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Technical Note

Comparative study of flywheel systems in an isolated wind plant

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ABSTRACT

Flywheels can be used as storage elements in islanded power systems and, as a special case, in isolated wind plants, especially those running at almost constant speed and included as a component in diesel groups. Nowadays, systems with variable speed are under development, so the amount of available energy in the flywheel is highly increased. In this paper, a variable speed flywheel based on hydrostatic transmission (HT) is presented. A comparison between an almost constant speed flywheel, a variable speed one based on a power electronic converter, and the proposed system is made by means of simulations in order to evaluate the behaviour of this configuration.

1. Introduction

Power systems based on renewable sources are affected by fluctuations on the generation side due to the seasonal and random nature of the energy resource. At the same time, the loads have also variable power demand. In this case, energy storage systems (batteries, flywheels and so on) play an important role matching up generation and demand. This fact is especially relevant in isolated plants [1–4].

Flywheels are a popular energy storage system in the short and medium term (from seconds to minutes) that can be used in isolated wind plants.

The simplest configuration is constituted by a flywheel coupled to a synchronous generator running at an almost constant speed (less than 5% variation) [4–6]. This set is usually driven by a diesel engine through a clutch (Fig. 1).

In an almost constant speed configuration, only a small part of the energy stored in the flywheel can be extracted, because a deviation of the speed from the nominal one means the same deviation in the isolated-network frequency. So, to keep the quality of power within acceptable levels, the maximum deviation must be limited. For example, for allowing a 1% deviation in speed or frequency, only a 4% of the energy stored in the flywheel can be extracted.

Variable speed flywheels can be used for improving the amount of available energy. Usually, in such a configuration, a flywheel is coupled to an electric machine and power is transferred to the network through an electronic converter (Fig. 2) [2,3,7]. Asynchronous, switched reluctance and permanent magnet machines are some of the generator types used in these applications [8]. Nowadays, light and high-speed flywheels, e.g., made from composite, are under development [9].

In this paper, a configuration that uses a hydrostatic transmission (HT) for power transmission between a flywheel and a synchronous generator is presented (Fig. 3) [10,11]. In this system, the flywheel speed can be greatly changed whereas the synchronous machine can run at an almost constant speed. This behaviour is achieved by means of HT that allows energy transference between systems rotating at different speeds. The robustness and the fact that this is a well-known technology are the main advantages, especially in remote plants [7].

A comparison between an almost constant speed flywheel, a variable speed flywheel with electronic converter and a variable speed flywheel with HT is made in order to validate the proposed system. All the models of these systems have been included in a more general wind energy plant model, in order to evaluate its effectiveness by means of simulation.

2. Almost constant speed flywheel with synchronous generator

The maximum amount of energy stored on a flywheel is given by the equation:

$$E_{\max} = \frac{1}{2} J \Omega^2 \tag{1}$$

where $E_{\max}$ is the energy in J, Ω is the rotational speed in rad/s and J is the inertia moment in kg m^2. However, only a part of this energy

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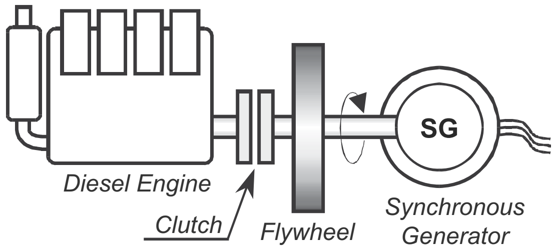

Fig. 1. Flywheel connected to a synchronous generator and diesel engine.

is available for the system, and it depends on the allowed speed variation (Fig. 4):

$$E_a = \left(\Omega_{max}^2 - \Omega_{min}^2\right)/\Omega_{max}^2 \tag{2}$$

where E_a is the percentage of available energy with respect to the maximum stored energy (E_{max}) and Ω_{max} and Ω_{min} are the maximum and minimum flywheel speeds, respectively.

An almost constant speed flywheel is usually connected to a synchronous machine whose speed and frequency are directly related. This is why only small variations in speed are allowed, and only a small amount of the stored energy is available.

In order to evaluate the behaviour of this configuration, the scheme of a real isolated wind plant located in the Canary Islands, formed by an almost constant speed flywheel and a wind energy converter (Fig. 5), has been used for modelling and simulation [5,6,12]. In this plant a set of dump loads driven by solid-state switches is used for consuming the excess energy production. Added to these elements, there is a blade pitch controller and also a dump load controller. With this configuration the frequency can be maintained within 50 Hz ± 2% [4,6,7,12] (Fig. 6). By using Eq. (2), this means that only 6% of the energy stored in flywheel is available.

The diesel engine works only when the power from the wind turbine is less than the load consumption. When the diesel engine is working and the wind increases, the power delivered from the wind turbine increases and the power from the diesel engine decreases. When the power from the diesel engine is close to zero and the energy from the wind is higher than load consumption, the flywheel begins to accelerate in order to store this energy difference. Then, the diesel engine is disconnected when the network frequency is just above 50 Hz + 2%, and is connected again when the frequency is below 50 Hz − 2%.

So, the energy storing behaviour of the flywheel can only be used between 50 Hz ± 2% or, in other words, ±2% around its nominal speed.

