

DISTRIBUTED FREQUENCY REGULATION IN SMART GRIDS

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Abstract—We present and analyze distributed control schemes for frequency regulation in a smart grid. We use energy storage, conventional generators, wind generators and demand response to provide frequency support while having no communication or data sharing between them. All participants observe the system frequency and act independently in a decentralized manner to provide frequency regulation. We also propose a novel control scheme for frequency support by energy storage in which the power output of energy storage changes proportionally with the reduction in available energy in energy storage. This prevents any sudden drop in system frequency and provides other participants an opportunity to compensate for the reduced power due to discharge of energy storage. We use our methods to observe the frequency regulation in a three area power system having conventional generators, wind generators energy storage and demand response. Our results show that the addition of demand response improves the value of initial frequency drop, settling frequency and settling time. Use of energy storage further improves these characteristics.

I. INTRODUCTION

Frequency regulation in power systems is traditionally provided by conventional generation units. Participation of Windfarms, Energy Storage (ES) and Demand Response (DR) towards frequency regulation is usually less than the conventional generators [1], [2]. The increase in renewable energy sources in future power systems will present significant frequency control challenges to the system operators [3]. Windfarms, energy storage and demand response would be essential to maintain the system frequency in smart grids with high penetration of intermittent renewable sources. In this paper, we address the issue of distributed frequency control in a power system comprising of conventional generators, windfarms, energy storage systems and flexible loads providing demand response. We use energy storage, conventional generators, wind generators and demand response to provide frequency support while having no communication or data sharing between them.

Most literature on frequency regulation by windfarms, energy storage and demand response deals with these entities individually and assumes certain coordination and communication between different participants providing frequency regulation. Some papers deal with two out of these three entities but still assume a certain communication between these participants. For example [4]–[7] present techniques for frequency support using both windfarms and energy storage

but they assume coordination, communication or some data sharing between energy storage, windfarm or conventional generators. Similarly [8] and [9] use demand response, energy storage and conventional generators to maintain system frequency but do not use wind generators in frequency regulation. The role of demand response to provide frequency regulation in micro grids and large interconnected systems is discussed in [10]–[12].

We extend this subject and add two novel contributions to the existing research. First, we employ a distributed control scheme for frequency regulation in a power system in which all participants including conventional generators (CG), wind generators (WG), energy storage operators and flexible loads participate to balance and maintain the system frequency. In our distributed control scheme, there is no communication or data sharing between these participants. Each entity observes the system frequency and acts to provide frequency regulation independent of the actions or state (charge, power rating etc.) of other participants or system operator response. We also observe how the absence and presence of energy storage and demand response impact the quality of frequency regulation in a power system in which conventional generators and wind generators are already participating in frequency regulation.

Our second contribution is a novel control scheme for energy storage in which the power supplied by ES towards frequency support changes as the amount of stored energy in the ES is changed. When energy storage supplies power for frequency support, the quantity of available storage is constantly decreasing and it can fall to a value below the recommended minimum capacity. In this case, the storage will stop its contribution to frequency regulation which can further cause a sudden drop in frequency. In our control scheme, power supplied by energy storage reduces proportionally to the decrease in available storage capacity. This would prevent any sudden change in amount of frequency support and allow the system operator or other market participants (wind generators, other storage systems, conventional generators or demand response) to react in a timely manner because any change in frequency due to reduced amount of power from energy storage will be gradual.

We use our proposed control methods to observe the frequency regulation in a three area power system having conventional generators, wind generators energy storage and demand

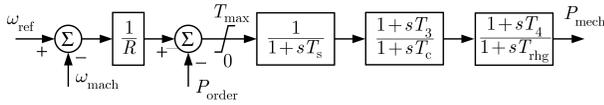


Fig. 1. Turbine Governor Model for Conventional Generators taken from [15].

response. Our results show that the addition of energy storage and demand response improves the frequency nadir, settling frequency and settling time. Moreover, the use of proposed scheme for energy storage improves the system frequency characteristics as compared to the situation when energy storage does not reduce its power output with the reduction in available energy. The rest of this paper is organized as follows. In Section II, we develop our frequency control methodologies for different participants (wind generators, ESS, DR) in the power system. In Section III, we describe the simulation setup details and the power system considered for simulation. We present and explain the simulation results of different case studies in Section IV. Section V summarizes and concludes the paper.

