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Implementation of a flywheel energy storage system to improve the integration of wind power generation in microgrids

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Abstract:

The incorporation of wind power generation (WPG) in power systems is growing progressively. This integration can introduce problems in the dynamics of the electrical system, which will be more severe in weak systems and in microgrids (MGs). On the other hand, new energy storage devices have emerged in recent years. These new devices allow to control the operation of electrical systems. In this work, a flywheel energy storage system (FESS) is proposed to mitigate problems introduced by WPG into MGs. The model of the FESS is presented, and the control algorithm used is described briefly. Simulation tests on the behavior of the FESS device are analyzed when it works in combination with WG in a MG. The study is carried out considering different penetration levels of WPG in the MG. Results show satisfactory performance of the proposed device to mitigate problems introduced by the WPG in the MG.

1. Introduction

Wind power generation (WPG) is considered the most economically viable alternative within the portfolio of renewable energy resources. Today, grid connection of wind power generation is becoming an important form of distributed generation (DG). The penetration of these DG units into microgrids (MGs) is growing rapidly, enabling them to reach a high percentage of the installed generating capacity. However, the fluctuating and intermittent nature of the wind and the type of generation system implemented, different from conventional generators, causes variations of power flow that can significantly affect the operation of the electrical grid [1], [2]. This situation can lead to severe problems that affect the power quality or dramatically jeopardize the microgrid security, such as violations of voltage limits and/or system frequency oscillations, among others. This condition is worsened by the low inertia present in the microgrid; thus requiring having available sufficient fast-acting spinning reserve.

On the other hand, the breakthrough of new technologies in the field of electric energy storage makes possible the incorporation of these innovative storage devices within the power systems [3]. These devices allow dynamic control over both voltages and active and reactive power flows. Therefore, they offer a great potential for mitigating problems introduced by WPG and thus, significantly improve the operation security and power quality of MGs.

Based on the results obtained by analyzing different selection criteria of the most innovative energy storage system currently available, Flywheel Energy Storage System (FESS) has been proposed as the most appropriate energy storage technology for participating in the smoothing of short-term wind power fluctuations [4]-[8]. Flywheels store kinetic energy in a rotating mass, and they have been used as short-term energy storage devices. They offer swift response speed, excellent cycling characteristics and high electric efficiency [9], [10]. All these combined characteristics allow the FESS to mitigate problems introduced by wind power systems in MGs.

The purpose of this article is to determine the consequences of the incorporation of a FESS in the operation of a MG considering high levels of penetration of WPG in the MG. The behavior of the voltage and the

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KEYWORDS
Wind power generation, Flywheel energy storage system, Microgrid, Voltage control, Frequency control.

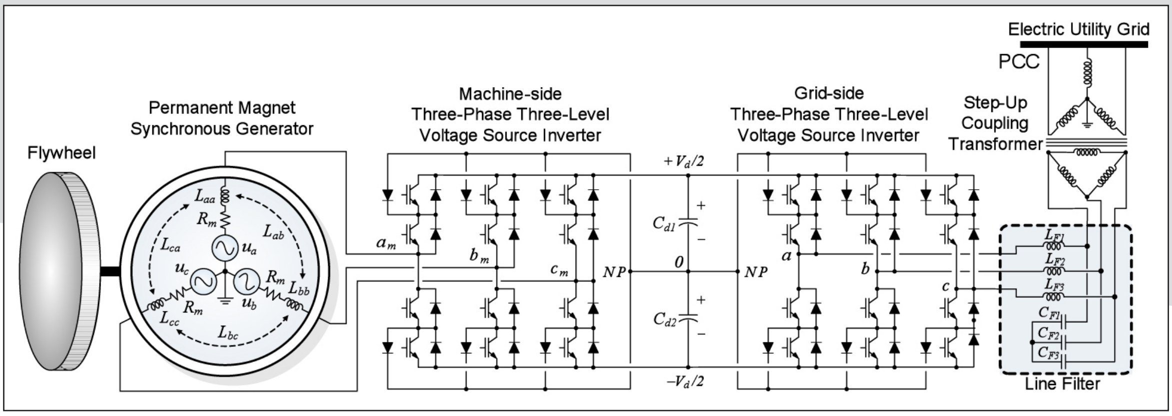

Fig. 1. Detailed model of the proposed FESS, including its power conditioning system.

frequency in the MG is mainly observed when the MG is isolated from the main grid, considering FESS connected and disconnected. When the level of penetration of WPG increases in the MG, the generation responsible for controlling the MG decreases. Therefore, the study is carried out considering different levels of penetration of WPG in the MG. The model of the FESS is presented, and the control algorithm used is briefly described. The dynamic performance of the proposed system and its impact on the MG operation is fully validated by computer simulation in the MATLAB/Simulink environment, by using SimPowerSystems.

