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Power Quality Improvement in Power Grids with the Integration of Energy Storage Systems

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***Abstract*— The increasing integration of distributed generation units into power grids has resulted the degradation of the quality of supplied power in the form of deviations in current, voltage and frequency from their standard values, leading to failures or miss operation of equipment. Energy storage systems (ESS) are being considered as a potential solution for this problem since they can regulate the power being injected to the grid, from the distributed generation units, making it more stable. In this paper, firstly the impact of a distributed generation unit (a wind power plant) to a power grid is analysed and then ESS of different capacities are integrated to the power grid in an effort to study the improvements in the power quality. The presented results show clearly the multiple obtained advantages from the integration of ESS to power grids something that can be extremely useful for system operators.**

Keywords— Distributed Generation; Energy Storage Systems; Power Grids; Power Quality.

I. INTRODUCTION

The last two decades changes are observed in the power grids all over world. In contrast to the conventional large scale power plants, today thousands of small scale generation units are connected to both distribution and transmission power grids. These small scale distribution units that are known as distributed generation (DG) or dispersed generation are usually driven by renewable sources and have the potential to reduce emissions. Furthermore DG helps to deliver backup power during times of increased electricity demand, avoiding the investment in further infrastructure. These benefits however are counterbalanced by several impacts on power grids since the integration of DG into them is not straightforward [1-4]. Among other impacts, the intermittency and variability in the DG's produced power (e.g. wind power plant generation depends on wind speed that varies from time to time) is of great importance for system operators, since they incur in additional power capacity available from conventional power plants in order to balance in a second by second basis the generation and demand across the power grid. In addition, ancillary services like demand response and voltage support are being required to keep the balance in the frequency of the grid and voltage stability on every bus bars [5].

Several studies have proposed the integration of energy storage systems (ESS) to power grids with distributed generation in an effort to reduce the negative impacts and the necessity to invest in additional pick power plants and transmission infrastructure [6, 7]. The ESS involves a process where the electrical energy is transformed into a particular form that can be stored and can be converted back to electrical energy when required. From a grid scale perspective, this process allows a smooth injection of power to the power grid (aiming to operate almost like a base power plant), controlling in a more efficient way the voltage stability, the loading of elements and the frequency of the grid. In addition, the introduction of ESS to the power grids is expected to reduce the intending by the system operator disconnection of intermittent power plants from the power grid to avoid any grid instabilities due to the injected intermittent power.

The increasing integration of DG units into power grids has also increased the demand for energy storage systems. However, since most of the energy storage systems are emerging technologies, the operational, technical performance and market integration of these into the power grids are underdeveloped. Further studies, tests and standards are required in order to integrate the ESS with power grids with DG [8].

To this direction this paper presents an analysis of a grid scale ESS integrated with a wind power plant (WPP) in an effort to study improvements in the power quality from the perspective of a system operator. Different ESS capacities are tested and interesting results and observations are extracted.

II. PROBLEM FORMULATION

A. Generic 12-bus Test System

Analysis is performed on the 12-bus test system proposed in [9] and refers to United Kingdom. This is a high voltage grid divided in four areas as shown in Fig. 1. Area 1 is characterized by a surplus of generation compared to the consumption and a relatively high installed power generating capacity. Area 3 is very congested and shows a significant lack of power generated compared to the high demand. On the other hand, in Area 2 has installed a large generation capacity, compared to its demand. Finally, Area 4 includes a relatively low power demand, null generation and high wind resources [9].

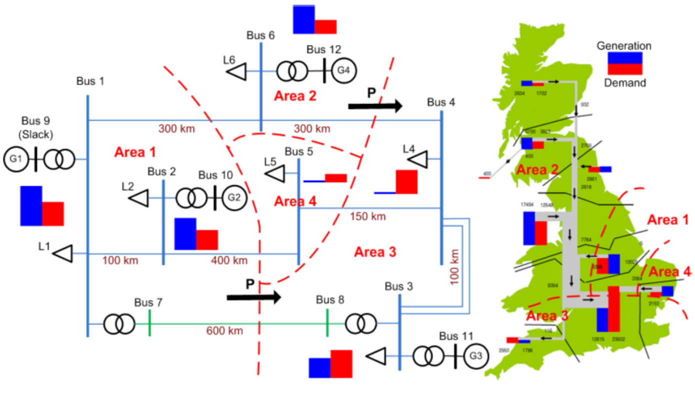

Fig. 1. Generic 12-bus test system [9].

