Implement a Model for Wind Turbine Water Pumping System based on Matlab Simulink

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ABSTRACT

Wind turbine technology has brought a milestone revolution in water pumping, especially in remote regions where electricity is absent This paper describes the requirement, design, and validation of a wind turbine-water pumping system for remote areas where there is a lack of electricity. A system of wind turbine–water pumping system has been studied, modeled, and simulated by Matlab-Simulink. The simulation supposes that a 1.2 kW wind turbine generates electric power; which is converted to DC power by using a full-wave rectifier. A rechargeable battery is used when the wind speed is below the cut-in-speed of the selected wind turbine and connected to the system in order to store and transfer the power to a DC motor, which used to drive a 1.5hp pump. A switching circuit consists of two relays and a logic gate used to control the flow of the required power. The simulation results illustrate that the pump water rate values are various according to the charge level of the rechargeable battery. Increasing the battery size extends the water pump period as well.

Keywords: Wind Turbine, Rectifier, Water Pumping System, Battery, Matlab Simulink

1 Introduction

The transition to using renewable energy sources is remarkably becoming a very significant trend in the coming years. Wind energy. Wind energy is one of the most important types of renewable energies that have spread rapidly in recent times since the massive amount of the air, which captured and transferred to mechanical power. This mechanical power converted into electrical power to provide electricity in order to use it for many purposes. Due to the increase in the demand for electric power and the great trend to integrate wind energy with different renewable sources, the concept of reliability has become a very important factor in the overall wind energy systems. In recent years, the production of electric power based on wind energy is developing remarkably, which results a great development in the performance of wind turbines in general. The main factor in making the wind energy industry more efficient is the improvement of the reliability of wind turbine performance. This has led to many wind turbine reliability models, which require development Therefore, it is very significant to continue developing new and accurate reliability models with high efficiency [1].

Wind turbines are used for water pumping purposes whereas they coupled with water pumps via a motor-generator connection. Wind pumping systems for livestock and domestic uses normally require at least 500 W of power, but sometimes range up to 2000 W in size. Small wind systems can easily meet this power demand as proven by a large number of mechanical water pumping systems installed over the years. In remote power generation systems, the utilization of variable speed operation applied to water pumping allows an economically attractive solution to the energy storage problem, mainly due to the uncertain nature of the primary driving source [2,3]. Previous studies indicate the possibility of using wind energy in water pumping operations with high reliability. For instance, an analysis of a wind-turbine water-pumping system is referred in [2]. The proposed system consists of a wind turbine with a permanent magnet generator electrically coupled with a water pump via a motor-generator configuration. The design demonstrates the effect of the water pumps characteristics on the performance of wind turbines. Further, the study discusses the cut-in and cut-off process in the wind turbine water-pumping system. In [4], the perspectives of wind mechanical pumping at the Tunisian south is presented. The feasibility study of wind-powered water pumping systems for rural Ethiopia is discussed in [5]. The suggested designed system has a capacity to supply a daily average drinking water 5 m^3 /day for 1000 people. The performance of a small wind-powered water pumping system is studied in [6]. A helical pump was powered by a small wind turbine over three years. The measured pumping performance was sufficient to pump enough water at a 50 m pumping depth water 120 cattle. The study confirms that additional system efficiency improvement is probable with modifications to the controller of the wind turbine. Tauseef Aized and Syed Rehman present the design of a wind-driven water pumping system and analysis of the design under different wind conditions in Pakistan [7]. The design is based on the use of ANSYS Fluent Simulation models. From the outcomes of the analysis, several designs having different power output and water pumping capacity have been proposed for different operating and wind conditions in the country. The current work describes the requirement, design, and validation of a wind turbine-water pumping system for remote areas where there is a lack of electricity. The proposed design is modelled based on Matlab-Simulink, which is used as a platform to model and simulate the wind energy systems. A rechargeable battery connected to the system in order to store and transfer the power to a DC motor, which used to drive the water pump. The rest of the paper is arranged as follows: Section 2 presents the wind turbine maximum power point tracking. The analysis of the proposed actuator is demonstrated through the wind turbine maximum power-point-tracking in Section 3. The design overview and system description are illustrated in Section 4. The rectifier circuit and water pump computations are explained via this section. The simulation results are displayed in Section 5. Finally, conclusions and suggestions for further research are presented in Section 6

