ENERGY MANAGEMENT OF A SMALL-SCALE WIND TURBINE SYSTEM COMBINED WITH BATTERY STORAGE SYSTEM

**RIM BEN ALI¹, MAUGHAL AHMED ALI BAIG², SALWA BOUADILA³
& ABDELKADER MAMI⁴**

^{1,4}*Department of Physics, Faculté des Sciences de Tunis, Université de Tunis El Manar,
Campus Universitaire Farhat Hached, Rommana, Tunis*

²*Department of Mechanical Engineering, CMR Technical Campus, Hyderabad, Telangana, India*

³*Research and Technology Center of Energy, Thermal Processes Laboratory, Hammam Lif, Tunis, Tunisia*

ABSTRACT

Battery storage system regarded as a viable solution to maintain the stability for the wind power generation regarding its availability to exchange active power. The proposed study is based on using a PMSG wind turbine system as primary power source and a battery as an auxiliary power source. The latter has been used as Energy Storage System ESS that has a dual role storing or providing the power mismatching between the generated wind power and load demand. Further, to coordinate operation of power sources, a supervisory control system is evaluated and simulated under three different scenarios of wind speed fluctuations with fixed load demand. The obtained simulation results induced at various situations of wind velocity and their analysis have been included in detail.

KEYWORDS: Energy Management, Wind Turbine System, PMSG Generator, Battery Storage System, Modeling & Simulation

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1. INTRODUCTION

Energy has a critical role in the economic growth and development that due to the significant relationship between electricity consumption and socioeconomic growth. However, the hybrid power system designing a combination of one or more renewable source and one or more conventional energy source worked in stand-alone mode in remote areas. They are used to convert the unregulated power, generated from sources of renewable energy, into useful power for the electrical load (Diab, Lan, Zhang, & Ali, 2016). Therefore, there are many topologies of hybrid power systems, among them: PV/wind/fuel cell/battery (Fathabadi, 2017), PV/Wind Turbine/Battery (Khan, Yadav, & Mathew, 2017), PV/FC/WIND (Nowdeh, Rajabi-ghahnavieh, & Khanabdal, 2012), PV/Wind Turbine (Amorndechaphon, Premrudeepreechacharn, Higuchi, & Roboam, 2012) and Wind Turbine/Battery (Sarrias, Fernández, García, & Jurado, 2012). The hybrid system aims to provide a specific pattern of load with minimum cost and maximum of response to load power demand (Nowdeh et al., 2012).

The wind power generation is experiencing a remarkable growth in terms of installed power and energy generation in many countries around the world over the past decade (Abdullah, Yatim, Tan, & Saidur, 2012). It is considerate as one of the most promising and inexhaustible sources of renewable energy due to its advantages in terms of efficiency, mobility, cost and reliability and also the negative environmental impacts to be one of the

potential sources of alternative energy for the future.

In other hand, energy storage systems play also an important role in hybrid power systems regarding their availability to exchange active power. Different aspects of ESS are studied for wind power, such as superconducting magnetic energy storage, compressed air energy storage, flywheels, hydro pumped storage, super capacitors and batteries, which are known as a viable solution to provide a satisfactory behavior with high energy requirements.

The wind turbine system combined to the battery storage system has been described in the literature as hybrid power systems. In(Sarrias-Mena, Fernández-Ramírez, García-Vázquez, & Jurado, 2014),a hybrid system consists of a wind turbine system and electrochemical batteries is studied for improving profitability of wind power. The hybrid system is simulated under various operating conditions. Indeed, a conventional wind turbine system without ESS is also considered as a base-case to highlight the main benefits of the hybrid power system. In another study (Saheb Koussa et al., 2017), a managing system consisting of a wind turbine equipped with battery and a generator supplying load is studied, designed and built for representing a typical house consumption. In addition, a home energy management system, including small-scale wind turbine system and battery bank is considered to determine optimal charging-discharging pattern for the battery and also to specify optimal capacity with optimal rated power of the battery at the same time(Hemmati, 2017).

Hence, the goal of this study is to develop an Energy Management Strategy of a hybrid wind turbine integrating an ESS operating in standalone mode (Figure. 1) using MATLAB-Simulink ® of MATLAB. This paper is organized as follows: The modeling of the mechanical and electrical main components of the small wind turbine based on PMSG generator is described in Section 2. The methodology of the battery storage system is given in Section 3. The supervisory control system is described in Section 4. The results and discussions are shown in Section 5. Finally, conclusions are given in Section 6.

