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Solar/wind pumping system with forecasting in Sharjah, United Arab Emirates

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ABSTRACT

This paper demonstrates a water pumping hybrid power system design. The proposed system was designed for water related applications in Sharjah (Latitude 25.29 ^{o}N and Longitude 55 ^{o}E), United Arab Emirates. The proposed water hybrid system has two primary renewable power systems: solar PV panels and wind turbines. The proposed hybrid system considers the changes in weather conditions (humidity, wind speed, and temperature) since wind speed affects the performance of the wind turbines and solar panels are affected by solar irradiance. The following components are involved in the proposed design: battery (to store the power from solar panels), voltage regulator circuit (for getting stable DC voltage), three-phase rectifier (to convert the reduced AC voltage to DC), three-phase transformer (for reducing the obtained AC voltage), and DC electric motor (the main output of the proposed water pumping system). The proposed water pumping system relies on neural network blocks to achieve weather forecasting by obtaining solar irradiance values from the input temperature, wind speed, and humidity in a span of five years. Both MATLAB and Simulink are used simulate the performance of the proposed system under different weather conditions by changing the values according to the measured weather conditions values over five years.

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1. INTRODUCTION

Water, environment, and energy are issues that are linked and are significant sustainable development elements. Many countries around the world are facing shortages of water and energy besides environmental problems due to the increasing demand on these resources constantly [1-2]. Water is important for surviving since it is required for drinking, domestic needs, and industrial applications. Large-scale irrigation besides construction and power production require available water source. Moreover, water has a significant impact on the development of countries since the quality of life is related to the quantity and quality of available water resources [3].

Photovoltaic water pumping system is a very popular promising application of photovoltaic systems that is utilizable to supply water to rural and isolated areas. The advancement in the PV technology resulted in reducing solar panels cost and increasing the feasibility solar water pumping systems [4]. Some drawbacks face this type of water pumping system such as the changes in temperature conditions and low conversion efficiency [5-7]. Wind has been used as a source of power for water pumping applications. Some disadvantage of using wind power systems are related to the changes in wind speed throughout the day and the noise that is produced from the movement of wind turbines. The applications include domestic and community water supply, irrigation, cattle watering, salt pans, and drainage [8].

Hybridizing solar and wind energy is a significant solution to reduce relying on fossil-based fuels. Other benefits for it are increasing the reliability and efficiency besides enabling distributed generation in locations that have no large power generation and small-scale power generation like individual PV panels and micro wind turbines [9]. Sharjah (Latitude 25.29^{o}N and Longitude 55^{o}E) is located within the Arabian Desert. This significant location is part of Solar-Belt of the earth. It is important to introduce clean and green agenda in the energy market for the purpose of covering the rapid growth of demand worldwide every year. Another important reason for involving renewable and hybrid renewable sources of energy is the impact on environment since renewable sources of enrgy such as solar and wind are clean and do not cause air pollution or greenhouse gases emissions. There are many applications in which renewable energy is involved. Several examples include UPS systems, communication systems, air conditioning, portable electronic devices, electric vehicles, electric boats, and electric water pumps [10]. In order to obtain higher reliablilty for a renewable energy system, some factors have to be considered that are related to the environment [11-13]. Some examples of these factors include availability of adequate solar irradiance quantity. To manage the effects of chaning weather conditions and solar irradiance, a real-time system has to be included for battery management and controlling charging process.

The behavior of solar PV panels is nonlinear based on the behavior of the measured voltage and power. An optimum value is related to the nonlinear curve of solar panel; this value indicates the maximum power point (MPP). The MPP refers to the maximum obtained power from the panels and it depends on solar irradiance. It is important in hybrid renewable energy systems to use algorithms such as machine learning ones [14] in order to perform prediction of solar irradiance values based on supplied atmosphere measures. Many techniques were proposed befor for MPP tracking using different approaches like the load marching technique, the curve-fitting scheme, the ripple correlation algorithm, the perturbation and observe method, the sliding mode approach, neural networks, incremental conductance, fractional-order, and fuzzy logic control [15-21]. The perturb and observe method is very commonly used to obtain maimum power due to its simplicity and being independent on the power system design.