2. Model of the FESS

In order to study the dynamic performance of the FESS controller, the model shown in Fig. 1 is proposed. This model consists mainly of a power conditioning system (PCS) composed of an ac/dc/ac converter (known as a back-to-back converter), and the FESS device. The main components of the PCS are two voltage source inverters (VSI) (one VSI on the grid side and another VSI on the machine side), the DC bus, the coupling transformer and the harmonic filter. The main components of the FESS are a motor/generator and an inertial wheel.

The commutation valves used in the VSIs are insulated gate bipolar transistors (IGBT) with anti-parallel diodes. The VSIs are modeled with detailed blocks of switches and diodes incorporated within the simulation program. The technique of sinusoidal pulse width modulation (SPWM) is used to obtain a sinusoidal voltage waveform. In order to reduce the disturbance caused on the distribution system by the high-frequency switching harmonics generated by the SPWM control, a low-pass sine wave filter is used. This filter is built with the leakage inductances of the step-up coupling transformer windings and a bank of capacitors.

FESSs extract the electric energy from a primary source, such as an electric grid, and store it as kinetic energy in its rotating mass. The energy stored by a flywheel is calculated by using (1).

$$\Delta E = J(\omega_{\max}^2 - \omega_{\min}^2)/2 \qquad (1)$$

where ΔE is the energy stored by the flywheel, $\omega_{\max}$ and $\omega_{\min}$ are, respectively, the maximum and minimum operation speeds of the flywheel, and J is the moment of inertia of the flywheel.

The exchange of power between the flywheel and the PCS is done by using a Permanent Magnet Synchronous Machine (PMSM). The PMSM is modeled with a detailed block included in the simulation program with parameters obtained from the manufacturer data sheets [9], [10]. The flywheel is modeled as an additional mass coupled to the rotor shaft of the PMSM [11], by using (2).

$$\frac{d\omega_m}{dt} = \frac{1}{2(H_m + H_f)}\left(T_e - (F_m + F_f)\omega_m - T_m\right) \qquad (2)$$

where ωm is the angular velocity of the rotor, Hm and Hf are the inertia constants of the PMSM and the FESS wheel respectively, Fm and Ff are the viscous friction coefficient of the PMSM and the FESS wheel respectively, Te is the electric torque and Tm the mechanical torque.

3. FESS Control

The control proposed for the FESS controller is divided into two parts, the grid-side VSI control and the machine-side VSI control. For each part, a multilevel control scheme is suggested. This scheme has its own control objectives for each level. In this way, a system of complex control is divided into several control levels, which are simpler to design [12]. The multilevel control scheme is shown in a simplified way in Fig. 2. The control algorithm for the FESS is fully developed in [7]. Only general information about the operative function of each control block is presented below in Sections 3.1 and 3.2.

3.1. Grid-Side VSI Control

Each control level of the grid-side VSI performs certain associated functions. The external level is responsible for determining the active and reactive power exchange between the grid-side VSI and the utility system, with the aim of reducing the problems that wind generation introduces in the power system.

