Stabilising the Grid Voltage and Frequency in Isolated Power Systems Using a Flywheel Energy Storage System

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Abstract: *This paper describes the control strategy and performance of a grid connected flywheel energy storage system (FESS) installed to stabilise an isolated grid. The paper aims to demonstrate the concept of introducing a flywheel and assisting its potential. The isolated power system studied includes diesel generators, hydro and wind turbines. The results from this study show that the stabilisation of an isolated power system is possible by the employment of a flywheel energy storage system. The simulation and measured results showed clearly the affirmative influence of the energy storage on the transient system performance. The energy transfer from the flywheel into the grid increases the stability of the isolated power system. The simulation results were verified on a real system.*

Keywords: hybrid power system, isolated grids, flywheel, hydropower, wind power.

1. Introduction

Energy plays a vital role in the development of any nation. The current electricity infrastructure in most countries consist of bulk centrally located power plants connected to highly meshed transmission networks [1]. However, a new trend is developing toward distributed energy generation, which means that energy conversion systems (ECSs) are situated close to energy consumers and large units are substituted by smaller ones [2, 3]. For the consumer the potential lower cost, higher service reliability, high power quality, increased energy efficiency, and energy independence are all reasons for interest in distributed energy resources (DER). The use of renewable distributed energy generation and "green power" such as wind turbines, photovoltaic solar systems, solar-thermo power, biomass power plants, fuel cells, gas micro-turbines, hydropower turbines, combined heat and power (CHP) micro-turbines and hybrid power systems can also provide a significant environmental benefit [1,4,5,6]. One of the existing challenges for distributed and isolated power systems is to handle the power fluctuation of renewable energy systems (RESs) e.g. wind turbines. In large national grids these variations and fluctuations of power are absorbed by the strong grid with little variation in frequency and voltage. In small and isolated grids it is more difficult to maintain the power balance and keep frequency and voltage within predefined limits. Therefore, storage has a role to play rule in future energy networks to help even out the fluctuating power output [1,7], increase renewable energy penetration, improve generator fuel efficiency, reduce generator emissions and increase generators service life [8].

This paper investigates the use of a FESS in an isolated power system on a Portuguese Island. The power system is modelled with and without the FESS. Step-changes in load are modelled and power system's dynamic behaviour shown. The flywheel was installed on the island and similar tests were performed; there is good correlation between simulated and measured dynamics. It is believed that this is one of the first successful flywheel installations in Europe used to stabilise and improve the dynamic grid performance.

2. Background

The environmental and economical attractiveness of RESs as a replacement for fossil fuels is obvious. Nevertheless, exploitation of renewable energy sources, even when there is a good potential resource, may be problematic due to their variable and intermittent nature especially if they are connected to weak grids. This exists when RESs are connected into the grid at remote points or when they are connected to isolated grids. The integration of RESs into a mains grid at remote points where the grid is weak may generate unacceptable voltage variations due to power fluctuations. Upgrading the power transmission line to cope with the power peaks may be uneconomic. Instead, the inclusion of a short-term energy store for power smoothing and voltage regulation at the remote point of connection would allow utilisation of the power and could offer an economic alternative to upgrading the transmission line. In isolated hybrid power systems, power quality and reliability are some of major difficulties due to the intermittent nature of RESs. On the other hand, the inclusion of RESs in a remote isolated power system is very attractive since it can reduce fuel usage and unit power costs because it is usually supplied from diesel generating sets, with inherent high costs due to fuel transportation. However, a high penetration of RESs can bring problems due to the variability of the wind/solar power, the variable reactive power requirements. Earlier studies have indicated that short-term energy storage can enable the reduction of the diesel generating sets online resulting in dramatic fuel savings. Sudden deficits of RESs can be compensated short periods by the energy storage without suffering loss of load events, and without needing to restart a diesel generating set for [9,10]. Weak grids, coupled with wind fluctuations, lightning strikes, sudden change of a load, or the occurrence of a line fault can cause sudden momentary dips in system voltage.

