing resources and tries to compensate the measured deficit or abundance in power proportional to its available capacity and permissible ramping rate.

Smoother output is equivalent to wider sliding window. Therefore, 200-Sec SWMAC produces a smoother aggregate output compared to 2-Sec SWMAC. The drawback is the induced delay caused by the inherent delay of SWMAC algorithm which is equal to half the window length in time.

A simplified block diagram of this control method for the smoothing agent power adjustment is illustrated in Fig.5.

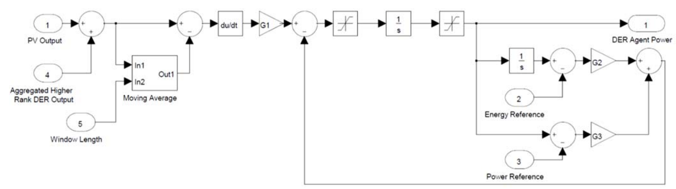

Fig. 5. Smoothing agent power reference block diagram implementing SWMAC method

The described controllers are designed and implemented in GridLAB as control modules. An instance of the appropriate controller adjusts each agent's power, and consequently energy level.

IV. Results

To illustrate how each agent can contribute to the smoothing process, the same PV power data is fed to both control systems. The controllers are tuned with experimental values. Frequency domain analysis is also performed on the results to clarify the effectiveness of the smoothing algorithms.

A. RRC

Fig. 6, shows the contribution of NGPG and BESS to smoothing process with RRC controller. Different parameters setting will produce different effects. In Fig. 7, the PV power and the total DER generation is shown. Smoothing algorithm has worked appropriately for most of its operation cycle except at around 12pm to 13pm which due to severe intermittency in PV generation, sharp changes in the aggregate output is noticeable.

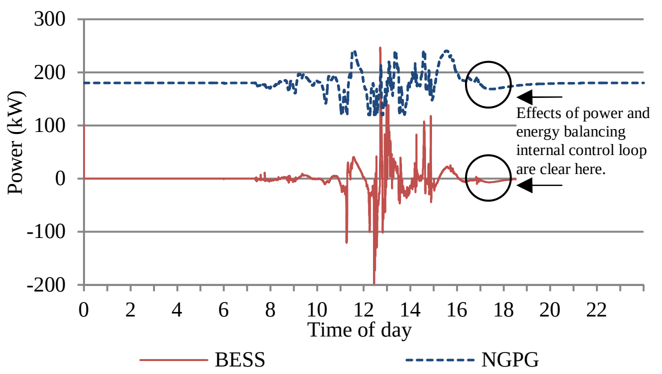

Fig. 6. NGPG and BESS contribution to RRC smoothing. NGPG has tried to follow the PV fluctuations, but due to limeted dynamic response and power capabilities, is not able to follow the fast varying portion of the PV. On the other hand, BESS ramps up and down keeping up with PV variations.

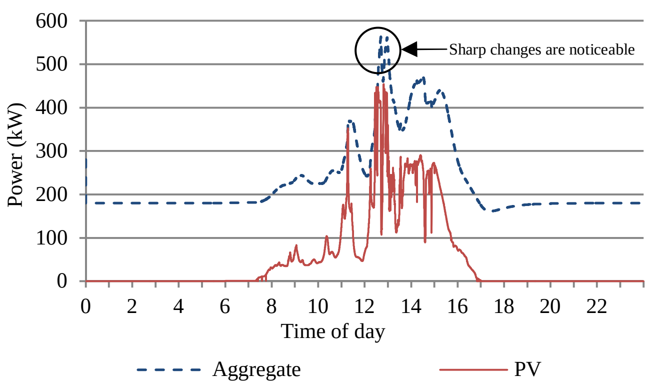

Fig. 7. PV power and the aggregate output. Inspite of smoothing, there is still signs of fluctuations in the total output.