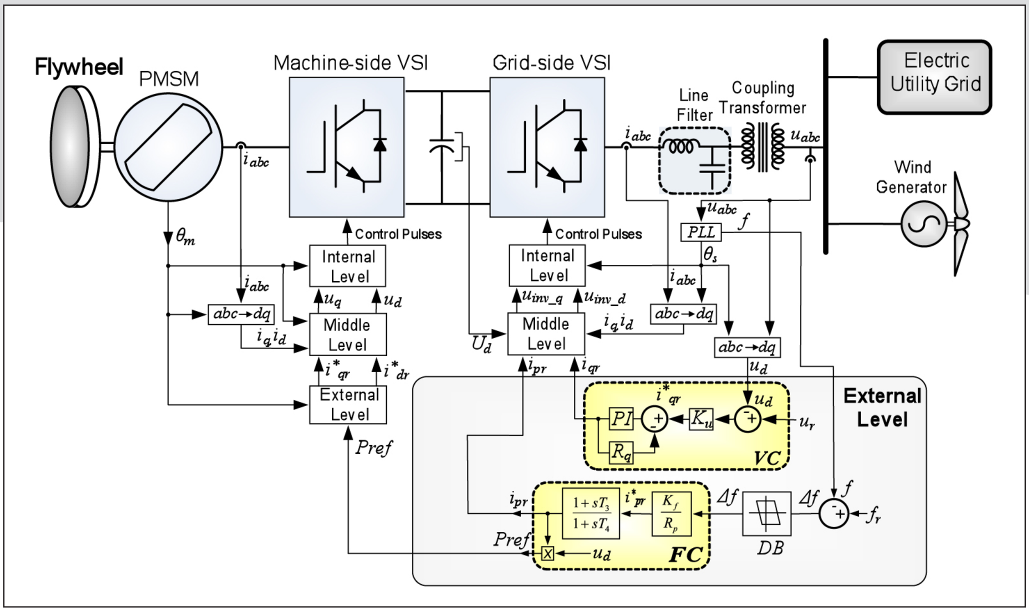

Fig. 2. Structure of the multilevel control of the FESS.

For this work, the reactive power control is designed to control the voltage at the point where the FESS device is connected, named Voltage Control (VC) mode. The VC consists in controlling the voltage at the PCC (Point of Common Coupling) of the FESS controller through the modulation of the reactive component of the output current. To this aim, the instantaneous voltage at the PCC (ud) is computed by using a synchronous rotating orthogonal reference frame and is then compared with a reference voltage (Ur). A voltage regulation droop (or slope) Rq is included in order to allow the terminal voltage of the FESS controller to vary in proportion with the compensating reactive current. For the active power control, frequency control (FC) mode is used. The frequency control is responsible for determining the active power exchange with the electrical system when it is necessary to recover the system frequency after eventual faults of some system components. A simple structure of the frequency control is shown in Fig. 2 (FC block). The purpose of this is to keep the system frequency above the acceptable minimum level during the transient dynamics. Power oscillations can be damped by the modulation of the active component of the output current. The output signals of the the external level control, active and reactive current components, are used as inputs for the middle level control. The middle level control allows the expected output to dynamically track the reference values set by the external level. At this level of control, several advanced control methodologies can be used without altering the levels of lower and higher hierarchical order. This block has two main parts, the current regulator and the DC voltage regulator. The internal level is responsible for generating the switching signals for the valves of the grid-side VSI according to the control mode (SPWM) and the valves used (IGBTs).

3.2. Machine-Side VSI Control

FESS control is achieved by controlling the machine-side VSI. By setting via VSI a three-phase voltage of controllable amplitude and phase, enables the PMSM to work as a motor that stores energy or as a generator that supplies energy. The control is exerted by using vector control; the main characteristic of this control is the synchronization of the stator flux with the rotor. With this type of control, performed in *dq0* coordinates, the currents on the q and d axes are regulated separately. The purpose of controlling the current in the q axis is to control the torque and consequently the power of the machine. In this type of machine, the i_d current is normally set to zero since this strategy provides maximum efficiency of the machine [13].

The external level is responsible for determining the power exchange between the DC bus and the PMSM, so as to fulfill the power requirements imposed by the grid-side VSI to reduce the problems introduced by the wind generation. The output signals of this block are used as inputs for the middle level control. Likewise the grid-side VSI, the middle level control allows the output current to dynamically track the reference values set by the external level control. One of the fundamental differences with the middle level control of the grid-side VSI is that the synchronism angle to produce the coordinate transformation (θs) is computed in a different way. In this case, the angle is obtained by measuring the position angle of the machine (θm) and multiplying by the number of pairs of poles. The internal level performs the dynamic control of the input signals for the different valves of the machine-side VSI.

