MODELING, ANALYSIS AND CONTROL OF A STAND-ALONE HYBRID WIND/BATTERY CHARGEABLE POWER SYSTEM

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Abstract: *The purpose of the present paper is to investigate a controller design and simulations of autonomous hybrid wind turbine system with variable-speed permanent magnet synchronous generator (PMSG) and a system for storing energy. The proposed system is mainly composed of a wind turbine drives permanent magnet synchronous generator, uncontrolled rectifier, DC/DC converter, DC/AC inverter and static loads. Furthermore, the mathematical model of the studied sub-systems and two control loops are considered. The first one is the controller which needed to preserve the DC-link voltage fixed at its desired value. The second one is the controller which needed to regulate the charge/discharge modes of the storage battery. The suggested hybrid wind/energy storage power generation model is considered and analyzed in case of without controller firstly. Then, the considered hybrid wind/energy storage power generation unit with the proposed controller is examined through a step change in wind speed. Digital simulation results show that the power desired by the linked loads may be successfully supplied and transported by the presented hybrid wind turbine and energy storage power generation system based on proportional-integral-derivative (PID) controller. Also, the emulation results show that there a good foretelling of the electrical variable waveforms and good achievement in case of the presented controller emulated with the case of without controller as maintaining the load voltage fixed at its reference values.*

Keywords: *Hybrid wind/storage generation unit; PID control; Stand-alone power system**;** Wind power, Energy storage.*

1. INTRODUCTION

The application for electric power is continuously mounting due to its use in many of the basics of everyday life. Traditional fossil fuel power is unable to reduce the demand of electric power that is required daily. So, today's science and technology require power transferred to be well-founded and must be eco friendly in nature. Thereby renewable sources are discovered to be more effective. One of them is wind-diesel hybrid power system. Recently, research into the employ of renewable energy sources (RES), like wind, hydro power plants and photovoltaic (Mastromauro et al. 2012), Liu et al. 2010) and (Kazmierkowski et al. 2011), for electricity production has been the topic of growing interest. (Mendis et al. 2012) illustrated a stand-alone procedure of wind turbine-based parameter speed generators with highest power pulling out capability. (Yousef 2011) studied the styling of load-frequency control model to upgrade power system dynamic achievement through an extensive domain of employing conditions in the context of predictive control framework. (Ali and Kassem 2011) proposed a power system stabilizer that designed on the context of optimal pole shifting. (Kassem 2016) investigated a model of robust controller system for an isolated generation unit based on a parameter of speed wind and conserving energy system powering dynamic load in the context of sliding mode control. The wind turbine with a variable-speed is suggested to obtain a PMSG that gives a saving energy unit and autonomous dynamic load.

The autonomous or stand-alone power system is an outstanding solution for faraway areas where advantageous services, especially transition lines, are not inexpensive to run or complicated to install because of their high prices and/or difficulties of topography, etc. The autonomous systems may be sub- categorized into popular DC bus or popular AC bus. Changeable feature of wind and solar exporters may be partly control by combination of the two exporters into a perfect collection and therefore the system becomes extra dependable.

The power of one exporter could beat the failure of the other through a specific period of time (Engin 2013 and Dalwadi et al. 2011). Recently, incorporation of diesel generator and battery storage with renewable energy generation is turning into cost-influential solution for determining less applicable and usable renewable energy (Elhadidy and Shaahid 1999 and Kumar et al. 2013). Sedaghat et al. (2012) analyzed a system composed of three wind turbines incorporated with two kinds of diesel generator linked to a changeable load and they proposed a modern multilevel control procedure to control this kind of power system. Then they implemented a novel load system by changeable power request according to load curve. Achievement the efficient Wind Energy Conversion, WEC systems may be used by numerous electrical generators, each of which has various disadvantages and advantages (see Monmasson et al. 2011). Furthermore, (Kassem and Abdelaziz 2014 and Behera et al. 2015) studied the stable of the final productivity voltage of a hybrid separated wind/diesel power generation model by directing the SVC phase angle and the synchronous generator voltage according to functional system oracular control. (Rajaei et al. 2013) presented Vienna rectifier with direct torque monitoring to control the product voltage and connecting a continuing magnet synchronous generator obtained by wind turbine to use grid. (Barote et al., 2013) illustrated a wind/energy storage power system by a supply an AC single phase load using PID control based on PWM techniques. (Hojabri et al., 2013) used matrix converter for interfacing PMSG driven by changeable speed wind turbine to utility grid based on reactive power control.(Nguyen and Naidu, 2012) gave a fuzzy adaptive control for autonomous Wind Energy Conversion Systems with (PMSG). (Abdalla et al. 2016) applied the adaptive fuzzy PID control for voltage regulation of an autonomous wind power model and a storage unit during load variations and wind speed.