2 Wind Turbine Maximum Power-Point-Tracking

Several methods are used to increase the efficiency of wind turbines. Maximum Power-Point-Tracking (MPPT) control is one of the beneficial methods that are used to track the wind direction. MPPT process is based on monitoring the wind-generator output power by using measurements of the wind generator output voltage and current in order to adjust the AC/DC converter duty cycle according to the result of the comparison between the successive output power values of the wind generator. Further use a controller to regulate the pitch angle in order to keep the speed of the generator constant as possible is a valuable methodology to maximize the wind turbines' efficiency that related to MPPT method. With the mathematical description of the system in terms of transfer functions, a proportional–integral–derivative controller PID can be designed using the root locus method [8,9]. In order to ensure that maximum power will be extracted, MPPT by controlling the pitch angle is applied in this design. The wind turbine is characterized by no dimensional curves of the power coefficient CP as a function of both the tip speed ratio λ and the blade pitch angle β. In order to fully utilize the available wind energy, the value of λ should be maintained at its optimum value. Therefore, the power coefficient corresponding to that value will be maximum. The tip speed ratio λ can be defined as the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades. It can be expressed as follows [8,9,10,11,12]:

$$\lambda = \omega_t R / V_{\mathcal{W}} \tag{1}$$

where R is the wind turbine rotor radius, Vw is the wind speed and ω_t is the mechanical angular rotor speed of the wind turbine. The output power of the wind turbine can be determined as follows:

$$P_m = \frac{1}{2} \rho A C_p V_{\mathcal{W}}^3 \tag{2}$$

where ρ is the air density, and A is the swept area by the blades. The power coefficient C_p calculated as follows:

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

The available torque in the wind is T_w, which is defined as follows:

$$T_w = \frac{1}{2} \rho A R C_T V_{\mathcal{W}}^2 \tag{4}$$

where C_T is the torque coefficient which is given by

$$CT = Cp/\lambda \tag{5}$$

The moment of inertia of the turbine rotor is given by:

$$J_t \omega_t = T_{\mathcal{W}} - T_m \tag{6}$$

where T_m is the aerodynamic torque. In order to use PID controller EQ (6) must be linearized as follows:

$$J_t \Delta\omega_t = \gamma \Delta\omega_t + \xi \Delta V_{\mathcal{W}} + \delta \Delta\beta \tag{7}$$

where $\Delta\omega_t$,$\Delta V_W and\ \Delta\beta$ represent the deviations from the chosen operating point, therefore, the maximum power is obtained as rated power. The γ, ξ and δ are parameters and defined respectively as follows:

$$\gamma = \frac{KV_{wop}^3}{R\omega_{Top}}\left(0.44 - 0.0167\beta_{op}\right) * \frac{\pi R}{V_{wop}(15-0.3\beta_{op}} * cos\left[\pi\left(\frac{\lambda_{op}-3}{15-0.3\beta_{op}}\right)\right] - \frac{KV_{wop}^3}{R\omega_{Top}^2} * (0.44 - 0.0167\beta_{op}) * \sin\left[\pi\left(\frac{\lambda_{op}-3}{15-0.3\beta_{op}}\right)\right] - 0.00184 * \left(\beta_{op}V_{wop}^2 + \frac{3\beta V_{wop}^3}{R\omega_{Top}^2}\right)k \quad (8)$$

$$\xi = \quad (0.44 - 0.0167 * \beta_{op}) * sin\left(\frac{\pi(\lambda_{op}-3)}{15-0.3\beta_{op}}\right) - (0.44 - 0.0167 * \beta_{op}) * \left(\frac{KV_{wop}^3}{R\omega_{Top}}\right) * \left(\frac{\pi\lambda_{op}}{V_{wop}^2(15-0.3\ \beta_{op}}\right) * cos\left(\frac{\pi(\lambda_{op}-3)}{15-0.3\ \beta_{op}}\right) - 0.00184K\left(2V_{wop}\beta_{op} - \frac{9\beta_{op}V_{wop}}{\lambda_{op}}\right) \quad (9)$$

