Overview of energy storage in renewable energy systems

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Abstract— **In this paper, we present an overview of energy storage in renewable energy systems. In fact, energy storage is a dominant factor. It can reduce power fluctuations, enhances the system flexibility, and enables the storage and dispatching of the electricity generated by variable renewable energy sources such as wind and solar. Different storage technologies are used in electric power systems. They can be chemical, electrochemical, mechanical, electromagnetic or thermal. Energy storage facility is comprised of a storage medium, a power conversion system and a balance of plant. In this work, an application to photovoltaic and wind electric power systems is made. The results obtained under Matlab/Simulink are presented.**

Keywords- Energy storage, Batteries, Hydrogen energy storage, Mechanical storage, Electromagnetic storage, Thermal energy storage.

I. INTRODUCTION

The development of renewable energies and the need for means of transport with reduced CO_2 emissions has generated new interest in storage, which has become a key component of sustainable development. Energy storage is a dominant factor in renewable energy plants. It can reduce power fluctuations, enhances the system flexibility, and enables the storage and dispatching of the electricity generated by variable renewable energy sources such as wind and solar. Different storage technologies are used in electric power systems. They can be chemical or electrochemical, mechanical, electromagnetic or thermal storage [1-12]. Generally, an energy storage facility is comprised of a storage medium, a power conversion system and a balance of plant. For electrochemical storage, there are many different types of batteries and most of them are subject to further research and development. In PV systems, several types of batteries can be used: Nickel-Cadmium (Ni-Cd), Nickel-Zinc (Ni-Zn), lead-acid. Nevertheless, it must have some important properties such as high charge or discharge efficiency, low self-discharge, long life under cyclic charge-discharge. For Hydrogen Energy Storage (HES), generally the hydrogen system consists of an electrolyser, a pressurized gas tank and fuel cells. The electrolyser converts electrical energy into chemical energy in the form of hydrogen during periods of surplus electrical generation. This hydrogen is stored until there is a shortage of electrical energy and then it is reconverted by a fuel cell (hydrogen and air oxygen) to electricity, to energize the loads of the power plant. Hydrogen can store energy for long periods. Different hydrogen storage modes are used [2].

Mechanical storage can be a flywheel energy storage (FES), a pumped hydro energy storage (PHES) or a compressed air energy storage (CAES) [3]. In an electromagnetic storage, we can have super capacitor energy storage (SES) and superconducting magnetic energy storage (SMES). In thermal energy storage (TES) system, we use materials that are kept at high/low temperature in enclosures [2].

In this paper, we present an overview of these different energy storages. An application of two types of storage to photovoltaic and wind electric power systems is made, and the results obtained under Matlab/Simulink are presented.

II. ENERGY STORAGE

Generally, energy storage facility includes a storage medium, a power conversion system and a balance of system. The various storage technologies used in renewable electricity systems can be chemical, electrochemical, mechanical, electromagnetic or thermal.

A. Electrochimical Storage

The desired battery is obtained when two or more cells are connected in an appropriate series/parallel arrangement to obtain the required operating voltage and capacity for a certain load. In the market, there are many different types of batteries and most of them are subject to further research and development. In PV systems, several types of batteries can be used: Nickel-Cadmium (Ni-Cd), Nickel-Zinc (Ni-Zn) or lead-acid. Nevertheless, it must have some important properties as high charge or discharge efficiency, low self-discharge and long cycle life [4-6].

1. Nickel-cadmium (NiCd) batteries

The Ni-Cd batteries are commonly known as relatively cheap and robust. The positive nickel electrode is a nickel hydroxide/nickel oxyhydroxide ($Ni(OH)_2$/$NiOOH$) compound, while the negative cadmium electrode consists of metallic cadmium (Cd) and cadmium hydroxide ($Cd(OH)_2$). The electrolyte is an aqueous solution of potassium hydroxide (KOH). Due to the disadvantages of its life span and the negative environmental impact of cadmium, the Ni-Cd technology is not very applicable in renewable energy systems.

