Flywheel Sizing for the Secure Operation of an Isolated Network with a High Level of Variable Generation

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***Abstract*—This paper presents the methodology followed for sizing a flywheel energy storage system (FESS), in order to prevent frequency stability problems in an isolated network with an increased production of renewable generation. The analyzed case study is a real isolated power system that includes diesel, wind and photovoltaic solar generation. In the proposed methodology, the flywheel sizing is obtained from performing dynamic simulations of the power system, considering foreseen wind and photovoltaic power variations, namely a severe major power loss or frequent and short-term typical fluctuations. The obtained results demonstrate that the dimensioned FESS, with a proper choice of the control parameter values, provides the necessary control action to avoid security problems in the analyzed power system. They also reveal that in order to obtain an efficient FESS operation, for different types or severity level of expected renewable disturbances, the amount of FESS stored energy and the values of the FESS control parameter must be adapted on line, by following the suggestions of intelligent control algorithms.**

Keywords- frequency stability, solar power generation, flywheels.

I. INTRODUCTION

Renewable power penetration is increasing all over the world, due to economic and environmental concerns. In the special case of remote isolated power systems, like in islands, these economic concerns are even more important because power production costs are usually very high, since power is mainly supplied by diesel generation, having high costs due to fuel transportation. Over the last years, wind has been a very popular renewable energy source for power production in islands. Last years, photovoltaic (PV) solar power generation has also become very attractive, due to the increased interest in exploiting PV and due to a decrease in the manufacturing costs of production of PV panels. However, power produced by exploiting this type of energy source has a very variable nature, which may create frequency stability problems, namely, in small and medium scale isolated power systems, like the ones that exist in islands. The automatic frequency control of diesel units may not be robust enough to cope with such power variability, given the slow response of the mechanical power output of these machines. Moreover, the permanent output variations in diesel units negatively affect their performance, due to increased fuel consumption and maintenance. In order to solve this problem, a fast acting frequency control system must be included in these power systems, which must be able to provide a large amount of power during a short period of time (in the time range of seconds). This type of fast acting power control can be efficiently provided by energy storage systems having a high power capacity and no special site requirements, like flywheels, batteries or supercapacitors [1]. Namely, the feasibility of installing a flywheel system, in isolated power systems, to reduce transient frequency deviations due to wind power fluctuation, has already been demonstrated in other works, like the ones presented in [2] and [3]. Besides rapid response of control due to power electronics interface, these devices usually present a long life (a 20 years design life, according to [4]) even under operating scenarios where they have to constantly consume and generate electricity, being therefore a more cost-effective solution than batteries [2]. Like flywheels, supercapacitors have a long life time and with negligible deterioration [5], however increasing the current low energy density provided by supercapacitors is still a challenge for developers [6].

In the present work, a flywheel solution was adopted due to its technology maturity and market availability for performing frequency control functions in a power systems [3][7][8][9]. The sizing of a Flywheel Energy Storage System (FESS) is performed to prevent frequency stability problems in a real isolated power system, where a high penetration of wind and solar PV power production is expected to be in operation. In the proposed methodology, for the control actions of the FESS, a primary frequency control action was considered, defined by a speed droop parameter. The FESS sizing includes defining the minimum necessary values of storing energy capacity (En in MJ) and the nominal value for the production/consumption active power (Pn in MW), and also coping with the values of the FESS control parameters, like frequency dead band (FDB in Hz) and speed droop (R in Hz/MW), in order to ensure system security. The FESS sizing is obtained from the dynamic simulation of the power system, for expected operating conditions with a high penetration of renewable, considering foreseen wind and PV power variations and different possibilities for the FESS under operation. These possibilities considered the set of En/Pn values of the FESS available in the market, appropriated to perform automatic frequency control in power systems. The foreseen power variations include not only severe major power losses, caused by a sudden power plant disconnection, but also frequent and short-term typical power fluctuations from the renewable power sources.

The obtained results demonstrate that the dimensioned FESS, with a proper choice of the control parameter values, provides the necessary control action to avoid security problems in the analyzed power system. They also reveal that the best choice for the control parameter values of the installed FESS, in order to minimize the necessary FESS energy consumption without losing system security, strongly depends on the type and severity of the renewable disturbance.

II. STUDY CASE

A. Power System

The power system under analysis is located at a small island, in Europe. Conventional power generation is performed by four diesel units, with an installed power of 4x4.32 MW. Renewable power production is obtained from two wind parks, comprising squirrel cage induction generators and having an installed capacity of 0.66 MW and 0.45 MW, and two conventional PV power plants, with 1 MW each. The expected off-peak load is 3 MW, during the night, and the peak load is 9 MW, in the summer.