II. FREQUENCY CONTROL SYSTEMS FOR DIFFERENT PARTICIPANTS

Primary frequency control in a power system is on the order of one second to sixty seconds whereas secondary frequency regulation is on the order of one minute to ten minutes [13]. We are focusing on primary frequency control via distributed control mechanisms for different participant in smart grids.

A. Frequency control system for conventional generators

Conventional generators using steam turbines and diesel generators use droop control to adjust their power output in response to a drop in system frequency. The amount of additional power provided by a generator depends on its droop characteristics and is determined by its droop gain or speed regulation parameter R with expressions provided in [14]. In our analysis, we use the same governor model for conventional generators as the ones used in [15]. The turbine governor model for conventional generators is shown in Figure 1 which was taken from [15] and use Type-ST3 exciter [16]. In Figure 1, T_3 , T_4 , T_s , T_g and T_{rhg} are different time constants for the governor and ω_{ref} is the reference frequency as per [15].

B. Frequency control system for wind generators

In the literature various techniques have been presented to improve the frequency regulation using wind turbines. One method for wind turbines to provide frequency regulation is by emulating inertial response to provide extra power from the rotor inertia in the turbine. These methods are discussed in [17]–[20]. Another technique for wind turbines to participate in frequency regulation is through deloading of wind turbine to provide extra available power in case some power is needed to stabilize the frequency. These type of frequency support schemes through wind turbine deloading are described in [21]–[24]. In [15], a combination of both rotor inertia and deloading

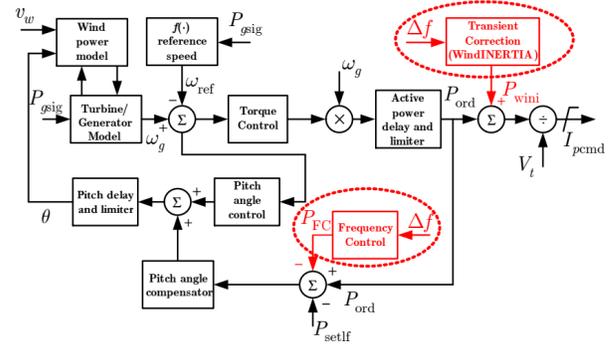


Fig. 2. Schematic diagram of the wind generator control system developed in [15], [25] and [26]. The frequency control parts are shown inside the dashed lines. Figure is taken from [15].

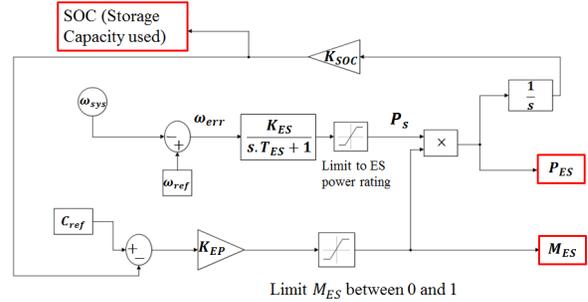


Fig. 3. Control system for energy storage to provide frequency regulation.

through pitch control is used by wind turbines to provide frequency regulation. Figure 2 was taken from [15] and we will use the same model for wind turbine as shown in Figure 2. These models were developed in [15], [25] and [26] and readers are encouraged to read the detailed modeling for wind generator frequency control in [15], [25] and [26].