The hybrid wind/PV system was studied before. A hybrid system with battery backup was demonstrated in [22] to be reliable in specific areas. It involved a mathematical analysis to simulate the behavior of the lead-acid battery in hybrid wind/solar power systems. The system considered some factors like the current rate, the self-charging rate, the efficiency of charging process, and the capacity of the battery. They found good level of matching between the field measured data and the predicted data of the hybrid system. They analyzed the battery state of charge statistically based on 1-year field data relatd to the model from simulation. They considered the hourly and monthly variations besides the distributions of probability. Their results demonstrated the working states of the battery in the real hybrid power system. Another hybrid power system was proposed. The system involved three main components: wind turbines, solar PV panels, and battery system. The rating of the wind turbines was 300 W turbine while the rating of the solar PV panels was 100 w. The system had two 12 V 100 A-h batteries. These batteries were utilized to supply power to a remote data acquisition system [23]. Another hybrid system with solar PV panels and wind turbine was proposed in [24], it represented off-grid wind turbine and solar photovoltaic array pumping systems that was analysed as a hybrid system. They aimed to achieve the following objectives: Determining whether it is beneficial to use a hybrid PV/wind system over using a single wind or PV power system, determining whether the wind or solar array affect each other's output, determining the most efficient hybrid sytem for the location. The power rating of their wind turbine system in their design was 900 w. Their analysis relied on three solar arrays, the power rating of these arrays were 640 w, 480 w, and 320 w. They used a three-phase rectifier to convert the AC voltage to DC. That obtained DC voltage was combined with the DC voltage from the solar PV panels. Their output was a single helical water pump. Their hybrid system was able to pump 28% more water when the demand was highest (peak demand month) than the individual solar and wind systems individually.

The primary objective of the proposed system is simulating the hybrid design of renewable energy system (solar PV panels and wind turbines) to cover the increasing demand of water in isolated and far areas in Sharjah since rainy days are few and occur mainly from December to March and temperature is high in all seasons during the year. The goal is using weather forecasting to obtain solar irradiance values over an interval of five years from the values of atmosphere and maintaining continuous operation despite the changes in these values.

2. RESEARCH METHOD

Renewable energy utilization interest grew rapidly in rural and isolated areas worldwide because of the increased demand for water supply there. One example for that is utilizing photovoltaic generator as energy source for several motor pumps to cover larger isolated areas. Economic and practical solutions to water availability in desert areas are obtained when realizing autonomous and reliable pumping systems with a good efficiency. The configuration of a typical PV pumping system involves the following components: PV panels, chopper circuit, regulator block, and output motor. Figures 1-2 show the circuit of a solar PV panel module and a DC chopper. Solar PV module involves two resistors R_s and R_{sh}, one diode, and a current source since a solar PV panel is considered as a parallel current source while the DC/DC converter has two capacitors connected in parallel where one is connected at input side and one is connected at output side, a diode that is connected in series, a series inductor, a MOSFET block that is controlled by frequency and pulse width, and the input and output voltages.

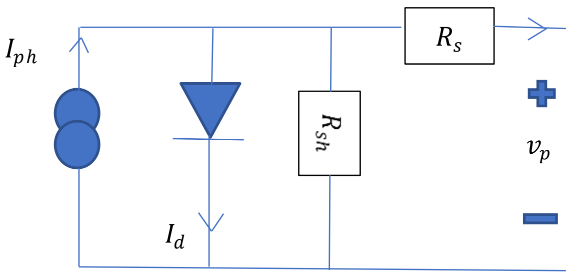

Figure 1. PV cell equivalent circuit

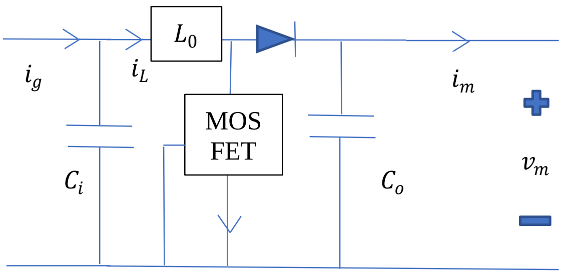

Figure 2. DC/DC converter equivalent circuit

The terminal PV module current equation is given by the expression (1).

