Energy Storage for Short-Term Frequency Stability Enhancement in Low-Inertia Power Systems

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***Abstract*—Power systems with large scale integration of inverter interfaced generation plants become vulnerable to short term frequency instability. The short term frequency stability is related to limiting the RoCoF and frequency nadir within acceptable standards following a contingency. Failure to limit frequency nadir and RoCoF can result in the activation of RoCoF relays and under frequency load shedding relays, leading to generation disconnection and unintentional load shedding. This can result in blackout. In this work energy storage system (ESS) is deployed in the two-area power system for improvement of short term frequency stability. A capacity optimization algorithm and dispatch scheme are developed for the ESS. The capacity estimation algorithm determines the required capacity of ESS. The proposed algorithm estimates the required capacity of energy storage while considering the complete dynamics of conventional generators, wind turbine, and power conversion systems. The dispatch scheme operates the ESS to inject the real power in the system to improve the short term frequency stability. The proposed methodology is verified in PSCAD. Simulation results depict the effectiveness of the proposed approach.**

***Index Terms*—Energy storage, frequency stability, renewable energy, RoCoF.**

I. Introduction

Short term frequency stability is related to the large contingencies resulting in significant loss of load or generation due to the activation of UFLS relays and/or RoCoF relays [1]. The UFLS and RoCoF relays trigger when the frequency nadir and RoCoF fall outside the allowable windows. Both frequency nadir and RoCoF are influenced by the system inertia. Before reaction of traditional ancillary control loops, the energy provided by system inertia is the key factor to improve the short term frequency stability thereby limiting both RoCoF and frequency nadir [2].

Inverter-based renewable generation sources are increasingly replacing conventional synchronous machine based generation plants, which result in reduction of inertia of the system [3]. The inverter-interfaced generation systems, for example, Type-IV wind generation (WG) system, are decoupled from the frequency of the host AC system. Therefore, intrinsically, unable to respond to deviations in frequency of the system [4]. Thus, large scale integration of inverter-based renewable generation sources may jeopardize the frequency stability of the power systems [5]. This motivates the need to deploy fast energy balancing sources to control frequency deviations in low inertia power systems. Energy storage system (ESS) is paramount among the various available sources to mitigate the undesired deviations in frequency [6].

The ESS deployed in power system with appropriate control can act a generator/load which can inject or take power to and from the system. Compact size, fast response, and flexibility of control make them favorable for frequency stability improvement in low inertia power systems [6]. The associated higher cost and limited cycle life motivates that suitable size of ESS must be properly deployed to achieve techno-economic solution. Estimation of ESS capacity to improve the short term frequency stability can be challenging. During the first few seconds the contingency affects both voltage and frequency. The variations in voltage effects the power flow along the lines, power output of generators and reactive power flow, and therefore the system frequency. Thus, to estimate the required capacity of ESS both frequency and voltage dynamics of the generators, converter-interfaced generations, energy storage, transmission network and loads must be considered.

Different works have been carried out on the application of ESS to provide frequency support services in power systems. A control strategy for multiple distributed ESSs is poposed in [7]. The proposed algorithm controls the output of multiple storage units based on their location in the system. In [8], ESS is deployed to provide inertial response and primary frequency regulation. It is demonstrated that supercapacitor energy storage is economical option for inertial response while battery energy storage is more economical for primary frequency regulation. In [9], sizing and location optimization techniques are proposed for ESS to provide frequency regulation. The sizing of ESS is done based on the minimization of RoCoF and frequency nadir. The location of ESS is determined using sensitivity analysis. In [10] battery-supercapcitor hybrid energy storage is used to provide frequency regulation in low inertia power system. The supercapacitor energy storage is placed in the inertial control loop. While the battery energy storage is placed in slower control loop. It is shown that the battery-supercapcitor hybrid energy storage can provide improved frequency regulation. A model predictive control based virtual inertia emulator for ESS is proposed in [11]. In [12], sizing and control strategies for ESS are proposed to provide inertial and primary frequency support. The sizing of ESS is done using equivalent inertia estimation. A derivative control is used to provide inertial support. While droop control