In this study, investigation of supplying isolated load by hybrid wind/storage generation unit is proposed. PID controller is applied to guarantee supplying the load with voltage which is constant amplitude and constant frequency. The application of power generation systems, remote area is now famous in faraway areas hybrids inclusive the islands which leads to the importance of designing and development of such presented generation system. (Achievement in design and power generation systems, insulated, frequency and effort included are the most important to be well organized (Mendes et al, 20).

2. SYSTEM CONFIGURATION

Wind energy conversion system connected to autonomous load through DC-link is presented in Figure 1. It is composed of a variable speed wind turbine (WT), which operates permanent magnet synchronous generator (PMSG). PMSG supplying an stand-alone load based on converting the un-constant AC power to DC power and then converting the DC power to a fixed amplitude and frequency AC power. It is connected chargeable battery lead-acid (LAB) as well as the DC- link. In this work, the DC-link includes two parts:

(a) generator side converter, which consists of an uncontrolled rectifier, the buck DC-DC converter.

(b) load side DC-AC, it consists of a three-phase PWM inverter.

In general, the voltage of the PMSG obtained by wind turbines and fuel load isolated mainly relies on the rotor speed and load resistance.

3. MATHEMATICAL MODELING THE SYSTEM

The complete model of the studied wind generation system may be bisected into sub-models as illustrated in Figure 1. Maximum Power Point Tracking (MPPT) may be applied with the aid of suitable algorithm to force changeable speed wind turbine to produce greatest power. As the wind speed is more than the classification wind speed, wind turbines generally work under continuous production of energy through either control or pitch control load generator, or both, if possible.

3.1 MODELING OF WIND TURBINE

Nondimensional curves of the power coefficient C_p, is used to characterize the wind turbine. Where, C_p is a function of both the blade pitch angle (β) and the tip speed ratio (λ). The value of λ may be stayed at its optimum value to fully extract the available maximum wind power. Subsequently, the power coefficient conformable with that value will turn into maximum also.

The tip speed ratio λ may be given as the following (Ali et al. 2011):

$$\lambda = \omega_t R / V_w \tag{1}$$

Where R [m] is the radius of wind turbine rotor, V_w [m/s] is the speed of the wind and ω_t is the speed of the mechanical angular rotor of the wind turbine.

The wind turbine output power may be obtained based on the following equation:

$$P_m = \frac{1}{2}\rho A C_p V_w^3 \tag{2}$$

with

$$C_p = \left(0.44 - 0.0167\beta\right)\sin\frac{\pi\left(\lambda - 3\right)}{15 - 0.3\beta} - 0.00184\left(\lambda - 3\right)\beta,$$

A is the swept area by the blades and ρ is the air density. Also, the wind turbine available torque T_m is given as:

$$T_m = \frac{1}{2}\rho A R C_T V_w^2 \tag{3}$$

Where the wind turbine torque coefficient C_T is expressed as $C_T = C_p / \lambda$. The aerodynamic torque, T_m in Eq. (3) becomes:

$$T_m = 0.5\rho A[\left(0.44 - 0.0167\beta\right)\sin\frac{\pi(\frac{\omega_t R}{V_w} - 3)}{15 - 0.3\beta} - 0.00184(\frac{\omega_t R}{V_w} - 3)\beta]\frac{V_w^3}{\omega_t} \tag{4}$$

3.2 DEVELOPING PMSG DYNAMICAL MODEL

To develop a PMSG dynamical model, it is important to make some postulates such as (Kassem 2016):

- Neglecting saturation.
- Assuming the induced electromotive force (EMF) is to be sinusoidal signal.
- Neglecting both eddy currents and hysteresis losses.
- Supposing that there is no field current dynamics.

With considering the above postulates, the wind turbine makes the rotor of the PMSG to rotate. This may be appeared in the direct-quadrature (DQ) coordinate framework, which can be given as, (Kassem 2016):

$$\frac{d}{dt} i_{sd} = \frac{1}{L_d}\left(- R_s\, i_{sd} + p\omega_r L_{sq} i_{sq} - V_{sd}\right), \qquad (5)$$

$$\frac{d}{dt} i_{sq} = \frac{1}{L_q}\left(- R_s\, i_{sq} + p\omega_r \left(L_{sd} i_{sd} + \lambda_{pm}\right) - V_q\right) \qquad (6)$$

The mechanical rate of the rotating speed given as:

$$\frac{d}{dt}\omega_r = \frac{1}{J}\left(T_m - T_e\right) \quad \text{with} \quad T_e = \frac{3}{2}\frac{P}{2}\lambda_m\, i_q \qquad (7)$$

where T_e is the electromagnetic torque.