In order to achieve a balance between generation and demand, the surplus of power generated in Areas 1 and 2 is transmitted mainly to Areas 3 and 4. Generators G2, G3 and G4 include an automatic voltage regulator (AVR) and a fixed generating active power. Therefore, buses 10, 11 and 12 are defined as PV nodes since the voltage and active power flow are fixed of known values. On the other hand, G1 plays the role of the main machine since it has the largest capacity available on the grid. Thus, it compensates the difference among the electric demand and power generated by G2, G3 and G4 plus the active power losses across the grid. Therefore, bus 9 is defined as a slack node since its phase angle will be the reference of the whole power grid.

B. Steady State Simulation of Wind Power Plant Variable Generation

For the estimation of the oscillations in power of the wind power plant (WPP) across a year, the database presented in [10] was used. As a reference, the wind speed distribution for Lydd Airport Meteorology station at 10 m height, from 2000 and 2010 was taken into account.

Considering that the average wind speed of the region at 10 m height is 7.13 m/s, there is a relatively low turbulence in the area due to an almost constant wind direction; a 3.3 MW wind generator was chosen due to its high performance at relatively slow wind speeds and slow turbulence conditions (IEC Class IIIA). According to the technical sheets, the rotor diameter of each wind generator is 126 m and the height of the hub is 117 m.

In order to estimate the power generated from the wind generators at different wind speeds, it is necessary to calculate the winds speeds at the hub height, using the climate information downloaded from [10]. By using the semi empirical wind gradient formula shown in (1), this wind speed can be estimated as follows:

$$U = \frac{U_{ref}}{\ln \frac{z_{ref}}{z_0}} \ln \frac{z}{z_0} \tag{1}$$

where:
U_{ref} is the wind speed values obtained from [10],
z_{ref} is the reference height where these results were measured (10 m above ground),
z_o is the surface roughness length of the region was defined as 0.25, considering the common landscape of the region, which includes high crops with scattered obstacles [11].

By combining the wind speed data with the power production projection, an estimate of wind power generation at the onshore data point could be generated. The rated power of each wind power generator is 3.3 MW and aggregating the output power of 30 wind generators totalizes an installed capacity of 99 MW. For this study, it was considered neither any aerodynamic losses due to wind power plant arrangement, nor any connection losses. Representative outputs from the hypothetical WPP are provided in Table I along with the probability of its output.

TABLE I. OUTPUT POWER AND PROBABILITY OF EACH WIND TURBINE

Speed at 10 m (m/s)	Speed at 117 m (m/s)	Output power range (kW)	Probability (%)
0-1	0-1.67	0-0	0.58
1-2	1.67-3.33	0-2100	2.88
2-3	3.33-5	2100-9000	6.43
3-4	5-6.67	9000-24600	10.31
4-5	6.67-8.33	24600-52500	11.95
5-6	8.33-10	52500-81000	13.16
6-7	10-11.67	81000-96000	11.69
7-8	11.67-13.33	96000-99000	10.78
8-9	13.33-15	99000-99000	9.93
9-10	15-16.67	99000-99000	7.23
10-11	16.67-18.33	99000-99000	5.42
11-12	18.33-20	99000-99000	3.89
12-13	20-21.67	99000-99000	2.57
13-14	21.67-23.34	99000-99000	1.36
14-15	23.34-25	99000-99000	0.86
15-16	25-26.67	0-0	0.45
16-17	26.67-28.34	0-0	0.23
17-18	28.34-30	0-0	0.05
18-19	30-31.67	0-0	0.06
19-20	31.67-33.34	0-0	0.06
20+	33.34+	0-0	0.1

C. WPP and Energy Storage System Modelling

In order to connect the WPP to the model grid, it has to be considered the common structure used for the design of this renewable technology. According to [12] a single wind generator has limited capacity and in consequence, a WPP normally consists of many wind generators connected together by overhead lines or cables in order to increase the production of power. The output power of each wind generator is collected and transmitted to the grid through an alternating current transmission line. For simplicity, a single wind generator with a rated capacity of 99 MW was considered in these studies, which represents the aggregation of the thirty 3.3 MW wind generators.