For FESS sizing purposes, only the operating conditions that provide the largest transient frequency variations need to be considered. To analyze the most severe scenario regarding high penetration of renewable power production, the expected load at noon time was considered to include maximum photovoltaic production. Summer was excluded since, during this season, the load is typically higher in the island due to touristic activities. The analyzed load scenario contemplates therefore noon hours of winter, characterized by an expected load of 4.62 MW. The considered photovoltaic generation was assumed to be at 100% of the installed power and the wind power production was considered to be at 90% of the rated power, totalizing 2 MW and 1 MW of PV and wind power generation. Thus, in the analyzed scenario, a renewable power penetration of 65% was considered. Due to security operating procedures, a minimum of two diesel units were required to be in operation, providing a total diesel spinning reserve of 7 MW.

B. Security Problem

The performed sizing of the FESS aimed to avoid frequency stability problems motivated by expected major renewable power losses or frequent and short-term typical renewable fluctuations.

The power system was considered to lose security if, in the first seconds after a sudden and severe power loss, the frequency of conventional generators drops in such a way that it provokes automatic load-shedding actuation. In the analyzed system, this happens for frequency drops higher than 1.5 Hz. By considering a security margin of 0.2 Hz, like the one considered by ENTSO-E [10], the applied security criterion regarding major renewable power losses was the following: *the maximum value of transient frequency drops, obtained by simulation, should not overpass 1.3 Hz.*

In the same power system, during normal operation with no major disturbances, the system frequency deviations must not systematically violate the range of $\pm$ 0.5 Hz. By also considering a security margin of 0.2 Hz, the applied security criterion regarding frequent renewable power variations was the following: *system frequency deviations, obtained by simulation, must not systematically violate the range of $\pm$ 0.3 Hz.*

III. RENEWABLE DISTURBANCES UNDER ANALYSIS

A. Major Renewable Power Loss

Since the two photovoltaic power plants of the analyzed power system are connected to the same substation, the sudden and simultaneous disconnection of these two power plants was considered to be, in this study case, the expected major renewable power loss (i.e., a 2 MW power loss).

B. Frequent Renewable Power Variations

In order to define the typical rate of change and magnitude values for the frequent and short-term renewable power variations, some wind and photovoltaic power production time series where provided by the system operator of the island, namely the following:

- Two daily wind time series, with a time step of 1 second;
- One daily PV time series, with a time step of 60 seconds;
- One monthly PV time series, with a time step of 15 minutes.

Both PV power time series were obtained from the same power plant, having a peak value of 1 MW (the nominal production).

Aiming to understand the relation between the analyzed time step and the magnitude of wind power variations, these variations were obtained, from both the daily wind time series, for the following three different time steps (Δt): 1 second (the original time step), 5 seconds and 60 seconds. The attained power variations are presented in the charts of Figure 1. In these charts, wind power variations are expressed in percentage of the time series peak value being, for an easier visual interpretation, sorted from the largest to the smallest value.

The results presented in Figure 1 clearly show that, for the analyzed time series, the magnitude of frequent wind power variations increases with the considered time step. These frequent changes reach a maximum value of $\pm$ 5% of the daily peak value, for a 1 second time step, and $\pm$ 10% and $\pm$ 15% for a 5 seconds and 60 seconds time step. Other higher magnitude variations are also presented, however in a very small amount. From some preliminary dynamic simulations of the power system, it was possible to realize that, among the three obtained frequent wind power rate of changes (namely, between $5\%/1\text{s}$, $10\%/5\text{s}$ and $15\%/60\text{s}$), a 10% variation within 5 seconds provides the largest transient frequency variations, being therefore the most appropriate rate of change to be considered for the FESS sizing procedure. In order to include, in the present study, some security margin, a *20% change within 5 seconds was considered for frequent wind power variations.*