3.3 MODEL OF UNCONTROLLED RECTIFIER

In this study, it is used an uncontrolled bridge rectifier to convert variable alternating voltage of the terminal of the PMSG to a varied DC voltage. Suppose that cut and induction angle is almost negligible, and the output DC voltage rectifier voltage and current may be presented in parameters of voltage and root mean square current of the PMSG respectively, as (Kassem 2016):

$$V_{DC(rect.)} = \frac{3\sqrt{3}}{\pi} V_g ,$$

$$I_{DC(rect.)} = \frac{\pi}{2\sqrt{3}} I_{g(rms)} . \qquad (8)$$

3.4 DC-DC CONVERTER

In this work, the buck converter has been used as a DC/DC converter. Mono buck converter is applied to achieve the interface between the inverter and the uncontrolled rectifier to ensure a quick power transformation. The relationship between the voltage and current of the two sides primary and secondary may be written as:

$$\frac{V_{rect}}{V_{DC-link}} = D , \qquad \frac{I_{rect}}{I_{DC-link}} = \frac{1}{D} . \qquad (9)$$

3.5 ENERGY STORAGE SYSTEM

In this study we suppose that, the energy storage unit is contained a one arm, single-phase, bidirectional inverter based on insulated gate bipolar transistor (IGBT) and a bank of LAB. When the wind speed is too low, the battery is compensating to supply the power needed by the load which was saving from the wind generation framework. The energy storage system is modeled as a monitored voltage source (E_b), connected in series with the interior resistance and the LAB voltage (V_{bat}). We can notice that the E_b voltage relies on the battery kind and the charging state.

4. PROPORTIONAL INTEGRAL DERIVATIVE (PID) CONTROLLER

The proportional integral derivative (PID) controller is the most marketable and helpful algorithm in control framework engineering. The reactions loops are planned employing PID algorithm. Feedback is significant in systems due to achievement a set point regardless of perturbations or any modification in characteristics of any form. PI controller is prepared to emend error between the evaluated process value and a special required set point in a system. PID controllers are prevalent, common and have been excessively applied due to his controlling a wide class of systems and getting the desired system responses. Furthermore, PID controllers have a straightforward control framework, economical cost. However, when bounded uncertainties present in the system and when the system is nonlinear, PID controllers are not completely capable to establish the system, specially, when the nonlinearity is very big or the bound of uncertainty is large (Mendis et al. 2012).

The transfer function of a PID controller may be written as :

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} + K_i \int_0^t e(t)dt \qquad (10)$$

Where u(t) is control signal, e(t) is error signal, K_p, K_i and K_d are proportional, integral and derivative control parameters respectively.

Therefore, the PID controller parameters are chosen by trial and errors such that the best performance (small maximum overshoot and small settling time) is obtained. The control parameters are:

a) control_1:

K_p= 0.01, $K_i = 1.3$, and $K_d = 5.0$.

a) control_2:

K_p= 0.4, $K_i = 2$, and

5. SIMULATION RESULTS IN THE ABSENCE OF CONTROL

The schematic graphic of the system in the absence of control is given in Figure 1. Firstly, simulation results are obtained in case of without control as shown in Figures 2 to Figure 5. These figures illustrate the alteration of wind speed, generator stator voltage, DC-link voltage and the load AC voltage respectively. Figure 2 shows the step variation in speed of the wind. The variation in generator output voltage regarding to the variation in wind speed is presented in Figure 3. The DC-link voltage is not constant because there is no controller applied to the system, as illustrated in Figure 4. The output voltage of the DC/AC inverter (load voltage) is considered in Figure 5. This figure explains that the load voltage is varied in amplitude and has constant frequency because the DC-link voltage is not constant.

So, from these figures we can notice that to have constant load voltage in amplitude and frequency, a suitable controller is needed

6. SIMULATION RESULTS BASED ON CLASICAL PID CONTROL

The studied hybrid isolated wind/storage generation system according to the proposed controllers is given in Figure 6. The simulation results are presented in Figure 7 to Figure 15. These Figures illustrate the alteration of various parameters with step variation in the speed of the wind in the context of the suggested PID controller. However, it proposed that the speed of the wind is considered to change from 9 to 14 m/s, as it is mentioned in Figure 2. It has been observed that as the speed of the wind rises, the wind turbine shaft torque goes up and leads to increasing the speed of the PMSG rotor as shown in Figure 7 and 8 respectively. This leads to increasing in PMSG stator voltage (see Figure 9). The sinusoidal signal of the stator voltage is shown in Figure 10. The control behavior may be written briefly as:

(a) If V_{dc} tends to go up due to the growing values of the wind speed, so the PID controller reaches into procedure and changes the obligation of the buck DC/DC converter cycle ratio to preserve V_{dc} at its recommendation value. Simultaneously, the second PID controller raises the battery charging current that to save any additional produced power and to conserve V_{dc} at its required value. Thus, this results to reduction in the terminal voltage of the PMSG and it is forced to settle lower than the appropriate value.