A step-up transformer with a capacity of 100 MVA was installed in the substation to increase the voltage up to 34.5 kV and connect the WPP to a rated bus for any potential system than can be integrated to it. Furthermore, two power transformers were installed in parallel (in order to increase the reliability of the system complying with the N-1 configuration) with a capacity of 100 MVA each, in order to increase the voltage up to 230 kV for the proper integration of the renewable generation plant to the power transmission grid. Finally, as shown in Fig. 2, two parallel transmission lines interconnect the WPP with the bus 5 of the power grid.

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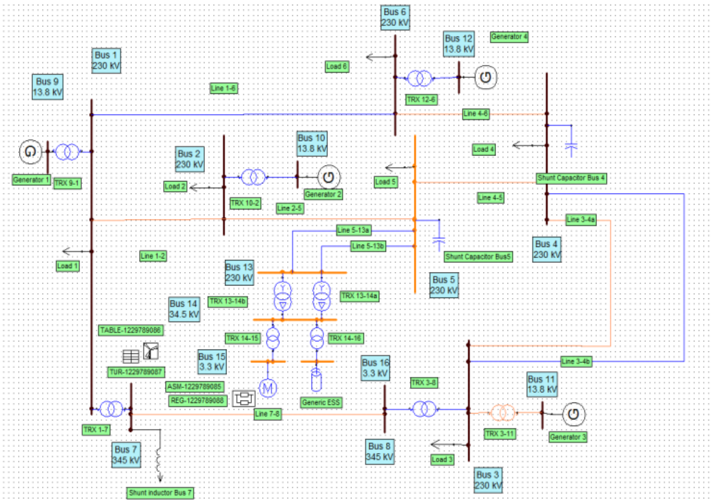

Fig. 2. Integration of wind power plant and ESS to the power grid.

For the integration of ESS with renewable sources, in [12] is recommended the parallel installation to the same bus through different transformers. Therefore, based on the generic power grid used for this study, it was incorporated a new transformer in bus 14 which will connect the ESS to the power grid, as shown in Fig. 2. The transformer was rated to 40 MVA based on the maximum capacity of the ESS which was designed to 40 MW for handling the maximum storage system. The other storage capacities that were studied include rating capacity of 25 MW and 30 MW, as suggested in [7].

D. Simulation Scenarios of the ESS Integrated with the WPP

In order to define simulation scenarios for the energy storage system integrated with the WPP, firstly the different power injecting values of the WPP have to be considered. Therefore, for each power output of the WPP, a potential operation scenario of the ESS was analysed, as shown in Table II. For this study, it was assumed the only occasion when the ESS is charging, occurs at the maximum generation of the wind power plant. It was also assumed two charging scenarios of the ESS; the first one at full capacity and the second one at 10 % of its rating power. Likewise, for lower output power scenarios of the WPP (96 MW and 91 MW), the ESS was assumed to provide only the necessary power to achieve the maximum power of the step-up transformers TRX13-14a and TRX13-14b, designed to manage 100 MW of power flow under N-1 configuration.

In addition, for even lower output power scenarios of the WPP, the ESS was simulated providing its maximum rated power, according to the different storage capacity set previously. This simulation model was proposed in order to keep the integrated system's injected power to the grid as higher as possible.

Finally, the stand by scenario simulation of the ESS represents the occasions when the storage technology neither consumes nor injects power to/from the grid; i.e., when the state of charge reaches its minimum.

TABLE II. DIFFERENT SCENARIOS STUDIED FOR ESS OPERATION

Scenarios	WPP capacity (MW)	WPP steady state power generation (MW)	Storage capacity (MW)	Steady state operation
1	99	99	40/30/25	Stand by
2	99	99	25	Consuming 25 MW
3	99	99	25	Consuming 2.5 MW
4	99	99	30	Consuming 30 MW
5	99	99	30	Consuming 3 MW
6	99	99	40	Consuming 40 MW
7	99	99	40	Consuming 4 MW
8	99	96	40/30/25	Injecting 25 MW
9	99	96	40/30/25	Stand by
10	99	81	40/30/25	Injecting 19 MW
11	99	81	40/30/25	Stand by
12	99	52.5	40	Injecting 40 MW
13	99	52.5	30	Injecting 30 MW
14	99	52.5	25	Injecting 25 MW
15	99	52.5	40/30/25	Stand by
16	99	24.6	40	Injecting 40 MW
17	99	24.6	30	Injecting 30 MW
18	99	24.6	25	Injecting 25 MW
19	99	24.6	40/30/25	Stand by
20	99	9	40	Injecting 40 MW
21	99	9	30	Injecting 30 MW
22	99	9	25	Injecting 25 MW
23	99	9	40/30/25	Stand by
24	99	0	40	Injecting 40 MW
25	99	0	30	Injecting 30 MW
26	99	0	25	Injecting 25 MW
27	99	0	40/30/25	Stand by

