Experimental Investigation and Control of a Hybrid (PV-Wind) Energy Power System.

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Abstract—The most essential infrastructure of today’s modern civilization is the energy system. A new energy revolution is ongoing worldwide in understanding the affordability, reliability, and sustainability of energy supply. One of the major challenges and opportunities considered in this energy revolution is the integration of the energy system. The varying dynamics of renewable energy production and the environmental conditions between the different energy sources are the major reasons for this challenge. Wind and solar energies are considered the best renewable sources and the foremost substitute sources for power generation. These energies are playing a vital role as alternates of nuclear energy and fossil fuels. Electricity is generated through wind energy conversion systems and photovoltaic (PV) cells. These technologies are clean and environmentally friendlier than non-renewable energies. A hybrid PV-wind generation system is more effective and consistent than a single-source system because the solar system cannot work at night or in cloudy weather and wind speed is varying. For achieving maximum power, DC/DC converters are used in systems [2-7]. Dual input recommendations are given in [2] in order to get maximum power by using buck/buck boost converters for solar and wind systems. The grid connection of a hybrid system based on solar/fuel and cell/wind was suggested in [3]. Another configuration of multi input booster was proposed for hybrid solar/wind generation systems in [8]. In [1], PMSG machines were utilized for the wind turbine and two DC/DC converters were used for wind and solar energy, whereas in the proposed work, a SCIG machine is used for the wind turbine, to get maximum power and two separate boost converters are used for the wind generator and the PV system. In the proposed model, the characteristic of wind energy conversion system, exhibits maximum power of 3kW and the PV module characteristic exhibits maximum generated power of 44.71W.

II. PROPOSED HYBRID SYSTEM CONFIGURATION

This hybrid system is an assemblage of SCIG based WECS, PV and super capacitor connected MPPT-based boost converters separately at the output of WECS and solar as displayed in Figure 1. The converter is easily controlled by varying the duty cycle with high efficiency and minimum

Keywords—WECS; PV cells; SCIG; MPPT

I. INTRODUCTION

Wind and solar energy are the most favorable renewable energy sources due to their low cost of energy production. Many studies have considered only one of these energy sources (solar or wind), which has disadvantages. Wind speed variations disturb the generated power through WECS, whereas the power produced through PVs is affected by the deviation in solar radiation and varying temperature. Hybrid solar/wind generation is much more effective and consistent, because the solar system cannot work at night or in cloudy weather and wind speed is varying with time and season. Moreover, usually low winds flow on sunny days when solar generation works with higher efficiency [1]. For achieving maximum power, DC/DC converters are used in systems [2-7]. Dual input recommendations are given in [2] in order to get maximum power by using buck/buck boost converters for solar and wind systems. The grid connection of a hybrid system based on solar/fuel and cell/wind was suggested in [3]. Another configuration of multi input booster was proposed for hybrid solar/wind generation systems in [8]. In [1], PMSG machines were utilized for the wind turbine and two DC/DC converters were used for wind and solar energy, whereas in the proposed work, a SCIG machine is used for the wind turbine, to get maximum power and two separate boost converters are used for the wind generator and the PV system. In the proposed model, the characteristic of wind energy conversion system, exhibits maximum power of 3kW and the PV module characteristic exhibits maximum generated power of 44.71W.

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power variability. The output of both boost converters is connected to a mutual DC bus bar.

Fig. 1. Diagram of the proposed hybrid system.

A. Maximum Power Point Tracking Algorithm

The algorithm used in this model is P&O (Perturbation and Observation). It is easy to device, low-cost, and simple. The flow chart of P&O MPPT is shown in Figure 2. The scheme constantly perturbs the operative voltage after equating the output power with its earlier value.

Fig. 2. P&O flow chart.

B. Characteristics of the WECS Generator Model

In the impacted area on the turbine, the power produced is articulated as [9]:

\[ P_w = 0.5 \rho \pi C_p (\lambda, \beta) \lambda V_w^3 \]  \( (1) \)

where the co-efficient of power is \( C_p = 0.3-0.59 \), \( V_w \) is the speed of wind, \( \beta \) is the pitch angle for Zone-2 supposing 0°, \( \rho = 1.25 \text{kg/m}^3 \), and \( \lambda \) is speed ratio of tip and can defined by:

\[ \lambda = \frac{\omega R}{v} \]  \( (2) \)

Here, \( \omega \) is denoted as the rotor speed of the wind generator. Wind power and the turbine power relations are expressed as:

\[ P_t = T \omega t = C_p(\lambda, \beta)P_w \]  \( (3) \)

Equation (4) illustrates wind generator’s turbine power captured by the wind turbine system. \( C_p \) is the performance coefficient, \( v \) is free wind speed and \( \omega \) is the turbine’s angular speed.

\[ C_p = (0.73)\exp\left[\frac{1}{R_{\text{rot}}} V_w - 13 \cdot 635 e \left(\frac{1}{R_{\text{rot}}} V_w - 0.003\right)\right]^{-1} \]  \( (4) \)

