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Modelling and Simulation of a Hybrid Renewable/Battery System Powering a Cathodic Protection Unit

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***Abstract*—In this paper, the performance of the proposed off-grid wind-solar PV hybrid system powering the cathodic protection unit is simulated and analyzed using MATLAB/SIMULINK. Furthermore, the performance simulation for the battery energy storage system with PV-wind hybrid energy system under variable solar irradiance and wind speed respectively is also conducted. The hybrid system consists of a wind turbine which uses a permanent magnet synchronous generator driven directly from the turbine, a PV array and a battery bank. The simulated results reflect that the designed hybrid system of such capacity can adequately supply a cathodic protection unit with no power shortage at different weather conditions.**

***Index Terms*—Battery energy storage, cathodic protection, hybrid, off-grid, wind-solar PV**

I. Introduction

Underground pipelines play a significant role throughout the world as means of transporting potable and raw water, oil and gases over distances of various lengths from the source to the ultimate consumers. In South Africa, particularly in KwaZulu-Natal, these pipelines run mostly in remote mountainous areas to achieve shorter routes. This brings the need for remote electrification via grid-extension, which is a challenging solution due to high connection costs and low electricity consumption rate for Cathodic Protection (CP) systems. Hence, it is difficult to recover the initial investment costs since there are monthly electricity bills to be paid for every Transformer Rectifier Unit (TRU) installed along the pipeline servitude [1]. Moreover, AC power is the main and most common supply of power to the TRU units [2]. In this kind of application, the supplied power has to be converted from AC to DC using a rectifier [3].

Most of electrical demands in rural and isolated areas are still supplied with diesel generators. However, in spite their advantages, they have long run operating cost implications as well as negative impacts on the environment [4]-[6].

In the remote areas where solar radiance can be highly expected throughout the year, a PV system with a battery bank can possibly supply a certain output of power to a CP installation. This power can meet the demand when the load has been correctly evaluated and with the correct sizing of the PV modules and hence the array where applicable [7], [8]. However, the PV array can be huge in high corrosive areas such as wetlands. Therefore, the addition of wind energy to form a combination of wind and PV power can significantly reduce the system size based on the availability of wind at the selected site [1], [9]. Permanent Magnet Synchronous Generator (PMSG) wind turbines are found to be more advantageous with gearless construction and it provides the advantages like good efficiency, low maintenance, reduced losses, reduced costs and good controllability [10], [11].

Republic of South Africa (RSA) has a total amount of about 47% wind energy capacity compared to other African counties, which clearly shows that the country has great interest and support of wind energy generation [12], [13]. With SA recently experiencing huge energy shortages which affect the CP systems negatively, it makes renewable energy sources to be among the most efficient and consistent solutions for sustainable and suitable energy. This paper focuses on the modelling and simulation of the dynamic performance of a Hybrid Wind solar PV with a battery storage system using MATLAB/Simulink.

II. Schematic Layout of the System

Fig. 1 shows the schematic diagram of the proposed wind-solar hybrid system powering a CPU. As shown in this figure, wind turbine and solar panels are both supplying energy to the load. However, due to intolerable potential power failures and the significant need for continuity of power supply to the CP system, the battery bank is incorporated into the system. The arrows in the diagram illustrate the flow of power in the system. The battery bank will store the energy when there is excessive power and assist to meet the load demand without shortage.

In Fig. 1, P_{PV} is the solar PV generated power supplying electrical energy to CPU, P_{WT} is the power generated by the turbine generator supplying power to CPU and both the generated powers are used to charge

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the battery bank when there is excess power. The battery power (P_{BAT}) has a bidirectional flow, depending on whether it is charging the battery or supplying the load when needed. P_L is the power supplied to the Cathodic Protection Unit either from P_{BAT}, P_{PV} or/and P_{WT}. The load power is expected to be uniform in consumption with a peak power demand of about 230W and running 24 hours a day.