III. SIMULATION RESULTS

A. Generic Power Grid Results

Load flow analysis of the generic power grid has shown (Tables III and IV) that all voltage magnitudes of different buses are within the limits (minimum 0.95 pu - maximum 1.05 pu for each transmission bus) established by the grid code, issued by the UK system operator (National Grid). Bus 8 is a sensitive node since it is very close to the maximum limit (1.038 pu) due to the intrinsic capacitance of the transmission line 7-8 and the length of the line (600 km) which is the largest in the power gird. Lines 4-6 and 2-5 are carrying a current value very close to the rated value, 98 % and 93 % respectively. Lines 7-8 and 1-6 are also overloaded by 79.19 % and 77.4 % respectively. Even though these lines are considerable less loaded than the previous ones, they are still overloaded since it was considered for this study that elements

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with 70 % and above of loading, with respect to the rated values, are overloaded. In addition, the power production from conventional power plants is led by G1 and G2, which both produce almost 60 % of the whole generation. This power is transmitted from Area 1 and 2, which have a surplus of production, to Area 3 and 4 with a lack of power generation. This power flow through the transmission lines produces power losses of 36.39 MW, which represents 2.45 % of the total production.

TABLE III. LOAD FLOW ANALYSIS RESULTS OF THE GENERIC POWER GRID

Node name	U (kV)	P load (MW)	Q load (MVar)	P gen (MW)	Q gen (MVar)	Q shunt (MVar)
Bus 1	226.99	300	180	0	0	0
Bus 2	227.08	250	121	0	0	0
Bus 3	230.92	350	115	0	0	0
Bus 4	230.54	300	186	0	0	-200.94
Bus 5	229.46	100	48	0	0	-39.81
Bus 6	229.40	100	49	0	0	0
Bus 7	349.97	0	0	0	0	34.29
Bus 8	356.74	0	0	0	0	0
Bus 9	13.8	0	0	486.39	65.051	0
Bus 10	13.93	0	0	400	114.31	0
Bus 11	13.93	0	0	270	6.59	0
Bus 12	13.93	0	0	330	40.14	0

TABLE IV. OVERLOADED ELEMENTS IN THE GENERIC POWER GRID

Element	Overloading (%)	Type
Line 4-6	97.86	Line
Line 2-5	93.08	Line
Line 7-8	79.19	Line

B. *Wind Power Plant Integration Results*

An increase in the generation of the wind power plant, results in significant reduction of the overloading percentage of lines 4-6 and 2-5 (Fig. 3). However the line 4-5 was proportionally overloaded with the WPP generation by reaching a critical value of 140 %. This happened due to the coverage from the generation in Area 4 of a significant part of the deficit power generated in Area 3. In consequence, less of the power produced by G2 and G4 is being transmitted to Area 3 and 4 and subsequently, more is supplied to Area 1 and 2, reducing the loading percentage of the transmission systems. This change in the load flow can be evaluated also by the reduction in the power generated from the slack generator which varies from 486 MW, without any output of the WPP, to 375 MW with a maximum power generated of 99 MW. Therefore, higher portion of the load located in Area 1 is being covered by generators G2 and G4. Similarly, the transmission line connecting Area 3 and 4 is overloaded to values that are not being designed previously. The line 4-5 is the second transmission line of the power grid with the lowest current carrying capacity. Thus, when the power output of the WPP is equal to 81 MW or higher, the transmission line will carry a steady state current of 210 A, when it is rated to a maximum of 140 A. Therefore, it is recommended to install another line in parallel to the existing line 4-5 in order to better manage the integration of the WPP to the grid.