2. *Nickel-Hydrogen batteries*

Nickel-Hydrogen battery has some advantages such as long cycle life, resistance to overcharge and good energy density, but it has a high cost, a high cell pressure and a low volumetric energy density. It is used generally in space applications and communication satellites.

3. *Nickel-Metal Hydride batteries*

These batteries are used generally as a commercial consumer product. Their disadvantages are high self-discharge and high pressure leading to failure.

4. *Nickel-zinc batteries*

The positive electrode is the nickel oxide but the negative electrode is composed of zinc metal. In addition to a better environmental impact, this type of battery has a high energy density (25% higher than nickel-cadmium).

5. *Lead-acid batteries*

The lead-acid batteries are the most used in PV applications, especially in stand-alone power systems because they are spill-proof and easy to transport. The lead-acid battery consists of two electrodes immersed in sulfuric acid electrolyte. The negative one is attached to a grid with sponge metallic lead, and the positive one is attached to a porous grid with granules of metallic lead dioxide. There are two types of lead acid batteries (flooded (FLA) and valve-regulated (VRLA)).

6. *Sodium-sulfur (NaS) batteries*

In a sodium-sulfur battery, sodium and sulfur are in liquid form and are the electrodes, sodium being the cathode and sulfur being the anode. They are separated by alumina which has the role of electrolyte. This one allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfide. This type of battery has a high energy density, high efficiency of charge/discharge (89–92%) and long cycle life, and it is fabricated from inexpensive materials.

7. *Sodium Nickel Chloride Batteries*

Sodium Nickel Chloride Battery is also known as ZEBRA (Zero Emission Battery Research Activity) battery and it's a system operating at around 270°C to 350°C. The chemical reaction in the battery converts sodium chloride and nickel to nickel chloride and sodium during the charging phase. During discharge, the reaction is reversed. Each cell is enclosed in a robust steel case.

8. *Lithium ion (Li-ion) batteries*

The operation of Li-ion batteries is based on the transfer of lithium ions from the positive electrode to the negative electrode during charging and vice versa during discharging. The positive electrode of a Li-ion battery consists of one of a number of lithium metal oxides, which can store lithium ions and the negative electrode of a Li-ion battery is a carbon electrode. The electrolyte is made up of lithium salts dissolved in organic carbonates.

9. *Flow batteries or Vanadium-Redox Flow Battery (VRB)*

The vanadium-redox flow battery stores energy in two tanks that are separated from the cell stack. There are three kinds of flow batteries:

- Vanadium Redox (VR),
- Polysulphide Bromide(PSB),
- Zinc Bromine (ZnBr).

In flow batteries, the energy is a potential chemical energy stored in the electrolyte solutions. The advantages of VRB are [1]:

- Increased energy densities by more than 70% due to increased vanadium ion concentrations
- Operation at increased current densities
- Increased operating temperature window
- Storage of megawatts/ megawatt-hours of power and energy in simple designs
- flexibility to design power and energy capacities separately
- Discharging power for up to 12 hours at a time
- Quickly brought up to full power when needed
- Long cycle life (>5,000 deep cycles) due to excellent electrochemical reversibility
- High energy efficiencies
- No highly reactive or toxic substances, minimizing safety and environmental issues
- Sit idle for long periods of time without losing storage capacity
- Low maintenance cost.

B. *Hydrogen energy storage (HES)*

Hydrogen is a key enabling technology for the advancement of renewable energy applications for electricity generation including wind and solar sources. Hydrogen is the fuel with the highest energy per mass as compared to the other ones. However, its low ambient temperature density requires the development of advanced storage technologies to reach higher energy density. Different hydrogen storage modes can be used:

- compressed,
- liquefied,
- metal hydride, etc.

For example for a wind system or a hybrid wind/ photovoltaic (or hydro) system supplying a load (Fig.1), we can add battery system for short term storage and also to stabilize the system against fluctuations in energy sources, but for a long-term storage, an electrolyzer coupled to a hydrogen storage tank is used.