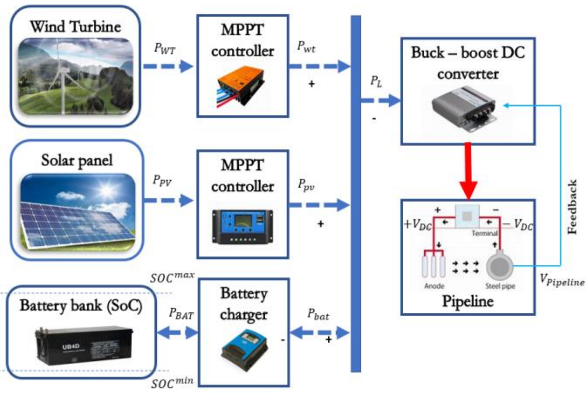

Fig. 1. Proposed system schematic diagram.

III. Simulink Model of an Off-Grid Hybrid Wind Solar-PV System

The Simulink model of an off-grid hybrid wind solar-PV system supplying a CP unit model is built by connecting different blocks from MATLAB/Simulink. The wind turbine, PMSG, PV system, MPPTs and CPU unit models are all configured separately and then converted to subsystem blocks for simplicity of the overall diagram. The overall system model is shown in Fig. 2. The output power of the system, which is from both PV and wind turbine (WT) as well as a battery bank depending on the weather conditions, is used to power the CP system. The inputs of the overall system are the wind speed, solar irradiance, ambient temperate, and turbine pitch angle.

The amount of electricity that can be generated from wind is dependent on the velocity of the wind resource. WT operates similar to a hydropower generation system in terms of operation and rotor blade configurations. The combination of wind turbine and permeant magnet synchronous generator (PMSG) joint using MATLAB/SIMULINK is shown in Fig. 3.

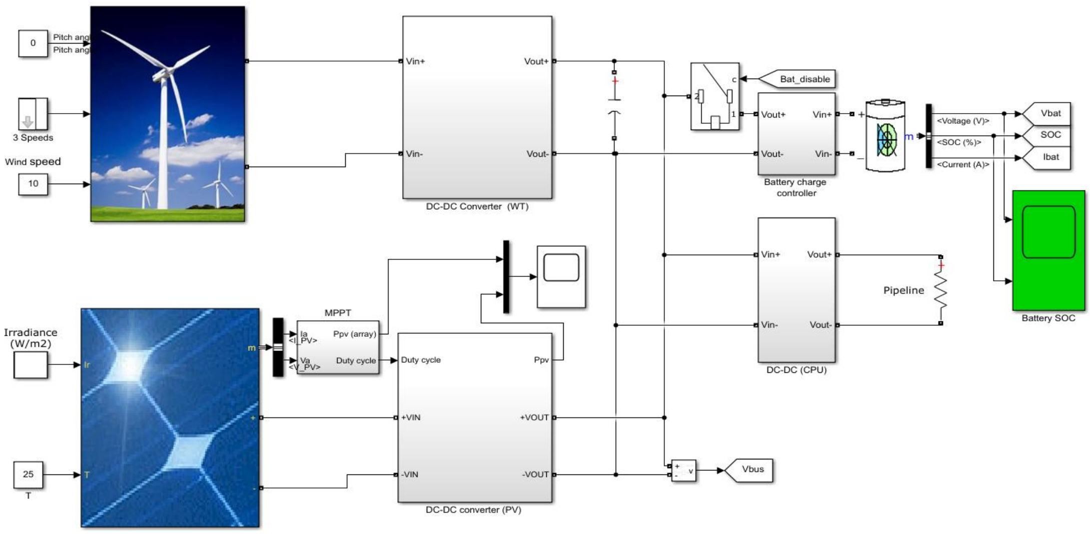

Fig. 2. Simulink model of an off-grid WT-PV hybrid system.