$$\delta = -\frac{0.0167KV_{wop}^2}{\lambda_{op}} * \ sin\left[\pi\left(\frac{\lambda_{op}-3}{15-0.3\beta_{op}}\right)\right] + \frac{0.0167KV_{wop}^2}{\lambda_{op}} * (0.44 - 0.0167\beta_{op}) * \left(0.3\pi\left(\frac{\lambda_{op}-3}{(15-0.3\beta_{op})^2}\right)\right) * cos\left[\pi\left(\frac{\lambda_{op}-3}{15-0.3\beta_{op}}\right)\right]\frac{-0.00184K(\lambda_{op}-3)V_{wop}^2}{\lambda_{op}} \quad (10)$$

The λ_{op} and K are defined respectively as follows:

$$\lambda_{op} = \frac{R\omega_{top}}{V_{wop}} \quad (11)$$

$$K = \frac{1}{2}\rho AR \quad (12)$$

By taking Laplace transform of EQ (6) and dividing by J_t :

$$\Delta\omega_t = \left[\frac{\xi}{J_t}\Delta V_w(s) + \frac{\delta}{J_t}\Delta U(s)\right]\frac{1}{s-D} \ \ (10), D \ = \ \frac{\gamma}{J_t} \quad (13)$$

Figure 1 represents the block diagram of EQ (13)

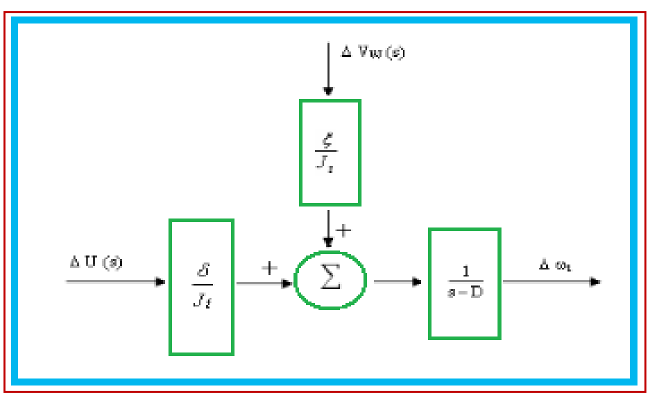

Figure 1: A block diagram representing the change in the mechanical angular rotor speed [8,910,11,12]

After obtaining the block diagram of the system, a PID may be used to control the pitch angle taking into account the actuator block diagram as shown in Figure 2.

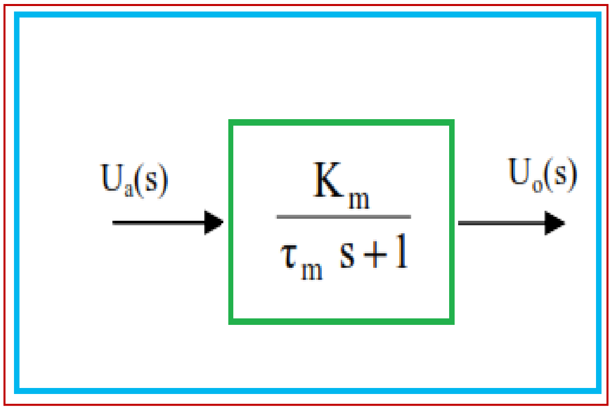

Figure 2: The block diagram of the actuator [8,9,10,11,12]

3 Design Overview and System Description

This document discusses a design with careful consideration of the respective probable impacts during operation The proposed design provides water to the remote and rural areas where a lack of electricity has existed and difficulties to supply power transmission lines. The design is based on the maximum power-point-tracking (MPPT) control technique, which is a method used to track the wind direction to increase the efficiency of wind turbines. The intended system should be capable, implementable and flexible to operate under extreme environmental conditions. Figure 3 shows the functional decomposition diagram, which breaks down these functions into the detailed functional units. Further Table 1 illustrates the function, constraints and the task description of the system components.