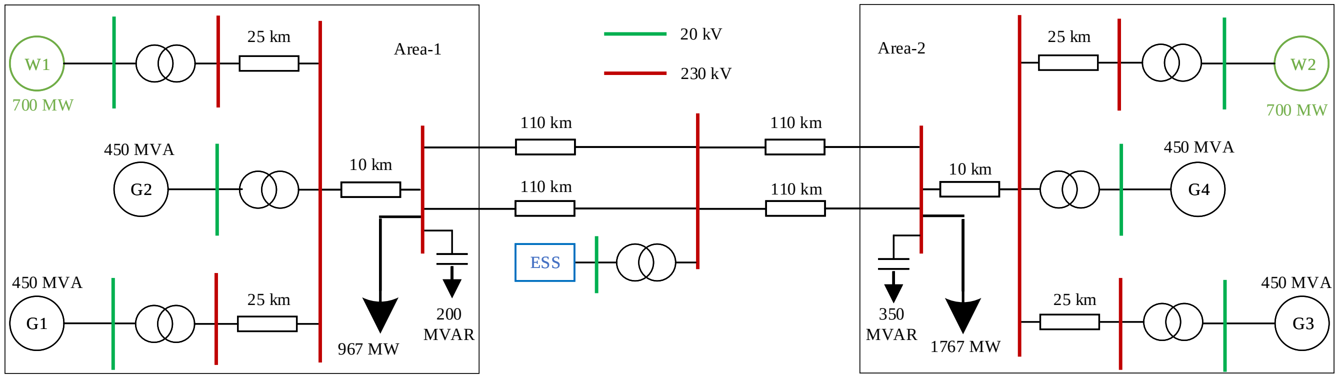

Fig. 1: Two-area power system.

is deployed to provide primary frequency support.

Most of the methodologies proposed in the literature are developed based on simplified models of the power systems. The simplified models are based on the fact that voltage and frequency dynamics are decoupled, which is a good approximation for slower frequency services. However, this approximation cannot be used for fast frequency services, i.e., fast frequency response and virtual inertia support, that deal with first few seconds of disturbance. During the first few seconds after the contingency both voltage and frequency dynamics are coupled. Therefore, to accurately design energy storage, providing fast frequency services, both frequency and voltage dynamics of the generators, converter-interfaced generations, energy storage, transmission network and loads must be considered. In this paper, an algorithm is developed to determine the required capacity of ESS to improve the short term frequency stability. The size of ESS is estimated based on the frequency nadir. The proposed algorithm is tested in the two-area power system in PSCAD. Simulation results show the effectiveness of the proposed approach.

The remainder of the paper is organized as follows. Section II contains the proposed methodology. Results and discussions are given in Section III. Conclusions are given in Section IV.

II. Proposed Methodology

The well known Kundur two-area system is used in this study. The power system used in this work is shown in Fig. 1. The system is modified to include the WG in both areas. The rating of each conventional generation plant is reduced by 50% to introduce the 50% renewable generation in the system. The WG plants are connected in both area via 25 km transmission lines and transformers. Each WG plant is rated 700 MW. The total power generated is the sum of conventional generation and WG power output.

$$P_g = P_{conv} + P_{WG} \tag{1}$$

In (1), P_g is the total power generation, P_{conv} is the total power generated by conventional generation plants, and P_{WG} is the WG plant power output. The power output of WG system can be estimated using equation given below [13].

$$P_w = \frac{1}{2} v_r^3 A_{wt} \sigma C_p(\gamma, \rho) \tag{2}$$

In (2), P_w is power output of wind generation system, v_r is the rated wind speed, A_{wt} is the rotor swept area, σ represents air density, and C_p is the power coefficient of the rotor blades. The replacement of conventional generation by the WG reduces the system inertia. The total inertia of the system can be estimated using the following equation.

$$H_s = \frac{\sum_{i=1}^{n} H_i S_i}{S_s} \tag{3}$$

In (3), H_s is the total inertia of the system, n is the total number of conventional generators, H_i and S_i are the inertia and MVA rating of the i^{th} generator. The variation in system frequency can be approximated using (4) [14].

$$\frac{2H_s}{f} \frac{d\Delta f}{dt} = \frac{P_g - P_l}{S_s} \tag{4}$$

In (4), P_l is the real power of load and f is the frequency. It is evident from (4) that frequency of the system gets effected by inertia and the size of contingency, i.e., $\Delta P = P_g - P_l$. The load demand has two components, real and reactive. The real and reactive loads are modeled as follows [14].