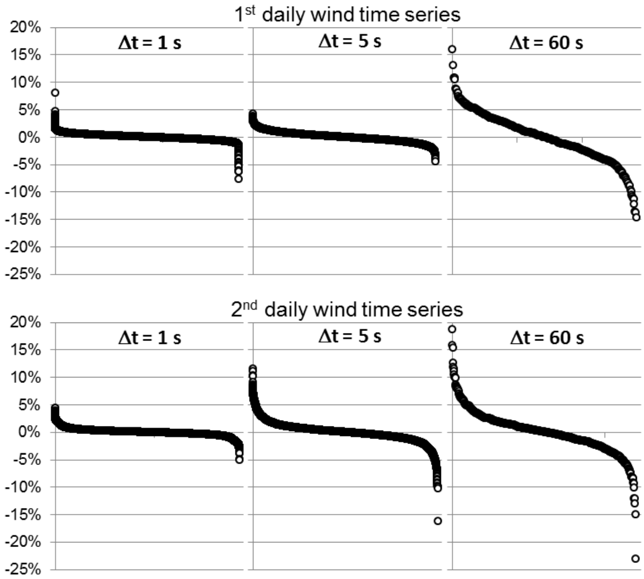


Figure 1. Obtained wind power variations for a time step of 1s, 5s and 60s (in % of the time series daily peak value and sorted in descending order)

PV power variations were also obtained from the daily and monthly PV time series, by considering the original time step. These variations were expressed in percentage of the nominal power production value and sorted from the largest to the smallest value. The attained PV power variations are presented in the charts of Figure 2.

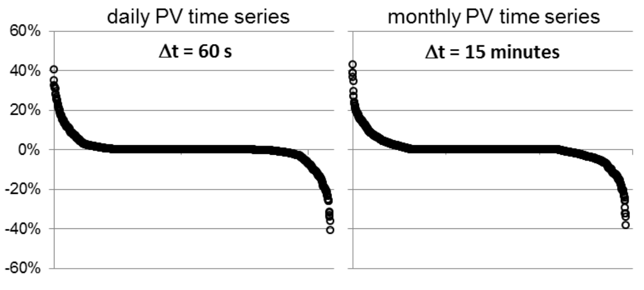


Figure 2. Obtained PV power variations for a daily and a monthly time series (in % of the nominal power production and sorted in descending order)

From analyzing the results presented in Figure 2, it is interesting to realize that, contrary to the wind power behavior, for the analyzed time series, the magnitude of frequent PV power variations does not seems to be affected by the considered time step. Namely, in both time series, with a time step of 1 minute and 15 minutes, the PV power variations present a similar frequency of occurrence for each variation magnitude, reaching a maximum value of ± 40% of the nominal PV power production. Assuming that these power variations result from the hiding/appearing of the sun, due to cloud movement, it is reasonable to assume that these usually occur within a very short-time period, namely within some seconds. Regarding these results and including some security margin for the FESS sizing procedure, in the present study *PV frequent power variations were considered to have a 50% change within 5 seconds.*

Moreover, aiming to consider the most severe time sequence of events for frequent renewable power variations, wind and PV power changes were considered to be simultaneous and some seconds of delay were introduced between each total power decrease and increase.

Regarding the previously described considerations, the time evolutions described in Figure 3 were considered, in the present study, to model total wind and PV power productions having frequent renewable power variations. In this disturbance, a magnitude of 0.2 MW and 1 MW was considered for wind and PV power production variations, having the following sequence: reduction within 5 seconds; constant value for 10 seconds; increase within 5 seconds; constant value for 10 seconds.

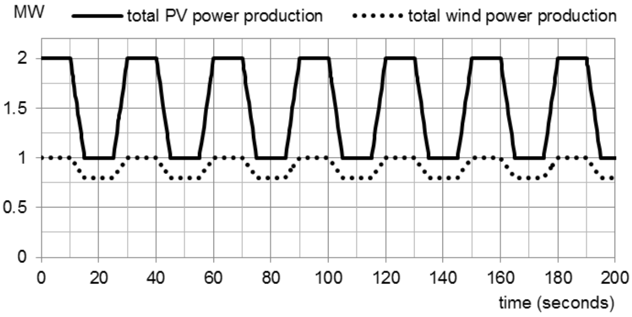


Figure 3. Time evolution of renewable power prodution having frequent variations, considered for the FESS sizing of the analyzed study case

IV. POWER SYSTEM DYNAMIC MODEL

A. General Dynamic Model

Dynamic simulations were performed in the Simulink toolbox of MATLAB software [11], by considering a single busbar power system dynamic model, appropriate to compute the time evolution of active powers, mechanical powers and system frequency. In this modelling, only the diesel machines swing equation and the automatic actions of the frequency control system installed in each diesel unit and in the FESS were considered.