C. Frequency control system for energy storage

The control system for energy storage to provide frequency regulation is shown in Figure 3. ω_{sys} and ω_{ref} represents the system frequency and reference frequency respectively. The term K_{ES} is the proportional gain to decide the amount of power provided by energy storage in response to frequency error ω_{err} . K_{ES} would be calculated as:

$$K_{ES} = \frac{\text{PU change in ES power}}{\text{PU change in frequency}} \times S_{max} = \frac{1}{0.03333} \quad (1)$$

The term $\frac{1}{1+sT_{ES}}$ in Figure 3 represents the 1st order delay of power converters in the energy storage system. We assume that the energy storage will not participate in frequency regulation in case of a situation when frequency is higher than 1 pu (60 Hz). In order to ensure that the energy storage does not exceed its minimum or maximum power ratings a limiter box is used to limit the ES power rating between 0 and its maximum power rating S_{max} . As the energy storage supplies power to provide frequency regulation, the available capacity

or charge in the storage decreases. Once the available storage capacity decreases below the minimum recommended (or safe operation) level, energy storage would stop contributing to frequency regulation. In order to prevent this sudden drop in power, we also introduce a method to gradually reduce the power supplied by energy storage as the available capacity or State Of Charge (SOC) is reduced. In Figure 3, the energy used by storage as it supplies the power is calculated through the integrator. The term K_{SOC} is used to convert the amount of supplied power to fraction of energy storage capacity that had been used.

$$K_{SOC} = \frac{1}{T_{SOC}} \quad (2)$$

Here, T_{SOC} is the time (in seconds) taken by energy storage to discharge completely if it supplies power at its maximum power rating. In order, to ensure that the amount of storage does not fall below the recommended minimum level C_{min} , the used amount of storage (SOC) is compared with C_{ref} , given by (3) to obtain C_{err} .

$$C_{ref} = 1 - C_{min} \quad (3)$$

In Figure 3, K_{EP} is used to convert C_{err} to the multiplying factor M_{ES} . The multiplying factor M_{ES} determines the amount of reduction in the power supply of energy storage due to reduced available capacity. Its value ranges from 0 to 1. M_{ES} is multiplied with the calculated storage power P_s to determine the power quantity “ P_{ES} ” that energy storage will provide for frequency regulation. The value of K_{EP} is determined from C_{min} and C_{max} , where C_{max} is the amount of available capacity in energy storage above which there is no restriction on the power supply from ES (i.e., the power from energy storage could be at its maximum power rating if the available storage capacity is above C_{max}). Therefore, K_{EP} is given as follows:

$$K_{EP} = \frac{1}{C_{max} - C_{min}} \quad (4)$$

Once the storage capacity is reduced below C_{min} , then the output from K_{EP} turns negative and the limiter box limits the value of M_{ES} to 0. This in turn sets P_{ES} to 0 and energy storage stops participating in frequency regulation because of lower amount of available energy.

D. Frequency control system for demand response

We employ a simple droop control for demand response in which the amount of flexible load decreases proportionally from its maximum value to its minimum allowable value as frequency decreases. This control strategy is shown in Figure 4. K_{DR} is the proportional gain to decide the reduction in load based on the frequency error ω_{err} . This is the counterpart of K_{ES} from (1) used for the same purpose in energy storage control system. This would be calculated as:

$$K_{DR} = \frac{\text{Per unit change in load}}{\text{Per unit change in frequency}} \times D_{max} \quad (5)$$

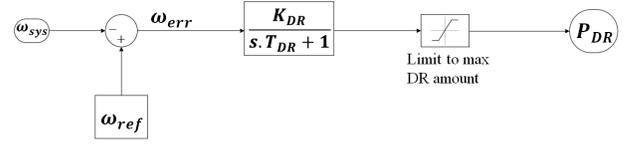


Fig. 4. The simple droop control for demand response.