Frequency spectrum of the original PV output and the aggregate power output of all available DER in the feeder are calculated and is shown in Fig. 8. The Cumulative Density Functions (CDF) of both spectrums are also added to the picture. The smoothed signal characteristics show that most of the original signal's energy which was spread over the frequency range of 1-Sec to DC, has moved toward lower frequencies. The CDF also shows that a higher percentage of the smoother signal energy is concentrated close to lower frequency vicinity compared to the original signal's energy.

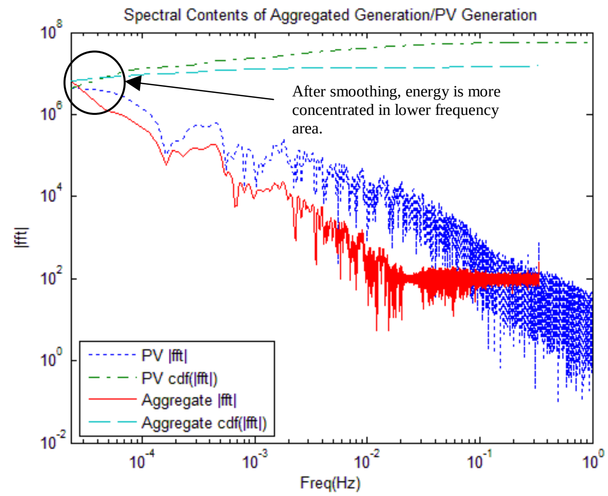

Fig. 8. Frequency spectrum of the PV output and the smoothed aggregate power. Concentration of the smoothed signal around lower frequencies is noteworthy.

Total energy contribution is also another important factor in battery based storage systems. A major goal of this study is to find such solutions that reduce the stress on the batteries and their cycling depth. In Fig. 9, the smoothing energy variation of both BESS and NGPG is shown. Clearly, the NGPG operation has successfully reduced the amount of energy delivered by the batteries. Therefore, any available DER with lower overall costs, can be used in order to reduce the need for more expensive battery or to reduce the required size of the BESS system.

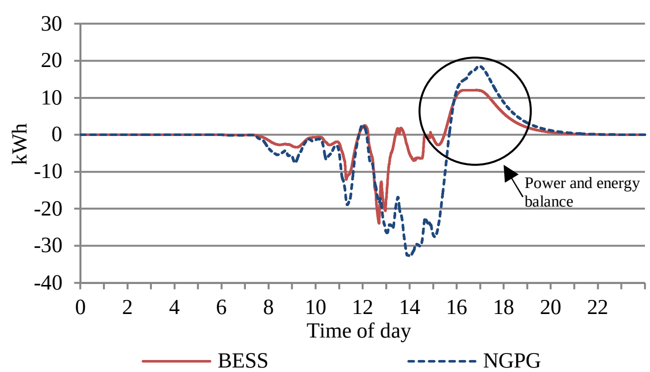

Fig. 9. Smoothing energy, exchanged between BESS, NGPG and the grid.

B. SWMAC

Similar study is conducted to investigate the advantages and possible drawbacks of the SWMAC method. Fig. 10 to Fig. 13 show the same graphs for the SWMAC method. Obviously, this method is more capable for smoothing the PV output to a high extent, by incorporating more energy from the storage system. The energy and power balance internal loops regulate the total power and energy with the expense of less smoothing which requires a trade-off between the degree of smoothness and the energy balance of the DER.

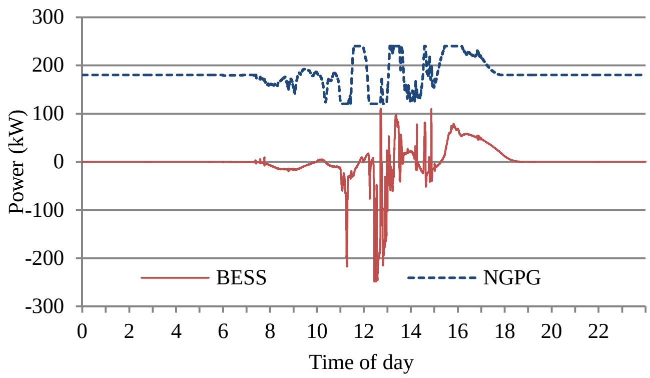

Figure 10. NGPG and BESS contribution to SWMAC smoothing.