C. *Mechanical storage*

1. *Flywheel electric energy storage*

Flywheel electric energy storage system includes a cylinder with a shaft connected to an electrical generator. Electric energy is converted by the generator to kinetic energy which is stored by increasing the flywheel's rotational speed. The stored energy is converted to electric energy via the generator, slowing the flywheel's rotational speed.

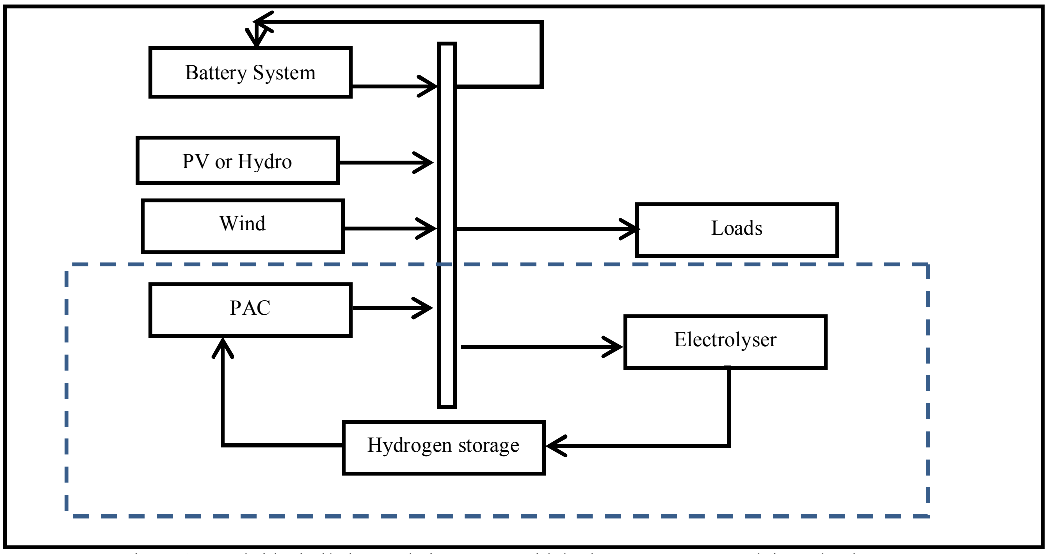


Figure 1. Hybrid wind/ photovoltaic system with hydrogen storage supplying a load

For wind standalone applications storage cost still represents a major economic restraint. Energy storage in wind systems can be achieved in different ways. However the inertial energy storage adapts well to sudden changes of the power from the wind generator. Moreover, it allows obtaining very interesting power-to-weight characteristic in storing and delivering power.

The reference speed for the flywheel is determined by:

$$\Omega_{ref} = \sqrt{\frac{2.E_{c\,ref}}{J_t}} \tag{1}$$

With:

$$J_t = J_{IG} + J_{Flywheel} \tag{2}$$

The reference speed is limited in order to maintain the IG in the area of operation at constant power and not exceed the maximum speed of the flywheel.

Figure 2 represents the torque and power as a function of speed. We notice that:

- For $0 \le \Omega \le \Omega_{rated}$ the torque may be maximal giving up a power proportional to the speed $P_{IG} = k \cdot \Omega$.
- For $\Omega \rangle \Omega_{rated}$ the power is maximum and corresponds to the rated power of the machine, the electromagnetic torque is inversely proportional to the speed $T_{em} = k/\Omega$

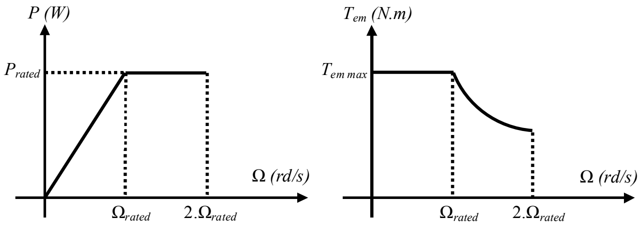


Figure 2. Power and torque as a function of speed

So, if we want to have the machine rated power, it is necessary to use it beyond its rated speed, which lets us to consider the speed as the lower limit storage and the dual value of speed as the upper limit storage.