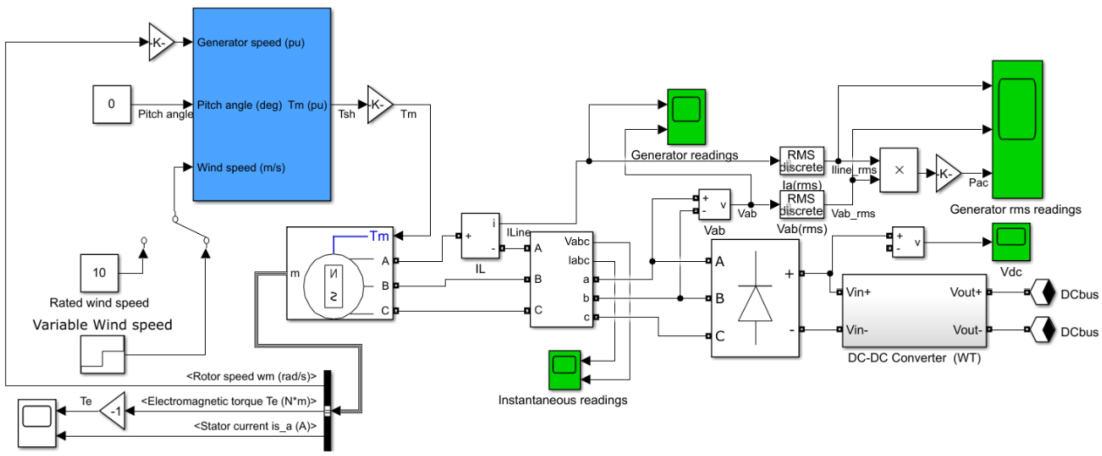

Fig. 3. Wind turbine model in Simulink with PMSG and Rectifier.

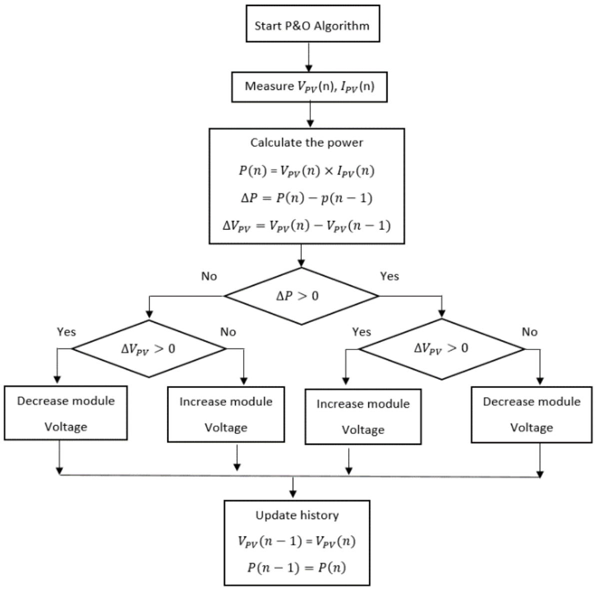

Fig. 4. P&O algorithm flow chart [18].

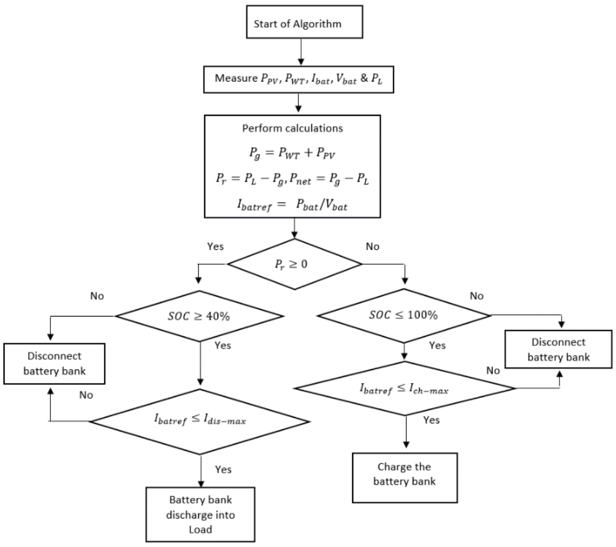

Fig. 5. Flow chart of the battery control algorithm.