(b) The controller number three force the DC/AC converter to transform a fixed value of V_{dc} into a fixed value of AC voltage with fixed amplitude and frequency that is desired by the load that controlling the modulation index of the PWM as shown in Figure 15.

By comparing the results in case of without DC-link control and in case of DC-link control, the following can be noticed:

- The DC-link controller based on PID control can preserve the DC-link voltage is fixed as illustrated in Figure 4 and Figure 5.
- Maintaining the DC-link voltage constant leads to constant amplitude of the load voltage as shown in Figure 13.
- Using the battery will compensate for any reduction in wind power generation

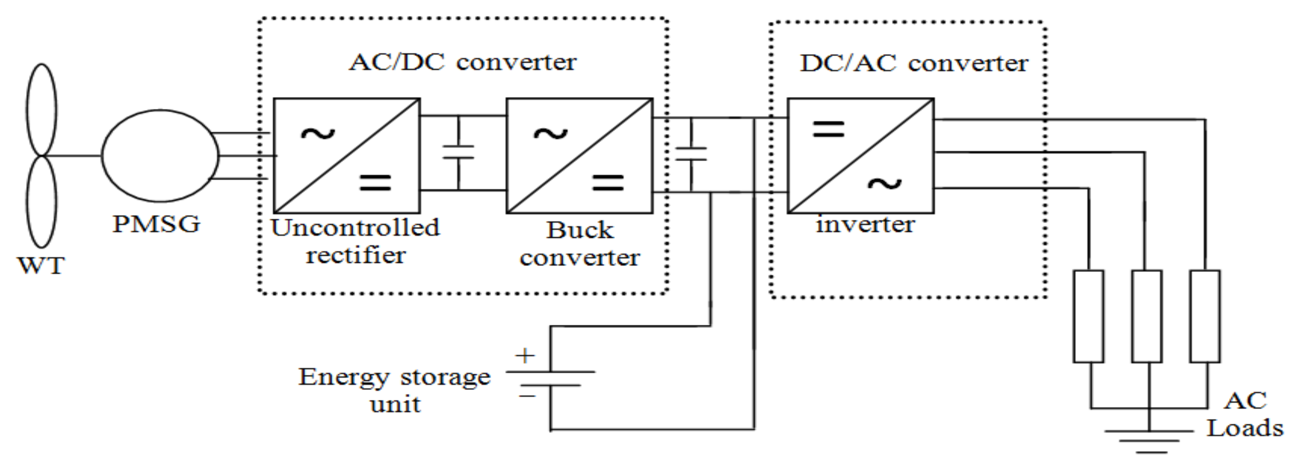

Figure 1. Graphical scheme of the suggested stand-alone WEC system.

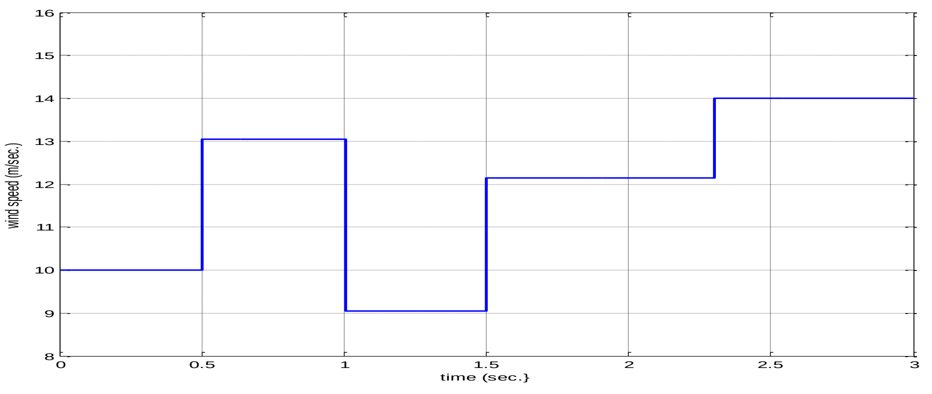

Figure 2: Wind speed variations.

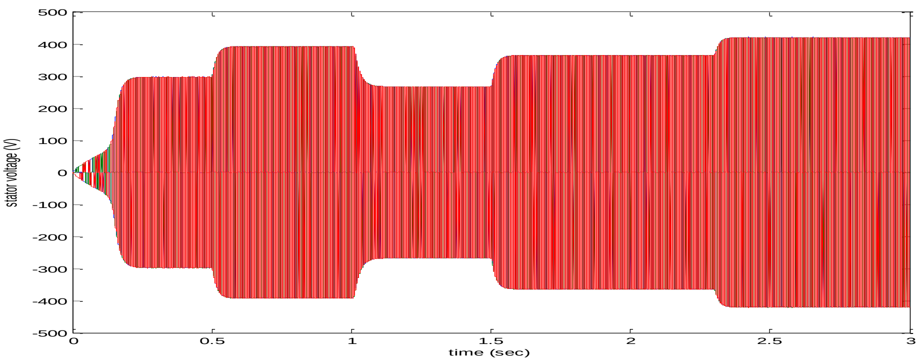

Figure 3: Dynamic response of generator stator voltage for step change in wind speed in case of without DC-link control.