During the stage of creating a proper dynamic model for the analyzed power system, some preliminary dynamic simulations of the considered renewable disturbances were performed, by applying this simplified model and also by applying a more complete model, namely a classical single-phase model, that includes the transmission network and the behavior of voltages magnitude and reactive powers, with electrical signals in phasor model. By comparing the results provided by the two models, the simplified dynamic model showed to be, for this study, appropriate to obtain an accurate simulation of the time evolution of system frequency. This simplification applies for this study, due to the small size of the analyzed power system and because no short-circuit situation was included within the analyzed disturbances.

B. FESS Dynamic Model

To properly model the FESS grid interface, performed by power electronics devices, it was necessary to define the control strategy to be adopted for these connections. This was modeled as a PQ inverter control strategy as described in [12]. In this strategy, the inverter is used to supply controlled values of active and reactive power, fixed by set-point values defined by a P_{ref} and Q_{ref} input signals. Being the FESS applied to perform primary frequency control functions, in the adopted model, the inverter operates with a unit power factor (i.e., with $Q_{ref} = 0$) and system frequency is used to adapt the active power charging/discharging of the FESS. A frequency control droop loop was therefore adopted to adjust the active power set-point of the PQ inverter interface, as described in Figure 4. In this control loop, the input signal consists on the system frequency deviation from the nominal value, Δf , and the output defines the active power production of the FESS, Pg, having this output a negative value for power consumptions.

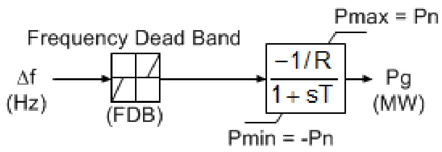


Figure 4. Block diagram of the FESS dynamic model

The FESS dynamic model presented in Figure 4 comprises the following parameters:

- FDB (Hz): Frequency dead band, necessary to avoid the FESS activation for non-significant frequency deviations;
- R (Hz/MW): Speed droop, defining the sensitivity of the FESS to perform primary frequency control actions (an increased sensitivity is achieved by reducing the R value);
- T (s): Time constant to model the time delay of power electronics control action. This parameter has usually a very small value, being therefore not relevant for the dynamic modelling;
- Pmax and Pmin (MW): Upper and lower limits of the FESS active power production. Assuming that this device can either absorb or inject active power from 0% to 100 % of its nominal value (Pn), the FESS range of active power production was defined to remain within Pn and $-$Pn .

Figure 5 presents the frequency droop characteristic defined by the control loop of Figure 4.

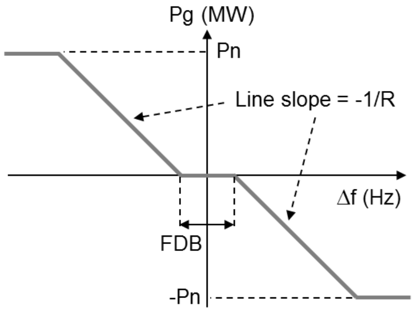


Figure 5. FESS frequency droop characteristic

As described in this figure, if the system frequency deviation is within the dead band, the FESS frequency control action is inactive. Otherwise, the FESS will respond by charging or discharging, within the range defined by $\pm$ Pn, according to the slope of the frequency droop characteristic, being the slope value defined by -1/R.

In this model, a pre-disturbance state of charge is assumed for the FESS, being the time evolution of this state of charge computed, in each simulation time step, by subtracting the FESS consumed energy caused by active power discharging or adding the FESS stored energy caused by active power charging. If, within the dynamic simulation, the FESS is fully charged, it is assumed as not being capable of consuming power. On the other hand, if the FESS reaches an empty state, it is assumed as not being capable of delivering power to the grid.

V. SIMULATION RESULTS

A. Simulation Assumptions

In the proposed methodology, different possibilities were considered for the FESS under operation. These possibilities are related to the set of values for the storing energy capacity (En in MJ) and nominal active power (Pn in MW) of the FESS available in the market, appropriated to perform automatic frequency control in power systems. Namely, based on the data sheets presented in [4], each single FESS was considered to have a storing energy capacity of 15 MJ and the following alternative nominal active power values: 0.5 MW, 1 MW, 1.5 MW and 2 MW. From the same data sheet, a typical value of 0.1 Hz was considered for the frequency dead band (FDB).

In all the performed dynamic simulations, the FESS was considered to be fully charged during pre-disturbance steady-state operation.