Thus, a field weakening operation will be necessary to obtain a constant power in the speed range 1500 to 3000 rpm. The reference flux is then determinate by:

$$\Phi_{ref} = \begin{cases} \Phi_{rated} & \Rightarrow \quad if\ |\Omega| \le \Omega_{rated} \\ \Phi_{rated} \cdot \dfrac{\Omega_{rated}}{|\Omega|} & \Rightarrow \quad if\ |\Omega| \rangle\ \Omega_{rated} \end{cases} \tag{3}$$

With Ω Flywheel speed, Ω_{rated} : rated speed, Φ_{rated} : rated flux and Φ_{ref} : Reference flux.

2. *Pumped Hydro Energy Storage (PHES)*

Pumped Hydro Energy Storage (PHES) system consists of a pumped hydro system with two large water reservoirs (upper and lower), an electric machine (motor/generator) and a reversible pump-turbine group (Fig.3). It is considered as an attractive alternative for energy storage due to its main advantages:

- provides ancillary services at high ramp rates,
- provides benefits from intraday energy price variation (releasing energy at high demand periods and buying energy at off-peak periods).
- can be started-up in few minutes
- its autonomy depends on the volume of stored water.

3. *Compressed Air Energy Storage (CAES)*

The basic idea of compressed air energy storage (CAES) is to compress air using inexpensive energy, and the compressed air (released into a combustion turbine generator system and sent through the system's turbine) is used to generate energy. There are two types of storage:

- Compressed air is stored in underground geologic formations (salt formations, aquifers) for larger CAES plants,