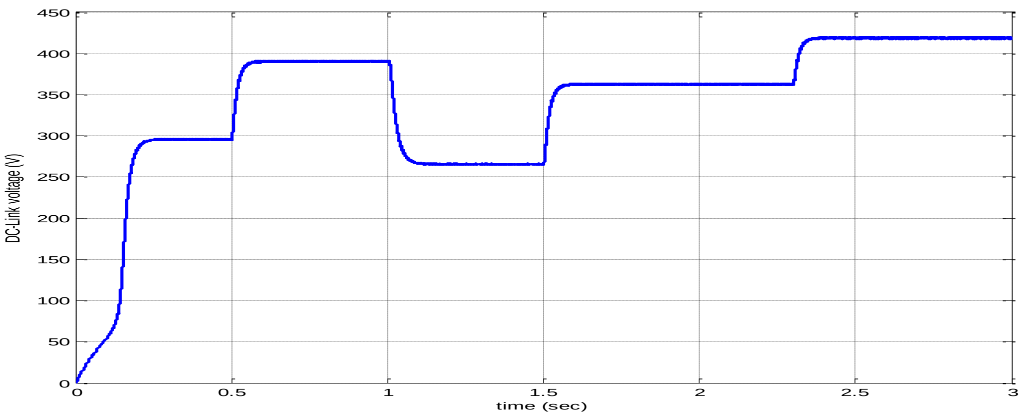

Figure 4: The response of DC-link voltage for step change in wind speed in case of without DC-link control.

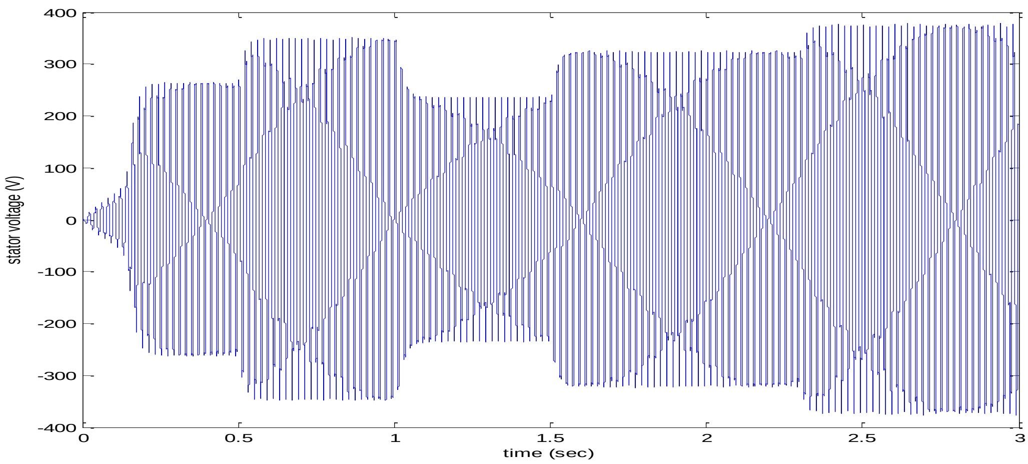

Figure 5: The response of load voltage for step change in wind speed in case of without DC-link control.