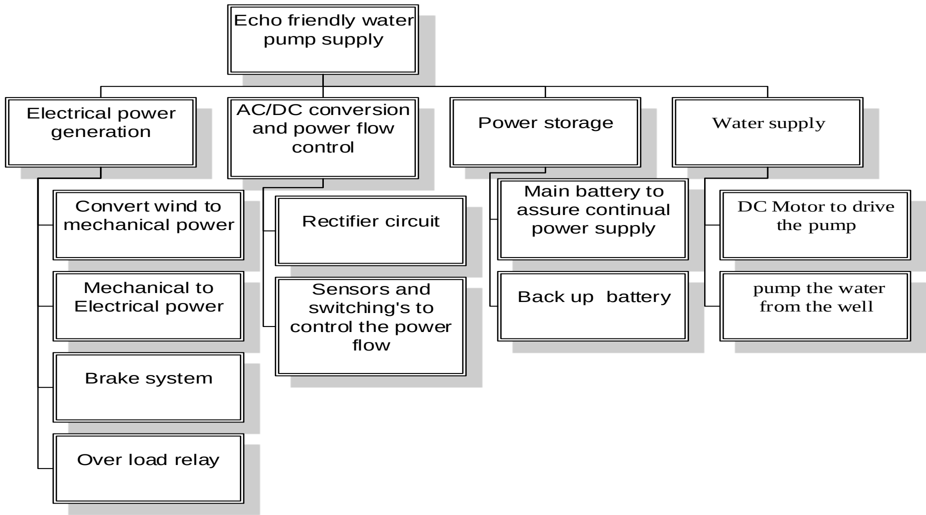

Figure 3: The traceability flow chart of the proposed design

Table 1: Traceability Analyses of the Proposed System

Function	Category	Requirement Description
Electrical Power Generation	Convert wind to mechanical power	A wind turbine is needed to convert the kinetic energy within the wind to mechanical power to drive the AC generator.
	Mechanical to electrical power	This application requires AC generator to convert the mechanical power to electrical power.
	Break system	The intended system must work under safe conditions. In order to protect the blades, a break system is necessary.
	Over load relays	Control the power transferred from the AC generator to the system.
AC/DC Conversion & Power Flow Control	Rectifier circuit	The main task of this element is to convert the AC voltage to DC to charge the storage battery.
	Sensors and switching's	Sensing the battery voltage , water level in the tank, and drive the whole system, this subsystem is needed
Power Storage	Main battery to assure continual power supply.	To ensure continuity for water supplying.
	Back up battery.	To increase efficiency of the system.
Water Supply	DC Motor to drive the pump	A DC motor output is needed to drive the pump.
	Pump the water from the well	A submersible pump work under various pressures.

Range of design alternatives is greatly considered by cost, continuity of water supply, maintenance, flexibility of installation, and also many other functional requirement considerations mentioned in the preceding table. Figure 4 displays a scheme of the suggested design whereas the wind turbine converts the wind power into mechanical power that transferred to electrical power by an attached generator. A rectifier circuit is needed to convert the AC voltage to a DC voltage. Then the output of the rectifier goes to a chargeable battery to store the generated electric charge. When the wind speed is below the cut-in speed the turbine cannot drive the motor, then a battery will perform this task. In order to charge the battery and running the load, a switching circuit consists of relays and switches are required. Finally, the pump is connected to the whole system in order to provide water to a tank.