The turbine power of the wind generator taken by the turbine system is defined by the wind speed given in (4)-(7), whereas the speed of the wind turbine is expressed as in [10, 11]. Equation (5) expresses the power of the wind turbine versus its speed, where \( P \) is mechanical power, \( \rho \) is air density, and \( A \) is the turbine swept area.

\[ P_t = 55 \cdot 155 p A^3 \left(\frac{V_w}{R_{\text{rot}}} - 0.09 \exp\left[\frac{V_w}{R_{\text{rot}}} - 0.003\right]\right)^{-1} \]  \( (5) \)

Figure 3 shows the speed of the wind turbine versus the wind turbine power expressed from (5), where \( V_w \) is wind velocity. It should be noted that at different wind speeds, the turbine power changes with respect to the speed of turbine. Figure 3 shows that the turbine power varies at differed wind speeds. The maximum power moves on a 3rd order curve, which shows the maximum power produced by the turbine at each wind speed.

Fig. 3. Turbine power versus turbine speed.

C. Wind Generator System’s Controller Model

Through a rectifier wind-generator system, the three-phase AC voltage is inverted to DC voltage (\( V_{in} \)) by back electromagentic force. This review mainly consists on maximum power tracking control performed by the varying duty cycle of the DC-DC boost converter to the DC side. Figure 4 shows the generator control of the DC-DC equivalent circuit. The input voltage adjusted through voltage/current is controlled by the DC-DC boost converter. As a control variable of the duty cycle, the speed of the generator is varied with respect to the turbine in the same proportion.
D. PV Cell Modeling

An equivalent circuit of a single PV cell can be shown by applying a source of current, two resistors, and a diode. The model of the PV cell with the single diode is shown in Figure 5, and its description in Table I.

\[
I = I_p - I_d - I_s h = I_p h - I_s h \exp \left[ \frac{q}{N A} (v + i R_s) - 1 \right] - i \frac{q}{N A} \left( \frac{1}{R_s} \frac{1}{R_p} \right) (8)
\]

\[
I_{ph} = I_{sc} + K (T - 298) (9)
\]

![Fig. 5. Equivalent circuit of the PV cell.](image)

The PV cell equation for V-I characteristic is expressed as:

\[
I = I_p h - I_d - I_s h = I_p h - I_s h \exp \left[ \frac{q}{N A} C (v + i R_s) - 1 \right] - i \frac{q}{N A} \left( \frac{1}{R_s} \frac{1}{R_p} \right) \exp \left[ \frac{q}{N A} C (v + i R_s) - 1 \right] - i \frac{q}{N A} \left( \frac{1}{R_s} \frac{1}{R_p} \right) (6)
\]

where:

\[
I_{sc} = I_{ph} \left( \frac{T_{ref}}{T} \right)^{3} \left( \frac{k}{b} \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right) (8)
\]

\[
I_{ph} = \left[ I_{sc} + K(T - 298) \right] (9)
\]

![Fig. 6. Equivalent model of the super-capacitor.](image)

E. Super-Capacitor

It comprises of two actuated carbon electrodes, which are electrically shielded by an absorbent separator. The current accumulators permit current transferring to the external terminals. The entire system is saturated with electrolyte permitting the ion transportation between both electrodes. Low internal resistance is a property of the super-capacitor. There is contact resistance in the electrode between the current collector and carbon particles, with increase to the non-significant resistance values given by electrode [12-14]. There are many advantages of super-capacitors for hybrid systems where energy storage devices are needed. The use of these capacitors as secondary power systems allows them to respond quickly during the high load demand. These capacitors have lower time constant than the conventional electrochemical generators (perhaps release charge in a few seconds). Moreover, these capacitors have the ability to deliver bulk power in a very short time. Due to the lack of electrochemical response at the electrodes, the super-capacitors are considered to be used for stability as storage devices [13].

The equivalent model of the super-capacitor is shown in Figure 6. Equation (10) gives the expression of \( V_{sc} \) of the voltage of the super-capacitor in relation with the internal resistance \( R_{sc} \) and the current \( I_{sc} \) of the super-capacitor as:

\[
V_{sc} = V_{1} - R_{sc} I_{sc} = \frac{V_{sc}}{C_{sc}} R_{sc} I_{sc} (10)
\]

![Fig. 7. Super capacitor bank.](image)

For the proposed hybrid system, the super-capacitor is used for storage and stability and is connected to the DC bus. The capacitor bank is shown in Figure 7 and the parameters of the super-capacitor are given in Table II.

III. EXPERIMENTAL MODEL AND ANALYSIS

To study the factual and tangible status, the real setup of the wind and solar energy conversion system is required, which is mostly set up to generate simulated controlled wind speed to
operate the WECS and extract solar energy, which requires high cost and big area. A simpler way is software simulation, but it has limitations for real-time investigation. The best way is to follow the wind turbine norms by using a Motor-Generator (MG) setup, where a motor replicates the wind turbine sketch under varying wind speed and a PV panel with artificial generated irradiation represents the solar setup.