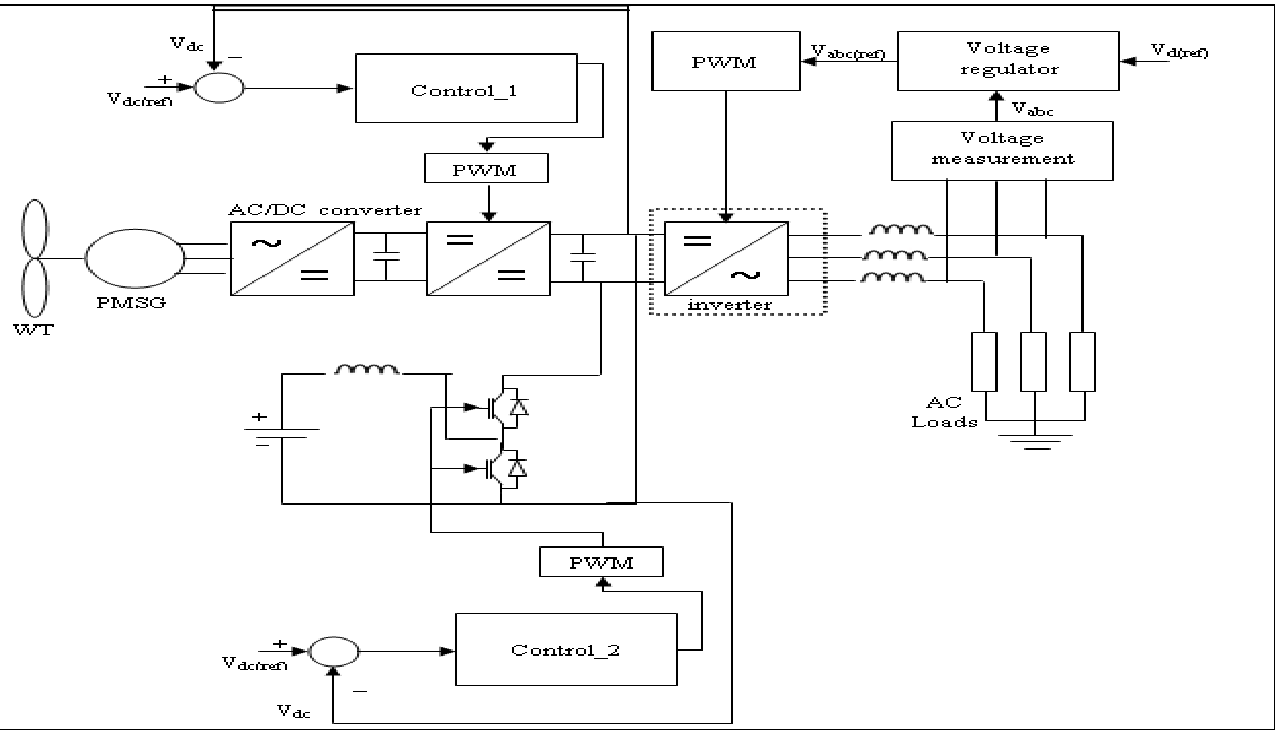

Figure 6: Autonomous wind/ storage generation unit schematic diagram with the suggested PID control system

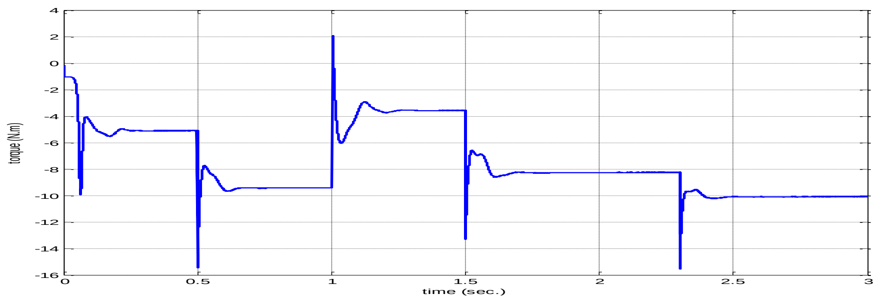

Figure 7: The response of generator input torque for step change in wind speed in case of proposed PID controller.

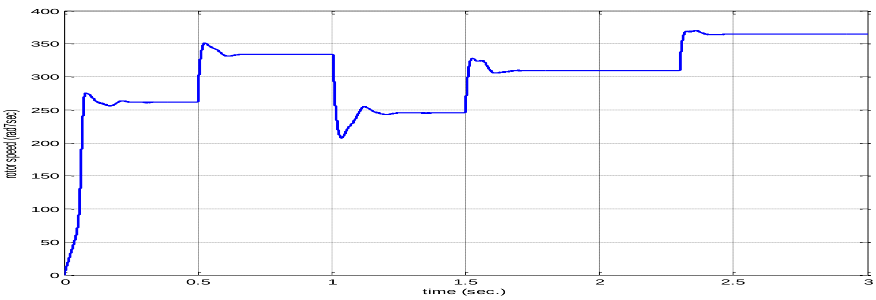

Figure 8: PMSG rotor speed dynamic response for step change in wind speed in case of proposed PID controller.