3. Variable speed flywheel in different configurations

3.1. Variable speed flywheel with synchronous generator and hydrostatic transmission

3.1.1. Hydrostatic transmission

The main feature of an HT is its ability to allow the energy transference between two systems rotating at different speeds. The main elements of an HT are a variable displacement pump, a fixed displacement motor and the conduits between them (pressure lines) [10]. An electrohydraulic stroke control is used to control the pump displacement volume, as can be seen in the approximate relationship between speeds and flow:

$$q = \alpha Q_{0p}\Omega_p = Q_{0m}\Omega_m \Rightarrow \Omega_p = \frac{Q_{0m}}{Q_{0p}}\frac{\Omega_m}{\alpha} \tag{3}$$

where q is the flow in the pressure lines, α is the effective hydrostatic pump displacement setting, which is the output of the electrohydraulic stroke control, Ω_p and Ω_m are the shaft rotational speeds of pump and motor, respectively, and Q_{0p} and Q_{0m} are the maximum displacement volume of the hydrostatic pump and motor, respectively.

As can be derived from Eq. (3), a wide range of speeds can be obtained in the motor shaft Ω_m; meanwhile, pump speed Ω_p, and so network frequency fr, can be maintained at a reference value by acting on the electrohydraulic stroke control (α) [13].

One of the main advantages of HT is its robustness against torque variations, since these variations are mainly reflected in the pressure. As a consequence, the motor and pump speeds remain almost constant during the steady state. This behaviour can be explained with the following torque equations [13–15]:

$$T_p = \alpha Q_{0p}\mathrm{Pr} \tag{4}$$

$$T_m = Q_{0m}\mathrm{Pr} \tag{5}$$

where T_p and T_m are the shaft torque in the hydrostatic pump and motor, respectively, and Pr is the pressure between the pressure lines.

However, during the transient period, the hydrostatic fluid acts as a spring and the speed oscillates around its final value when the

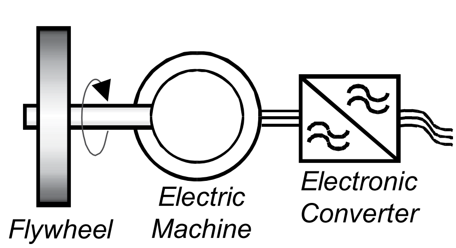

Fig. 2. Variable speed flywheel with electronic converter.

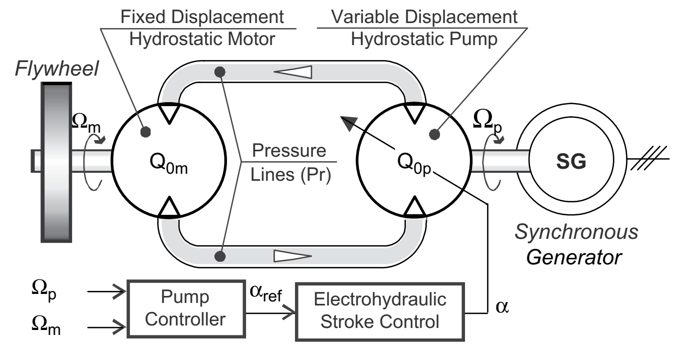

Fig. 3. Energy storage system formed by a flywheel, HT and synchronous generator.

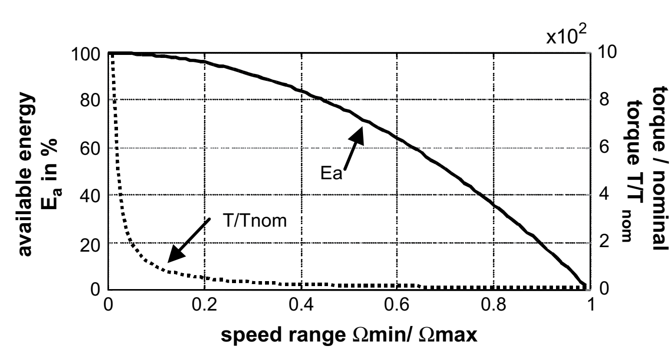

Fig. 4. Available energy (E_a) and torque (T/T_{nom}) vs speed variation range ($\Omega_{min}/\Omega_{max}$) when the nominal power is delivered.

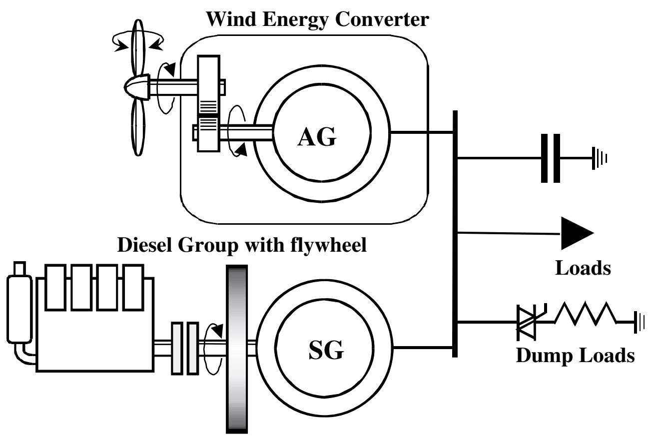

Fig. 5. Wind–diesel plant with almost constant speed flywheel.