$$P_l = P_o \left(\frac{V}{V_o}\right)^a (1 + K_{pf}\Delta f) \tag{5}$$

$$Q_l = Q_o \left(\frac{V}{V_o}\right)^b (1 + K_{qf}\Delta f) \tag{6}$$

In (5) and (6), P_l is the real power of load, Q_l is the reactive power of load, P_o and Q_o are rated real and reactive powers of load, V_o is the nominal voltage, a and b are constants, K_{pf} and K_{qf} are the constants that relate change in real and reactive powers of load with the change in system frequency. Thus, it is evident from (5) and (6) that variations in voltage and frequency effect the real and reactive demand. In addition, the frequency excursions, during transients, effects voltage profile which in turn effects the load flow and power output of generators.

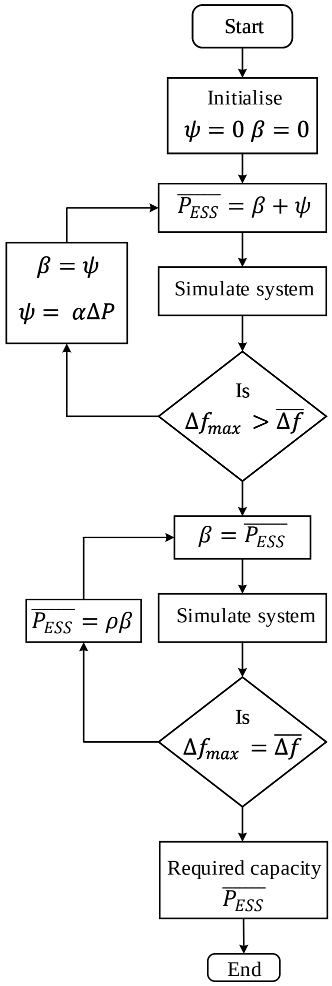

Fig. 2: Flowchart of capacity estimation algorithm.

In this work, ESS is deployed to limit the frequency excursions within the acceptable limits. It is evident from the prior discussion that during transients frequency deviation, real and reactive power consumption, voltage profile, power flow in the system are coupled. Therefore, it is important to include all those dynamics while designing energy storage for improvement of short term frequency stability. The proposed algorithm for ESS capacity estimation is given in Fig. 2. In Fig. 2, ψ, β, are variables which get updated at the end of each iteration. The unit of ψ, β, is MW. α, and ρ are the constants and both are unit less. $\overline{\Delta f}$ is the target frequency nadir point, and Δf_{max} is the frequency nadir point, and $\overline{P_{ESS}}$ is the required capacity of ESS. The algorithm estimates the capacity of ESS required to limit the frequency nadir to any target value. In this work $\overline{\Delta f} = 1\ Hz$ is used as target value.

III. Results and Discussions

The variation in frequency of system, with and without RES, in response to step increase in load is shown in Fig. 3a. It can be observed that the frequency of the system with 50% RES falls outside the contingency frequency deviation limit. This can result in activation of under frequency load shedding relays. The frequency of the system without RES remains well within the limit. The corresponding variation in RoCoF is shown in Fig. 3b. The RoCoF is calculated using moving average window of 500 ms because instantaneous values of RoCoF are not reliable. It can be observed that the RoCoF is higher in case of 50% RES. This is due to the fact that the introduction of RES reduces the system inertia which directly effects the RoCoF. The large deviations in frequency and RoCoF of system with 50% RES suggest that frequency support reserve must be deployed for stable operation. Therefore, ESS is designed to operate the system in stable mode.

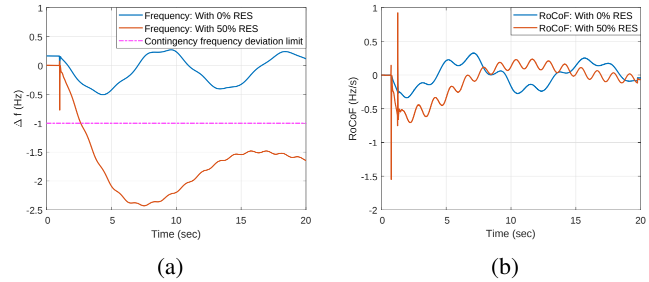

Fig. 3: Variations in (a) system frequency; (b) RoCoF.