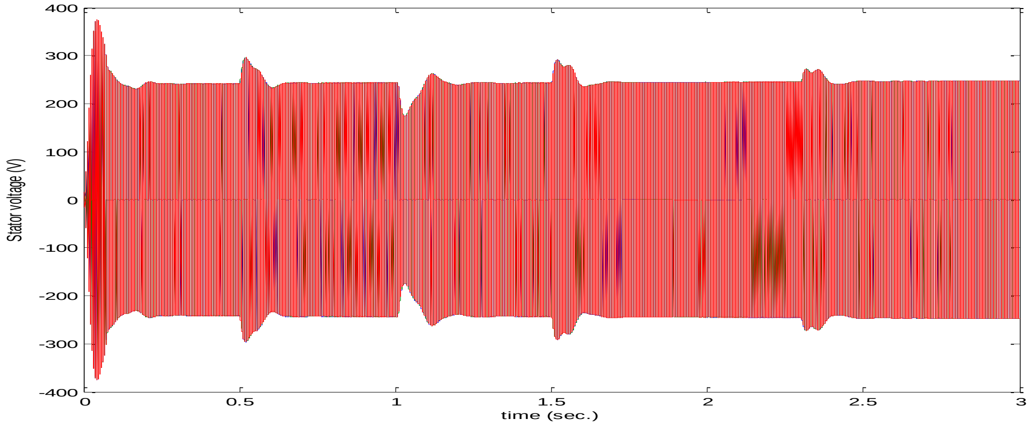

Figure 9: The response of generator stator voltage for step change in wind speed in case of proposed PID controller.

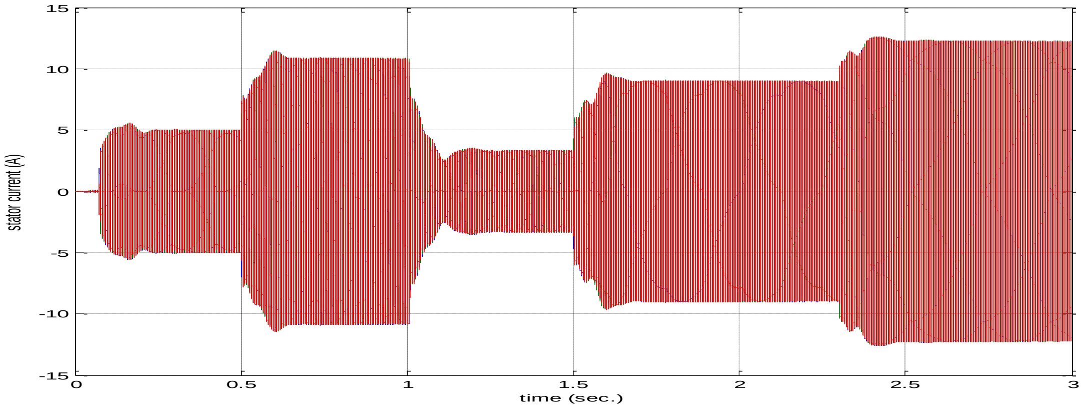

Figure 10: The response of generator stator current for step change in wind speed in case of proposed PID controller.

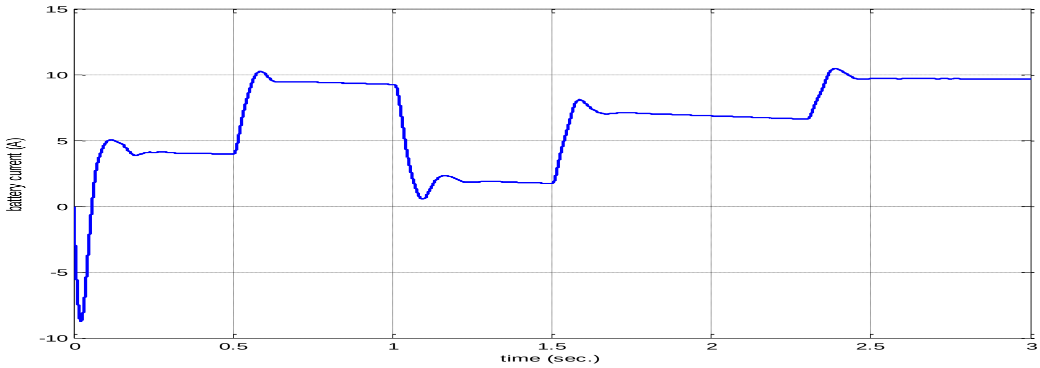

Figure 11: The response of battery current for step change in wind speed in case of proposed PID controller.

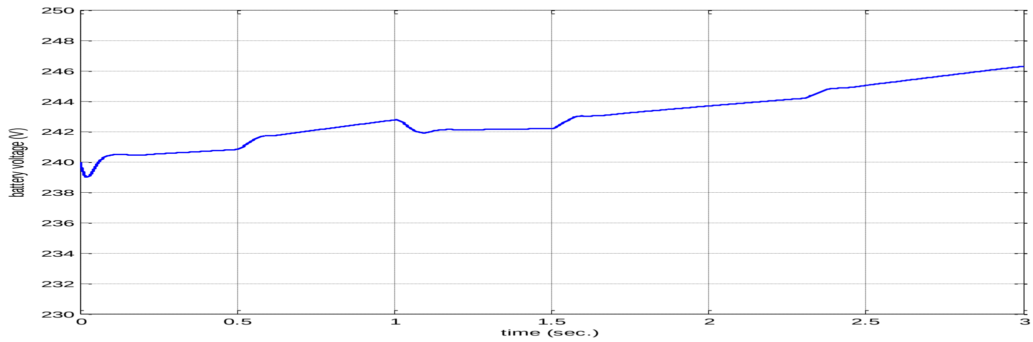

Figure 12: The response of battery voltage for step change in wind speed in case of proposed PID controller.