The power grid voltage profiles are being controlled within the transmission system constrains (Fig. 4). Overall, the voltage profiles of the nodes increase proportionally to the power generated from WPP. This occurs due to the increase of generation in Area 4 that reduced the transmitted power from Area 1 and 2 to Area 4. This reduction in power implies a reduction in current carried by the transmission lines and, hence, decreases the voltage drop across the system. Despite the tendency of increasing the voltage magnitudes with the power generated from the WPP, there are some exceptions which include buses 5, 13, 14 and 15. Due to the radial connection between these nodes and the lack of reactive power injected by the WPP, the voltage magnitude of buses 13, 14 and 15 are highly dependent in the magnitude of bus 5. When the power injected by the WPP is higher than 24.6 MW, the shunt capacitor connected to bus 5 is injecting more reactive power to the bus (41.65 MVAr) than the one consumed by the load 5 (40 MVAr). Since the shunt capacitor is a fixed reactance, the magnitude of reactive power injected to the grid will vary according to the voltage magnitude of the node. Therefore when this excess of reactive power occurs, it must be transmitted to the nearby bus such as bus 4 and 2. Then, considering that the reactive power in a line will flow from the node with highest voltage magnitude to the lower one, it is explained why the voltage magnitude in bus 5 is higher than in bus 4, only when the power generated by WPP is higher than 24.6 MW.

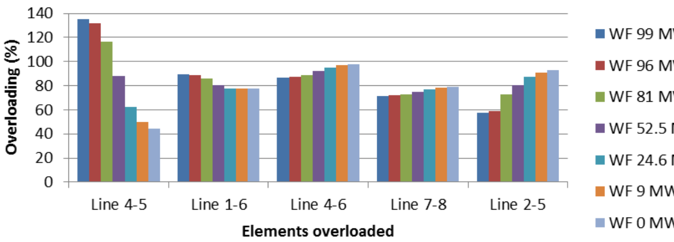

Fig. 3. Overloaded elements for different WPP output scenarios.

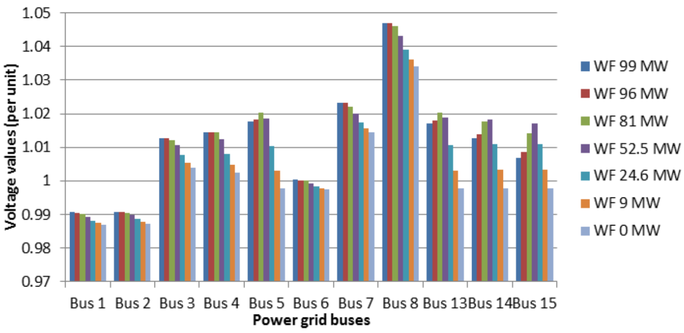

Fig. 4. Voltage magnitudes in buses for different WPP output scenarios.

Finally, the power grid losses are reduced proportionally with the increase of generation from the WPP. The maximum reduction achieved is 24.73 % comparing the 36.39 MW produced in the original power plant with the 27.4 MW of losses at the maximum output of WPP. This reduction can be explained due to the fact that less power is being transmitted to Area 4 from G1 and G2, when there is a local generation of power in this area. Therefore, assuming that renewable power producers will increase in Area 4 due to the high wind resources, their main objective should be the mitigation of the variability of WPP output. One of the methods used to achieve this smooth output production includes the integration of storage systems.

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C. Energy Storage System Integration Results

With the integration of the energy storage system to the power grid, one more bus and one power transformer have been included to the grid as explained on a previous section. Therefore the inclusion of more elements may impact the efficiency of the power grid by increasing the active losses. However, this configuration with the WPP and ESS connected to different power transformers improve the reliability of the grid since in case that a transformers fails the second one could still inject power either from the WPP or the ESS.

In all studied scenarios with the ESS integrated, the voltage profiles of the power grid s stayed within the restrictions stated by the Grid Code (Figs 5-7). The voltage magnitudes increased proportionally with the combination of power injected from the WPP and ESS, something that is related to the reduction of transmitted power from Areas 1 and 2 to Areas 3 and 4. The decrease in power flow implies less current being carried by the transmission lines that creates the voltage drop on the grid. For this study, the voltage magnitude reached by the most sensitive node, bus 8, is 1.0478 pu when the total power injected by the WPP is 81 MW and the power coming from the ESS is 19 MW. This is a slight increase compared to the peak reached in the study with only the integration of WPP. This increase is due to the fact that the total power injected by the WPP and ESS sum 100 MW, compared to 99 MW maximum capacity of WPP.