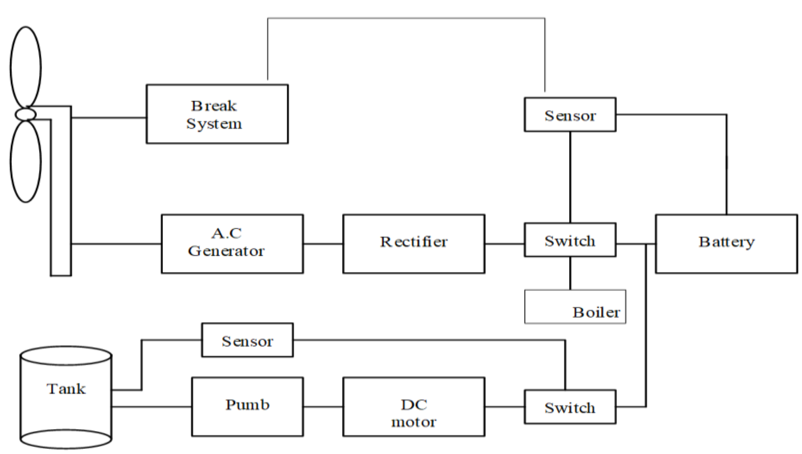

Figure 4: The design diagram

Part of the wind energy will be wasted when the battery is fully charged; therefore, the wasted power can be utilized in other purposes such as heating purposes. For instance, a boiler could be connected to the system consequently increases the design efficiency. Furthermore, there is break system that protects the system (blades) from being damaged when the wind speed is high or when the battery is fully charged. Subsequently, the system lifetime will be increased and the system efficiency improved.

4 The Electric Rectifier, Water Pump and Battery Computations

This section discusses the calculations of the electric rectifier and water pump that attached to the proposed design. Further, the selected rechargeable battery specifications are displayed.

4.1 The Rectifier Circuit

A full-bridge diode rectifier circuit must be employed to convert the AC voltage to DC. In order to senses the voltage, a switching circuit consists of two relays and a NOT gate has been used. The first relay operates when the battery voltage crosses the allowable limit. In this situation, the signal of the NOT gate highly increases and the relay allows to switch on the motor. The second relay senses the battery charge percentage. When the battery is fully charged, the connection between the rectifier and battery will be disconnected. Consequently, the boiler will be connected to the rectifier output. A basic three-phase star rectifier circuit is shown in Figure 5 whereas the circuit is considered as three single-phase half-wave rectifiers combined together [10]. Therefore, the circuit is referred to a three-phase half-wave rectifier. The diode is a particular phase conducts during the period when the voltage on that phase is higher than the other two phases. In Figure 5, the diode D conducts from $\pi/6$ **to** $5\pi/6$**.** Therefore, the average value of the output can be found as follows:

$$V_{dc} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_m \ sin\theta \ d\theta \quad (14)$$

$$V_{dc} = V_m \frac{3}{2\pi}\sqrt{3} = 0.827\, V_m \quad (15)$$

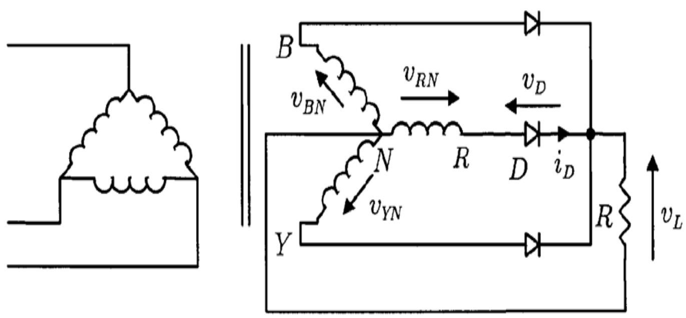

Figure 5: Three phase rectifier [10]

Figure 6 displays the signal behaviour of the rectifier output

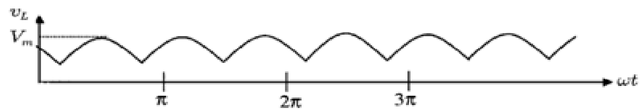

Figure 6: The output signal of the rectifier circuit [10]

