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Power Management and Dynamic Assessment of a Hybrid Wind, PV, and Battery Energy System

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Abstract

This paper presents power management and dynamic assessment of a small hybrid wind and photovoltaic (PV) energy system integrated with battery storage as the auxiliary power source. The system consists of a small wind turbine, photovoltaic cells, a battery, and an electric power converter. The load is supplied with the contribution of all renewable energy sources through an energy management system. Excess wind and photovoltaic energy are redirected to charge the battery. This hybrid energy system is stand-alone, reliable, and ultra-high efficient. A boost converter and a DC/AC inverter are utilized to produce a constant and reliable AC output voltage. The control strategy of voltage regulators is based on PI controllers that are tuned using the particle swarm optimization (PSO) algorithm. The dynamic response of the system to variations in the power source and the load is investigated. Simulation results show the strong self-adaption of the system to sudden operational variations. The combination of wind and PV sources is well-suited for the geographical regions with both windy and sunny days. This standalone system is ideal for suburban and rural areas remote from the electrical grids.

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1. Introduction

Power renewable energy sources have enormous potential and can meet a part of the present world's energy demand. They can enhance diversity in energy supply markets while ensuring long-term sustainable energy supply and reducing local and global atmospheric emissions [1]. The last few years have seen rapid growth in renewable energy systems worldwide, mainly in wind and solar energy systems. PV and wind generation systems have proven to be the most promising technologies for supplying remote and rural areas [2]. A drawback, common to these units, is the intermittence and unpredictable nature of solar and wind energy sources. Additionally, the hourly variations of the output energy of the aforementioned sources may not match the load demand over the time intervals [3]. For example, the output power of a wind turbine is almost zero on calm days. Also, a PV system does not generate power during cloudy periods and at night [3]. Therefore, to satisfy the continuous load demand in these conditions, hybrid energy systems, including PV and wind resources with backup storage have gained attention both at low and high-power levels. Hence, it is necessary to analyse these systems in all aspects, such as costs, sizing, efficiency, reliability, dynamic response to load demands, and the design of the control system. In [4-9] researches have been focused on the sizing and optimization of hybrid energy systems. In [10] a management strategy is suggested for a wind /PV /fuel-cell hybrid energy system to control the power flow between the system components and supply the load. The idea of an ultra-high-efficiency hybrid energy system, consisting of a wind turbine, PV, and the fuel cell is proposed in [11, 12]. In [13] a simple and economic control scheme with a DC/DC converter is used for maximum power extraction from the wind turbine and PV arrays. A typical fuel cell is also used to ensure continuous power delivery. In [14] a hybrid scheme for Iraq energy complex based on an integrated PV array and a wind-driven induction generator is discussed. A techno-economic analysis and the design of a hybrid system that comprises PV panels, a battery system, and a micro-turbine as a backup power source for a remote community is presented in [15]. The authors in [16] analyse the economic feasibility of installing and operating hybrid systems in remote areas. In [17], a complex PV/wind/diesel/battery system has been designed with an optimization method that improves its functionality. An overview of the real-time power management procedures considered for hybrid renewable energy systems was done in [18]. For a standalone electricity generation system consisting of a solar photovoltaic battery integrated with a pumped-hydro-storage system, power management was assessed in [19]. Rehman et al. proposed an optimal power management structure for smart systems considering electric vehicles and energy storage systems [20]. A power management strategy for efficient optimal operation of the wind energy system that ensures minimal stress on the used storage batteries was presented in [21].

The authors in [22], assessed the power management of a wind turbine power system, a permanent magnet synchronous generator, a water pumping system, and a battery. In [23], a power management strategy based on an artificial neural network was presented to manage power-sharing among photovoltaics, loads, hybrid battery, and supercapacitor energy storage.

Because of the intermittent characteristics of wind speed and solar radiation, the most important design issues regarding hybrid systems are dynamic performance. Therefore, in this paper, a power management system is proposed for a wind/PV/battery hybrid energy system. A control strategy based on optimal PI controllers that are tuned with particle swarm optimization (PSO) algorithm is implemented for this system. The control system is robust under various load and source conditions. It is assumed that the output power of PV and wind turbine can supply the nominal load demand. However, during the lack of wind or ambient irradiation, a part of the load demand can be supplied from the battery. If the integration of the PV and wind turbine output power exceeds the demand, the excess power is stored in the battery.

The paper is organized as follows. The next section gives a general overview of the proposed hybrid energy system. The system component characteristics and mathematical models are given in section 3. Simulation results are summarized in section 4. Section 5 is devoted to the conclusion and a brief introduction to future research.