To achieve maximum power extraction from a varying speed wind turbine, a turbine must operate at a maximum power point (MPP). For every wind speed, there is an MPP. There are two traditional methods to achieve MPP, which is by parameter selection based control methods and direct MPPT control algorithms based on sampled data [14]. In [15] the author performed the speed and torque control by the control of interfacing DC-DC converter. Due to the fluctuating nature of wind, tracking the MPP requires the use of algorithms, such as perturb and observe (P&O), optimal torque control (OTC), fuzzy logic or any other applicable algorithm presented in the literature [15]. In this study, the control used is the P&O algorithm with the DC-DC converter, where the rectified output voltage and current are measured and used as inputs to the MPPT. Reference [16] revealed that DC-DC converter with zero voltage switching (ZVS) techniques is more efficient. Moreover, hybrid algorithms has less occurrence of transients from the point where they keep track of the maximum power using common MPPT techniques [17].

One of the biggest challenges in solar power generation is the change in generated power when irradiance and temperatures continuously change. This becomes a huge concern due to the very low efficiency in solar energy generation, which ranges from 9%-20% [19]. However, if the output power of the PV array is maintained at the maximum power point (MPP), the given efficiency can be also maintained. The P&O algorithm was implemented in this model using a MATLAB function and Fig. 4 shows the flow chart of the algorithm for $n>0$, where n is the term at which data is requested. In P&O, algorithm direct measurements of voltage, current and power are taken to perform the hill-climbing algorithm. A perturbation is provided to a PV module or array voltage to translate an increase or decrease in power [20].

The excess energy from the PV system and WT may be stored in the battery bank. The stored energy is used for supplementing the unmet load demand when the net generated power by WT and PV system is insufficient to meet the load demand [20]. For safe operation of the battery bank, the storage limit is restricted according to the designed specified limits. The total battery bank capacity is 9.6kWh, with only 5.76kWh useful due to the 40% selected DOD. The flow chart of the battery control algorithm is presented in Fig. 5.

IV. SIMULATION RESULTS AND DISCUSSION

This section presents the results of the simulations. The inputs are the wind speed, solar irradiance, Temperature and technical specification of the selected equipment. Fig. 6 below shows the performance of the PV array in different irradiances at a constant temperature of 25°C and different irradiance.

The performance of the array is also evaluated by simulating the output power for five different irradiance levels (200W/m^2, 400W/m^2, 600W/m^2, 800W/m^2 and 1000W/m^2) at a constant temperature of 25°C. The output is recorded for both the MPPT and the array power output, and it can be seen that as the irradiance increases the power also increases. However, the power increases with the irradiance while the temperature remains constant. Furthermore, the PV array output is seen to be higher than the MPPT output at all times, but the MPPT output has no harmonics caused by a change in irradiation.

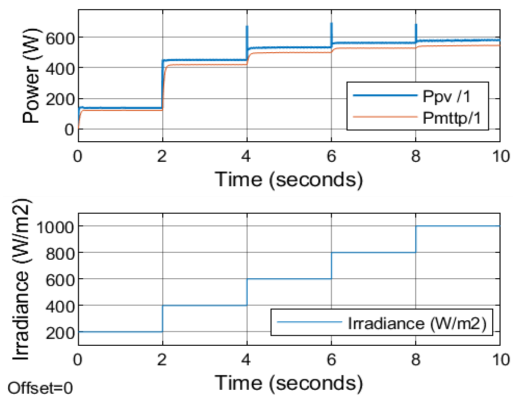

Fig. 6. PV array and MPPT output power.

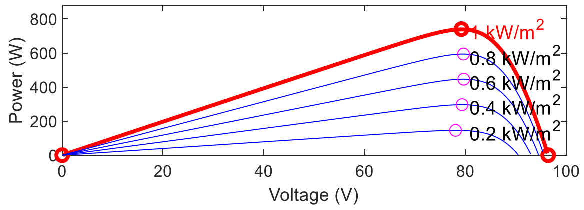

Fig. 7. Array P-V characteristic curve for different irradiance levels.

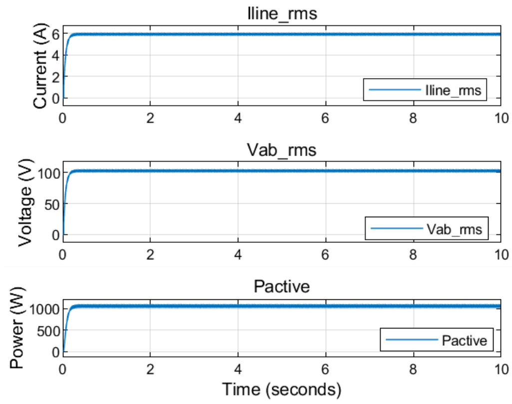

Fig. 8. RMS voltage, current and active power (P_{active}) at the rated wind speed of 10m/s.