3. Flores Island Isolated Power System

The investigated system is located at the island of Flores – Azores, see "Fig. 1". The Azores is two and a half hours flying time of the Portugal capital city Lisbon and has several islands that are powered by diesel generators and hydro power plants. There are two main islands with a population of 100,000 each and another 7 smaller islands. Over the last couple of years the local utility Electricity de Acores (EDA) has installed a number of Enercon E-30 wind turbines on these islands to reduce the cost of diesel power generation. After the wind turbines were installed EDA found that they had to limit the amount of wind power injected into the system to avoid power fluctuations and blackouts.

The power system investigated has a mix of diesel, wind and hydro generation. The installed system consists of four hydro power generators (3x250 kW + 600 kW), two wind turbines (2x315 kW) and four diesel generators (3x550 kW + 810 kW). The flywheel (500kW/5kWh) is connected to the 400V bus. The principle system layout is shown in "Fig. 2". The main objective of the project was to operate with the minimum number of diesel generators online as far as possible in order to supply the island; it is possible to run the power system with hydro and wind power only.

Fig. 1. The Azores Islands.

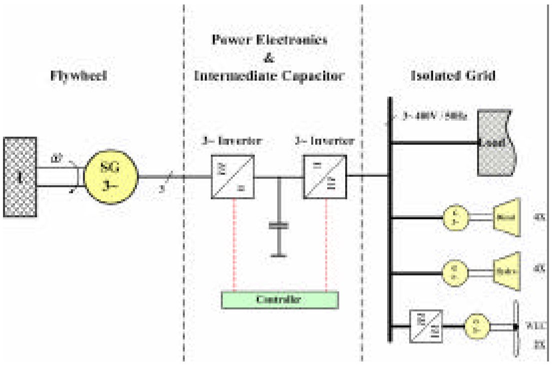

Fig. 2. Overview of the system under study.

4. Flywheel Energy Storage System

Traditionally flywheels have been used to achieve smooth operation of machines. The early systems were purely mechanical, consisting of only a wheel attached to an axle. Nowadays, flywheels are complex constructions where energy is stored mechanically and transferred to and from the flywheel by an integrated motor/generator and possibly power electronics [11].

"Fig. 3" shows the general construction of the Flywheel Energy Storage System (FESS) considered in this paper. The kinetic energy stored in a flywheel is proportional to the inertia and to the square of its rotational speed. The main parts of the modern flywheels are a power converter, a controller, a stator, bearings and a rotor. The rotor includes the rotating part of the motor/generator and the flywheel proper [8]. The flywheel unit uses a pressurised helium environment to reduce frictional losses. It has standard mechanical bearing that holds the weight of the 3,000 kg flywheel during operation. The addition of a lifting magnet ensures reduces the load on the bearings and gives the unit a long life and low maintenance. In addition, catch bearings are installed to slow the flywheel to a stop if the primary bearings fail, making a fail-safe system [12]. The motor/generator is driven by a variable frequency and variable voltage power electronic converter. The entire system (Flywheel and Power electronic) is called PowerStore and is housed in one 20-foot shipping container [12].

The PowerStore combines the 18 MWs low-speed flywheel with two solid state IGBT inverters. The converter and the inverter are coupled via an intermediate voltage circuit. PowerStore is able to sink or source up to it is maximum power rating and is also capable of responding sub-cyclically to power system changes, with a ramp-up time of approximately 4 ms to change from sourcing 100% to sinking 100% of the peak power rating [12]. There are a number of attributes that make flywheels useful for applications where other storing units are now used. These include the high power density, high energy density, short recharge time and the state of charge can easily be measured, since it is related to the rotational speed. Furthermore, there is no capacity degradation and the lifetime of the flywheel is almost independent of the depth of the charge and discharge cycle. It can operate equally well on shallow and on deep discharges while e.g. optimizing battery design for load variations is difficult [11]. These characteristics give the flywheel an attractive potential for stabilizing the grid state variables.

5.System Simulation

5.1. Diesel Engines

"Fig. 4" shows the general control structure for the load sharing and voltage control of one Diesel generator. The generators are operating in droop mode; each generator contains a frequency and voltage droop function for symmetrical real and reactive power sharing.