The proposed scheme is outlined in Figure 1 that is combined the PMSG wind turbine and battery as a hybrid power system. A resistance has been used as a load shedding system to dissipate the surplus energy. In this configuration the battery was directly attached to the DC bus without a DC/DC converter that poses two major advantages, which are higher voltage requirements for the ESS and less controllable parameters in the control strategy.

Figure 1: Hybrid PMSG Wind Turbine Plant with Battery Storage System

2. MODELLING OF THE PMSG WIND TURBINE SYSTEM

Firstly, the wind turbine converts the kinetic energy (wind speed) into mechanical energy and then with the help of the PMSG generator mechanical energy is converted into electrical energy.

2.1. Mechanical System Model

The mechanical power output from the turbine is expressed by Eq. 1. (Ben Ali, SCHULTE, & MAMI, 2017)

$$P_w = \frac{1}{2} \rho \pi R^2 V^3 C_p \quad (1)$$

with, ρ is the air density, R is the blade radius and V is the wind speed.

The power coefficient C_p and the torque coefficient C_q can be determined by using, respectively, Eq. 2 and Eq. 3:

$$C_p = C_q \lambda \quad (2)$$

$$C_q(\lambda, \beta) = C_1 (1 + C_2 (\beta + C_3)^{1/2}) + \frac{C_4}{\lambda} (C_5 \lambda_i(\lambda, \beta) - C_6 \beta - C_7 \beta^{C_8} - C_9) e^{-C_{10} \lambda_i(\lambda, \beta)} \quad (3)$$

with:

$$\lambda_i(\lambda, \beta) = 1 / (\lambda + 0.08 \beta) - 0.035 / (C_{11} + C_{12} \beta^3) \quad (4)$$

where, β is the pitch angle and λ is the tip speed ratio, which is calculated as follows:

$$\lambda = \frac{\omega_r R}{V} \quad (5)$$

ω_r is the rotor speed and can be written by Eq. 6.

$$\frac{d\omega_r}{dt} = \frac{P}{J} (T_e - T_w) \quad (6)$$

where, P is the number of pole pairs and J is the moment of inertia.

The torque of the turbine T_w is obtained by Eq. 7. (Wu, Lang, Zargari, & Kouro, 2011)

$$T_w = \frac{1}{2} \rho \pi R^3 V^2 C_q \quad (7)$$

2.2. Electrical System Model

The electromagnetic torque produced by the PMSG generator is given by Eq. 8. (Wu et al., 2011)

$$T_e = \frac{3P}{2} (\lambda_r i_{qs} - (L_d - L_q) i_{ds} i_{qs}) \quad (8)$$

where, λ_r is the rotor flux linkages, L_d and L_q are the dq -axis self-inductance of the synchronous generator.

The dq -axis stator currents and voltages of the PMSG generator are computed as follows:

$$\frac{di_{ds}}{dt} = -\frac{R_s}{L_d} i_{ds} + \frac{L_q}{L_d} \omega_r i_{qs} - \frac{1}{L_d} v_{ds} \quad (9)$$

$$\frac{di_{qs}}{dt} = -\frac{R_s}{L_q} i_{qs} + \frac{L_d}{L_q} \omega_r i_{ds} - \frac{1}{L_q} \omega_r \lambda_r - \frac{1}{L_q} v_{qs} \quad (10)$$

$$v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d \frac{di_{ds}}{dt} \quad (11)$$

$$v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q \frac{di_{qs}}{dt} \quad (12)$$

with, R_s is the stator winding resistance of the synchronous generator.

Furthermore, the mechanical, active and reactive powers are calculated by using respectively Eq. 13, Eq. 14 and Eq. 15:

$$P_m = T_m \omega_m = \frac{T_w \omega_r}{P} \quad (13)$$

$$P_L = 1.5 (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (14)$$

$$P_Q = 1.5 (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (15)$$

The Zero D-axis Current Controller (ZDC) is proposed for control PMSG Generator side Voltage Source Converter to achieve pure DC link voltage. The controller aims to set to zero the d -axis stator current, therefore, the stator current will be equal to i_{qs} (Wu et al., 2011). In this case, the reference dq -axis stator currents of the PMSG generator are calculated as follows:

$$i_{qs}^* = \frac{2}{3P\lambda_r} T_e^* \quad (16)$$

$$i_{ds}^* = 0 \quad (17)$$

with, T_e^* is the electromagnetic torque reference:

$$T_e^* = K_{opt} \omega_r^2 \quad (18)$$

$$\text{with: } K_{opt} = \frac{0.5 \rho \pi R^5 C_p(\lambda_{opt})}{\lambda_{opt}^3} \quad (19)$$

The maximum of power is reached with $\lambda_{opt} = 8.1$ that gives $C_p(\lambda_{opt}) = 0.48$. Therefore, two PI controllers are used to generate the dq -axis reference voltages v_{ds}^* and v_{qs}^* for the AC/DC rectifier.

