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Viability of using energy storage for frequency regulation on power grid

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Abstract. This project is about the development and integration of a real-time network simulator in the laboratory using hardware in the loop (HIL) for the purpose of frequency regulation. Frequency regulation is done using the energy storage system (ESS) and a real-time network test bed developed in the smart energy laboratory in Newcastle University. An IEEE Test System was built in the OPAL-RT network simulator to mimic the power grid with renewable energy sources. The study demonstrates the viability of using an ESS to regulate the frequency under an increased penetration of renewable energy sources.

1. Introduction
Frequency is a very important parameter to be regulated at 50 Hz or 60 Hz at all times in an AC electric network. Any deviation of frequency from the nominal value is caused by the imbalance between generation and demand. An excess in the demand yields the decrease in the frequency and vice versa [1]-[2]. Any significant deviation of frequency can trigger the power plants to shut down, hence causing power interruptions to the customers. Therefore, any power mismatch has to be corrected by the governors in the synchronous generators through the primary and secondary control actions. The primary control action is the first to be carried out to stabilize the frequency within seconds before the secondary action takes over to restore the frequency to the nominal value. The tertiary control will come into effect if the secondary action has not successfully restored the frequency [3].

The restoration of frequency is achieved through a sequence of control actions which may take up to several minutes. This is because the rotors in the generators have high moment of inertia that slows down the response of the generators towards any frequency changes [4]-[6]. As a result, the generators carry out the frequency regulation with low ramping rate in terms of power supply.

At present, this mechanism of frequency regulation may not pose any major concern to the utility companies or network operators because the frequency is not easily changed and the magnitudes of changes are not significant on the networks where the total inertia of the generators is still high. However, with the increased penetration of the renewable energy sources on the networks, some generators will be replaced by renewable energy sources such as wind farms or solar farms for power generation, hence reducing the total inertia of the networks. The frequency can then be volatile and susceptible to the power mismatches. In addition, the power outputs of the wind or solar generating
systems are usually intermittent, hence increasing the occurrence of power mismatches and hence the occurrence of frequency deviations.

As such, additional standby generators may be required to manage a large number of frequency changes. However, this approach can increase the cost of ancillary service to be borne by the consumers through the increase in the electricity tariffs [7]-[9]. Furthermore, the generators with low ramping rates may not be an effective means to regulate the frequency on the low-inertia networks.

Energy storage system (ESS) can be used as an effective means for frequency regulation on the low-inertia networks because it has high ramping rate that allows ESS to respond to frequency changes much faster than that of the generators.

Based on the literature review, most of the authors focused mainly on the control performance of the ESS for frequency regulation without considering how it can continuously regulate the frequency under a narrow window of state of charge (SOC). Also, the authors have not considered the best locations of the networks that ESS should be placed in order to avoid any voltage regulation issues. Apart from that, the effects of reducing the capacity of ESS on the quality of frequency regulation should be studied in order to determine the optimum capacity of ESS, so as to achieve a balance between the quality of frequency regulation and the cost of investment.

2. Methodology

2.1. Experimental model

A 4GW network model in Figure 1 was developed using Matlab Simulink as illustrated in Figure 2. Using the OPAL-RT network simulator in the laboratory, the model was run in real-time to mimic an actual network. The network is split into 3 processes in order to prevent overruns during the simulation. When a frequency deviation occurs, the model detects and reacts to the changes.

![Figure 1. A 4GW Single Line Diagram of the Network Model](image-url)
A 15 kW Triphase AC/AC converter (Triphase Grid) shown in Figure 3 is used to act as the grid generation. It can be controlled in real-time to output the desired voltage magnitude and frequency, converting the signals sent from the OPAL real-time network simulator into actual voltage and frequency values on the 415 V isolated grid of the laboratory.