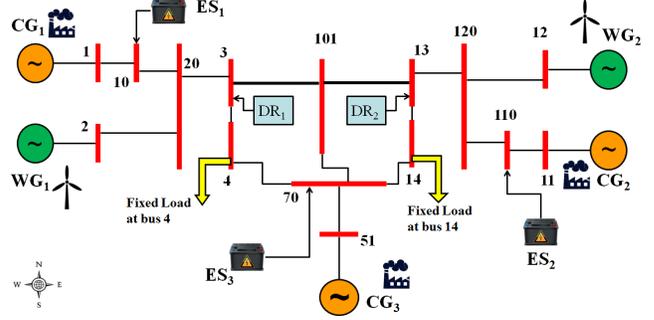


Fig. 5. Power system for simulation of distributed frequency control.

III. SIMULATION SETUP

In this section we describe the power system model, different control parameters, settings and set-ups used for our simulation and analysis.

A. Power network

We simulate the proposed frequency control schemes on a three area power system shown in Figure 5. The proposed power network is a three area system consisting of 15 buses which are interconnected with each other. Each of the three areas (East, West and South) are equipped with one conventional generator. Area 1 (West) and area 2 (East) also have one wind generator but there is no wind generator in Area 3 (South). There is one energy storage in each of the three areas. The fixed load is located on bus 4 in area 1 (West) and bus 14 in area 2 (East). We place the demand response near the two fixed load centers. The first demand response (DR_1) is located at bus 3 which is connected to fixed load on bus 4 in Area 1 and the second demand response (DR_2) is located at bus 13 which is connected to fixed load on bus 14 in Area 2 as shown in Figure 5. The power ratings of all conventional and wind generators is 10 per unit on base of 100 MVA. All three ES have a power rating of 5 per unit on base of 100 MVA. Both the demand response (DR_1 and DR_2) are assumed to be identical. Under normal operations both DR_1 and DR_2 operate at a load of 5 MW. In case, demand response is needed to provide frequency regulation, DR_1 and DR_2 can reduce their value to 3 MW each. This results in a reduction of 2 MW from each demand response participant.

B. Control system parameters

We use the same parameters for wind turbine control model as the ones used in [15], [25] and [26]. The important

TABLE I
CONTROL SYSTEM PARAMETERS FOR DISTRIBUTED CONTROL SCHEMES
DESCRIBED IN SECTION II.

Parameter	Value	Parameter	Value
ω_{ref}	1 pu	T_{DR}	0.25 seconds
K_{ES}	300 pu/pu	L_{ex}	0.5 pu
T_{ES}	0.05 seconds	R	0.04 pu/pu
C_{min}	0.2 pu	T_s	0.1 Seconds
C_{max}	0.8 pu	T_3	0 Seconds
K_{EP}	$\frac{10}{6}$ pu/pu	T_4	1.25 Seconds
K_{DR}	-120 pu/pu	T_c	1 Second

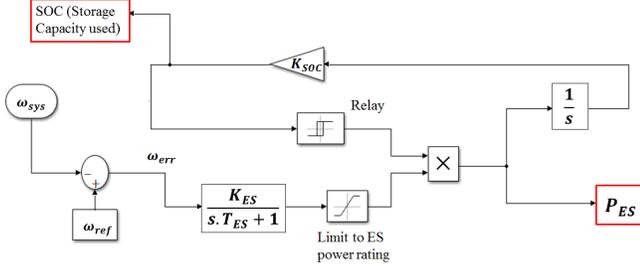


Fig. 6. Reduced control system for energy storage (without M_{ES}) to be used in Case 1.

parameters for distributed control schemes for conventional generators, energy storage and demand response are provided in Table I.

C. Simulation case studies

We study the frequency regulation in the power system of Figure 5 due to a sudden drop of generation or sudden increase in load. We study two cases for our simulation study (Case 1 and Case 2). In Case 1, we do not use the control scheme proposed in Figure 3 for energy storage. We do not reduce the power output by energy storage as its available capacity is reduced. We eliminate the control loop for M_{ES} in Figure 3 and use a reduced control system for energy storage in Case 1. This is shown in Figure 6. The relay in Figure 6 is used to stop the power output from energy storage when the energy level in energy storage reaches c_{min} . In Case 2, we use the control scheme described in Section II-C and Figure 3 for energy storage.