$$i_P = I_{Ph} - I_o\left[exp\left(\frac{v_P+R_s i_P}{V_T}\right) - 1\right] - \frac{v_P+R_s i_P}{R_{sh}} \tag{1}$$

The expressions of Io and Iph are given by the equations:

$$I_o = I_{or}\left[\frac{T}{T_r}\right]^3 exp\ \left[\frac{qE_{GO}}{\gamma k}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right]$$

$$I_{ph} = [I_{SCR} + K_I(T - T_r)]\frac{\lambda}{1000}\ and\ v_t = \frac{N_\gamma KT}{q}$$

where i_p and v_p are the output voltage and current, q is the charge of an electron, Io refers to the reverse saturation current, N is the p-n junction's ideality factor, K is a constant number that is called Boltzmann constant, T represents the absolute temperature, R_{sh} is the intrinsic parallel resistance, and R_s is the series intrinsic resistance.

Additional variables can be added to the main expression in order to include the effect of the number of cells that are connected in series and parallel. The PV system has multiple PV modules in series, connected in parallel, in order to match the desired values of output current and voltage to the DC motor. For solar PV panels, if the solar irradiance values decreased, the short circuit current as well as the output power decrease but the internal resistance increases. Moreover, the output power of the solar PV panel decreases if the open circuit voltage decreases. This PVG exhibits a nonlinear characteristic given, approximately, by the expression (2) numerically.

$$i_g = I_{Phg} - I_o \left[exp\left(\frac{v_g+R_s i_g}{v_{tg}}\right) - 1\right] - \frac{v_g+R_{sg} i_g}{R_{shg}} \quad (2)$$

where

$$R_{sg} = R_s(N_s/N_P)\,, \quad R_{shg} = R_{sh}(N_s/N_P)$$
$$I_{phg} = N_p\, I_{ph}\;, I_{og} = N_p\, I_o \text{ and } v_{tg} = N_s\, v_{vt}$$

The power electronic DC/DC converter in Figure 2 is used between the PV panels and the motor with a variable duty cycle. The input capacitor and the inductor are chosen for limiting ripple of the input and output voltages that is caused by switching the gate terminal of the MOSFET block. The DC/DC converter equations are (3), (4) and (5).

$$C_i \frac{dv_g}{dt} = i_g - i_L \quad (3)$$

$$C_o \frac{dv_m}{dt} = (1-\alpha)i_L - i_m \quad (4)$$

$$L_o \frac{di_L}{dt} = v_g - (1-\alpha)v_m \quad (5)$$

where Ci is the input capacitance, C_o is the capacitance at output side, i_g is the input current, i_m is the output current, vg is the input voltage, and vm is the obtained output DC voltage. The first DC converter equation relates the input capacitor C_i with the currents i_g (input current) and I_L (inductor current). The second equation relates the output capacitor C_o with the currents I_L (inductor current) and i_m (output current). The third equation is related to the voltage across the inductor L_o.