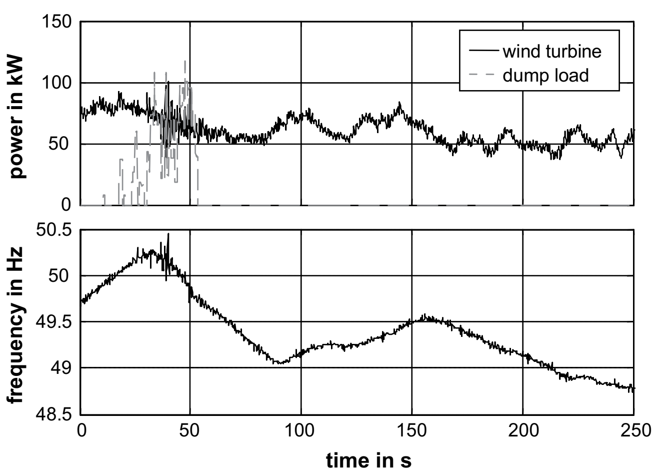

Fig. 6. Power delivered by the WEC vs frequency.

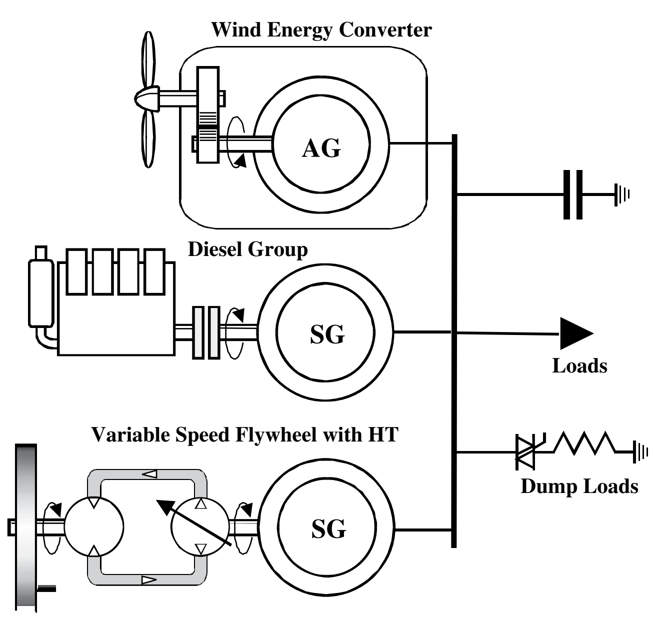

Fig. 7. Wind plant with a variable speed flywheel based on HT.

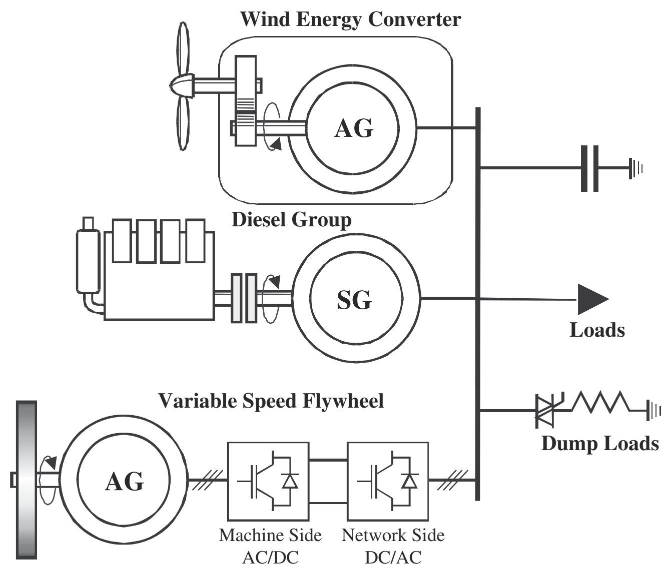

Fig. 8. Wind plant with a variable speed flywheel based on electronic converter.

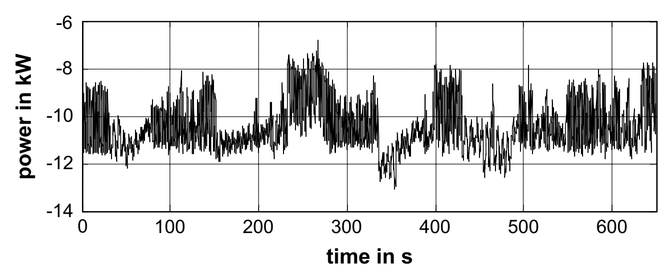

Fig. 9. Power consumption of the flywheel and synchronous generator with no load conditions (Canary Islands – Spain).

Table 1
Operational characteristics of flywheel storage systems

	Flywheel + SG	Flywheel + AG + AC/AC	Flywheel + HT + SG
Nominal speed in rpm	1500	1500	1500
Maximum speed in %	102	102	102
Minimum speed in %	98.00	33.00	33.00
Inertia moment in kg m^2	1067	210	210
Efficiency in %	86.33	84.18	69.93
Maximum stored energy in MJ	13.70	2.70	2.70
Useful energy in MJ	0.91	2.03	1.69
Useful energy in %	6.64	75.36	62.61
Time at nominal load in s	6.06	13.54	11.25
Maximum torque in N m	974.42	2893.73	2893.73
Maximum torque/ nominal torque	102.04	303.03	303.03

leakage flow is taken into account. The controller design and servovalve dynamic characteristic must be able to manage these oscillations (see controller model in Appendix II) [13].

One of the worst characteristics of HT is its efficiency, with values below 70%, especially when the system is not running at nominal conditions.