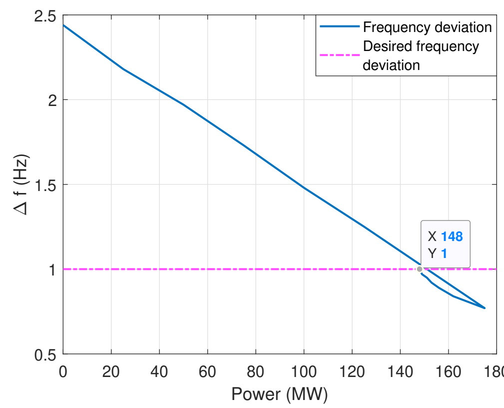

Fig. 4: Variation in power capacity of energy storage with the frequency nadir.

The ESS is deployed at the center of both areas shown in Fig. 1. The algorithm presented in Section II is used to estimate the required capacity of ESS. The variation in frequency nadir and the capacity of ESS selected by the proposed algorithm is shown in Fig. 4. The desired deviation is 1 Hz. It can be observed that the algorithm quickly converges to desired solution. The capacity of ESS estimated by the algorithm is 148 MW. Although, an ESS is completely characterized by both power and energy capacities. In this case power capacity is calculated only because for short-term frequency stability the power capacity is of more importance. Moreover, with the knowledge of power capacity and operation trajectory of ESS the energy capacity can be easily computed.

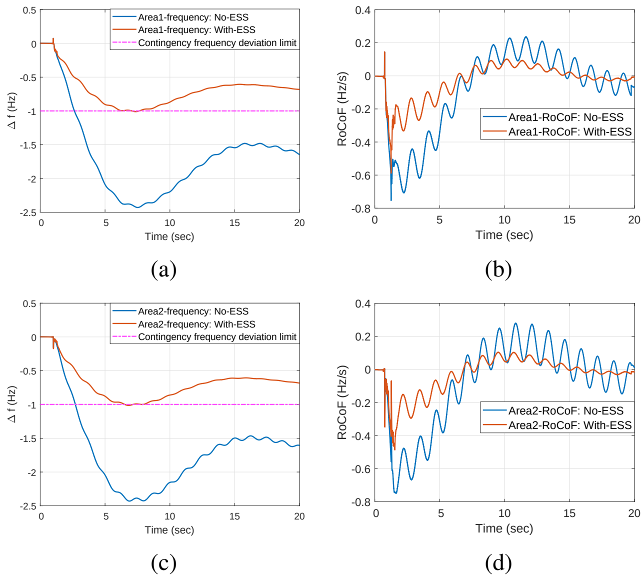

Fig. 5: Variations in frequency and RoCoF when fault applied in area-1 (a) frequency of area-1; (b) RoCoF of area-1; (c) frequency of area-2; (d) RoCoF of area-2.

The variation in frequency and RoCoF of area-1 of the system with 50% RES are presented in Fig. 5a and 5b, respectively. This variation in frequency and RoCoF is due to step increase in load in area-1 of the system. It is evident that the area-1 frequency with ESS is constrained within the limit. While the frequency of the system without ESS falls outside the maximum deviation limit. Similarly, RoCoF of the system is higher in case of the system without ESS compared to the system with with ESS. For similar contingency, the variations in frequency and RoCoF of area-2 of system with and without ESS are shown in 5c and 5d, respectively. It can be observed that ESS constraints both frequency and RoCoF of area-2 within the safe limits. The above results proves the efficacy of the proposed sizing algorithm.

The variation in power output of ESS in response to the contingency in area-1 of the system is shown in Fig. 6. It can be observed that upon the occurrence of contingency the ESS ramps up to rated capacity. The ESS injects the real power in the system, thus, slowing down the rate of fall of frequency, which improves frequency nadir and RoCoF. It can be observed that ESS is operated within the rated capacity limit.