4.2 The Water Pump Calculations

The selection of pump size is made on the basis of flow rate requirement and rotational speed to meet the desired output. The actual power needed for pumping water is called water horsepower (hp) and is calculated based on the next relation [13]:

$$P_{actual} = \frac{\text{gpm x TDH(ft)}}{\eta p \text{ x } 3960} \quad (16)$$

where: gpm is the pumping rate in gallons per minute, which is 10 gpm based on the datasheet of the selected water pump that related to the simulation. ηp is the pump's efficiency and TDH is the total dynamic head in feet, which is viewed as the total load on the pumping. This load is usually expressed in feet of head and calculated as follows [2,13]:

$$\text{TDH = Pumping lift +friction loss+ operating pressure +elevation change} \quad (17)$$

where Pumping lift: is the vertical distance from the water level in the well to the pump outlet as shown in Figure 7. Friction loss is water flowing past the rough walls in a pipe that creates friction and causes a loss in pressure. Friction losses also occur when water flows through pipe fittings, or when the pipe suddenly increases or decreases in its diameter. Tables with values for friction loss through pipe and fittings are widely available. The elevation change: is assumed equal zero (There is no elevation change). Manufacturers provide recommended operating pressures for specific water applicators in different systems. Operating pressure in psi is converted to feet of the head by the relationship:

$$1 \text{ psi} = 2.31 \text{ ft} \quad (18)$$

The operating pressure is the sum of the pressure due to the inlet and outlet conditions and pressure loss due to friction as follows [2,13]:

$$\Delta P_{operating} = (\Delta P_{static} + \Delta P_{velocity} + \Delta P_{elevation})_{inlet\text{-}outlet} + \Delta P_{fricition} \quad (19)$$

where:

ΔP_{static} is the static pressure

$\Delta P_{velocity}$ is the pressure change due to pump speed

$\Delta P_{elevation}$ is the pressure change due to elevation

$\Delta P_{fricition}$ is the pressure change due to friction

To simplify the calculations, the static pressure only will be considered since the other values of pressure are very small values compared with the static pressure and they can be negligible. The static pressure determined based on the next formula [2,13]:

$$\Delta P_{STATIC} = (\rho g h)_{water} + (\rho g h)_{air} \quad (20)$$

Table 2 displays a water well specifications according to the selected water pump

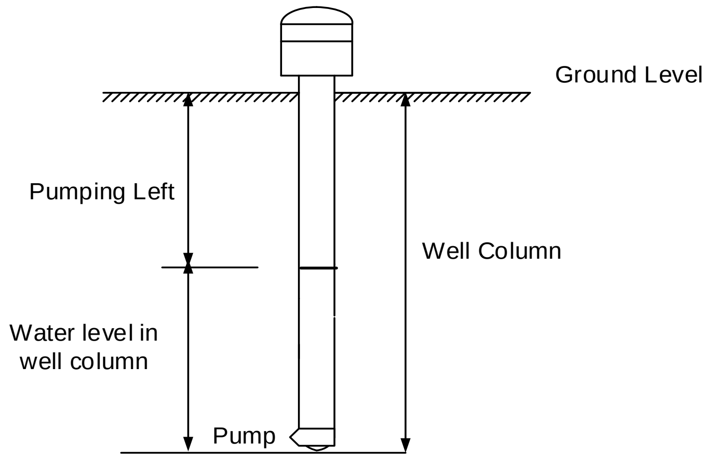

Figure 7: Well Scheme

Table 2 displays a water well specifications according to the selected water pump.

Table 2: datasheet of the selected water well [14]

Water Pump Tipe	5K Series - single stage centrifugal pump
Pumping rate in gallons per minute	10 gpm
Pump's efficiency	80 %
The elevation change	zero
Loss of head in feet due to friction per 100 feet of pipe	100.1ft
Static pressure	142 Psi
Operating pressure in psi is converted to feet of head	109.34 psi * 2.31 = 252.6 ft
Water column in the well $(h)_{water}$	100 m
Pump column pipe diameter	¾ in
Head losses	28.6/100ft
TDH	603.7 ft
P_{actual}	1.905 hp = 2 hp
Water density $(\rho)_{water}$	997 kg/m^3
Air density $(\rho)_{air}$	1.169 kg/m^3
Air column $(h)_{air}$ = Pumping lift	350 ft$\approx$ $106.7\ m$
Water density $(\rho)_{water}$	997 kg/m^3
Actual power of the water pump	2 hp

4.3 The selected Battery Specifications

A deep cycle rechargeable battery is selected according to the specifications mentioned in Table 3.