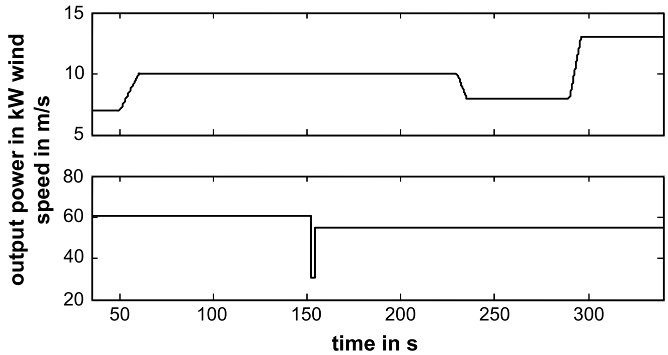

Fig. 10. Wind speed and load conditions during the simulation.

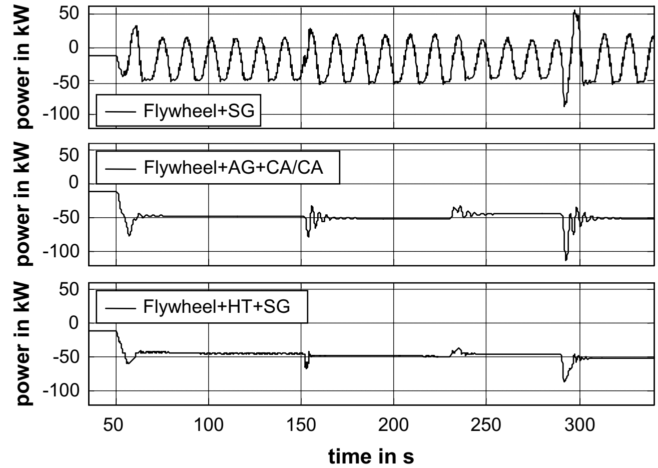

Fig. 12. Power consumption in the storage system.

3.1.2. Storage system based on HT

Once the HT has been described, the storage system can be introduced. A synchronous generator connected to a flywheel by means of an HT forms the proposed system. The control strategy for this system consists of keeping the synchronous machine speed at the synchronous value; meanwhile, the flywheel speed varies in order to compensate the energy balance in the system. This is obtained by means of a pump controller that acts on electrohydraulic stroke control (model given in Appendix II) [7,11,13].

An example of a wind plant with an energy storage system based on flywheel and HT is shown in Fig. 7 [7].

With the variable speed flywheel the energy available is dramatically raised when compared with an almost constant speed configuration, e.g., with a 1:3 speed variation ($\Omega_{\min}/\Omega_{\max} = 1/3$) the amount of available energy, obtained with Eq. (2), is 90%. However, one limitation for speed variation is torque, which is closely related to pressure in HT. When a flywheel is delivering (or storing) the nominal power at low speeds, the torque (or pressure) in the flywheel shaft will be much higher than its nominal value ($T/T_{\mathrm{nom}} \gg 1$), so mechanical parts must be oversized to manage this situation and/or a limit to the managed power as a function of speed must be applied [2].

3.2. Variable speed flywheel with asynchronous generator and AC/AC converter

As an example of variable speed flywheels with electronic converters a configuration formed by a flywheel, an asynchronous generator and an AC/AC PWM bridge has been chosen [8]. This storage system can be seen in Fig. 8 as part of an isolated wind plant, and its model is derived in Appendix II.

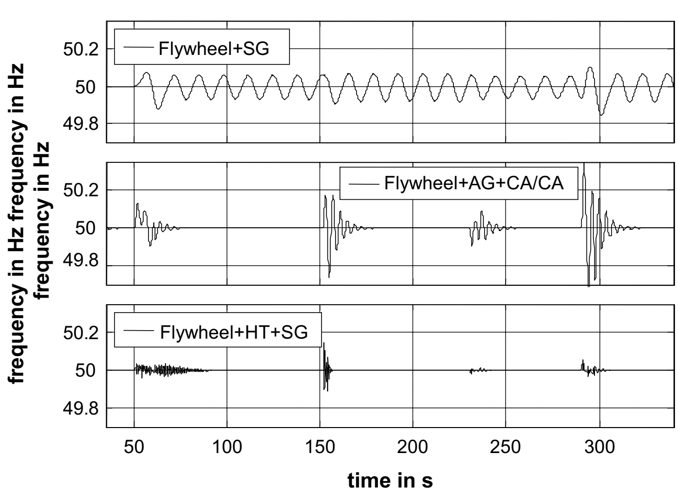

Fig. 11. Frequency in the isolated network.

3.3. Comparison between different flywheel configurations

The three configurations mentioned above must be compared in order to evaluate their capabilities. The parameters used for this purpose are shown in Appendix III and the comparison has been done in two ways:

- Operational characteristics, the steady-state capabilities are analyzed.
- Dynamic simulation, in this section an example of the dynamic behaviour of the three configurations is shown.

3.3.1. Operational characteristics

As shown above, for an ideal storage system driven by a flywheel, the parameters that determine the amount of available energy from storage for being converted into electricity are the inertia moment and the rotational speed variation (maximum and minimum speed). In this way, in the variable speed configuration, the amount of available energy is much higher than in an almost constant system. But the efficiency of the energy conversion system (mechanical from/to electricity) must be taken into account.

The power consumption of the almost constant flywheel running at no load (constant frequency) is one of the values needed for efficiency estimation. This is shown in Fig. 9 for a plant in the Canary Islands [5,6] where a mean power consumption of 10 kW has been measured.