In both cases, we first observe the frequency regulation of power system when only conventional generators and windfarms participate in frequency regulation (Case 1a and Case 2a). We then add the demand response in each case and observe the frequency regulation characteristics (Case 1b and Case 2b). Lastly, we allow the energy storage to also provide frequency regulation in both cases and try different values of energy storage capacities. In Case 1c and 2c, ES_1 has available energy of 50 seconds, while ES_2 and ES_3 have available energy of 20 seconds. In Case 1d and Case 2d, all three energy storage systems have available energy of only 20 seconds.

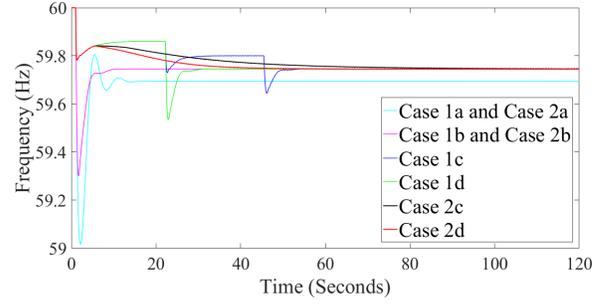


Fig. 7. System frequency for all scenarios of Case 1 and Case 2.

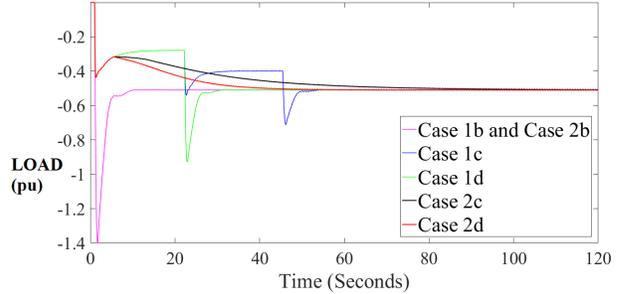


Fig. 8. Demand response provided by DR_1 and DR_2 for all scenarios of Case 1 and Case 2.

IV. RESULTS AND DISCUSSION

We obtain the steady state operation point for the power network of Figure 5. We obtain the state-space representation for the power system using PST [27]. We increase the load at bus 4 by 6 pu to observe the frequency regulation performance under the different simulation cases. This is equivalent to a loss of 6 pu of generation.

The system frequency for all scenarios of Case 1 and Case 2 is shown in Figure 7. The contribution of demand response for all scenarios of Case 1 and Case 2 is shown in Figure 8. In Case 1c, ES_1 has available energy of 50 seconds whereas ES_2 and ES_3 have available energy for only 20 seconds at their full power rating. In Case 1d, all three energy storage systems have available energy for only 20 seconds at their full power rating. The power output by different energy storage devices is shown in Figure 9(a-c) for both Case 1c and Case 1d.

In Case 2, we use the control scheme proposed in Section II-C and Figure 3 for energy storage. Therefore, energy storage will gradually reduce its power output as its available energy is reduced. There is no role of energy storage in scenario “a” and “b” of both cases. Therefore, the system frequency characteristics and contribution from demand response for Case 2a and Case 2b are identical to that of Case 1a and Case 1b respectively. The system frequency for Case 2c and Case 2d is shown in Figure 7. The contribution of demand response for Case 2c and Case 2d is shown in Figure 8. The power output for different energy storage devices is shown in Figure 9(d-f) for both Case 2c and Case 2d.