Table 3: Battery specifications [15]

Battery type	LEAD ACID
Battery capacity	300 Ah
Voltage	12/240 Volt
Battery weight	60 Kg
Operating temperature	Up to 60℃
Life cycle	6000 cycles

5 The Model Result

A Matlab Simulink has been used to simulate the system as shown in Figure 8. A 1.2 kW wind turbine generates electric power; which is converted to DC by using a full-wave rectifier. When the wind speed is above the cut-in-speed of the selected wind turbine, the full-wave rectifier converts the AC current to DC and run the DC motor, which drives the water pump without the need of the rechargeable battery. On the other hand, the generated power can be stored via the rechargeable battery when the wind speed is below the cut-in-speed of the selected wind turbine in order to provide electric power to the DC motor and run the entire system. The Simulink model of the proposed system is shown in Figure 8 [16]. The main target of the current study is to test the proposed system when the wind speed is below the cut-in-speed.

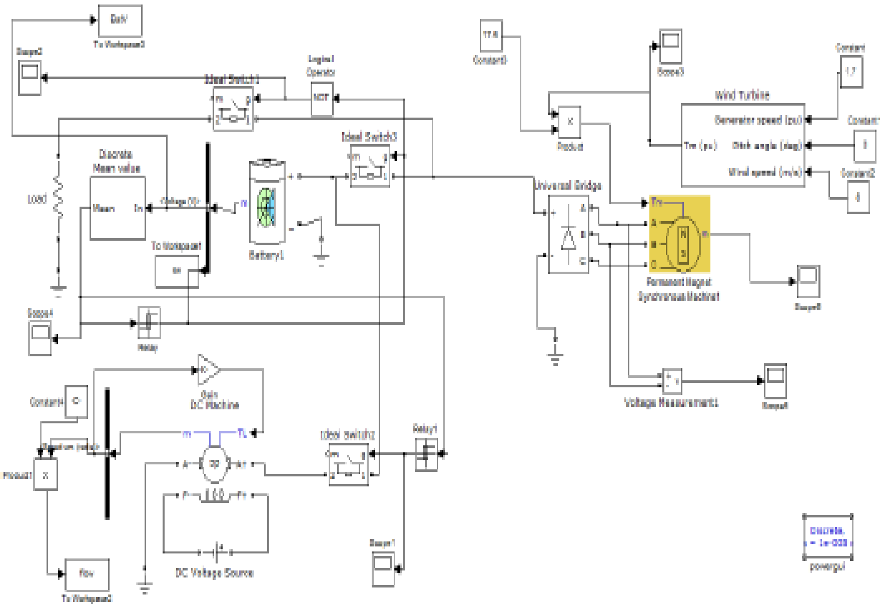

Figure 8: The Simulink model for the proposed system

First, the system has been investigated when the battery charge until 15% and the simulation is run for 4 seconds. In this situation, the motor does not work and the battery is charging hence the relay signal is 1. Figure 9 shows the relay voltage signal of the model with respect to the time when the cattery charge level is 15%. Second, the model system has been investigated when the battery is fully charged and the simulation is run for 4 seconds likewise. In this position, the motor leads the water pump to operate and fill the tank. The water flow rate approximately reaches 9.7gpm, and the relay voltage signal of the model with respect to the time equals zero1 as shown in Figures 10 and 11. According to the simulation results, the pumping water rate depends on the battery charge level. It is very obvious that the increase in the battery charge raises the rate at which the water is pumped as shown in Table 4. Further, Increase the capacity of the rechargeable battery extends the time period of the pump operation, which is very significant in the agricultural irrigation field. From the economic aspect, rising the capacity size of the battery clearly increases the cost of the suggested. At the same time rising the capacity size of the battery extends the pump operation period. Table 5 illiterates the time period of the pump operation with respect to the battery size according to the applied simulation.