2. 3. AC/DC Rectifier

The output voltage and the dq -axis stator currents are expressed as follows:

$$\dot{V}_c = \frac{3}{2C} \frac{V_{ds}^* i_{ds}}{V_c} + \frac{3}{2C} \frac{V_{qs}^* i_{qs}}{V_c} - \frac{1}{C} i_v \quad (20)$$

$$\frac{d}{dt} i_{ds} = \frac{1}{L} V_{ds} - \frac{1}{L} V_{ds}^* + \omega i_{qs} \quad (21)$$

$$\frac{d}{dt} i_{qs} = \frac{1}{L} V_{qs} - \frac{1}{L} V_{qs}^* - \omega i_{ds} \quad (22)$$

with, ω is the electrical angular speed of the generator, L is the stator induction of the generator, i_v is the current in the DC-link and C is the DC-link capacitor.

3. BATTERY STORAGE SYSTEM

The battery bank has a dual role mismatching between the actual generated wind power and load demand. It can be considerate as a storage device powered only when there is a surplus of energy generated by the wind turbine system or a source of power to cover the required power needed by the load when the generated power is not enough to ensure the required power for the load.

The process of charging and discharging can be modeled as follows (Borowy & Salameh, 1996):

$$E_{B_charge}(t) = E_B(t-1) + (E_{WT}(t) - E_L(t)) \eta_b \quad (23)$$

$$E_{B_discharge}(t) = E_B(t-1) - (E_L(t) - E_{WT}(t)) \quad (24)$$

where, E_L is the load demand (W), E_{WT} is the generated power from the wind turbine system (W) and η_b is the battery efficiency (%).

The battery capacity can be calculated according to the following relation (Daud & Ismail, 2012):

$$C_{Battery} = DA(E_L - E_{WT}) / (\eta_{inv} \eta_b \cdot DOD) \quad (25)$$

with, DA is the Daily Autonomy, η_{inv} is the inverter efficiency (%) and DOD is the Depth Of Discharge of the battery (%).

Limitations of battery charging and discharging operations related to the State of Charge (SOC), which is constrained as follows:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (26)$$

$$SOC_{min} = (1 - DOD) * C_{battery} \quad (27)$$

with, $C_{battery}$ is the nominal capacity of the battery, SOC_{max} presents upper limit that considered 100% and SOC_{min} is the lower limit.

3. 1. Performance Evaluation

To prevent battery storage system against shortening their life or even their destruction, the charge and discharge operations were controlled according to the state of the device to avoid the overcharge when high power is produced by the wind turbine system and/or when low load demand exists. Besides, the charging process is stopped when the state of charge reaches its maximum value and it's the same for the discharging process when the state of battery power decreases to its minimum level. Therefore, the Loss of Power Supply Probability can be computed as (Borowy & Salameh, 1996):

$$LPSP = \Pr\{E_B(t) \leq E_{Bmin}; \text{ for } t \leq T\} \quad (28)$$

$E_B(t)$ is the actual energy in the battery and E_{Bmin} is the minimum energy can be stored in the battery.

4. SUPERVISORY CONTROL SYSTEM

To ensure load demand, a lead-acid battery storage system has been associated with the wind turbine system that has many advantages in term of price and satisfactory life. Indeed, a load shedding system is used to offload the surplus generated energy. However, a supervisory control system is required to manage the generated electrical energy and to coordinate the performance of the hybrid power system (wind turbine and ESS). It allows to optimize the use of the energy produced with a reliable response by controlling the active power flow from or to the battery system, considering the SOC of the device and the power mismatching between the power demanded by the load and the power generated by the PMSG wind turbine. Besides, if the wind turbine system does not provide enough power and the battery capacity is sufficient, then the battery will provide the missing power. If the generated power from the PMSG wind turbine exceeds the demand of the load, the excess will be stored in the battery and if the latter is full, the surplus energy will be dissipated in a load shedding system (a resistance). The battery system will be controlled to be activated whenever the SOC state is within the secure operating range. Then, its charge/discharge rate is reduced and the battery life is extended.