From Figure 7, it is visible that without any contribution from energy storage or demand response, the system frequency drops to 59 Hz, when there is a sudden increase in load or loss of generation. The addition of demand response improves the frequency nadir to 59.3 Hz. The settling frequency is also increased to 59.75 Hz from 59.7 Hz in Case 1a. The contribution from DR₁ and DR₂ reduces as the system frequency increases to the settling value and settles at about 0.5 pu of load reduction. Moreover, the oscillations in system frequency which happened in Case 1a disappear and the settling time reduces to 12 seconds from its value of 20 seconds in Case 1a. We also observe that after the addition of energy storage the frequency nadir was improved to 59.78 Hz as compared to Case 1a and Case 1b. The system frequency initially settles to 59.86 Hz at about 12 seconds (i.e., same settling time as Case 1b). The power output from energy storage devices is shown in Figure 9a and 9b. ES₂ and ES₃ reach c_{min} at about 20 seconds and their power output turns zero. At this instance system frequency drops to 59.72 Hz. ES₁ and demand response increase their contribution along with wind and conventional generators and raise the system frequency to 59.78 Hz. ES₁ reaches the minimum allowable energy level at 45 seconds and its power output turns zero. Therefore system frequency experiences another drastic drop from 59.78 Hz to 59.64 Hz.

A similar scenario is experienced in Case 1d where all three energy storage devices only have 20 seconds of available capacity. Initially the frequency nadir, settling frequency and settling time have same values as Case 1c. However, energy storage devices do not reduce their power with reduction in available energy. Therefore, when ES₁, ES₂ and ES₃ run out of available energy at around 21 seconds, their power output suddenly reduces to zero and this results in a sudden drop in frequency to 59.54 Hz. Demand response increases its contribution at this point as shown in Figure 8 and restores the system frequency to 59.75 Hz as shown in Figure 7.

The only difference between Case 1 and Case 2 is the type of control strategy for energy storage. In Case 2, energy storage uses the control strategy shown in Figure 3 and gradually reduces its power output as its available energy is reduced. Since Case 2a and Case 2b do not use energy storage to provide frequency regulation, therefore the results for Case 2a and Case 2b are identical to Case 1a and Case 1b respectively. In Case 2c, the initial frequency drop is still 59.78 Hz but the system frequency does not reach the settling value of 59.86 Hz that it reached in all the previous cases. System frequency only recovers to 59.84 Hz and starts its gradual reduction within 4 to 5 seconds. This is because the power output from ES₂ and ES₃ starts reducing at a very quick rate as shown in Figure 9e. The available energy in ES₂ and ES₃ falls to the recommended minimum level of $c_{min} = 0.2$ pu by 60 seconds and this stops any frequency support from ES₂ and ES₃. The system frequency falls to 59.76 Hz at 60 second interval and it is reduced to 59.75 Hz at about 120 seconds.

The results of Case 2d are quite similar to Case 2c. As shown in Figure 7, frequency nadir is still 59.78 Hz and similar to Case 2c, frequency only recovers to 59.84 Hz and