2. Description of the system

The system under study relies on solar and wind energies as the primary power sources and it is backed up with the battery stored energy. Figure 1 shows the configuration of the system. It consists of a PV array, a wind turbine, lead-acid batteries, a power conditioner, a dump load and controllers. A diode rectifier connects the wind generator to the DC bus. The PV array and the battery are also connected to the DC bus through DC/DC converters. An inverter converts the DC power to AC to supply the AC load. The load electricity demand is supplied from the wind turbine and the PV array in normal conditions. This system also includes a power conditioner block which is composed of a boost converter that regulates the DC bus voltage at 200 volts and an inverter that converts this DC power into AC power to supply the system load. The system is modeled by standard classical methods. The power management system block diagram is shown in Figure 2 The management strategy is as follows:

- If the load demand (P_{Load}) exceeds the available power generated from wind (P_{wind}) and solar sources (P_{PV}), then the battery ($P_{battery}$) supplies the shortage of power. Therefore, the power balance equation can be written as:

$$P_{Load} = P_{wind} + P_{PV} + P_{battery} , \qquad P_{p-controller} > 0 \qquad (1)$$

in which, $P_{p\text{-}controller}$ is the difference between the renewable sources' power and the load demand and is calculated as:

$$P_{p-controller} = P_{Load} - (P_{wind} + P_{PV}) \qquad (2)$$

- If the wind and solar generations exceed the load demand, then the surplus power is used to charge the battery. Therefore, the power balance equation can be written as:

$$P_{battery} = P_{wind} + P_{PV} - P_{Load} , \qquad P_{p-controller} < 0 \qquad (3)$$

- If the wind and solar generations equal the load demand, then the whole power generated from renewable sources is injected into the load. Therefore, the power balance equation can be written as:

$$P_{Load} = P_{wind} + P_{PV} , \qquad P_{p-controller} = 0 \qquad (4)$$

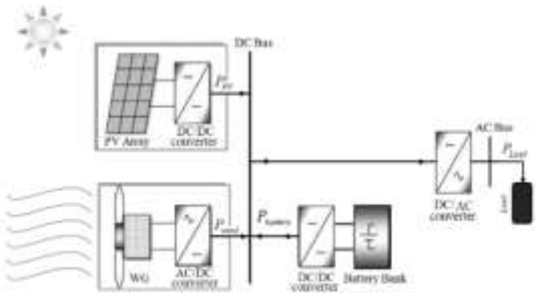

Fig. 1. Configuration of hybrid energy system

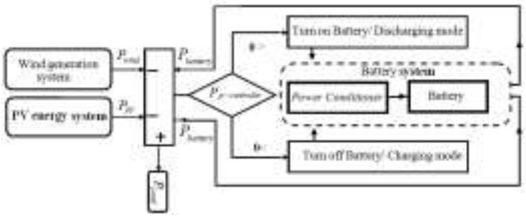

Fig. 2. Block diagram of the overall control scheme for the proposed hybrid energy system

3. Pv/wg/battery dynamic modeling

As can be seen in Figure 1, the system consists of 5 major components, including a wind turbine, PV arrays, battery, power converter, and controller. Mathematical models for all subsystems used in this study are presented in the following subsections.

A) Wind turbine model

The variable speed wind turbine is self-regulating with a permanent magnet generator. Self-regulation is achieved by twisting of blades (passive stall control). If the wind speed increases to more than a specific limit, the wind turbine quickly enters stall mode. It avoids over speeding by twisting its blades. This small wind turbine has the ability to adapt itself to wind speeds up to 17.9 m/s to extract the maximum available power. The turbine rotor diameter is 1.14 m. The dynamic of the wind turbine due to its rotor inertia (J) and controller action is presented in (5), where a friction-based dynamic model for the wind turbine rotor and a first-order model for the permanent magnet generator are used [24].

$$\frac{y(s)}{x(s)} = \frac{0.25}{s^2 + 0.7s + 0.25} \tag{5}$$

In the above equation, the input x(t) is the power obtained from the power curve for a given wind speed, and the output y(t) is the actual power of the wind turbine considering the dynamic effects.

B) PV model

In this paper, solar cells are presented by an electrical equivalent one-diode model [25], as shown in Figure 3. The model contains a current source I_L, one diode, and a series of resistance R_s (in ohms), which represents the resistance inside each cell and in the connection between the cells. Relationship between the output voltage V (in volts), and the load current I (in amperes) of a PV cell or a module can be expressed as:

$$I = I_L - I_D = I_L - I_0(\exp\frac{e.(V + IR_s)}{m.k.T_c} - 1) \tag{6}$$

where I_0 is the saturation current, m is the idealizing factor, k is Boltzmann's gas constant, T_c is the absolute temperature of the cell and e is the electron charge.