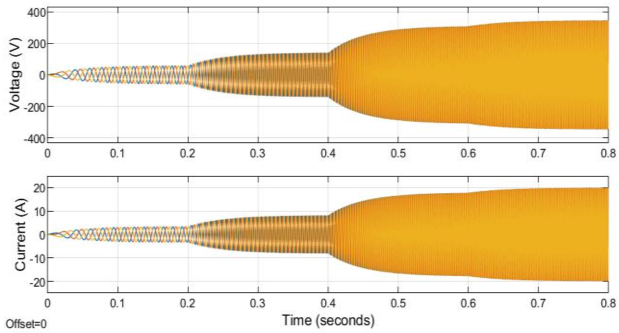

Fig. 9. Generated voltage and load current for different wind speeds.

In Fig. 6 and Fig. 7, it can be seen that when the irradiance is 200W/m^2 the array output is around 150W, slightly above 400W for 400W/m^2, 500W for 600W/m^2 and for the irradiance at standard test conditions (STC) which is 1000W/m^2 gives the output of about 590W. The DC-DC converter output driven by the MPPT gives an output that is a couple of watts lower than the PV array output, the power difference varies with the change in irradiance.

To study the dynamic response of the wind turbine system, the model is simulated first with the rated wind speed of 10m/s at the rated power of 1kW. The system is then simulated at four (4) different wind speeds of 8m/s, 10m/s, 15m/s, and 20m/s, respectively, at the time interval of 0.2 seconds, these speeds include the rated wind speed of 10m/s.

Fig. 8 below gives the active power (P_{active}), RMS line voltage and load current. It takes the generator 0.2s to reach steady-state line voltage, current and power respectively. The steady-state RMS line voltage is about 100V with RMS line current of 6A and hence the power of 1kW. Furthermore, the generator produces nothing for the first 20 µs and this will result in the load draining from the battery bank if the PV array will also be producing insufficient power to meet the load demand.

From Fig. 9, it can be seen that as the wind speed increases, the generated voltage and load current are gradually increasing as well. Furthermore, as the torque increases the current also increases as well. The output voltage at 8m/s is around a peak value of 50V, 100V for 10m/s which is the rated wind speed and it keeps increasing to a value of 350V at 20m/s. These voltages in RMS are 35V, 71V and 247V respectively.

The output voltages of both Wind turbine and PV array are connected to the DC bus through DC-DC converters. These converters are used to track the maximum power while regulating the output voltages to match that which is desired at the DC bus, for Battery bank charging and for supplying the load. The DC bus reference voltage (V_{busref}) is 48V DC, Fig. 10 below shows the bus actual voltage with the bus reference or desired voltage. It can be seen that within the first 10ms the actual bus voltage shoots up to a value around 90V, which is due to system start-up, but it quickly drops to the expected voltage output of 48V.

Power flow analysis of the modelled system are presented in Fig. 11 for different cases to show the dynamic operation of the system. Different cases are achieved by using different irradiance and wind speeds to acquire less or no power generation at desired times of simulation. The inputs are changed every 2 seconds of simulation, at the start of the first interval (0-2) seconds, the irradiance is set to 200W/m^2 with the wind speed of 0m/s. During this period the load power demand (P_L) remains constant at 230W and for the rest of the simulation, while there is no wind power (P_{wt}) production since the turbine is expected to be stationary. Furthermore, the PV generated power (P_{pv}) is insufficient to meet the load, hence the battery is discharged to supplement the load demand and there is no excess power available during this interval.