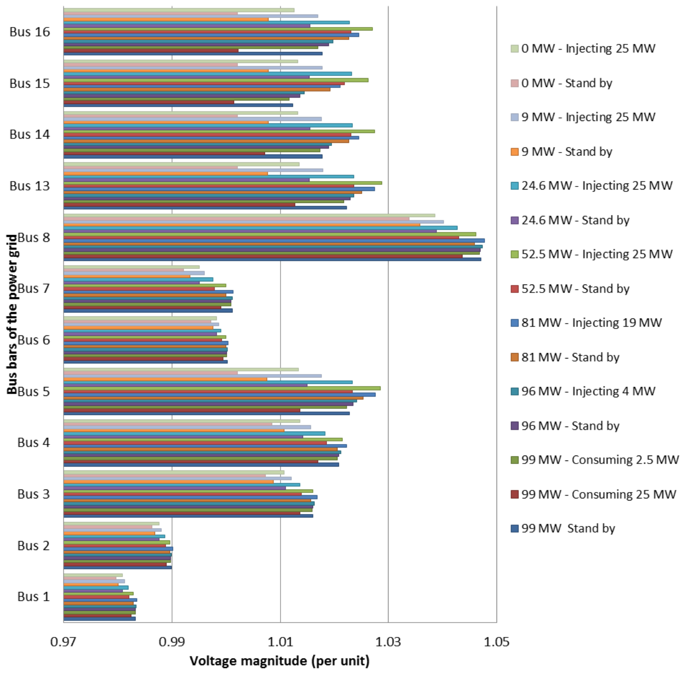

Fig. 5. Voltage magnitudes in buses with the integration of a 25 MW EES.

The radial structure of the grid composed by buses 13, 14, 15 and 16 is the most affected in terms of variation percentage with the integration of the ESS. When the ESS is charged at full capacity, it generates a dramatic decrease in the voltage magnitudes of buses 16 and 15. When the capacity of the ESS is evaluated at 40 MW, the voltage in bus 16 plummeted to 0.983 pu. When comparing this last magnitude with the highest voltage achieved of 1.0245 pu, with the ESS injecting 19 MW and the WPP 81 MW, then the difference reaches 0.0415 pu, which is the highest variation across the entire grid. Compared to the other storage capacities, this difference is reduced to 0.029 pu for 30 MW ESS and 0.025 pu for the 25 MW scenario. Therefore, in order to reduce the fluctuations of the voltage magnitudes for the different WPP generation scenarios, the best solution is to use the 25 MW ESS. In overall, with the integration of the ESS, the most remarkable improvement in the voltage profiles is achieved in the scenarios of low power WPP production. It is worth to mention that all the wind turbines have a regulation mechanism that protects the wind turbine from mechanical stresses due to high wind speeds. The maximum wind speed allowed by a turbine is called cut-off speed. Therefore, for large wind speeds scenarios when the turbine is producing its nominal power, it can suddenly decrease the output power from the maximum to zero in few seconds, if the wind speed reaches or surpasses the cut-off value. This would lead to a voltage plummet in all buses but especially in bus 5 which perceives a difference of 0.0227 pu. With the integration of storage technologies, this variation can be reduced up to 0.0117 pu when using a 40 MW ESS; 0.014 pu with 30 MW ESS and could be reduced up to 0.0151 pu when using a 25 MW ESS.

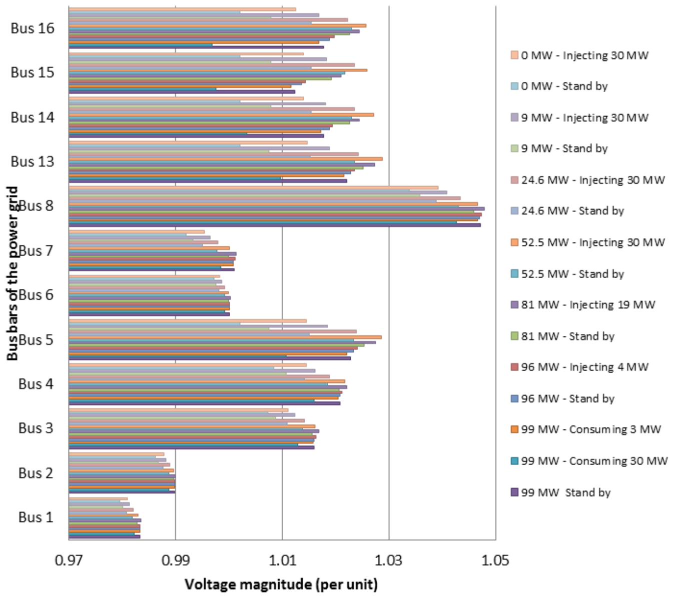

Fig. 6. Voltage magnitudes in buses with the integration of a 30 MW EES.