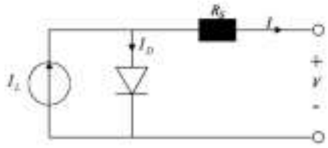

Fig. 3. Model for a single solar cell

The I–V characteristic curve of the PV model for a certain ambient irradiation and cell temperature is given in Figure 4. The effect of cell temperature variation in open circuit voltage is also considered in this model. In Figure 4, I_{sc} is the short circuit current, V_{oc} is the open circuit voltage. Point A on the curve (corresponding to V_{max} I_{max}) is the maximum power point where the load resistance is R_{opt}. The manufacturers supply PV cells in modules consisting of N_{PM} parallel branches and N_{SM} solar cells in series. In this study, N_{PM}=10000 and N_{SM}=2000 are selected, respectively.

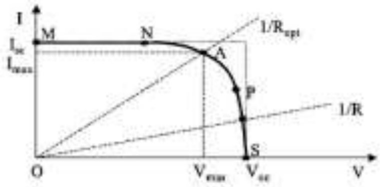

Fig. 4. The current-voltage curve of a PV cell

C) Battery model

Although scientific development continues at an astonishing rate, the storage of electrical power is still a challenge. The proper modeling of the battery storage system is very important in stand-alone energy systems. Battery system compensates for the intermittencies associated with renewable energy sources and balances the power flow between the renewable energy generation and the loads. Several battery models have been proposed by different researchers. For example, Facinelli [26], Hyman, et al. [27], and Manwell et al. [28-30] have presented accurate models. Most of these models are phenomenological, namely, they are based on observable quantities such as voltage, current, and time and do not depend on the internal structure of the system. Other models are based on physical or electrochemical processes and are not appropriate for system-level studies. In general, battery models consist of a voltage source E in series with an internal resistance R0, as shown in Figure 5. Then the terminal voltage V is given by,

$$V = E - IR_0 \tag{7}$$

Most batteries used in hybrid systems are deep-cycle lead-acid batteries. There are several other appropriate types (nickel-cadmium, nickel-iron, iron-air, and sodium sulfur) but these are generally either expensive or unreliable for practical applications. The lead-acid battery is widely used and, although complex, is well known.

The power input to the battery is $\Delta P(t) = P_{RENEWABLE}(t) - P_{Load}(t)$ in which $P_{RENEWABLE}(t)$ is the accumulated power produced by the renewable energy source (PV and wind) at time instant t. Also, $P_{Load}(t)$ is the power demanded by the load. It is evident that the power generated by the hybrid system and the amount of energy stored are time dependent. For the charging ($P_{RENEWABLE}(t) > P_{Load}(t)$) and discharging ($P_{RENEWABLE}(t) < P_{Load}(t)$) processes of the battery, the state of charge (SOC) can be calculated from the following equation:

$$\%SOC = 100\left(1 - \frac{Q \times 1.05}{\int i\,dt}\right) \tag{8}$$

where Q is the battery capacity (Ah) and i is the battery current. The SOC for a fully charged battery is 100% and for an empty battery is 0%. In this study, the initial SOC [%] of the battery storage has been considered as 100%.

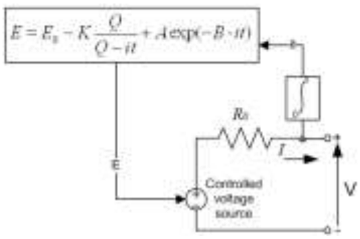

Fig. 5. Differential Schematic diagram of the battery

D) Power conditioner

The system is designed for stand-alone applications. Therefore, a two-stage power converter module is utilized to regulate both output voltage magnitude and frequency. The first stage is a boost converter, which is responsible for regulating the DC voltage at a high level that is appropriate for generating the required AC voltage. Here, the boost converter is controlled by a PI controller to regulate the high voltage bus at 200 V. This could be achieved by adjusting the duty ratio, D, as specified by:

$$\frac{V_{boost}}{V_{battery}} = \frac{1}{1-D} \tag{9}$$

The boost converter is followed by an inverter stage, which in this study is a pulse width modulated (PWM) single-phase voltage source converter. A PI controller is used to regulate the voltage magnitude at 120 V, while the frequency is fixed at 60 Hz. The switching frequency is chosen to be 8 kHz.