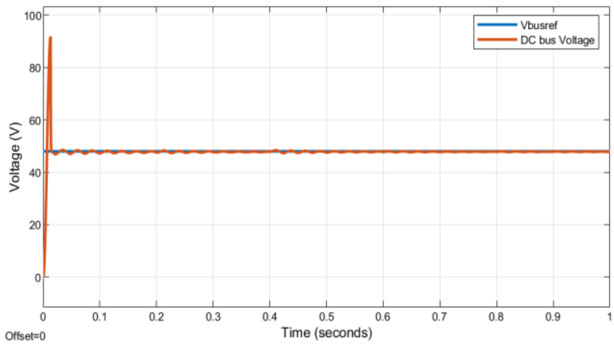

Fig. 10. DC bus voltages.

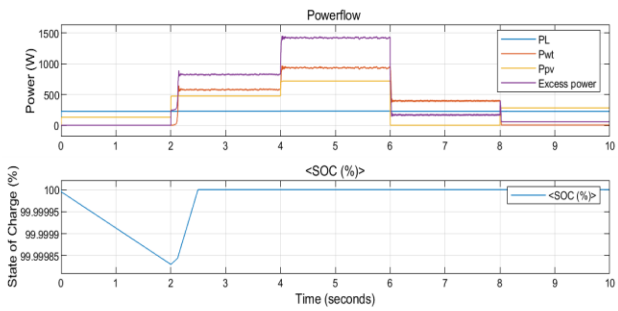

Fig. 11. Power flow and Battery State of Charge (SOC).

A second case is presented in an interval between 2 and 4 where the PV irradiance is increased to 800W/m^2, with the wind speed of 8m/s. At the beginning of this period, the wind turbine shows no production but in few milliseconds it picks up and produces about 600W, while the PV is generating 500W immediately after the irradiance increases. Since the power demand starts to be less than the supplied power, the load is met and there is excess power of about 870W, and this energy charges the battery until it gets to 100% state of charge.

A third case is similar to the one previously explained except that the irradiance is increased to 1000W/m^2 with the wind speed of 10m/s, to evaluate the performance of the system at the rated inputs of both the wind turbine and PV panels. The case is presented between 4 and 6 seconds of the figure and it is clear that both wind turbine and PV array get very close to their rated power outputs of 1KW and 740W respectively, during this period the excess power gets too close to 1500W. The fourth case is presented in an interval (6-8) seconds where the irradiance is set to 0W/m^2 with the speed set at 7m/s, during this period the PV array generates no power while the wind turbine generates about 400W giving an excess power of about 170W but because the battery is full the power will be dumped.

The last evaluated case is of the interval 8 to 10 seconds where the wind speed is set to 2m/s and the irradiance is set to 600W/m^2. The results indicate that the PV array will produce the power amounting to 250W, which is sufficient to meet the load demand with a power excess of 20W. At this period, the wind turbine produces no power due to the set speed being out of the working speed of 3-25 m/s.

V. Conclusions

In this paper, a MATLAB/SIMULINK model of an off-grid wind solar-PV hybrid system proposed to supply the CP system and the essential models of the system components are addressed. The model of a wind turbine is connected to a PMSG to model a standalone wind power generation system and it is further combined with the PV array to evaluate their performance when functioning as a combination. The rectified output voltage of PMSG is connected to the DC-DC buck converter, which has an MPPT to control the output power and voltage. Likewise, the PV array output is connected to the DC-DC buck-boost converter with an MPPT to track the maximum power while regulating the voltage.

The two outputs are combined on the DC bus to charge the batteries through a charge controller and to supply the CPU based CP system (Load) through DC-DC buck converter. The proposed model is simulated and it is observed that with a change in wind speed, the output power of the wind turbine also changes with relation to the generator parameters. Likewise, for the PV array, as the solar irradiance change the output power changes accordingly. Furthermore, it is observed that when the generated power fails to meet the load demand, the system discharges the battery bank to supply the load and when there is excess power it charges the battery bank. Hence, the simulation results revealed the effectiveness of the proposed model.

Further research studies have to be conducted on the viability of the system using economic factors such as payback period, life cycle cost or breakeven analysis.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Cyncol A. Sibiya conducted the research, developed the model and wrote the paper; Bubele P. Numbi analyzed the data, edited the paper and contributed to the development of the model; Kanzumba Kusakana analyzed results, expanded the model and reviewed the paper; all authors had approved the final version.

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