3. RESULTS AND DISCUSSION

The system has the following components: MPPT controlled solar PV panels that charge the battery system, wind turbine system, three-phase step-down transformer to reduce the output wind turbine voltage, three-phase rectifier to convert the voltage from the transformer to DC, voltage regulator to maintain stable output DC voltage for battery recharging from solar PV panels, and DC motor for pumping as shown in Figure 3. The blocks of the solar PV system included two capacitors, a custom neural network block that takes the three atmosphere parameters (wind speed, humidity, and temperature) as input and gives the irradiance values as an output to the solar PV block. It also included the MPPT blocks that takes the input from the output voltage of the solar PV panels to achieve the MPPT operation. The components of the voltage regulator are three resistors, one NPN transistor, a diode, and band limited op amp. The three-phase rectifier was similar to six pulse rectifier configuration, it consisted of a diode bridge and an output filter that has an inductor which is connected in series and a capacitor that is connected in parallel with the output voltage. The three-phase transformer was connected in a star connection type. The values of the irradiance over time were obtained over five years interval from June 2014 till June 2019 using custom neural network based on the average temperature in Celsius, average wind speed in m/s, and average humidity percentage. Figures 4, 5, and 6 show the average measured temperature, wind speed, and humidity. The temperature has lower values at the middle since it refers to December and January. It can be noted that the maximum average temperature during that period was 37 Celsius during both June 2019 and July 2017. The minimum average temperature was 21 Celsius during both January 2015 and January 2018. The maximum obtained wind speed was during March 2019 (5.2 m/s). The minimum average humidity percentage was during May 2015. Figure 7 shows the corresponding solar irradiance values based on these measured atmosphere values. The largest solar irradiance value was obtained between June 2014 and June 2015 (1030 w/m^2) while the lowest solar irradiance value was between June 2018 and June 2019 (280 w/m^2). The wind power system combines wind turbine block, asynchronous generator block, and synchronous condenser block. The wind turbine system is affected by wind speed value.