So, taking efficiency into account, the results in Table 1 show the main operational characteristic of the three storage systems:

- *Flywheel + SG*: formed by a synchronous generator (SG) and the flywheel, which rotates at almost constant speed.

Table 2
Results of dynamic simulation for the three systems

	Flywheel + SG	Flywheel + AG + AC/AC	Flywheel + HT + SG
Maximum frequency deviation (Hz)	0.15	0.35	0.15
Duration of frequency oscillations (s)	>100	≈25	≈15

Table 3
Classification of flywheel storage systems

	Flywheel + SG	Flywheel + AG + AC/AC	Flywheel + HT + SG
Available energy	+	+++	+++
Overload capability	+++	+	+++
Robustness	+++	+	+++
Dynamic response	+++	++	+
Efficiency	+++	+++	++

- *Flywheel + AG + AC/AC*: formed by a flywheel connected to an asynchronous generator (AG) and electronic AC/AC converter.
- *Flywheel + HT + SG*: formed by a flywheel connected to an SG by means of an HT.

The time during which an electrical load can be supplied solely from the storage system is much higher for the variable speed configurations, even when the inertia moment is much lower. However, the torque at flywheel shaft is much higher in the variable speed configurations and the mechanical parts must be oversized in comparison with the almost constant speed one.

The lowest efficiency corresponds to the Flywheel + HT + SG due to the efficiency of hydrostatic transmission [13].

3.3.2. Dynamic simulation

In order to simulate and compare the behaviour of the three configurations depicted in this paper, their models are derived in Appendices I and II, and have been implemented using MATLAB©/SIMULINK. The increase in available energy allows the flywheel inertia in variable speed configurations to be much lower than in an almost constant one.

In this section, simulation results for the three isolated wind plants are shown. These systems are studied under two different kinds of perturbations: wind speed variations and electric load variations (Fig. 10). These variations can be numerically described as follows:

- $t = 50$–60 s: wind speed changes from 7 to 10 m/s.
- $t = 152$ s: load changes from 60.5 to 30.3 kW.
- $t = 154$ s: load changes from 30.3 to 54.5 kW.
- $t = 230$–235 s: wind speed changes from 10 to 8 m/s.
- $t = 290$–296 s: wind speed changes from 8 to 13 m/s.

In Figs. 11 and 12 the simulation results are shown. The frequency of the isolated network (Fig. 11) and the power demand in the storage system (Fig. 12) have been chosen to compare the behaviour of the different configurations.

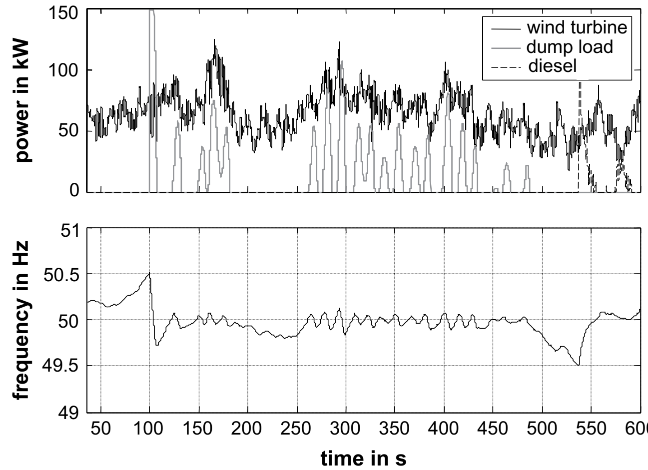

Fig. 14. Power and frequency for the Flywheel + SG configuration.

The frequency can be considered as a quality indicator for the energy delivered by the wind plant. Taking this into account, variable speed configurations have the best response.

However, the instantaneous response of variable speed storage systems against load variations ($t \approx 150$ s) is worse than the response of the almost constant one. In a Flywheel + AG + AC/AC configuration, the system response depends heavily on the ability of the controller to manage it. Instantaneous frequency deviations have very short duration, in the order of milliseconds, and the overall behaviour is not affected.

The case of the Flywheel + HT + SG configuration is quite different, because the response is closely related to the response of electrohydraulic stroke control and the oscillatory behaviour of HT during sudden load variations [13]. The modelled HT (based on a real one) has a commercial electrohydraulic stroke control with a regular response time. A faster control could be implemented. In this way, instantaneous frequency deviations and oscillatory behaviour could be corrected with the appropriate controller.

Results are summarized in Table 2.

The amount of energy transferred between the storage system and the rest of the plant can be seen in Fig. 12. Another consequence

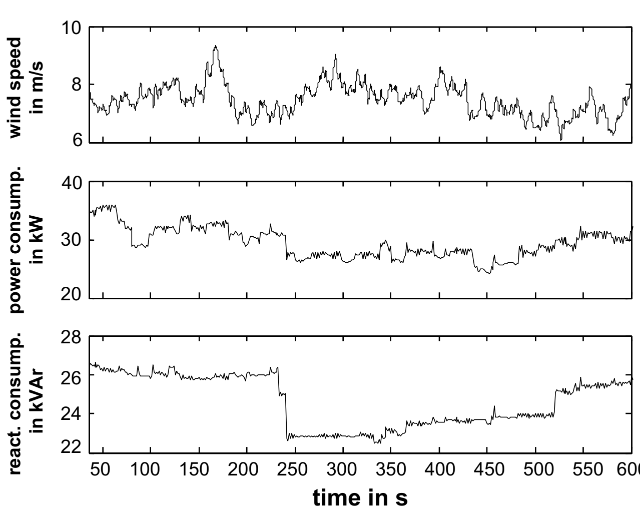

Fig. 13. Measured wind speed and load profiles.