4. Test System

The test power system used to analyze the FESS working with the WPG in the MG consists of a power system containing a MG, which includes distributed generation based on fossil and renewable fuels, the FESS and loads. The test system operates at 132 kV/50

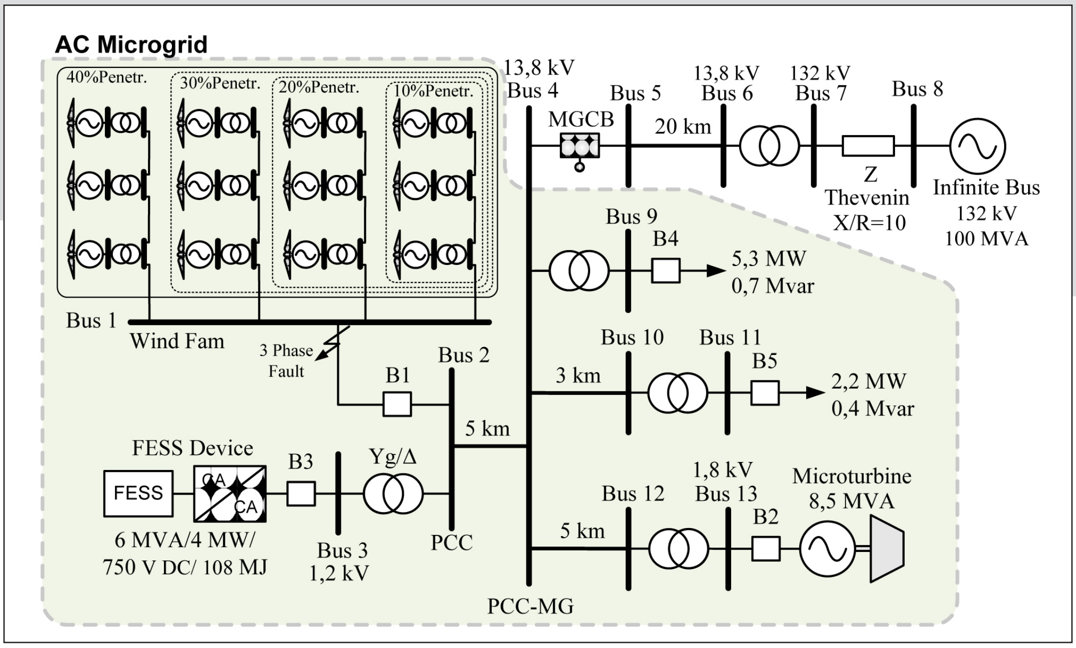

Fig. 3. Test power system

Hz in the bulk system side (main grid) and at 13,8 kV in the MG side, and implements a 100 MVA short circuit power level infinite bus through a Thevenin equivalent. The DG based on fossil fuel (8.5 MVA rated power) is composed of a dispatchable unit powered by a gas microturbine and includes a voltage regulator and a speed governor. The DG based on renewable resource is made up of a wind farm with variable rated power for the purposes of this study. Two sets of sheddable linear loads (C1: 5,3 MW, 0,7Mvar; and C2: 3MW, 0,4 Mvar) are considered in the MG, and are modeled as constant impedances. A microgrid central breaker with automatic reclosing capabilities is employed for the interconnection of the MG to the bulk power network. In this study, this central breaker is considered to be in an open state and operating the MG in isolation. The penetration levels of WPG in the MG considered in this work are 10%, 20%, 30% and 40%. These percentages represent powers of wind farms of 0.75 MW, 1.5 MW, 2.25 MW and 3 MW, respectively. The model of the wind farm is composed of several sections with wind generators in each section, totaling wind farms with rated powers indicated above. Each wind turbine used inside the farm is connected to the grid through a transformer with star-triangle winding. The wind turbine uses an induction generator with a squirrel-cage rotor.

The FESS device proposed is connected through breaker 3 to bus 2, the same connection point of the wind farm. For simplicity, the FESS device is represented in Fig. 3 as a single block. However, the FESS consists of four modules with ten flywheel units each (40 flywheel units of 100 kW rated power each). Therefore the 40 flywheel units have a total of 4 MW rated power. The maximum and minimum operational speeds of the flywheel are 15,500 and 31,000 rpm, respectively. The rated storage capacity of the FESS is 30 kWh (27 s to maximum power).