The 15 kW Triphase DC/AC converter (Triphase ESS) of Figure 4(a) is used to convert the DC source from the 30kW GSS Regatron battery emulator shown in Figure 4(b) to AC power and vice versa. Being a fast-response switching power electronics device, it is capable of reacting instantaneously to the deviations in frequency.

A PI controller as shown in Figure 5 is used to control the response and output of the ESS. In reality, not all the ESSs have the same controller and response time. In the design, a different slew rate (rate limiter) was added to have a different response time as simultaneous output power from multiple ESSs may create a big power surge to the network, causing instability. A lead acid battery was modelled and used in the experiments.

The hardware in the loop (HIL) was done by a dynamic load named as ‘power change’ in the model. Any power changes in the actual 415 V isolated network will be reflected in the network model of the OPAL-RT simulator. There are controllable loads in the model to emulate the load demand in the network. In addition, 3 photovoltaic (PV) generators were connected to the network to emulate the future grid where PV panels are installed. The overview of the laboratory integration is shown in the Figure 6.
Figure 4. (a) Triphase ESS.

Figure 4. (b) Battery Emulator.

Figure 5. Design of PI Controller.

Figure 6. Overview of Laboratory Integration.
3. Results

3.1. Experimental model

Several scenarios have been depicted to verify the practicability of the ESS.

3.1.1. Case Study 1: Experiment with network simulator

IEEE 24-bus network is used in the simulation. There are 17 customer loads in the network. 4 of them are static loads while 13 of them have dynamic load profiles (30 seconds per sample). The total load demand in the network is 2850 MW while the total generation is 4037 MW. Therefore, the total loading of the network is 70.6%. PVs are introduced in different buses in the network to demonstrate the future scenario. 10%, 20%, 40%, 60%, 80%, and 100% of PVs are introduced in the experiments with the different PV profiles of 30 seconds per sample. Simulation was done using the real-time network simulator for a duration of 350 seconds (around 5 minutes) for each of the simulation. The results obtained were plotted in Figure 7.

![Figure 7](image1)

**Figure 7.** Frequency fluctuations with the different percentage of PVs are introduced in the 24-bus network.

When there is 100% PV in the network, the network will be disconnected due to the instability of the network. The ESS was then introduced to the network. 20% of ESS was installed when 20% of PVs are integrated in the network in order to compensate the excess power flow in the network, similarly for 40%, 60%, 80% and 100%. The results obtained are shown in Figure 8.

![Figure 8](image2)

**Figure 8.** ESS is integrated with the ratio of 1:1 to the PVs integration in the network.
From the results, it can be seen that the fluctuation of the frequency is reduced tremendously. However, there are still some minor fluctuations due to the limited capacity of the ESS. From this, we can see that the ESS can improve the stability of the network where PVs are integrated to the network in the future.

3.1.2. Case study 2: Experiment with the laboratory setup
With the same 24-bus network used in the first case study, experiments were done using actual equipment in the laboratory. The experiment is on regulating the frequency in the event of a 50 MW and 200 MW load change using the energy storage in the laboratory. The fluctuations in the frequency are reduced with the ESS when the 50 MW and 200 MW loads were turned on and off as illustrated in Figures 9(a) and 9(b).

4. Conclusion
The ESS effectively mitigates the frequency fluctuation as demonstrated in the project. The laboratory in which the experiment was carried out can be integrated with different smart appliances where they
can be used with different applications and research testing in the future. An important achievement of the project is that it can be extended for future work. Besides, HIL can solve the limitations of the hardware and software by using them together. More and more ESS applications will be developed and enhanced in the near future as ESSs become integrated into the grid to counter the intermittent output of renewables which form part of the carbon reduction plan. Besides setting up an environment for future testing, the laboratory also provides a safe environment for engineers to test out their ideas without being exposed to hazards on the actual grid. Lastly, this project also proves that the ESS is feasible to be used in frequency regulation and may help to reduce dependence on excess rotating capacity employed in conventional strategies leading to a reduction in carbon emissions.

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6. References