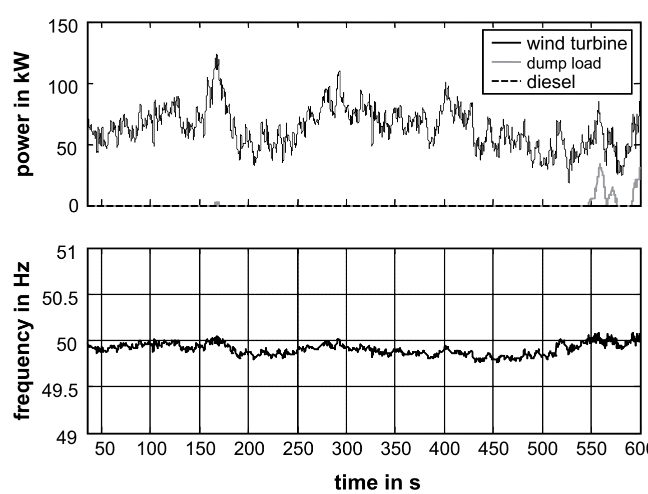

Fig. 15. Power and frequency for the Flywheel + HT + SG configuration.

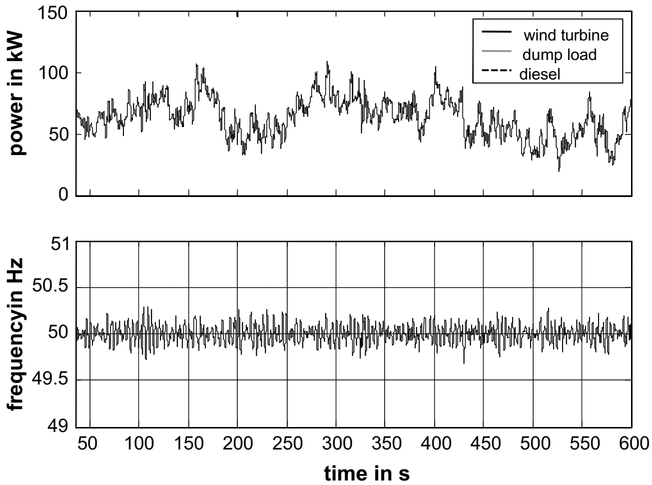

Fig. 16. Power and frequency for the Flywheel + AG + AC/AC configuration.

is that in variable speed configurations the use of dump loads is greatly reduced due to the extra storage capacity.

The response of the storage system based on an AC/AC converter and an HT is very similar. However, this last configuration as a mechanical system could be more robust, and so could be more appropriate for remote installations.

As a summary, in Table 3, a classification under several behaviour aspects is shown.

In Figs. 13–16 a more realistic simulation has been included, in order to evaluate the system behaviour under real conditions. The load profile has been obtained from measurements in a real system [5], and the wind speed has been measured in a wind park. For the simulations, a mean value of wind speed of 7.4 m/s has been considered. The medium values of the consumed real and reactive powers were 33.3 kW and 25.0 kVAR. Results are summarized in Table 4.

The results of these simulations show that similar conclusions can be obtained, where variable speed systems have better frequency performance, less dump load and less diesel units have to be in use.

4. Conclusions

Different storage configurations based on flywheels have been studied in this paper: one of them consisting of an almost constant speed system and two more at variable speed. The main difference between them is the amount of available energy in the flywheel.

The variable speed configurations have a more appropriate behaviour against wind speed variations. However, the almost constant speed configuration has the best response against load variations.

Storage systems based on HT, whose response is very close to that based on an AC/AC converter, are introduced. Systems based on HT are more robust but those based on an AC/AC converter are more efficient.

Table 4
Results of dynamic simulation with more realistic input data

	Flywheel + SG	Flywheel + AG + AC/AC	Flywheel + HT + SG
Maximum frequency deviation (Hz)	0.50493	0.31611	0.2349
Energy lost in dump loads (kWh)	179.8035	0	14.487
Energy generated by diesel engine (kWh)	30.8994	4.5199	8.72

Table 5
Coefficients for power curves

U (m/s)	c_4	c_3	c_2	c_1	c_0
5.7	0	0	−0.51	−1.07	25.09
8.3	7.0e−4	0.009	−0.83	−3.46	98.42
10.8	−2.0e−4	0.025	−1.16	−1.9	178.56
13.4	1.6e−2	−0.001	−1.75	7.63	250.61
16.0	2.7e−2	−0.049	−1.76	19.61	286.95
18.5	2.8e−2	−0.086	−1.33	29.59	293.93
21.1	2.8e−2	−0.116	−0.69	36.82	285.61
23.6	1.0e−2	−0.063	−0.55	34.8	275.93

Appendix I. Wind energy converter model

In this paper, a constant speed wind turbine with variable pitch has been chosen to model a wind energy converter. Its main elements are the turbine (blades, hub and low-speed shaft), the drive train and the asynchronous generator. In the following sections the models for the two first elements are depicted [16], whereas for the asynchronous machine a well-known fourth-order model has been used [17].

Another important component is the power controller that acts on blade pitch to vary electric power delivered by the wind energy converter.