B. FESS Sizing for the Major Renewable Power Loss

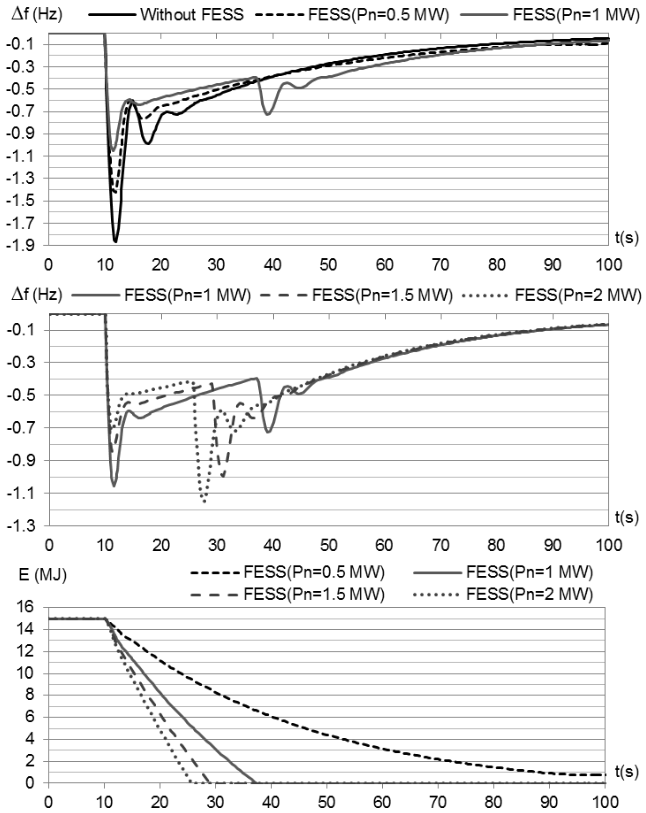
1) Minimum Pn required value

To find the minimum required FESS Pn value that ensures system security to the major expected renewable power loss (a 2 MW loss), the dynamic simulation of this disturbance was performed without a FESS and also by considering the primary frequency control action of a FESS with alternative nominal active power values, namely with a Pn value of 0.5 MW, 1 MW, 1.5 MW or 2 MW. A typical value of 0.1 Hz and 1/Pn Hz/MW was considered for the FDB and R parameter. The obtained simulation results are presented in Figure 6. In these simulations, renewable power loss was considered to appear at the 10 seconds instant.

The presented simulation results comprise the obtained time evolution for the system frequency deviation (Δf) and for the FESS stored energy (E), for all the considered FESS alternative situations. The obtained results without a FESS present a transient frequency drop with a maximum value of almost 2 Hz. This result reveals that, although having, in the analyzed scenario, enough diesel spinning reserve to accommodate a 2 MW power loss, without a FESS this renewable power loss may endanger the power system security, by provoking transient frequency drops with magnitudes, obtained by simulation, falling above 1.3 Hz.

The obtained dynamic results also show that, among the tested situations, a 1 MW FESS has the minimum required Pn value to avoid violating the previously described security criterion. Indeed, in this simulated situation, the obtained transient frequency drops reach a maximum value of just 1 Hz.

By comparing the results obtained with a FESS of 1 MW, 1.5 MW and 2 MW, it is interesting to realize that, for the sake of frequency dynamic performance, it is not recommended to oversize the FESS Pn value. In fact, although showing to provide a better frequency performance in the first post-disturbance seconds, the 1.5 MW and 2 MW FESS present a fast end of their stored energy, leading to an early end of the FESS control action. Like exemplified by the results obtained with a 2 MW FESS, this Pn oversize may deteriorate the obtained post-disturbance frequency dynamic behavior, by presenting transient frequency deviations with increased magnitude.



Legend: Δf - Frequency deviation from the nominal value; E - FESS stored energy.

Figure 6. Dynamic simulation results for the major power loss, without/with a FESS having En=15 MJ, R=1/Pn Hz/MW and FDB=0.1 Hz, including diferent Pn values for the FESS

2) Influence of the speed droop value

From the previously described simulations, a 1 MW FESS was selected as being the best solution to ensure system security to the major expected renewable power loss. Aiming to understand the influence of the R parameter value in the system security, the same power loss disturbance was simulated by considering the, until now, selected best FESS solution (with Pn = 1 MW, R = 1 Hz/MW and FDB = 0.1 Hz) and also with the following extreme values for the R parameter: 2 Hz/MW and 0.5 Hz/MW. The obtained simulation results are presented in Figure 7. In this figure, the presented results obtained with the considered largest R value (a 2 Hz/MW value) showed to be ineffective to guard system security, since the obtained transient frequency drop violates the 1.3 Hz security margin. Therefore, these results show that oversizing the R parameter may jeopardize the system security, by reducing too much the sensitivity of the FESS control action.