The frequency droop controls the generator speed since it is related to the frequency in the mechanical control loop. The frequency droop factor, $-K_f = \Delta P/\Delta n$, describes the frequency operating point and is dependant on the load. ?P is the difference between the measured power and the rated power of the generator and ?n is the speed reference offset. "Fig. 5" expresses this graphically. Using droop the load is shared automatically between the diesel generators online.

The voltage is controlled using a voltage droop function where the droop factor can be calculated by, $-K_v = \Delta Q/\Delta V$, where ?Q is the difference between the measured reactive power (Q) and the rated reactive power of the generator, and ?V is the voltage reference offset. This function moves the voltage operating point based on the measured reactive power, as shown graphically in "Fig. 5". As a result of this function the reactive power in the grid is also automatically shared by the generators in the same way as the active power.

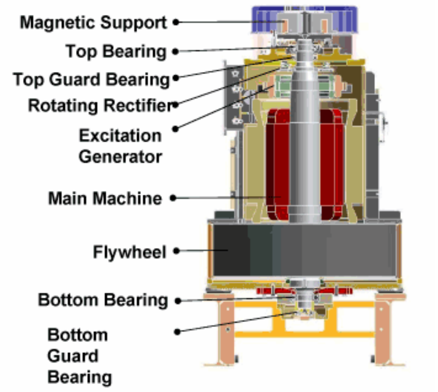

Fig. 3. Construction of the flywheel.

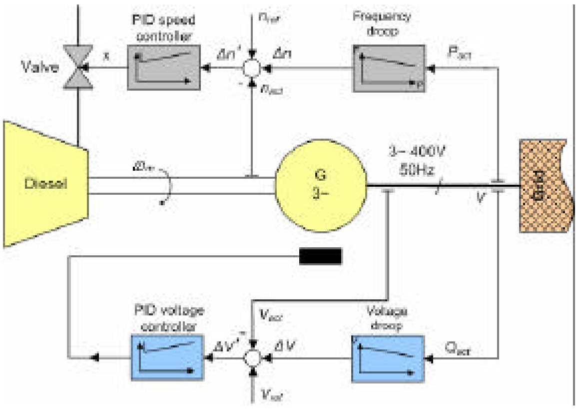

Fig. 4. Control structure of a Diesel or Hydro generator [13].

5.2. Hydro Generators

Apart form different parameters (eg. moment of inertia), the hydro generators operate in the same way as the Diesel generators, so they were modelled with the same control structure, as shown in Figure 4. The hydraulic characteristics of the penstock were neglected in the modelling of the Flores power system.

5.3. Wind Turbines

The wind turbines generators (WTGs) operate as power sources with power output independent on system voltage or frequency. The power output of the WTGs is related to wind speed with power output proportional to wind speed cubed. The WTGs used in Flores also have a manually set output power limit; if the available output power is larger than the power limit, the WTGs limit their output to be equal to the power limit.

5.4. Flywheel Energy Storage System

"Fig. 6" shows the control strategy and the principle layout of the FESS. The grid-side inverter operates as a Unified Power Flow Controller (UPFC) with the real power setpoint (Pset) and the reactive power setpoint (Qset) being supplied by DFS and DVS functions respectively (described below); Pset has an additional input derived from the state of charge controller.

The flywheel side inverter is responsible for the control of the intermediate dc bus voltage. This control is based on the rotor flux and therefore a flux observer (FO) is implemented. The control unit (CU) determines the target values for the inverter and the control of the switches is based on the space vector modulation (SVM) technique. A state of charge (SOC) controller regulates the nominal speed of the flywheel.

The Dynamic Frequency Support (DFS) algorithm measures the system frequency and sets the real power setpoint (Pset). When the frequency is reduced due to a load change, Pset is made positive and the energy stored in the flywheel is fed into the grid. During a frequency increase, Pset is made negative and the surplus energy in the system is stored back in the flywheel.

The Dynamic Voltage Support (DVS) algorithm operates in a similar way as the DFS algorithm; when measured system voltage is low Qset is made positive and reactive power is fed into the grid; when system voltage is high, Qset is made negative and reactive power is consumed from the grid; thus the FESS helps regulate the grid voltage during system dynamic.