A. Turbine model

The wind turbine captures the wind power and transfers it to the low-speed shaft of the wind turbine, which is attached to the gearbox. In order to model this element, the manufacturer curves for a V27 wind turbine [18] have been approximated by fourth-order polynomials [7]. The result is a set of power curves at different wind speeds whose coefficients are shown in Table 5 and have the following expression:

$$P_{\mathrm{m}}(\beta)|_{U=\mathrm{cte}} = \sum_{k=1}^{4} c_k \beta^k \tag{I.1}$$

where P_{m} is the mechanical power in low-speed shaft, U is the wind speed, β is the pitch angle and c_k are the polynomial coefficients, given in Table 5.

B. Drive train model

The drive train is the part of a wind energy converter that transfers the energy from the low-speed shaft to the high-speed shaft attached to the asynchronous machine. The model for this element involves turbine side inertia, gearbox, flexible coupling

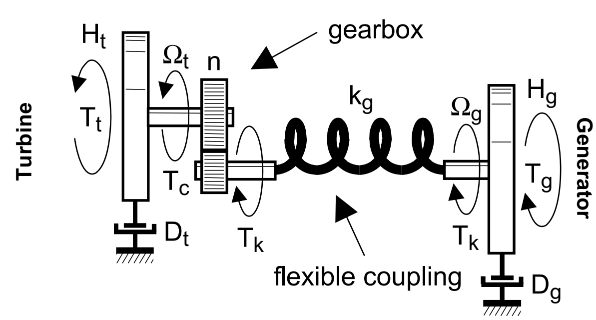

Fig. 17. Drive train elements.

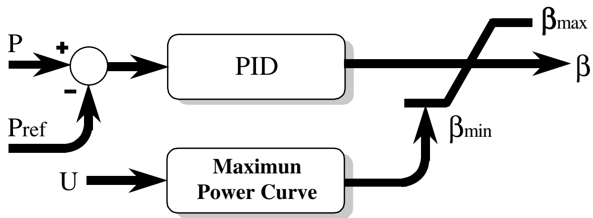

Fig. 18. Blade pitch controller.

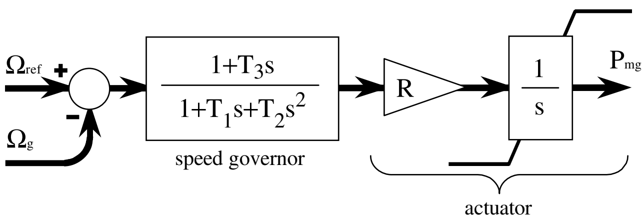

Fig. 19. Diesel engine mode.

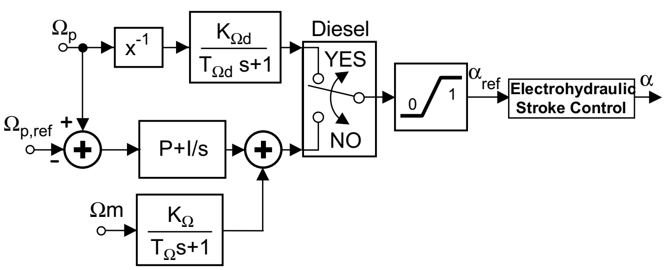

Fig. 20. Pump controller.

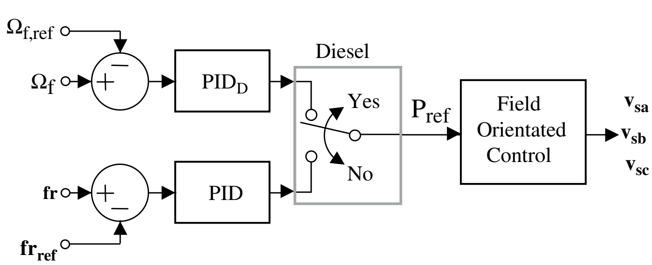

Fig. 21. Block diagram of the machine side converter.

Table 6
WEC parameters

Nominal power (kW)	200
Blades	13.5 m, pitch controlled
Generator	Asynchronous
Number of poles	6
Nominal speed (rpm)	1000
Gearbox ratio	1:23.4

Table 7
Diesel unit parameters

Diesel engine (kW)	236
Generator	Synchronous
Power (kVA)	150
Poles	2

and generator side inertia (Fig. 17). The equations for this element referred to the high-speed shaft are

$$T_t - T_k = \frac{1}{2} H_t \mathrm{d}\Omega_t/\mathrm{d}t + D_t \Omega_t \tag{I.2}$$

$$\mathrm{d}T_k/\mathrm{d}t = k_g(\Omega_t' - \Omega_g) \tag{I.3}$$

$$T_k - T_g = \frac{1}{2} H_g \mathrm{d}\Omega_g/\mathrm{d}t + D_g \Omega_g \tag{I.4}$$

where T_t, T_k and T_g are the mechanical torques in the turbine, coupling and generator shaft, respectively, H_t and H_g are the inertia constants for the turbine side and generator side, respectively, D_t and D_g are the friction constants for the turbine side and generator side, respectively, k_g is the coefficient for the flexible coupling, Ω_g is the speed on the high-speed shaft and Ω_t' is the speed on the low-speed shaft divided by the gearbox ratio (n).