When this abrupt variation in the power injected from the WPP occurs, it also affects the power demanded from frequency regulation plants to stabilize the grid between power generated and demanded. For this case, the slack generator is the element that will support the variations implemented in the system, since the other generators are considered to have a controlled and fixed active power, for the load flow purposes. When the WPP varies its output power from 99 MW to zero, the G1 has to increase its output generation by 28.54 % (from 3.78 MW to 4.86 MW) in order to keep the frequency of the grid into acceptable values.

With the integration of the ESS the backup power being required from the slack generator is reduced to 16.82 % with the application of a 40 MW ESS, 19.72 % with a 30 MW ESS and 21.17 % with a 25 MW ESS. In addition, considering a scenario with WPP output of 52.5 MW or above, the 40 MW ESS would support the injection of active power to the bus 5 for being above 92.5 MW. According to Table I, this storage

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capacity will support a power injection to the grid between 92.5 MW and 99 MW for the 66.89 % of the year. This would help WPP to sustain an almost constant output power and support the power dispatch studies.

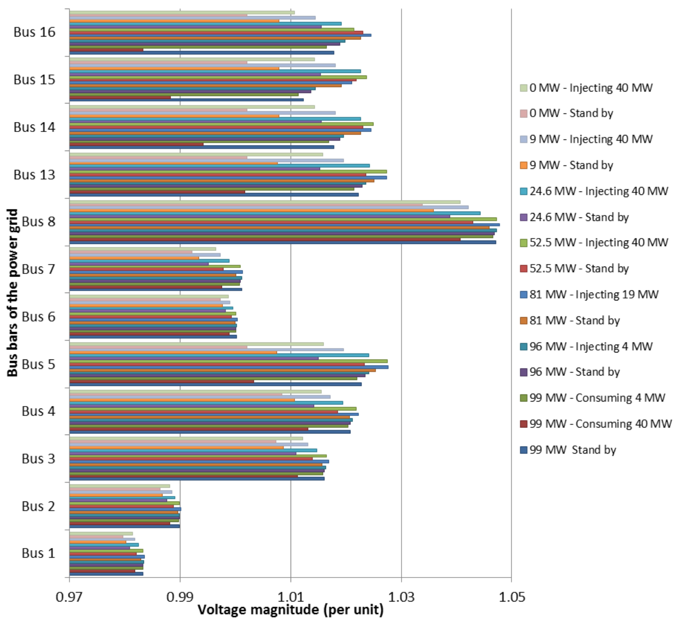

Fig. 7. Voltage magnitudes in buses with the integration of a 40 MW EES.

On the other hand, if the ESS can support for some time the power injected to the grid in bus 5, it would allow additional time for the system operator to activate the secondary control of the frequency response. This secondary control would involve perhaps some demand side response to reduce the power demand or even distribute the required extra generated power between different machines, avoiding relying only on peek generation plants. For this particular application the 40 MW ESS provides a better solution, since it has a larger backup power capacity, compared to the other solutions studied.

Finally, by increasing the capacity of the storage system, the losses of the grid are being considerable reduced. When used the 40 MW ESS, the losses were reduced to 12 % compared to the case of 25 MW and 10 % when being compared to the scenario of 30 MW.

IV. CONCLUSIONS

In this paper has been studied the impact of the integration of a wind power plant, into a generic power grid. Wind power plants, as well as other variable energy technologies, depend on resources that cannot be controlled and are intermittent in nature. Even if the output power of these power plants can be predicted using the state-of-the-art in weather forecast technologies, the abrupt variations on the produced power being injected to the grid can generate perturbations on electric power network that may become uncontrollable. In an effort to address the expected increase of the installed capacity of wind power plants into the power grid and ensure the power grid stability, energy storage systems were proposed in this paper and analytical studies were conducted. The obtained results have shown that the integration of energy storage systems to the power gird improves the power quality of the grid something that can be extremely useful for system operators.

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