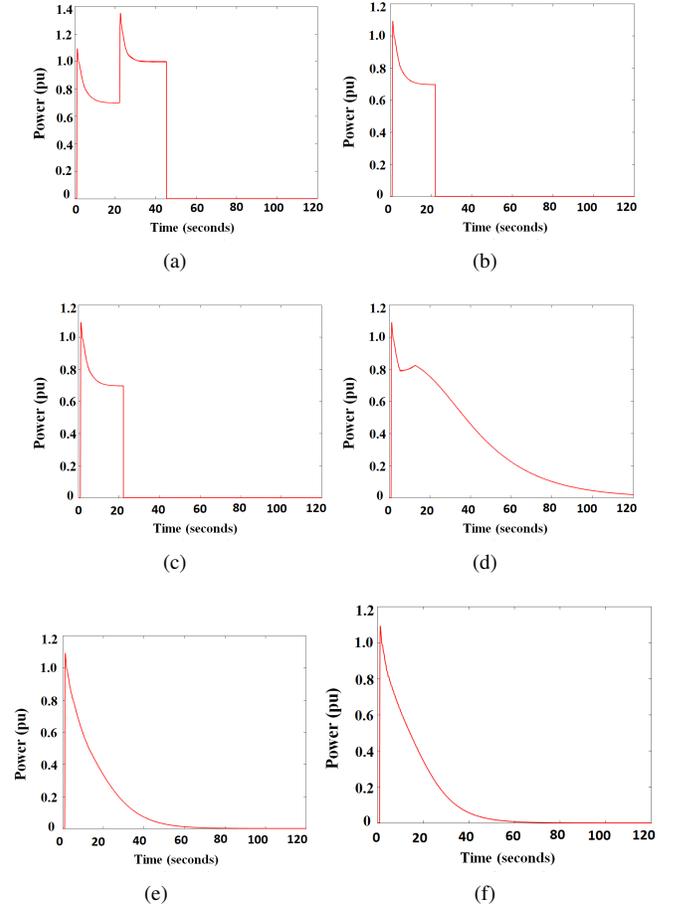


Fig. 9. (a) Power contributed by ES₁ for frequency support in Case 1c (b) Power contributed by ES₂ and ES₃ for frequency support in Case 1c (c) Power contributed by ES₁, ES₂ and ES₃ for frequency support in Case 1d, (d) Power contributed by ES₁ for frequency support in Case 2c (e) Power contributed by ES₂ and ES₃ for frequency support in Case 2c (f) Power contributed by ES₁, ES₂ and ES₃ for frequency support in Case 2d.

starts its gradual reduction at 4 to 5 seconds. All three energy storage devices had an available energy capacity of only 20 seconds and the power contribution from energy storage began to reduce at a faster rate as shown in Figure 9f. All energy storage devices stop their participation in frequency regulation after about 60 seconds and system frequency drops to 59.75 Hz and remains at that level until the end of the simulation.

We observe the advantage of the proposed control scheme for energy storage over the control scheme shown in Figure 6. There are no sudden and large drops in system frequency in Case 2 simulations as compared to the sudden and large drops observed in Case 1. When energy storage gradually reduces its power output with decreasing available energy, the system frequency reduces gradually and other market participants increase their contribution preventing any sudden drop in system frequency. The sudden drops in frequency observed in Case 1 can cause further instability in the system. This problem is fixed in Case 2 when energy storage uses the control strategy proposed in Section II-C.

V. CONCLUSION

We observed the role of energy storage, windfarms, conventional generators and flexible loads towards maintaining the system frequency. All these participants provide primary frequency regulation with no communication, coordination or data sharing in between them. These participants observe the system frequency and act in a decentralized manner to provide frequency support regardless of the state or actions of other market participants or system operator. Our results showed that there is an improvement in frequency nadir, settling frequency and settling time, when demand response is added to provide frequency regulation in addition to conventional generators and wind generators. The frequency nadir and settling frequency are further improved when energy storage is also added in the system to provide frequency support.

We also presented a new control scheme for frequency regulation by energy storage in which the energy storage gradually reduces its power output as its available energy is reduced. An advantage of the proposed control scheme is that the energy storage will not stop its participation in frequency regulation instantly if it runs out of available energy. In a traditional control scheme, energy storage will suddenly drop out of frequency regulation market if the available energy falls below the minimum level as observed in Case 1 results. In a system, where a large burden of frequency regulation is undertaken by energy storage devices, this could be detrimental to system stability as this would cause a further decrease in system frequency. However, in the proposed control scheme, energy storage gradually reduces its power output as its available stored energy is decreased. This provides other market participants like generators, demand response or system operator ample time to act accordingly in response to decreasing outputs from energy storage. Therefore, other market participants can take over the frequency support role from energy storage as the power output from energy storage decreases. This is very important for decentralized control schemes for frequency regulation because there may not be any coordination or data sharing between market participants which operate independently and do not have any knowledge about the state and contribution from other market participants.

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