C. Blade pitch controller

The model for the blade pitch β controller has three inputs: wind speed U, delivered power P and the reference power P_{ref}, and it has two different strategies (Fig. 18):

- at low wind speed ($P < P_{ref}$) the pitch angle β is adjusted following a curve that sets, as a function of wind speed U, the value for the minimum pitch angle (β_{min}). In this way, as much energy as possible is extracted from the wind;
- at high wind speed ($P \approx P_{ref}$) the pitch angle is controlled by means of a PID regulator in order to keep the delivered power P at a constant value P_{ref}.

Appendix II. Storage system modelling

A. Almost constant speed flywheel

The almost constant speed flywheel is made up of a flywheel attached to a synchronous machine.

In order to model the generator, a well-known third-order model for synchronous machines has been used [17]. This model also includes the equations for the IEEE type 1S automatic voltage regulator [17].

The diesel engine has been modelled using the expression [19] (Fig. 19):

$$\frac{P_{mg}(s)}{\Omega_{ref}(s) - \Omega_g(s)} = \frac{(1 + T_3 s)R}{s + T_1 s^2 + T_2 s^3} \tag{II.1}$$

Table 8
Storage system parameters

Flywheel (variable speed) (kg m^2)	210
Flywheel (constant speed) (kg m^2)	1067
Generator	Synchronous or asynchronous
Power (kVA)	150
Number of poles	2

Table 9
HT parameters

Pump displacement volume Q_{0b} (cm^3/rev)	250
Motor displacement volume Q_m (cm^3/rev)	200
Maximum pressure (bar)	400

where T_1, T_2, T_3 and R are constants for the model, Ω_g and Ω_{ref} are the synchronous machine speed and its reference value and P_{mg} is the mechanical power on the synchronous machine shaft.

B. Variable speed flywheel with synchronous generator and hydrostatic transmission

In the variable speed flywheel with synchronous generator and hydrostatic transmission, there are two main elements apart from flywheel and synchronous machine: the hydrostatic transmission and the pump controller. The models of these elements are as follows.

(1). Hydrostatic transmission

The dynamic behaviour of HT is affected greatly by the leakage flow (q_l), which has been neglected in Eq. (3) and that can be modelled as [10,13–15]:

$$q_l = \alpha Q_{0p}\Omega_p - Q_{0m}\Omega_m = (C_{lt} + V_b p)\mathrm{Pr} + q_{l0} \tag{II.2}$$

where p is the time derivative operator, Pr is the static pressure, q_l is the leakage flow, q_{l0} is the leakage flow at low pressure, C_{lt} is the ratio between the leakage flow and the pressure and V_b is the ratio between the leakage flow and pressure variations, and is related to compressibility of hydrostatic fluid.

The two terms on the left side of Eq. (II.2) are the flows of pump and motor, respectively, whose difference, on the right, is the leakage flow.

As can be seen in Eqs. (4) and (5) the torque is related to pressure and the flow is only affected by pressure through the leakage flow, see Eq. (II.2).

The mechanical equations for the pump–SG and the motor–flywheel are

$$T_m = (B_m + J_m p)\Omega_m + B_{Pr}\mathrm{Pr} \tag{II.3}$$

$$T_{es} - T_p = \left(B_p + J_p p\right)\Omega_p \tag{II.4}$$

where J_p is the inertia of the set formed by the hydrostatic pump and the synchronous generator, J_m is the inertia of the set formed by the hydrostatic motor and the flywheel, B_p and B_m are constants for the mechanical losses, B_{Pr} is the dry friction coefficient and T_{es} is the electromagnetic torque in the SG.

The electrohydraulic stroke control can be modelled as a second-order lineal system (Fig. 20):

$$G(s) = \frac{\alpha}{\alpha_{ref}} = \frac{c}{s^2 + bs + c} \tag{II.5}$$

(2). Pump controller

In this variable speed configuration a pump controller is needed in order to act over electrohydraulic stroke control and to allow the correct storage operation. The model for this controller is shown in Fig. 20 [7,13]. The controller behaviour depends on the diesel group operation. When the diesel group is running, the controller keeps the flywheel–motor speed (Ω_m) close to its nominal value (see block with $K_{\Omega d}$ and $T_{\Omega d}$ in Fig. 20) [7,13]. However, when the diesel engine is disconnected, the controller tries to maintain the pump–SG speed (Ω_p) at the synchronous one ($\Omega_{p,ref}$) by means of a classical PI regulator.

C. Variable speed flywheel with asynchronous generator and AC/AC converter

For variable speed flywheel with asynchronous generator and AC/AC converter, the model for each component has been depicted before, so only the converter case is explained in the following paragraphs.

The AC/AC converter is formed by a PWM converter in the network side and a PWM converter in the machine side that are connected through a DC link. The dynamic behaviour of the electronic converter has been neglected because its time constants are much lower than the electromagnetic and mechanical ones. In this way, steady-state equations have been employed.

In the machine side converter, as shown in Fig. 21, an indirect field-orientation control of PWM voltage-regulated inverter [17,20] has been used together with a PID regulator in order to maintain the network frequency fr at its rated value fr_{ref}, e.g., 50 Hz [7]. The outputs for this controller are stator voltages of asynchronous machine: v_{sa}, v_{sb} and v_{sc}.

When the diesel group is connected the controller behaviour is altered in order to keep the flywheel speed Ω at its nominal value Ω_{ref} (see PID_D in Fig. 21).

The network side converter is PWM current-regulated, where the injected reactive power is zero and the real power is the same as that delivered by the machine stator.

Appendix III. Main simulation parameters

In Tables 6–9, the main simulation parameters used during the simulation are presented.

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