5. Simulation Results

The analysis of the system proposed for the FESS device in the MG with WPG is carried out through simple events that impose high demands upon the dynamic response of the device. For this study, the basic test-power system shown in Fig. 3 is used. The study is performed with the operation of the MG in isolated mode, with the open MGCB breaker. In this mode of operation, a three-phase fault is applied at bus 1 in the wind farm system (at t = 3 seconds). Immediately after de fault, the wind farm is disconnected through the opening of the breaker B1. Such perturbation causes deviations on the MG voltage and frequency. When the level of penetration of WPG increases in the MG, the generation responsible for controlling the MG decreases. Therefore, the study is carried out considering different levels of penetration of WPG in the MG. The results for two conditions in the system are shown: without compensation (base case) and with compensation of the FESS device.

For the topology presented in the test case, in the steady state previous to the fault, the 7.5 MWs required by the loads are supplied as follows: for 10% wind penetration level (WPL), 6.75 MW (microturbine) and 0.75 MW (wind farm); for 20% WPL, 6 MW (microturbine) and 1.5 MW (wind farm); for 30% WPL, 5.25 MW (microturbine) and 2.25 MW (wind farm); and for 40% WPL, 4.5 MW (microturbine) and 3 MW (wind farm). In these states, the system frequency is at its rated value (50 Hz) and the voltage at bus 4 (PCC) is 1 p.u. After the fault, the microturbine has to supply all the power required by the load; therefore, the speed governor of the microturbine must automatically recover the system frequency to its rated value. As observed from the simulation results of Figs 4(a) to 4(d) (showing the MG frequency), and Figs. 5(a) to 5(d) (showing the bus 4 voltage), in the base case (without the FESS device), the microturbine unit is capable of recovering the system frequency and the voltage for all considered cases of different levels of wind penetration.

Now, the connection of a FESS is considered. The results of Fig. 4 and Fig. 5 clearly show the action of the FESS device and the excellent performance of the controls of the FESS. After the fault, when the frequency deviation exceeds the dead-band limits (0.15 Hz for this case), the FESS device is activated. The rapid active power generation of the FESS supplies the sudden consumption surplus in the microgrid occurred after the wind farm disconnection. This condition permits to greatly decrease the power strain of the microturbine (shown in Fig. 6), since the generator is able to find the balance with the load at a lower speed than in the case without the FESS without producing a significant frequency deviation. In fact, the frequency drop is drastically reduced and maintained far away from the load-shedding limit. For the most severe case of penetration level of 40% of wind generation, the minimum frequency reached during the disturbance is 49.7 Hz (with the FESS compensation) versus 48.15 Hz for the base case. The improvement of the frequency control is obtained by the action of the FESS device, which generates active power for several seconds. Regarding the voltage, depending on the penetration level of wind generation, the voltage at bus 4 has significant variations at the moment of the fault when there is no compensation. When the FESS device is connected in the proposed voltage control mode, the voltage remains close to the reference value and with minor oscillations.

Finally, the active power injected by the FESS is shown in Fig. 7 and the rotational speed for one of the flywheels of the FESS is shown in Fig. 8. It is observed in all cases, how the FESS injects a maximum power at the moment of fault and then gradually reduces its value as the frequency recovers. It should be noted that in no case the maximum power value of the FESS (4 MW) was reached since it was oversized so that all cases had sufficient capacity to make the compensation. Regarding the power injected by the FESS, it is observed that as the penetration level of the wind generation increases, the maximum power injected increases in an approximately linear relation; for 10% WPL, the maximum power injected by the FESS is P_{FESS_Max} = 670 kW; for 20% WPL, P_{FESS_Max} = 1410 kW; for 30% WPL, P_{FESS_Max} = 2135 kW; and for 40% WPL, P_{FESS_Max} = 2790 kW. Regarding the rotational speed of the FESS, which measures the state of charge of the storage and therefore the energy used of the same, a marked decrease of the speed during the fault is observed. Fig. 8 shows the energy generated by the FESS in each case, observing that, different from the power, as the penetration level of wind generation increases, the energy generated to maintain the frequency within the limits increases in an approximately quadratic relation.