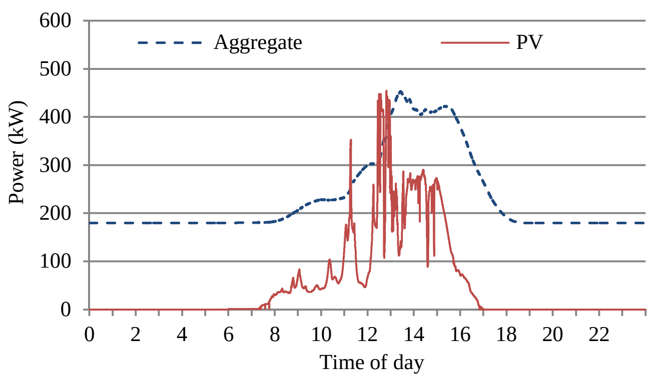

Figure 11. PV power and the aggregated output. Aggregate output is smoother than previous method at the expense of higher energy exchange for the battery

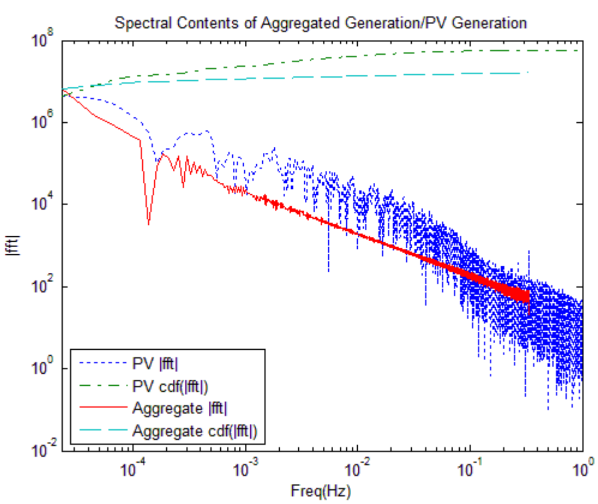

Figure 12. Frequency spectrum of the PV output and the smoothed aggregate power. High energy concentration in the lower frequency range is prevalent.

V. Conclusion

The same analysis performed in this study, could be conducted for a collection of DER, connected to the feeder. Every DER has to be associated with a cost function which could be calculated independently based on operating costs, fuel costs and other parameters. The calculated cost function can be used to define their rank, which is the basis for the algorithm to assign the appropriate output power control signal.

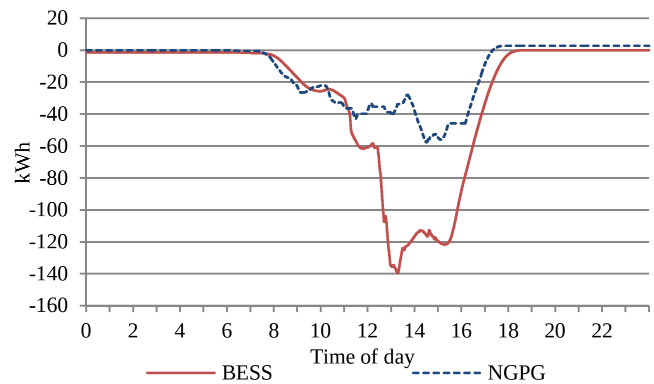

Figure 13. Smoothing energy, exchanged between BESS, NGPG and the grid. Apparently, the storage system is under more stress than RRC method.

As indicated before, delay in data transfer is not considered in the described simulations. Nonetheless, delay is inevitable and could be added to the model for further analysis.