E) Controllers

PID-type controllers are used for the boost converter and inverter. The general transfer function of a PID controller can be written as (10). The controller parameters are presented in Table. 1.

$$T(s) = \frac{K_p(s + T_d s^2 + 1/T_i)}{s} \tag{10}$$

The optimal design procedure of PID controllers used in this system is based on the PSO optimization algorithm defined in [31]. For this purpose, the cost function and the design vector are defined according to the following equations.

$$F_c(\nu_d) = \int_{t=0}^{t=T_m} \left(\left| V_{ref.}^{Bcon.}(t) - V^{Bcon.}(t) \right| + \left| V_{ref.}^{inv.}(t) - V^{inv.}(t) \right| \right) dt \tag{11}$$

$$\nu_d = [K_p^{Bcon.}\ T_i^{Bcon.}\ T_d^{Bcon.}\ K_p^{inv.}\ T_i^{inv.}\ T_d^{inv.}]^T \tag{12}$$

where $V^{Bcon.}$ and $V^{inv.}$ are the output voltage of the boost converter and inverter, respectively. Also, F_c and ν_d are the cost function and the design vector, respectively.

The upper and lower limits of the controller parameters are defined as $0 \le K_p \le 10$, $0 \le T_i \le 10$ and $0 \le T_d \le 10$. In the optimization procedure, the population size is 100 and the iteration number is 50. After implementing the controller design procedure, the obtained optimal parameters are according to Table 1.

Table.1.
PID Controllers parameters

	K_p	T_i	T_d
Boost converter	6.91	0.21	0
Inverter	0.05	0.45	0

As can be seen from this table, the coefficient of the derivative term in the optimal response is zero, so the controllers for this system are considered two optimal PI controllers.

4. Simulations and discussions

Numerical simulations on the studied power system are performed using Matlab/Simulink software. According to Fig. 6, the simulated system consists of five main subsystems that have been described in previous sections. The wind speed, solar radiation, and load resistance are inputs to the system. The load is a fixed inductive load (100 mH) in series with a variable resistive load. Several step changes in the load resistance and the wind speed are applied to the simulated model to analyze the dynamic performance of the system.

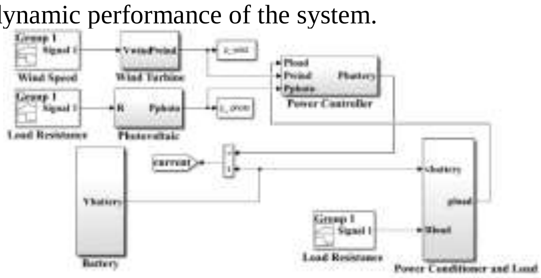

Fig. 6. Simulated system in Matlab SIMULINK with all subsystems

In this study, load resistance decreases at t=10 s from 35Ω to 10Ω and increases at t=20 s from 10Ω to 25Ω, as depicted in Figure 7. At the same time, the wind speed increases at t=20 s from 9 to 12 m/s and returns to 9 m/s at t=30 s, as shown in Figure 8. The simulation is conducted for 40 seconds. Results are presented in Figures 9-13.

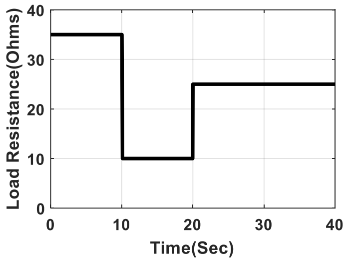

Fig. 7. Load resistance

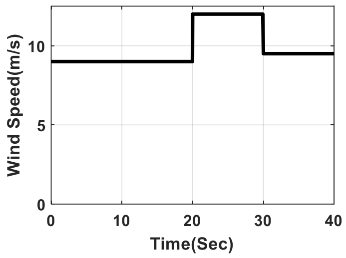

Fig. 8. Wind turbine input

Figure 9 shows the load power as well as the wind turbine, PV, and battery outputs. One can conclude that the demanded power increases at t=10 s and decreases at t=20 s following the changes in the load resistance (from 280.3 to 373 W (at t = 10 s) and 373 to 321.5 W (at t = 20 s)). The lack of power at t=10 s is immediately compensated by the battery. Indeed, the very fast dynamic response of the battery results in a step change in the output power of this device. The effect of load variations is also significant on the output power of the PV as shown in Figure 9. Both PV and battery outputs decrease when the load resistance is increased at t=20 s.

Note that, the output power of the wind generator at t=20 s is increased after variations in wind speed. The PV and wind turbine generated power is more than load demand at t=22 s. The extra generated power is saved in the battery as the backup supply.