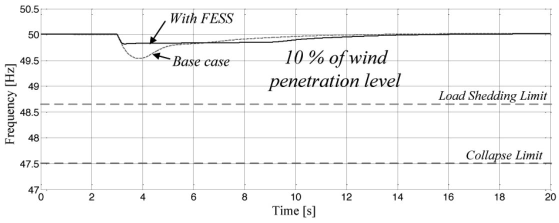

Fig. 4-(a). MG frequency for 10% WPL

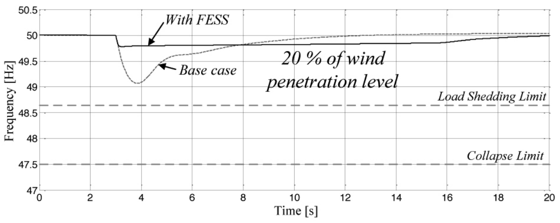

Fig. 4-(b). MG frequency for 20% WPL

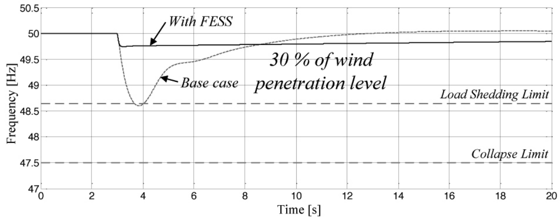

Fig. 4-(c). MG frequency for 30% WPL

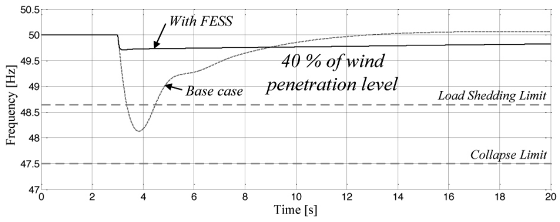

Fig. 4-(d). MG frequency for 40% WPL

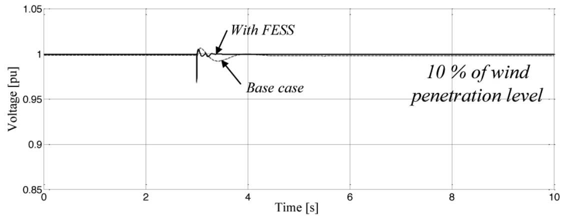

Fig. 5-(a). Voltage at Bus 4 for 10% WPL

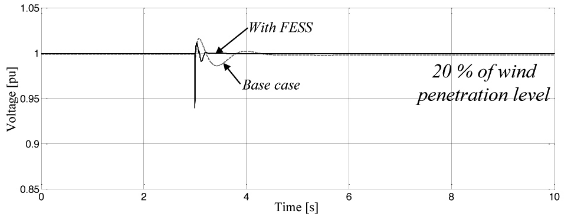

Fig. 5-(b). Voltage at Bus 4 for 20% WPL

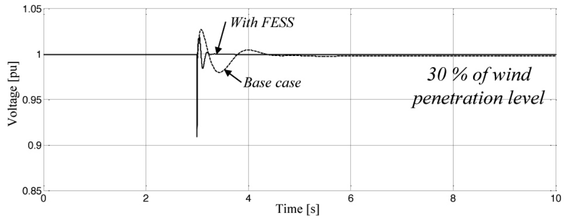

Fig. 5-(c). Voltage at Bus 4 for 30% WPL

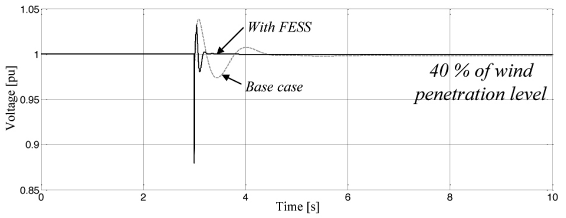

Fig. 5-(d). Voltage at Bus 4 for 40% WPL

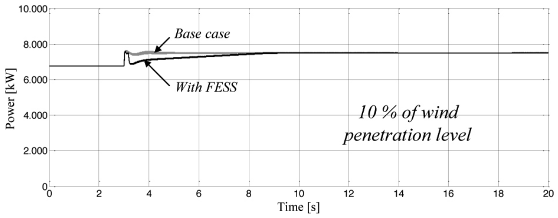

Fig. 6-(a). Microturbine power for 10% WPL

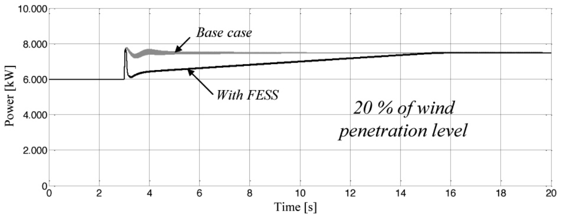

Fig. 6-(b). Microturbine power for 20% WPL

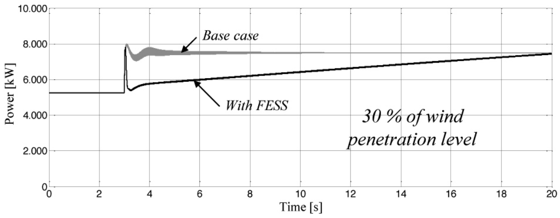

Fig. 6-(c). Microturbine power for 30% WPL

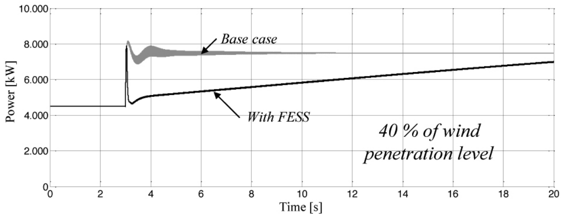

Fig. 6-(d). Microturbine power for 40% WPL

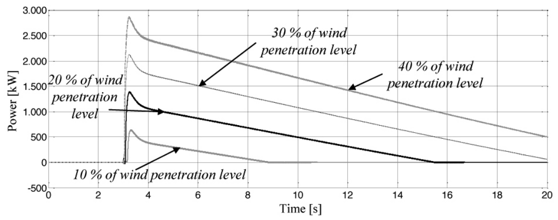

Fig. 7. Powers injected by the FESS

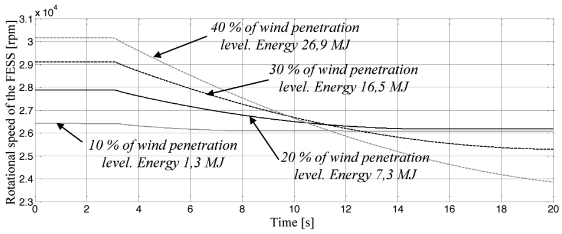

Fig. 8. Rotational speed of the FESS

6. Conclusions

This paper presents control aspects of a flywheel energy storage system to improve the integration of wind turbines within microgrids, considering different levels of penetration of wind power generation. A proposal is made for the control algorithm of the device using two control modes. The first control mode is used to contribute to the frequency control when important faults arise in the system whereas the second control mode is used to maintain the voltage constant at the point of common coupling. From the results obtained, authors concluded that the developed control algorithms work satisfactorily. The FESS device contributes to the recovery of the frequency when significant faults occur in the system, as in the case of the island operation of the microgrid and the total disconnection of the wind farm. In addition, the FESS also