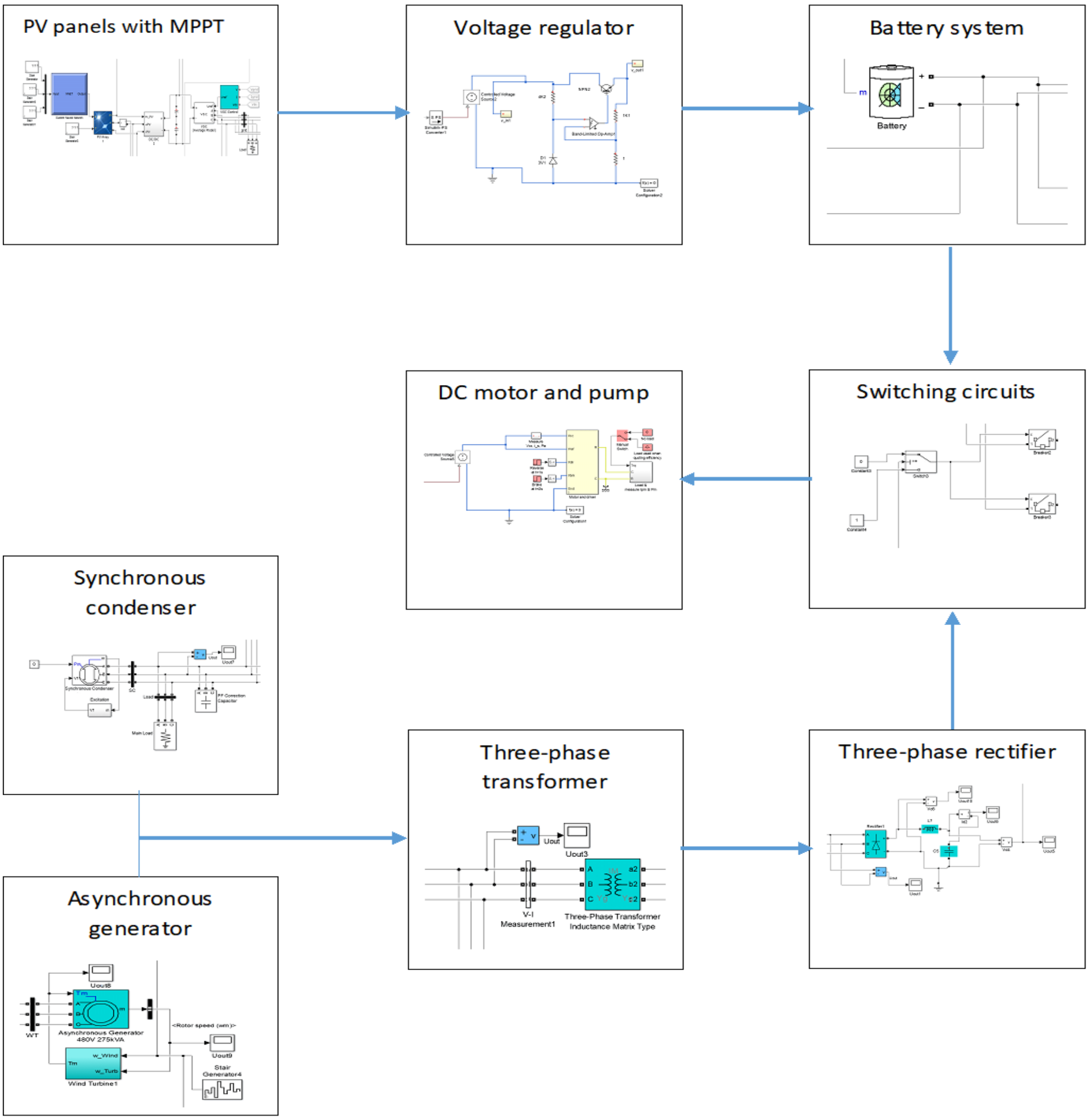

Figure 3. The proposed hybrid system

Switching between solar and wind operation was done using circuit breakers based on wind speed value. The system is operated by wind turbine if the wind speed is above a threshold value, otherwise the system is operated by the battery bank that is charged by solar PV panels. The wind speed threshold value is 3.5 m/s [25]. The output solar PV voltage is shown in Figure 8. Figure 9 shows the obtained voltage from wind system. The obtained voltages from the rectifier and regulator blocks are shown in Figure 10. The largest and smallest DC voltages of the regulator output are 12.525 V and 12.487 V respectively. The maximum obtained output DC voltage from the solar PV panels is 170 V while the minimum DC voltage is 50 V. The output three phase voltage of the wind turbines was close to 600 V. The step-down transformer reduced the wind power system voltage to be suitable for operating the motor after converting the voltage to DC. It can be noted that the DC voltages values are close to each other. The speed of the DC motor is shown in Figure 11. It can be seen that the speed was maintained at a stable rpm value regardless of the changes in temperature, wind speed, and humidity. The output power for solar PV panels is shown in Figure 12. The maximum obtained power from solar panels is 43 kW and the minimum obtained power is 4 kW. The maximum obtained solar PV voltage and power were directly related to the maximum obtained solar irradiance values.

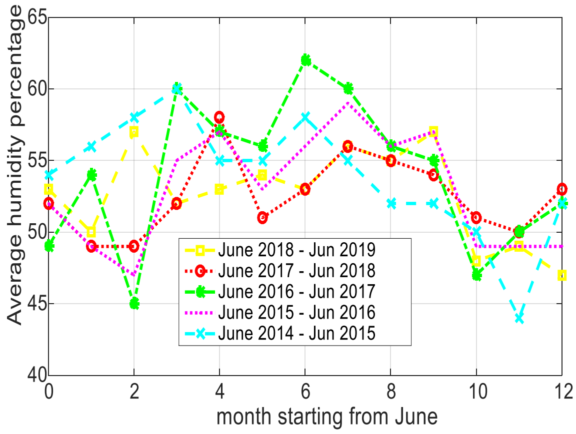

Figure 4. The average values of temperature over five years from June 2014 till June 2019