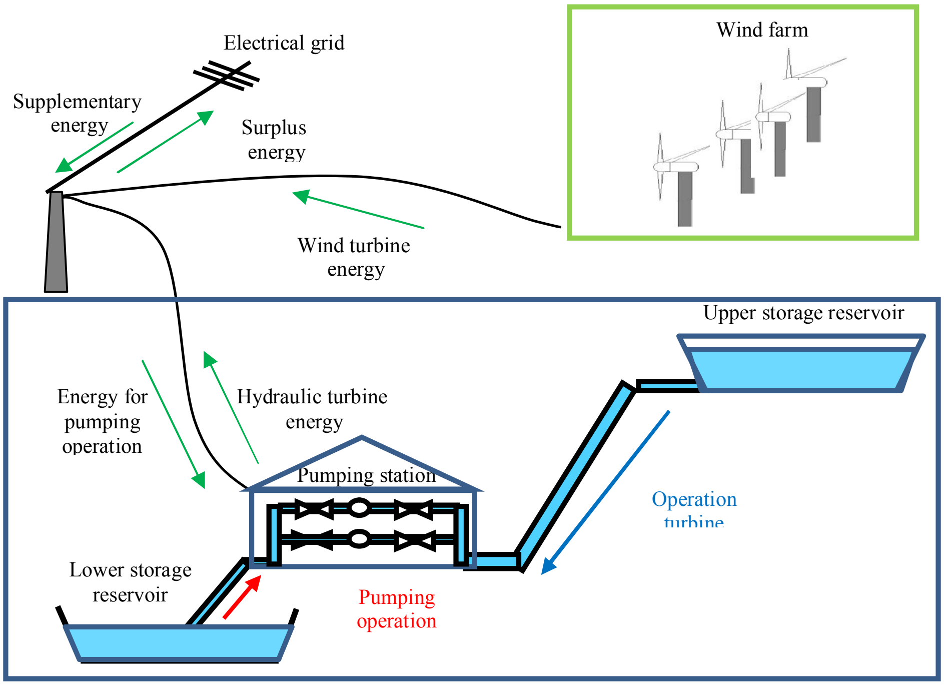


Figure 3. Hybrid pumped hydro/wind energy

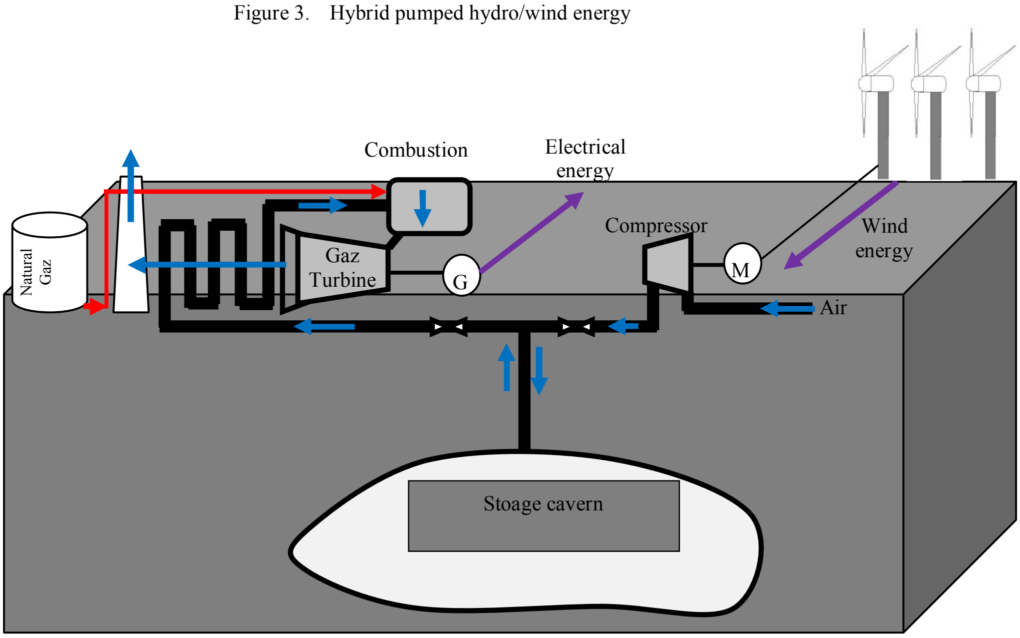


Figure 4. Compressed air energy storage basis

- Compressed air is stored in tanks or large on-site pipes for smaller CAES plants.

In offshore wind systems, pipelines are used as an alternative storage for compressed air. The proposed system (Fig.4) is able to provide large energy storage.

D. Electromagnetic storage

1. Super capacitor energy storage (SES)

It is known as electric double-layer capacitors, as super capacitors (SC), electrochemical double layer capacitors (EDLCs), or ultra-capacitors. They use polarized liquid layers between conducting ionic electrolyte and conducting electrode to increase the capacitance. They allow a much higher energy density, with a high power density, but the voltage varies with the energy stored and it has a higher dielectric absorption. Their important parameter is the relatively low, state-of-charge-dependent maximum voltage of 2.5 volts and a great efficiency (around 95 %). In wind energy conversion system, SES are used to suppress fast wind power fluctuations but with a small time scale, thus they can be considered only as a support for wind turbines systems and generally they are combined with a battery system as an hybrid storage system.

2. Superconducting Magnetic Energy Storage (SMES)

This system consists essentially of a coil of cryogenically cooled with a superconducting material, a power conditioning system and a refrigeration system. Energy is stored in the magnetic field created by the flow of direct current in the coil.

This one can be stored as long as the refrigeration is operational. The main advantage of this system is its great efficiency and it can be applied to systems requiring continuous operation and a large number of complete cycles of discharge load. In wind energy conversion system, SMES are generally not used due to the coil which is very sensitive to temperature changes.

E. Thermal energy storage (TES)

In thermal energy storage system, we use materials that kept at high / low temperature in enclosures. We use after a heat engine to produce electrical energy, which will be powered by the recovered heat/cold. Energy input can be provided by the heat from an electrical resistor or by refrigeration/cryogenic procedures. The main applications of TES system are [1-2]:

- industrial cooling (below -18 °C)
- building cooling (at 0-12 °C),
- building heating (at 25-50 °C)
- Industrial heat storage (higher than 175 °C).