contributes to maintaining the voltage profile with smaller oscillations at the connection point when the fault occurs. With this proposed device, it has been possible to enhance the power quality of a microgrid integrated with wind power generation by improving the voltage profile, as well as enhancing the system security in the operation of the microgrid by contributing to the recovery of frequency when faults occur. Therefore, the integration of wind turbines in microgrids is improved with the compensation provided by the FESS controller. Finally, it is also concluded that as the penetration level of wind power in the microgrid increases, the power requirement of the storage device increases approximately linearly and the energy requirement of the storage device increases approximately in a quadratic form.

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8. Biographies

Gastón Orlando Suvire was born in San Juan, Argentina. He graduated as an electric engineer from the National University of San Juan (UNSJ), Argentina in 2002. He received his Ph.D. from the same University in 2009, carrying out part in the COPPE institute, in the Federal University of Rio de Janeiro in Brazil. Dr. Suvire is currently a professor of electrical engineering at the UNSJ and a researcher with CONICET. His research interests include simulation methods, power systems dynamics and control, power electronics modeling and design, and the application of wind energy and energy storage in power systems.

Pedro Enrique Mercado was born in San Juan, Argentina. He graduated as an electromechanical engineer from the UNSJ, and received his Ph.D. from the Aachen University of Technology, Germany. Dr. Mercado is currently a professor of electrical engineering at the UNSJ and a researcher with CONICET. He is a Senior Member of the IEEE Power Engineering Society. His research activities are focused on dynamic simulation, operation security, power electronics, economic operation and control of electric power systems.