There are step variations in the load and wind turbine outputs. However, as it is clear in Figure 10, the inverter and boost converter could regulate the voltage properly. The controller in the boost converter regulates the duty ratio to attain a fixed 200 V DC in the inverter's input. The inverter, on the other hand, delivers a 120 V, 60 Hz AC to the load. The load current and voltage waveforms at around t=20 s are shown in Figures 11 and 12, respectively. This is where the load current decreases from 2.23 to 1.89 A. It can be seen that the voltage waveform is almost constant.

The contribution of the battery is decreased by using the combination of the PV arrays and the wind turbine. During t=22 to 35 s the sum of wind and PV generations exceeds the load demand. Therefore, the extra power is used to charge the battery. The SOC of the battery is presented in Figure 13. The main advantage of this system is its high reliability. This is so because three different power sources are used in parallel. Wind and PV energy sources demonstrate complementary characteristics under different environmental conditions.

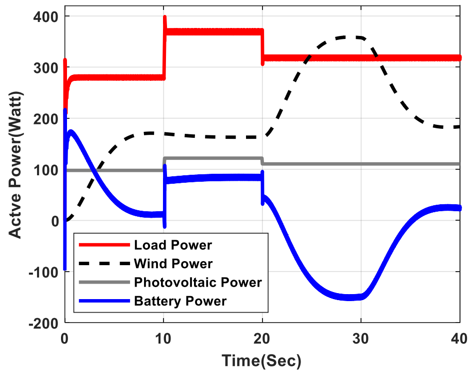

Fig. 9. Wind, PV, battery, and load powers

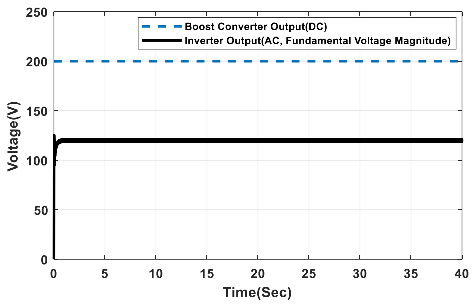

Fig. 10. Inverter and converter output voltages

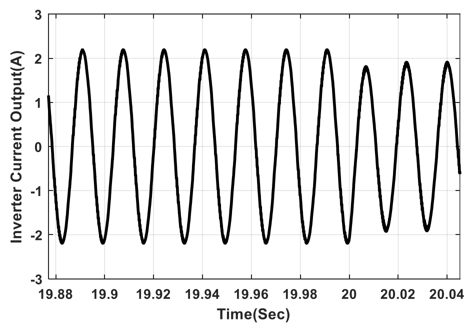

Fig. 11. Load current zoomed in t=20 s

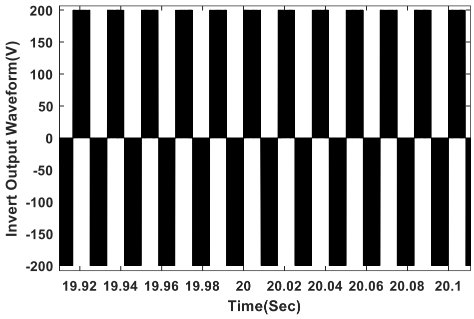

Fig. 12. Load voltage waveform

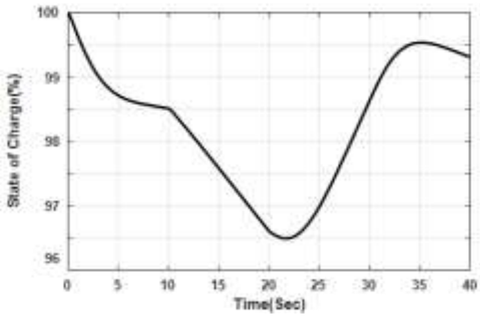

Fig. 13. Battery state of charge

5. Conclusion

A small 500 W wind/PV/battery hybrid energy system is proposed for stand-alone applications. The mathematical models of the individual components and also the design of the controllers is reported. The design and analysis of the dynamic behavior of such a system are presented. Simulation results show the applicability of the hybrid energy system under variable load without any interruption or deficiencies. The system is more reliable in comparison to a wind/PV hybrid energy system. The system performance can satisfy the user with reliability, sustainability, and efficiency. Simulation results also demonstrate that the control system is capable to regulate the outputs properly to damp the dynamic oscillations very quickly. Further work can be done on the analysis and improvement of the power quality of such a hybrid system, and the logics of the management system.

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