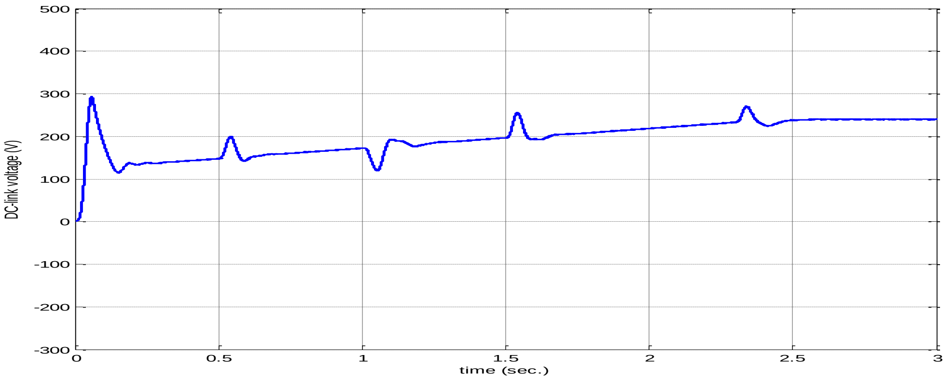

Figure 13: The response of DC-link voltage for step change in wind speed in case of proposed PID controller.

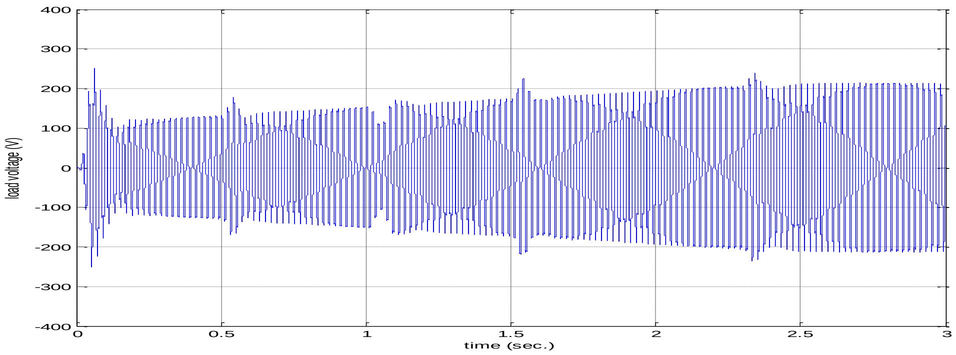

Figure 14: The response of load voltage for step change in wind speed in case of proposed PID controller.

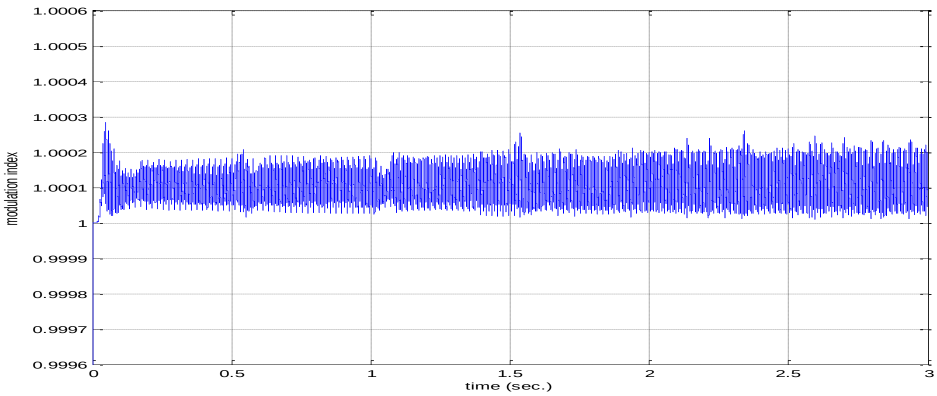

Figure 15: Modulation index dynamic response for step variation in wind speed for suggested PID controller.

3.6. CONCLUSION

The objective of this paper is to study the PID control for voltage regulation of an isolated wind generation model. This utilizes an accompanying energy storage framework, with the role to stabilize the produced voltage in autonomous utilizations. The essential achievement of this research is the design of a control strategy which accomplishes voltage and battery state of charge monitoring, with optimum conditions for battery charging. Emulations have been achieved to examine the efficiency of the suggested model. The hybrid wind-battery generation model with the presented PID controller has been examined by means of step change in the speed of the wind. The outcomes confirm that the suggested controller is successful in preserving the load voltage of a stand-alone hybrid wind-battery generation model versus wind speed deviation.

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