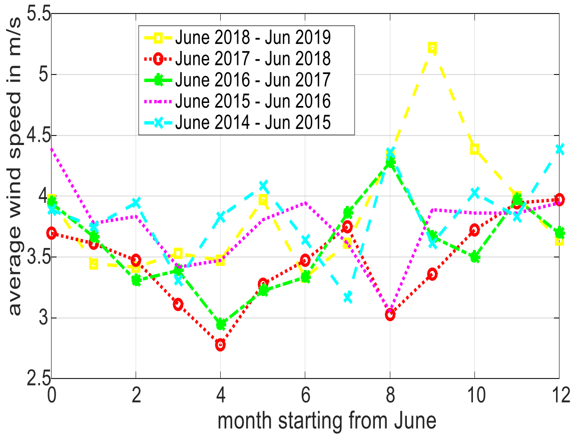

Figure 5. The average values of wind speed over five years from June 2014 till June 2019

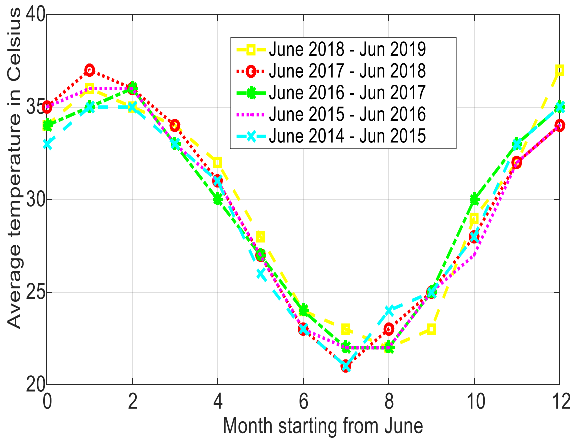

Figure 6. The average values of temperature over five years (June 2014 till June 2019)

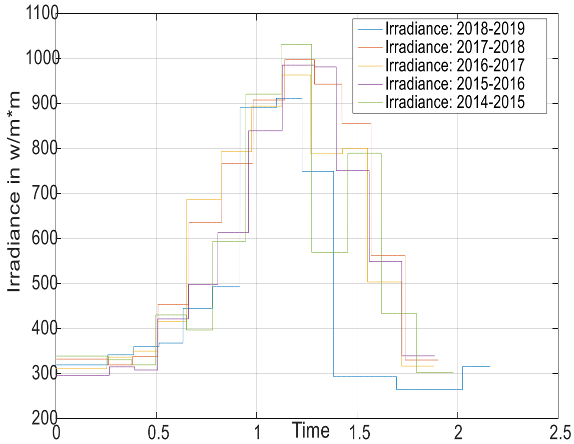

Figure 7. The obtained solar irradiance based on the average values by neural network