Based on the analysis, a resource assignment strategy is suggested. Based on this strategy:

1- Cheaper resources with slower response, compensate the PV source – or any other major renewable resource like wind turbine – adopting the SWMAC method.
2- Fast response BESS – may be equipped with ultra batteries – compensate the aggregate generation with RRC method.
3- Slow response BESS – which could be a collection of small community storage systems distributed along the feeder – compensate aggregate power with SWMAC method. The aggregate power of the higher ranked resources has now low frequency contents.

The described strategy helps avoid the need for extra expensive fast response batteries while attaining the required level of smoothness of the aggregate local power generation. On the other hand, if the collection of the distributed resources be equipped with autonomous controllers which may have the required connectivity to the central controller, the complete feeder may be considered as a dispatcheble distributed resource.

Having discussed both smoothing methods, the selection of the smoothing method is dominantly affected by the policy of the system operator -if the microgrid is operated independently- or the utility. In other words, there is no unique strategy for smoothing. Each case has to be studied individually to find the optimum solutions.

A Latin Hypercube Sampling(LHS) method is used to find the statistical correlation between each control parameter and the quality of the response. In this method several simulations is performed with randomly changed controller settings. A collective statistical analysis then can show every parameter's effects on the performance and on the system stability. The results of the LHS algorithm will be presented in future publications.

VI. Future Research

The current research will be continued on developing autonomous algorithms for distributed agents. Need for real time information about other distributed resources which may be spatially dispersed is a challenge. Required bandwidth, communication equipments and big data management may be a bottleneck for the DER widespread popularity. If the required data for the agents could be reduced to local information, utilities or microgrid operators and customers will benefit from large scale deployment of small DER.

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VIII. Biographies

Shahin Abdollahy (SM'11) received the B.Sc. degree in electrical engineering from IUT, Isfahan in 1998 and the M.Sc. degree in electrical engineering from Tehran Polytechnic in 2000. He worked in industry from 2000 to 2009 as a design engineer and R&D manager. His career continued with designing electric drives and power converters as senior design engineer. He is currently pursuing his Ph.D. in electrical engineering at the University of New Mexico, Albuquerque, NM.

Andrea Mammoli was born in Ancona, Italy on April 18, 1968. He graduated with a Bachelor of Engineering in 1991, and with a Ph.D. in 1995, from the Department of Mechanical & Materials Engineering at the University of Western Australia. He was a Director Funded Postdoctoral Fellow at Los Alamos National Laboratory from 1995 to 1997. He subsequently joined the University of New Mexico as a research faculty member, and is now Associate Professor in Mechanical Engineering, and co-Director of the Center for Emerging Energy Technologies. His current research deals with the integration of building-scale energy systems with the electricity grid, particularly as applied to energy storage and distributed systems management. Mammoli is Regents' Lecturer and Halliburton Professor at the University of New Mexico. His projects received several awards, including the Association of Energy Engineers Region 4 Renewable Energy Project of the Year in 2009 and the GridWise Architecture Council's GridWise Applied Award in 2008.

Feng Cheng was born in Shanxi, China. She g raduated from Beijing Jiaotong University in 2007 with the major of power system and automation. Now she is pursuing her Ph.D. in electrical and computer engineering at the University of New Mexico, Albuquerque, NM. Her research interests are in the area of smart grids, energy storage system, and renewable energy. She is a member of the Institute of Electrical and Electronics Engineers (IEEE).

Jay Johnson is a member of technical staff at Sandia National Laboratories. He received his B.S. in mechanical engineering at the University of Missouri-Rolla in 2006 and his M.S. in mechanical engineering at Georgia Tech in 2009. Jay has focused on renewable energy research throughout his career—working in wind and solar thermal at the National Renewable Energy Laboratory, fuel cells at Georgia Tech, demand response and smart grid systems at the Palo Alto Research Center, and most recently photovoltaic reliability and high penetration grid studies at Sandia National Labs.

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