III. APPLICATION IN RENEWABLE ENERGY POWER SYSTEM

A. Storage in photovoltaic system

The simplest models are based on electrochemistry. These models can predict energy storage but they are not able to model phenomena such as the time rate of change of voltage under load nor do they include temperature and age effects. A cell is characterized by its capacity. It is an amount of electricity, expressed in Ah, and that it is able to return back after a full charge, and discharged at a constant current. The Peukert equation is an empirical formula which approximates how the available capacity of a battery changes according to the rate of discharge [4, 5].

$$I_{batt}^{n}.t = C \tag{4}$$

Where I_{batt} is the discharge current, n is the Peukert constant, t is the time to discharge at current I_{batt}, C is the capacity according to Peukert, at a one-ampere discharge rate, expressed in Ah.

We can relate the discharge current at one discharge rate to another combination of current and discharge rate. Then we obtain:

$$C_1 = C_2 . \left(\frac{I_{batt\ 2}}{I_{batt\ 1}}\right)^{n-1} \tag{5}$$

Where C_1 and C_2 are capacities of the battery at different discharge-rate states

The state of charge (SOC) at a constant discharge rate can be obtained by the following equation:

$$SOC(t) = 1 - \left(\frac{I_{batt}}{C}\right).t \tag{6}$$

The current is continuously variable over time. We discretize then the above equation by considering the constant current between two calculation steps. We can determine the expression of the change in charge state of the cell at time t_k:

$$\Delta SOC\ (t_k) = \frac{I_{batt\ \ k}}{C_1} . \left(\frac{I_{batt\ \ k}}{I_{batt\ 1}}\right)^{n-1} . \Delta t \tag{7}$$

This approach also takes into account the phases of recharging the battery. Indeed, if the current in the cell becomes negative, its state of charge increases. Ultimately, cell state of charge expressed by:

$$SOC\ (t_k) = SOC\ (t_{k-1}) + \Delta SOC\ (t_k) \tag{8}$$

An application is made under Matlab/Simulink, using CIEMAT model. Simulation results are presented in Fig.5.