By making a comparative analysis between the obtained results with a typical value of 1 Hz/MW and with the considered smallest R value (0.5 Hz/MW), it is clear that undersizing the R parameter is also not recommended, since it leads to a fast end of the FESS stored energy, which may deteriorate the obtained post-disturbance frequency dynamic behavior.

Therefore, among the testes R values, the 1 Hz/MW value was selected as being the best solution to improve the post-disturbance frequency dynamic behavior after the major expected renewable power loss.

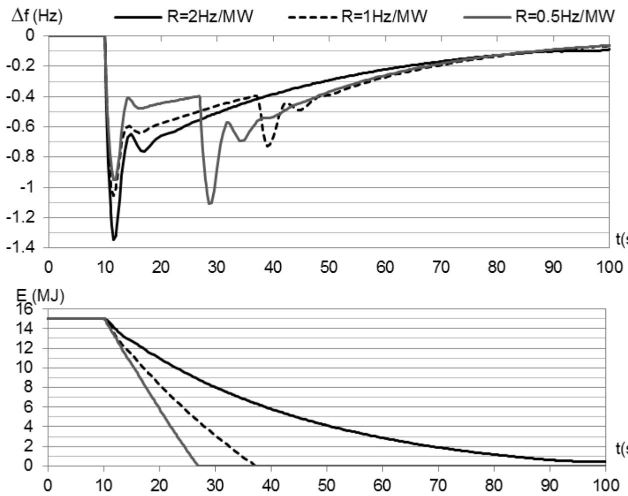


Figure 7. Dynamic simulation results for the major power loss, with a FESS of 1 MW and 15 MJ, including diferent R values for the FESS and with FDB=0.1 Hz

3) Influence of the frequency dead band value

Finally, in order to understand the influence of the FESS FDB parameter value in the power system behavior, the same disturbance was simulated by considering the selected best FESS solution (with Pn = 1 MW, R = 1 Hz/MW and FDB = 0.1 Hz) and also with the following alternative increased values for the FDB parameter: 0.7 Hz and 1 Hz. The obtained simulation results are presented in Figure 8.

These obtained results demonstrate that adopting an increased FDB value of 0.7 Hz becomes a more interesting solution to guard the security for the analyzed power loss disturbance, since the FESS spent energy caused by active power discharging showed to be significantly reduced from 15 MJ to approximately 7 MJ, without damaging the maximum magnitude of transient frequency drops. Therefore, adopting an increased FDB of 0.7 Hz may reduce the power system operating costs, since the amount of FESS stored energy, required to prevent security loss to a major power loss, can be significantly reduced.

The obtained results also show that adopting an even higher FDB value of 1 Hz is not recommended because, although reducing even more the FESS spent energy in active power discharging, the obtained maximum magnitude of transient frequency drops is deteriorated.

loss to a major power loss can be considerable reduced, if the severity of the disturbance is decreased. This last conclusion is very interesting since, in a daily time frame, the severity of the major expected renewable power loss disturbance may change a lot due to the usual modifications of the power system operating conditions, like load scenario or solar conditions. Therefore, the results presented in Figure 9 show that having proper intelligent tools that provide, in real time, an accurate estimation of the FESS stored energy required to prevent security loss for each expected operating conditions, could reduce the power system operating costs. This cost reduction would be achieved by minimizing the amount of energy consumed by the FESS, in a daily time frame, required to guard system security for the major expected renewable disturbances.

This minimization could be achieved not only by adapting the required FESS stored energy to the disturbance severity, but also by coping with the values of the FESS control parameters, like frequency dead band (FDB in Hz) and speed droop (R in Hz/MW). To demonstrate this last conclusion, the same 1.5 MW power loss was simulated for the previously considered FESS solution, but now with an increased value of its R parameter, namely with a 2.5 Hz/MW value. The obtained dynamic simulation results are presented in Figure 10. For comparison purposes, this figure also includes the results provided by the previously considered FESS solution (i.e., having a 1 Hz/MW value).