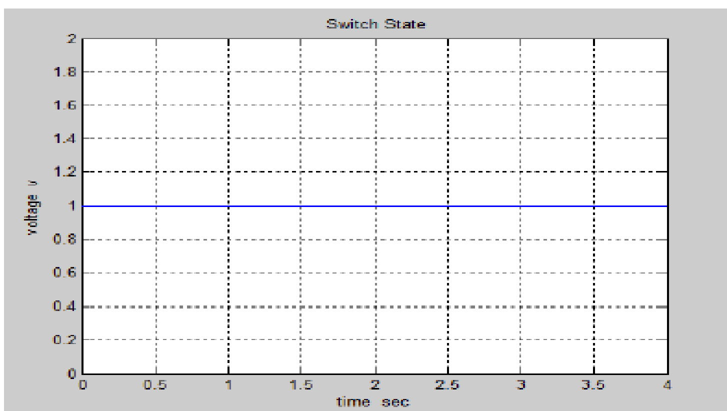

Figure 8: The relay voltage signal when the battery charge is 15%

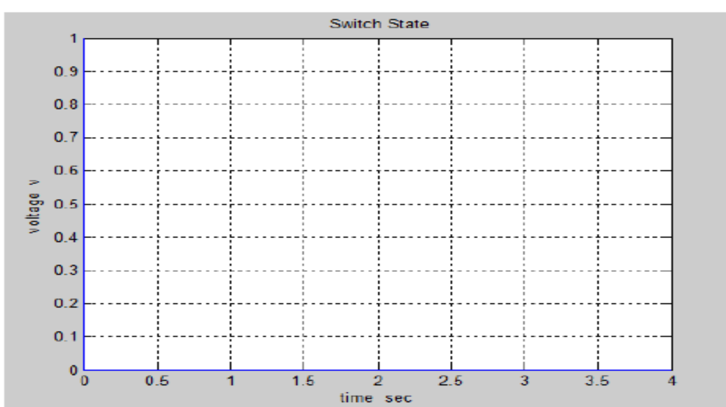

Figure 9: The relay voltage signal when the battery charge is 100%

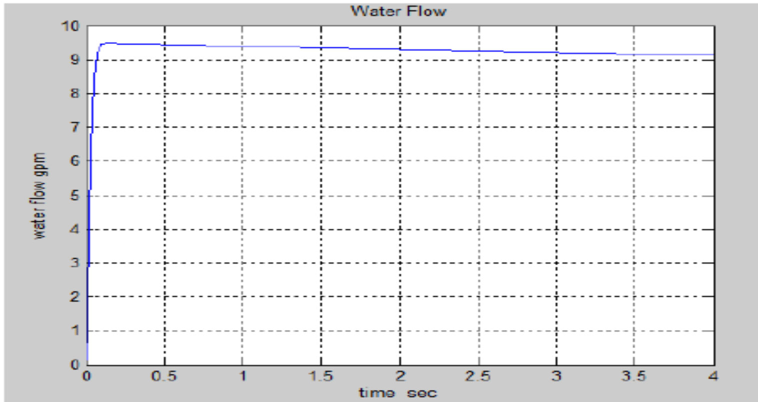

Figure 10: The water flow rate behaviour when the battery charge is 100%

Table 4: Summation Results

Battery charge rate	Rectifier volt signal (volt)	Water pumping Rate (Gpm)
15%	1	1.3
50%	0.7	4.9
75%	0.3	7.3
100%	0	9.7

Table 5: Summation Results

Battery size	pump operation time period (hrs)
100Ah	2
200Ah	4
300Ah	5
400 Ah	7
500Ah	8

6 Conclusions

In this study, an effective simulation based on Matlab-Simulink is applied in order to test and. demonstrates the requirement, design, and validation of a wind turbine-water pumping system for remote areas where there is a lack of electricity. A 1.2 kW wind turbine is proposed in this simulation since is a proper size to generate electric power that utilizes in the water pump systems. A rechargeable battery is used when the wind speed is below the cut-in-speed of the selected wind turbine and connected to the system in order to store and transfer the power to a DC motor, which used to drive a 1.5hp pump. The switching circuit consists of two relays and a logic gate used to control the flow of the required power. The simulation results illustrate that the pump water rate values are various according to the charge level of the rechargeable battery. Increasing the battery size extends the water pump period obviously.

Future work should be focused on different sizes of wind turbines and rechargeable batteries in order to estimate the reliability of wind energy systems to provide electric power to the water pumping systems.

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