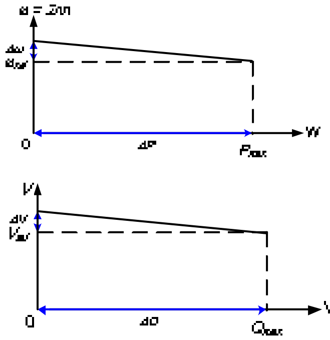

Fig. 5. Frequency droop and voltage droop graphs.

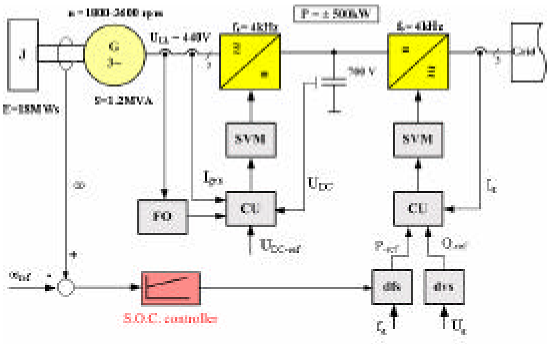

Fig. 6. FESS control.

6.Simulation Results

6.1. Power System without FESS

In the past the system has run with only Diesel, WTGs and Hydro generation. It was found that if the amount of generation provided by the WTGs and hydro generators was increased the system would become unstable, often leading to outages. A particular problem was the cascading tripping of the WTGs during gusty wind conditions or after a line fault. To compensate for this the system was often run with an excess of Diesel generators online.

To observe this problematic behaviour the complete power system was simulated without the FESS. Fig 7 shows the system response to a 350kW step increase in load. This is representative of a single WTG or hydro trip. The system frequency displayed an oscillatory underdamped response; the oscillation frequency of approximately 3Hz and the damping factor was minimal. Notable is the minimum frequency of approximately 48.5Hz and a maximum frequency of 50.5Hz.

A further simulation was done with a 350kW step decrease in load. This represents a small feeder shed or circuit breaker tripping. Fig 8 shows the system response. Again we see the oscillatory underdamped system response.

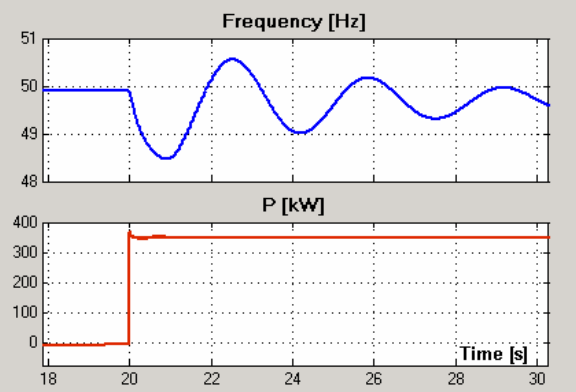

Fig.7: Simulated system response to a 350kW step increase in load with no FESS; blue line shows system frequency; red line shows step load power.

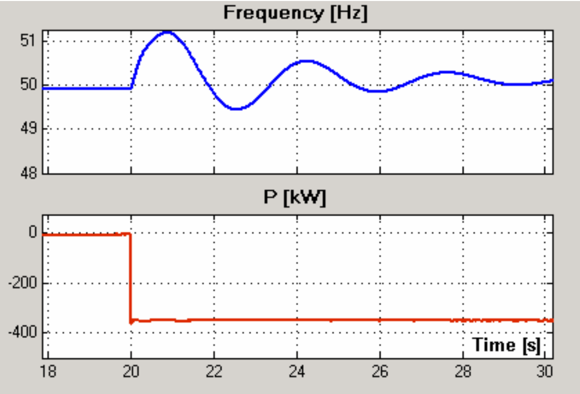

Fig. 8: Simulated system response to a 350kW step decrease in load with no FESS; blue line shows system frequency; red line shows step load power.