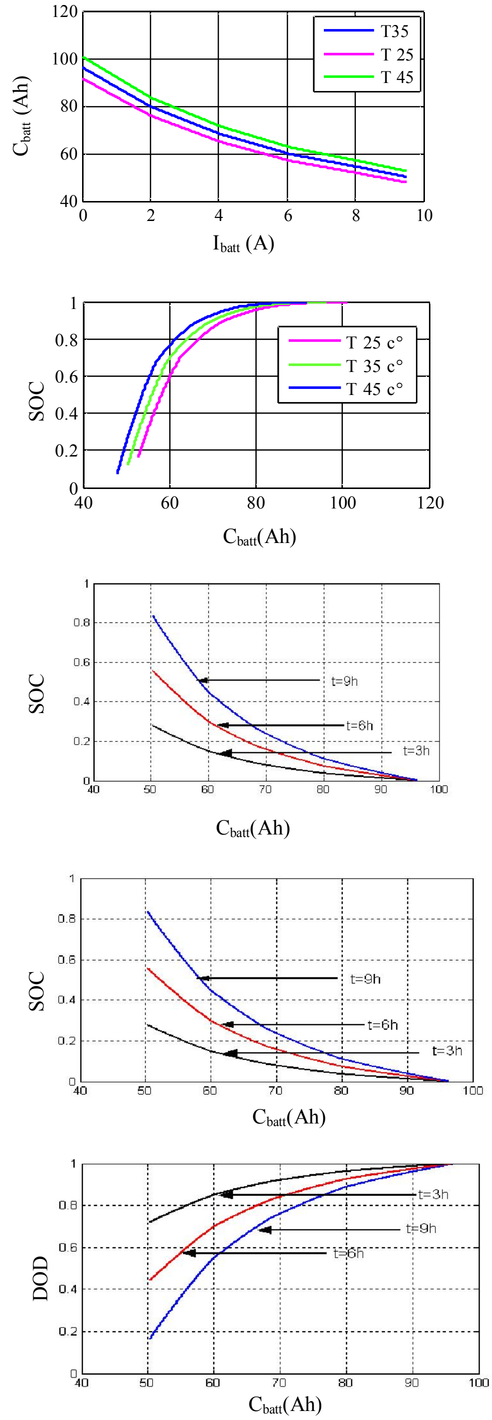


Figure 5. Simulation results with CIEMAT model

B. Storage in Wind system

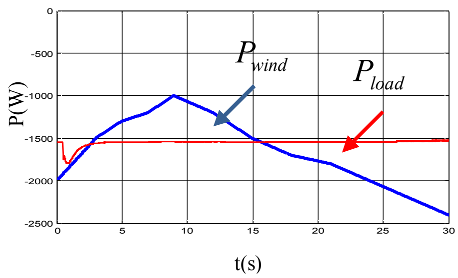
In wind energy conversion system, FES are able to suppress fast wind power fluctuations .We make an application to a WECS based on induction generator. The system is constituted of a wind turbine, an induction generator, a rectifier/inverter, and a flywheel energy storage system

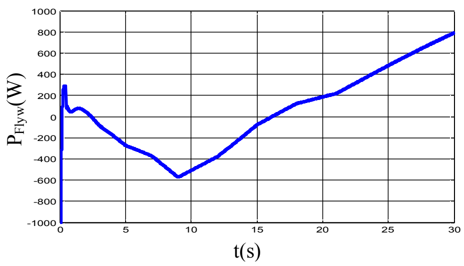
The goal of the device is to provide a constant power and voltage to the load connected to the rectifier/inverter even if the speed varies. This can be achieved mainly by the control of the DC bus voltage at a constant value, and the flywheel energy storage system participates to maintain the power of the load constant as long as the wind power is sufficient. To control the speed of the flywheel energy storage system, we must find a reference speed which must make the system ensure the required energy transfer at any time. The reference speed can be determined by the reference energy. The power assessment of the overall system is given by [3]:

$$P_{ref} = Pl_{oad} - P_{wind} - \Delta P \tag{9}$$

Where P_{ref} is the reference power, P_{load} is the load power, P_{wind} is the wind power and ΔP is the power required to control the DC voltage V_{dc} at constant value.

The application is made under Matlab/Simulink under a wind power profile which provides power continuously required by the load through the SISE. Fig.6 shows that the wind power varies between 1000W and 2400W. It is noted that the power supplied to the load is kept constant through the use of a flywheel energy storage system. The storage power flywheel energy storage depends on the available wind power and the required power by the load. We note that it is positive when the wind power produced is larger than the load power and is negative when there is less power produced than required by the load.





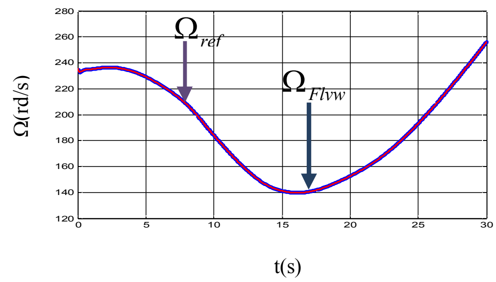


Figure 6. Simulation results with flywheel energy storage

IV. Conclusion

An overview of energy Storage in electric power systems has been presented in this paper. There are various energy storage systems. Each one of them has its own characteristics, such as lifetime, costs, density and efficiency. We can conclude that for energy management applications we use PHS, CAES, electrochemical batteries, flow batteries, fuel cells, solar fuels, and TES. For power quality and short duration, we use flywheels, batteries, capacitors and super capacitors. In other applications, we can use batteries, flow batteries, fuel cells or Metal-Air cells

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