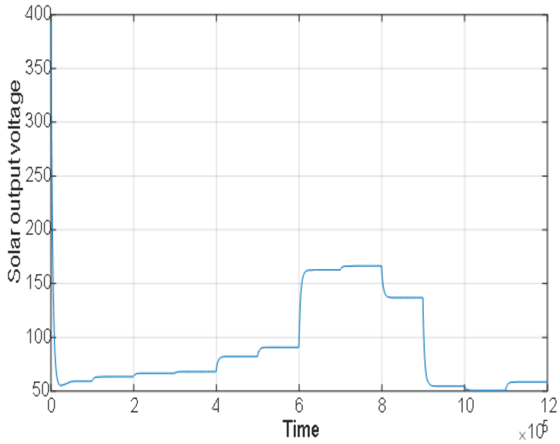

Figure 8. The obtained PV panels' DC voltage

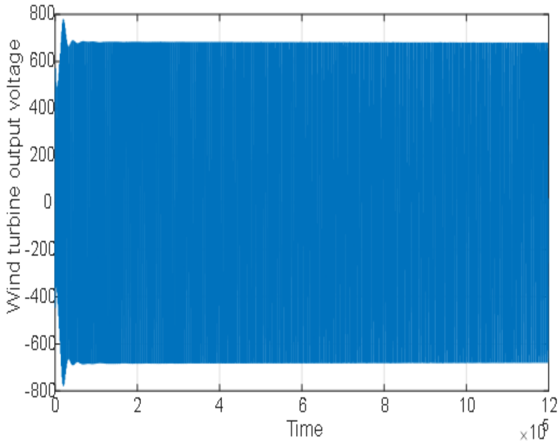

Figure 9. The output AC voltage from wind turbine operation

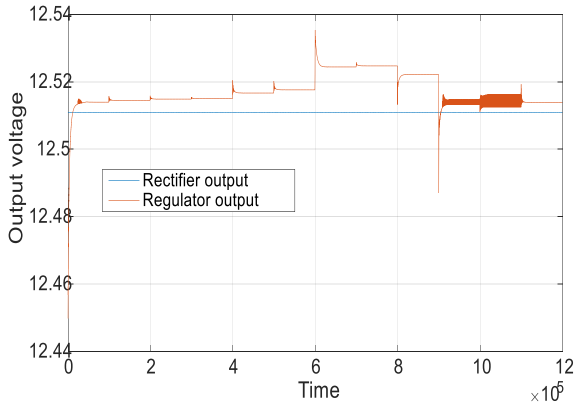

Figure 10. The DC voltage output from the regulator and rectifier blocks

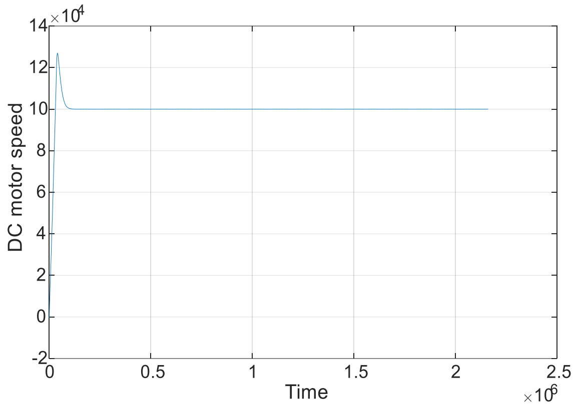

Figure 11. The output DC motor speed

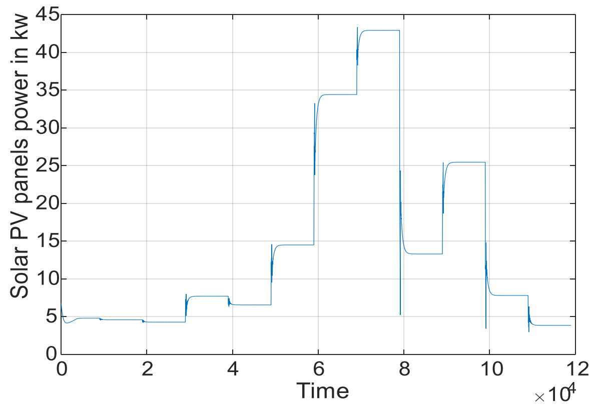

Figure 12. The output power in kW from solar PV panels

4. CONCLUSION

We proposed a hybrid power design for water pumping. The system was simulated to be suitable for implementation in Sharjah, United Arab Emirates. The proposed system had two renewable energy systems: solar photovoltaic panels and wind turbines. The components of the system are solar panels with perturb and obsreve algorithm MPPT control system, AC transformer, battery system for storage, output motor, condenser with generator, DC to AC rectifier, and regulator. Neural network blocks were used in order to obtain solar irradiance values based on temperature, wind speed, and humidity values over five years. The measured time interval of these values was from June 2014 till June 2019. Switching between solar and wind operation was done based on wind speed using circuit breakers. The performance of the proposed system was demonstrated using MATLAB and Simulink simulations to obtain the output voltages and corresponding speed of the DC motor. The system maintained stable output voltage and speed despite the effect of weather factors.

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