6.2. Power System with FESS

With the FESS included in the model the power system was simulated with the 350kW step loads. Fig 9 shows the system response to a 350kW step increase in load and Fig 10 shows the system response to a 350kW step decrease in load. The system frequency is now very well damped, with no oscillation apparent, and it settles to the new steady-state frequency is approximately four seconds. Notable is the minimum frequency of approximately 49.4Hz for the positive load step, and 50.9Hz for the negative load step; a vast improvement on the non-FESS system.

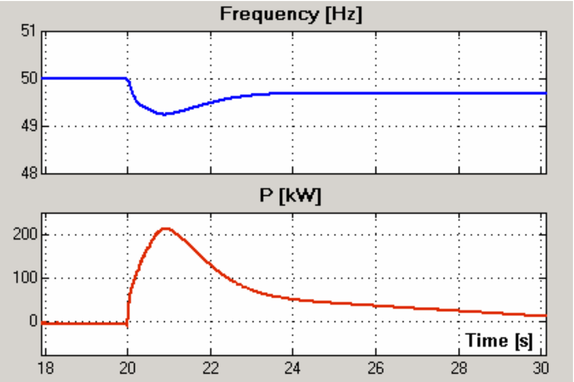

Fig.9: Simulated system response to a 350kW step increase in load with FESS providing dynamic frequency support; blue line shows system frequency; red line shows FESS power.

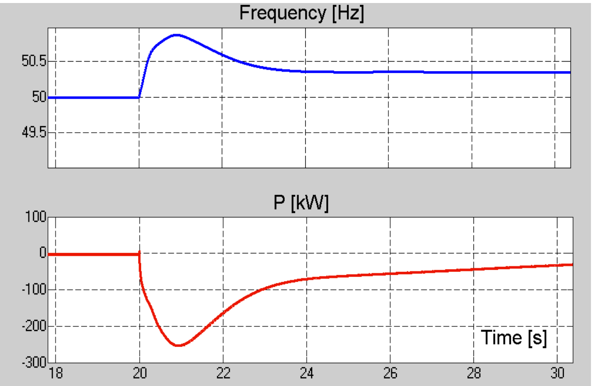

Fig.10: Simulated system response to a 350kW step decrease in load with FESS providing dynamic frequency support; blue line shows system frequency; red line shows FESS power.

7.Measured Results

Prior to enabling the FESS a 350kW step load was put on the system and the system response measured. This is shown in Fig 11. The system frequency displayed an expected underdamped oscillatory response with an oscillation frequency of approximately 3Hz, a minimum frequency of approximately 48.6Hz and a maximum frequency of 50.4Hz; very similar to the simulated results. It is worth noting that the damping of the measured system was significantly larger than simulated. This can be accounted for by the fact that the dynamics of the load add some damping which was not included in the model.

Again, without the FESS enabled, a 350kW step decrease in load was put on the system and the response measured; this is shown in Fig 12. In this case the response of the system was damped significantly more than expected. Further investigation is required to determine the reason for this.

After enabling the FESS a 300kW step load was put on the system and the system response measured. This is shown in Fig 13. The system frequency is now well damped, with no oscillation apparent, and settles to the new steady-state frequency is approximately four seconds. Notable is the minimum frequency of approximately 49.2Hz. It was not possible to create a negative step load on the real system.

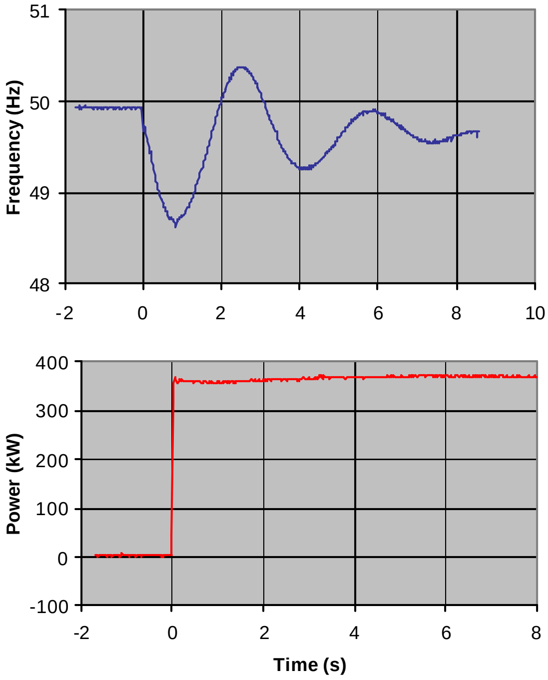

Fig. 11. Measured system response to a 350kW step increase in load with no FESS; blue line shows system frequency; red line shows step load power.