The power system under study has two areas. Therefore a contingency is also created in area-2 by increasing load of area-2 in step fashion. The variations in frequency and RoCoF of area-1 and area-2 are given in 7. It can be seen that the RoCoF values in both areas with ESS are significantly small compared to system without ESS cases. It can also be observed that ESS limits the frequency within the desirable limit in both areas. It is important to note that the ESS is designed to limit the frequency deviation to 1 Hz. It can be observed that ESS limits the frequency deviation to very close to 1 Hz. This

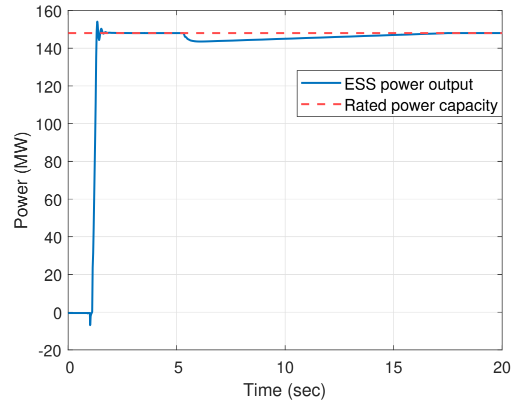

Fig. 6: Power output of ESS when fault applied in area-1.

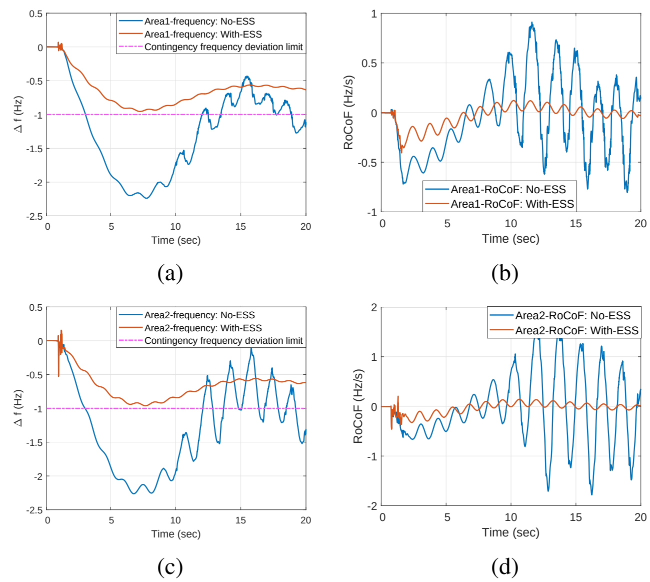

Fig. 7: Variations in frequency and RoCoF when fault applied in area-2 (a) frequency of area-1; (b) RoCoF of area-1; (c) frequency of area-2; (d) RoCoF of area-2.

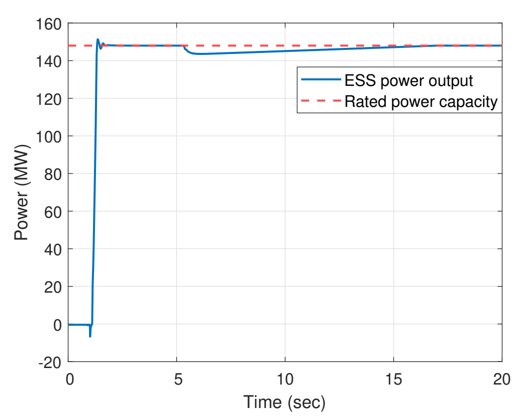

Fig. 8: Power output of ESS when fault applied in area-2.

shows the efficacy of the proposed algorithm. As a maximum frequency deviation less than 1 Hz means over-sized storage which results in extra investment. While, maximum frequency deviation more than 1 Hz means under-sized storage.

The variation in output power of ESS is shown in Fig. 8. It can be observed that ESS ramps to rated capacity upon the occurrence of contingency of system. The ESS injects rated real power in the system to slowdown the rate of fall of frequency. It is important to note that the output of ESS does not vary with the variation in RoCoF or frequency. Rather when switched in the ESS ramps up to rated capacity and injects rated real power in the system. Because in real world the fast response assets, when switched in, inject predetermined power in the system. It can be observed that ESS is operated within the rated capacity limit.

IV. Conclusion

In this paper, energy storage system is designed to improve short term frequency stability of power system with high penetration of converter interfaced generation sources. A methodology is developed to calculate the required size of energy storage. The proposed methodology considers the complete dynamics that affects the frequency response of the system. The methodology is tested on two-area four machine system. Simulations are carried out in PSCAD. Simulation results show that the proposed methodology improve the short term frequency stability by limiting the frequency nadir and RoCoF.

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