Further, there are three operating conditions can be observed, which are summarized in Table 1:

Table.1: Exploitation Strategy

Operating conditions	Battery role	Operating system
$E_{WT}(t) > \frac{E_L(t)}{\eta_{inv}}$	The battery is a load (<i>Charge</i>)	The generated power from the wind turbine system exceeds the demanded power needed by the load. The supplementary power stored in the battery from its nominal capacity and the extra power is lost in a load shedding system, which is a resistance in this study.
$E_{WT}(t) = \frac{E_L(t)}{\eta_{inv}}$	The battery is an inactive device	The generated power by the wind turbine system is totally injected to the load through DC/AC converter.
$E_{WT}(t) < \frac{E_L(t)}{\eta_{inv}}$	The battery is a source (<i>Discharge</i>)	The deficit of power demanded by the load is supplied by the battery.

The primary power source is the wind turbine system, whereas the ESS is an auxiliary power source, storing or providing the power. Therefore, the exploitation mode of the battery is determined only when the production energy from the wind turbine system is deficient.

5. SIMULATION RESULTS

Coordinate operation of a PMSG wind turbine and a battery bank through a supervisory control system is the aim of the present study. The proposed scheme was described and modeled in the previous sections. In the present section, it will be evaluated by simulation under three different scenarios of wind speed fluctuations (High/ Moderate/ Low) with a fixed load demand under MATLAB/Simulink environment.

The first scenario focused on the hybrid system operation with a low wind speed variety; in this case the battery achieved low SOC state. In the second scenario, the hybrid system operation with a moderate wind velocity, then the illustrated battery SOC was varied between 0 and 100%. In the last simulation, the wind power generation was overloaded when the maximum SOC was reached. For this reason, the load shedding system is used to avoid generating surpluses.

The wind speed profile and the measured active powers at different points of the hybrid power system, during the three simulations, are shown in the following figures:

- First scenario: Low wind speed

Figure 2: Wind velocity

Figure 3: Output Measurements According to the Wind Speed Variation

Figure 4: Powers Variation with Low Battery SOC

- Second scenario: Moderate wind speed

Figure 5: Wind Speed Profile

Figure 6: Variation of the Output Measurements

Figure 7: Measured Powers and SOC State

- Third scenario: high wind speed

Figure 8: High Wind Velocity

Figure 9: Flow Measurements of the Output Parameters

Figure 10: Output Powers and SOC Measurement

The output active power generated by the PMSG wind turbine is caused by the wind speed variability, which is used as input variable to the model of wind turbine system. It presents the principal parameter to evaluate the hybrid generation system according to the power mismatching between its variation and the load demand. In this study, the power demanded by the load was fixed at 1.5 kW that is satisfied during the windy period (third scenario) where the produced

wind power is varied between 0 and 4.5 kW. In this case, the power accumulates at the battery reached its maximum value (2 kW) when the wind speed achieves 15.7 m/s and the surplus of power is dissipated through the resistance.

Under a moderate wind velocity, the battery supplemented the output active power reached its lowest recommended SOC (discharge) in order to provide the demanded power, which is exceeded the available wind power. Likewise, the power surplus was stored in the battery when the demanded power was reduced below the output active power enabling a battery SOC increase. The measured powers showed in Figure 7 proved the inability of the wind turbine system to ensure the required power when the wind speed is less than 12.4 m/s. Whereas during the windless period (first scenario), the total output active power of hybrid system was only the wind power, which is totally delivered to the load. Nevertheless, its power consumption could not be completely fulfilled.

6. CONCLUSIONS

To coordinate the performance of a hybrid power system incorporated a PMSG wind turbine and a battery bank, a supervisory control system is developed that aims to manage the generated wind energy. The considered configuration is simulated under varied operating conditions of wind velocity with a constant load demand. The results showed the main benefits of incorporating a battery as an ESS to wind power generation. That is able to perform power management, according to load requirement and also it can contribute to the fault ride-through capabilities of wind turbine. In future work, a photovoltaic array can be added to the present power system to generate the electrical energy in the presence of the wind velocity or the lightness and to ensure the maximum SOC state of the battery.

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