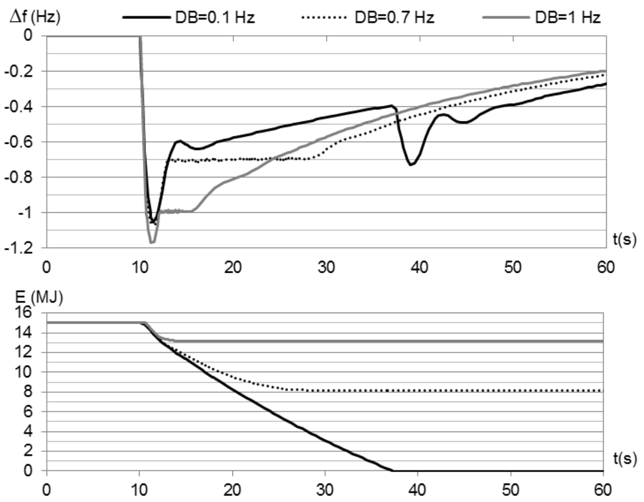


Figure 8. Dynamic simulation results for the major power loss, with a FESS of 1 MW and 15 MJ, including diferent FDB values for the FESS and with R=1 Hz/MW

C. *Performace of the Sized FESS Following a Less Severe Power Loss*

From the previously described simulations, a 1 MW FESS with a R value of 1 Hz/MW and a FDB of 0.7 Hz, was selected as being the best solution to ensure system security to the major expected renewable power loss. Aiming to understand the influence of the disturbance severity on the effectiveness of the FESS behavior, the same FESS solution was considered to simulate a less severe power loss, namely with a 1.5 MW magnitude. The obtained dynamic simulation results for this disturbance are presented in Figure 9. For comparison purposes, this figure also includes the obtained results for the 2 MW major power loss.

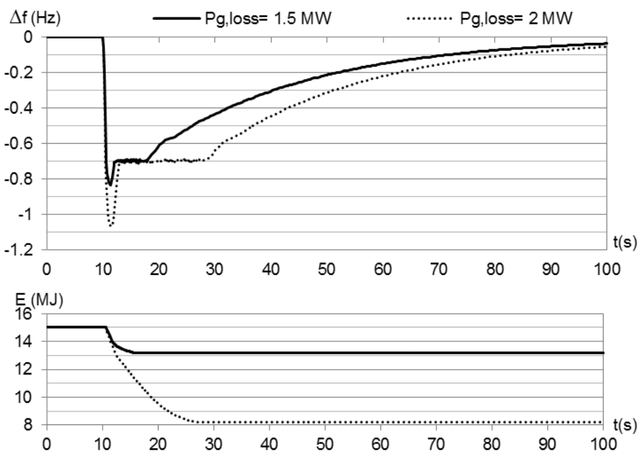


Figure 9. Dynamic simulation results for a less severe power loss, with the FESS sized and tuned for the major power loss (Pn=1 MW, En=15 MJ, R=0.1 Hz/MW and FDB=0.7 Hz)

As expected, the simulation results demonstrate that the FESS sized and tuned for the major power loss also ensures system security for the same type of disturbance, but with a less severe power unbalance magnitude. They also show that by reducing in 25 % the severity of the disturbance, the amount of required FESS stored energy is considerably reduced, from approximately 7 MJ to 2 MJ, which means a 70% reduction. Therefore, this result demonstrates that the amount of FESS stored energy required to prevent security

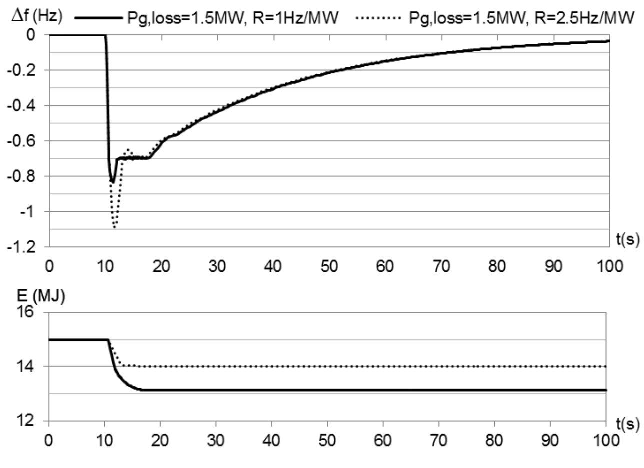


Figure 10. Dynamic simulation results for a less severe power loss, with the FESS sized and tuned for the major power loss (Pn=1 MW, En=15 MJ, R=0.1 Hz/MW and FDB=0.7 Hz) and also with an increased R value (R=2.5 Hz/MW)

As expected, these results show that by adopting an increased R value of 2.5 Hz/MW, the FESS spent energy motivated by a 1.5 MW power loss was able to be further reduced, from 2 MJ to just 1 MJ, without violating the security criterion defined for severe power losses.