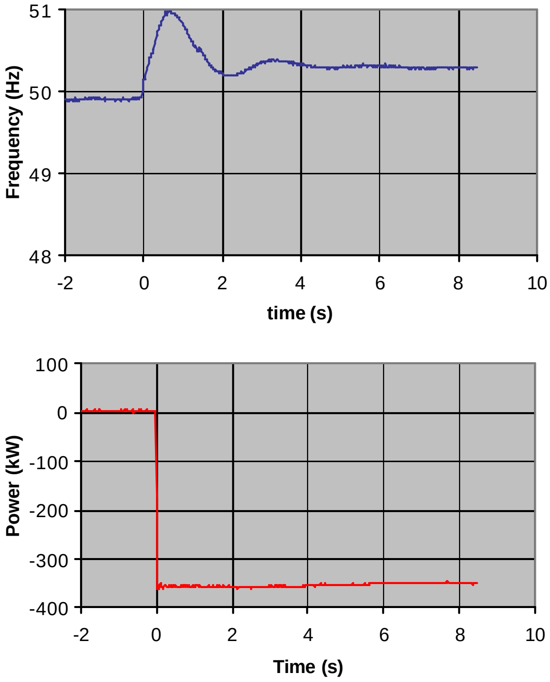

Fig. 12. Measured system response to a 350kW step decrease in load with no FESS; blue line shows system frequency; red line shows step load power.

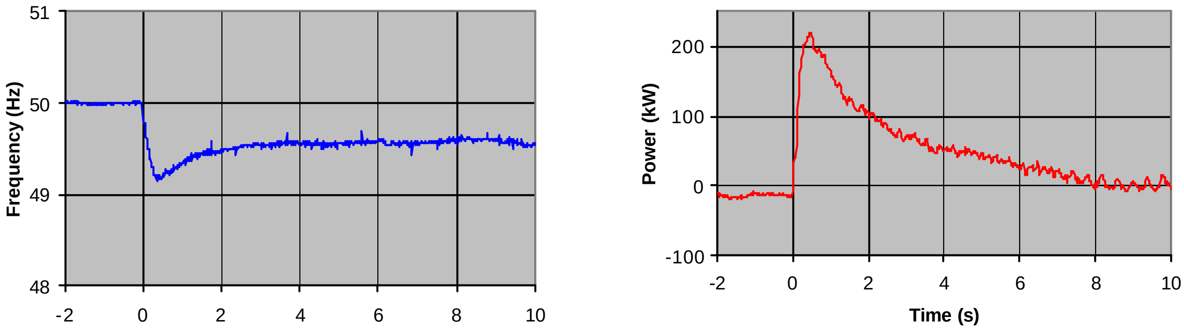

Fig. 13. Measured system response to a 350kW step increase in load with FESS providing dynamic frequency support; blue line shows system frequency; red line shows FESS power.

8.Conclusions

The advantages of connecting a flywheel energy storage system to an isolated power system and the control strategy have been introduced. An existing isolated hybrid power system was modelled highlighting the difficulty of controlling system frequency with high renewable energy penetration. The simulated results and the measured data from the real system were presented. This study shows that the stabilization of an isolated power system is feasible by implementing a high dynamic FESS. The simulation results show clearly the affirmative influence of the energy storage on the transient system performance. Both the simulated and the real system results pointed out that a flywheel in combination with power electronics grid interface is an attractive innovative technology to stabilise isolated weak grids with a high penetration of RESs. Additional to the dynamic performance, installing the flywheel has also a positive fuel saving outcome and reduces load changing stress over the diesel generators. This leads to an increase in the generators life-time and include positive environmental and economical effects.

9. References

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