**TABLE III. EQUIPMENT AND TOOL LIST WITH DESCRIPTION**

| Equipment name                              | Description                                                                 |
|---------------------------------------------|-----------------------------------------------------------------------------|
| Prime mover (DC permanent magnet machine)   | 180Vdc, 2.7A, 0.4KW, 2500rpm. Type:EM-3330-1A, S/N: 201                     |
| 3 phase squirrel motor (SCIG)               | 3-phase; 220V, 1.4A, 50/60Hz, 0.3KW, 1420/1678rpm. Type:EM-3330-3C S/N: 201 |
| Solar panel                                 | Maximum power 260W                                                          |
| Tachometer                                  | Tachometer 20713A                                                           |
| Rectifier (for 3phase)                      | PE-5310-5A                                                                 |
| Measuring instrument                        | Company Yalong: YL195                                                       |
|                                            | Company Rohde & Schwarz                                                      |
|                                            | RTH1002                                                                     |
| Load (resistor)                             | 3.3kΩ (variable)                                                            |
| Capacitor (excitation cap)                  | 10µf ±5%, 350-400VAC                                                        |
| Super capacitor bank                        | 2.640µF; 450V                                                               |
| Power supply                                | Power Electronics Universal                                                 |
|                                            | SupplyMod: AEP-1/EV                                                          |
| Booster                                     | Capacitor: 470µf 450Vx3                                                     |
|                                            | Inductor: 1.8mH                                                              |
|                                            | 5ADiode: FR205                                                               |
| Digital oscilloscope                        | GWInstek GDS-2074A, 60Mhz                                                   |

After ample study, an MG set was taken as a prototype for WECS based entirely on the experimental model. A squirrel cage induction motor machine generated power and a permanent magnet DC machine was chosen to emulate the wind turbine in order to investigate the wind turbine non-linear performance. For the analysis of the output power of SCIG, the motor operated at variable speed. The aim is to experimentally investigate and control the hybrid power system, which is based on WECS and PV through MPPT. The model setup is shown in Figure 8. The WECS was operated with a DC-DC converter connected to SCIG rectified output. The PV was operated with a DC-DC converter connected to the panel output in order to analyze output factors, i.e. power, voltage, and current. To get the succeeding power values a resistive load was connected as dummy load.

**IV. RESULTS AND DISCUSSION**

The experimental results of the hybrid wind/PV power system under different scenarios and conditions are discussed below.

Figure 9 shows the bus bar output voltages when both sources are available and ON (hybrid state). Maximum output voltage of 320V is generated by the hybrid system on the bus bar by maintaining the common bus voltage and Figure 10 shows the output current of the hybrid system (0.408A). Figure 11 shows the maximum output power (130.56W) generated by the proposed hybrid system when maintaining common bus power sharing.

Figure 12 shows the voltages before and after the boost converter with respect to generator speed (rpm), when WECS us ON and PV is OFF. It is clearly shown from the output results that at 37s a high rectified output voltage of 280V is generated while out of the DC/DC boost converter the output voltage received is 340V. The speed of the generator was 660rpm when these maximum voltages were recorded. So the voltages of WECS before boost converter was augmented by...
21% by using the designed boost converter, working on the principle of P&O algorithm.

Figure 13 shows the voltage before and after the boost converter along with the power after the boost converter (44.71W). It is clearly shown from the output results that at 31s, the maximum generated output voltage of the solar panel is 34V while at out of DC/DC boost converter the output voltage received is 324V. The voltage of the solar source before the boost converter is maximized by using the designed Buck-boost converter working on the principles of genetic algorithm. The results are summarized in Table IV.

The hardware-based experimental model of the hybrid system proved to provide fruitful results under varying environmental conditions. In the proposed model, two boost converters are separately used for PV and wind having MPPT functions. The converters were based on the P&O and Genetic MPPT algorithms, which transferred maximum power to the DC bus from the WECS and the PV cell.

V. CONCLUSION

The achieved experimental results show the below mentioned conclusions, which can be extracted from this study. At present, standalone wind and PV systems are globally supported on a relatively large-scale but are not able to give consistence energy. The hybrid system based on Wind/PV is a smart scheme for the utilization of the emergent substitute and renewable sources of energy. This study shows a hybrid WECS/PV system connected to a DC bus with MPPT. The analysis and results of the proposed experimental model signified the output power produced by the hybrid scheme which can supply continuous power with improved consistency in comparison with a single power source system. The results of the system in three different conditions were analyzed.

- When the WECS system was ON and the PV was OFF, the characteristic of wind energy conversion system, exhibited maximum power of 100.3W.
- When the WECS system was OFF and the PV was ON, the PV module characteristic exhibited maximum power of 44.71W.
- When both sources were ON (hybrid state), the maximum power generated by the hybrid system was 130.56W by maintaining the common bus voltages and power-sharing.

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