D. *FESS Sizing for Frequent Renewable Power Variations*

Finally, the capability of the 15 MJ/1MW FESS sized for the major expected renewable power loss was evaluated to, alternatively, guard security for frequent renewable power variations, like the ones presented in Figure 3 of section III. As already explained, during normal operation, the system frequency deviations obtained by dynamic simulation must not, systematically, violate the range of ± 0.3 Hz. Therefore, to obtain an effective FESS action to compensate frequent renewable power variations, the FESS must have a reduced FDB value. Thus, in the dynamic simulations of the frequent renewable power variations of Figure 3, a 0.1 Hz value was considered for the FESS FDB. This disturbance was simulated without a FESS and also by considering the primary frequency control action of a 1 MW or a 1.5 MW FESS, having a 1/Pn Hz/MW value for the R parameter. The obtained results are presented in Figure 11.

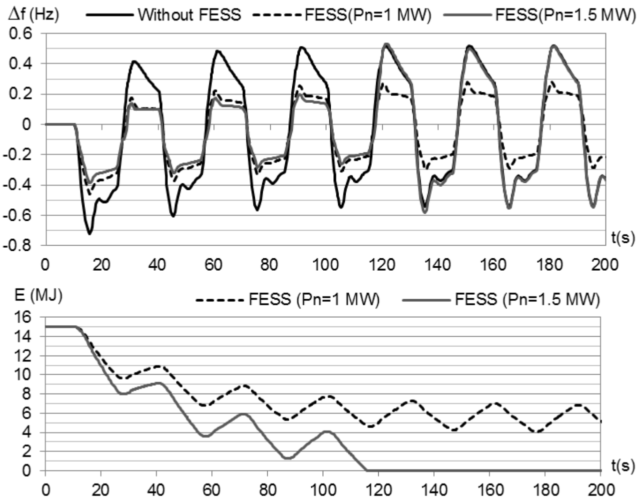


Figure 11. Dynamic simulation results for the frequente renewable power variations presented in Figure 3, without/with a FESS having 15 MJ/1MW or 15 MJ/1.5 MW and with FDB=0.1 Hz and R=1/Pn Hz/MW

The obtained simulation results without a FESS yield transient frequency variations that, systematically, reach +0.5 Hz and -0.6Hz and, therefore, violate the considered security criterion defined for frequent renewable variations.

On the other hand, the 15 MJ/1 MW FESS sized for the major expected power loss was, in the dynamic simulation, able to guard system security for frequent renewable variations, since the obtained transient frequency variations are, after the first post-disturbance seconds, stabilized within $\pm$ 0.3 Hz. These results also show that, previously to this disturbance, the required stored energy in the FESS must be around 12 MJ.

Once again, the obtained results with a 15 MJ/1.5 MW FESS exemplifies the problems that can arise from oversizing the FESS Pn value. In fact, although showing to provide the best frequency performance in the first 100 seconds of post-disturbance behavior, the 1.5 MW FESS exhausts the stored energy after this time, leading, at the same time, to the end of the FESS control action.

E. Final FESS Sizing Results

From the simulation results, it was observed that without a FESS, the analyzed renewable disturbances could endanger the system security, by violating the pre-defined security criteria. A 15MJ/1MW flywheel, with a frequency dead-band of 0.1 Hz and a speed droop of 1 Hz/MW, would solve the problem. Namely, from the obtained simulation results, this FESS solution proved to be capable of avoiding frequency stability problems for the major expected power loss or, alternatively, for the most expected severe frequent renewable power variations. Moreover, the obtained results also revealed that having an oversizing value for the FESS active nominal power, or an undersized value for the FESS speed droop, is not recommended, because this can lead to a fast end of the FESS stored energy, during the time when it is still performing crucial frequency control actions.

In order to minimize the FESS stored energy required to prevent security loss, this amount of required energy should be adapted, by some intelligent control tool, to the current severity of expected renewable disturbances. This energy minimization could be further improved by also tackling with the value of the FESS control parameters. These tools would certainly reduce the power system operating costs, by minimizing the amount of energy consumed by the FESS required to guard the power system security.

VI. CONCLUSIONS

The main conclusion that can be obtained from the developed work is that the installation of fast acting energy storage systems, like a flywheel energy storage system (FESS), is, nowadays, fundamental to obtain a large integration of wind and PV power generation in an isolated power system. In order to obtain an efficient FESS operation, for different types or severity level of expected renewable disturbances, the amount of FESS stored energy and the values of the FESS control parameter must be adapted on line, by following the suggestions of intelligent control algorithms.

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