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Design and implementation of a microcontroller-based wind energy conversion system

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Abstract: In this study, a dsPIC-controlled DC/DC boost converter and a wind turbine control system that tracks the maximum power point are designed and implemented. In practice, the energy generated by a permanent magnet synchronous wind turbine is applied to the load using a circuit that consists of a rectifier, boost converter, and protective load. The converter operates in the designed mode 35% more efficiently than in the normal operation mode. In addition, the wind turbine is protected from overvoltages in strong windy weather using the protective circuit. Experimental results show that the ripple value on the direct current belonging to the converter output complies with the IEC 61204 standard. Moreover, the designed system is fast and easily programmable, and it can be adapted to other wind turbine models.

Key words: Boost converter, wind energy, maximum power point tracking, dump load, dsPIC

1. Introduction

Due to the depletion of fossil fuels and their environmental pollution, recent studies have generally focused on renewable energy sources such as solar, wind, biomass, hydrogen, and geothermal energy [1]. The main is to achieve secure, efficient, and sustainable energy conversion and consumption. Among alternative energy sources, wind energy systems are more important due to the fact that they can be installed faster compared to other resources and traditional stations. Furthermore, wind energy systems are more economic, clean, easily accessible, and commonly used energy resources [2].

Although wind is a difficult type of energy to control, energy conversion is achieved using constant-speed wind turbines in applications for locations where wind is continually at constant speeds. However, doubly fed induction generators (DFIGs), wound-rotor induction generators (WFSGs), and permanent magnet synchronous generators (PMSGs) are used in variable-speed environments [3]. The usage of PMSGs has been particularly increasing in recent years for variable-speed systems [4–6]. Along with large-power turbines at MW levels, small-power and variable-speed wind turbines are also used in off-grid operations, farm applications, wireless antennas, and battery charging systems. PMSG turbines are more preferred among small-power wind turbines, as they can produce energy at lower speeds, do not require a gear box, and have lower maintenance and operation costs [3,7].

For energy production, maximum power point tracking (MPPT) is performed at variable wind speeds by using the power electronic circuits located at the output of turbine [7–9]. Furthermore, the MPPT operation

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minimizes the mechanical stress and breakdowns in variable-speed turbine systems [10]. Briefly, the MPPT operation can be defined as controlling the current and the voltage generated by the turbine continuously with the help of a converter or an inverter located at the turbine output. It enables maximum efficient conversion of the energy obtained from the turbine to the loads [11]. In order to keep the power at a maximum level with the MPPT operation, power tracking methods such as perturb and observe (P&O), incremental conductance, disruptive capacity, current-based control, and voltage-based control are used [12]. Furthermore, microcontroller-based processors such as digital signal processors or field-programmable gate arrays are used during operations performed on the MPPT and algorithms like neuro-fuzzy are included in order to perform the operation faster [13–16]. Additional dump loads are connected during the MPPT operation in situations where the output power continuously increases, the load volume decreases, and the turbine speed increases. Therefore, the system is operated securely [17]. When studies in the related literature are examined, it is seen that some studies have focused especially on the controlling of small-power and variable-speed wind turbines using semiconductor components [1–9]. However, no study that checks both the MPPT and the dump load was encountered in small-power turbine applications.

This study presents the design and implementation of a dsPIC-controlled DC/DC boost converter and a wind turbine control system, which performs the MPPT operation for variable-speed wind energy systems. A 2.5-kW PMSG turbine is used in practice. The difference of the applied system from other applications is that the dsPIC-controlled 2.5-kW system has a boost converter based on P&O logic while keeping control of both current and voltage.

The designed system with a dump load has some features such as being fast and easily programmable, economical, and productive. The proposed study also protects the system by switching the dump load without any overshoot. Therefore, the output voltage of the converter can be increased and decreased step by step in accordance with its reference voltage in 10 ms. In addition, the output voltage ripple of the designed converter is achieved as 0.72% and this value is within the limits of IEC 61204 ($0.72\% < 1\%$). This result indicates that the designed converter has high-quality output.

2. Converting wind energy to electrical energy

Wind turbines are used in order to convert wind energy to electrical energy. DFIG, WFSG, and PMSG are the most commonly used alternators in the turbines [3]. Regardless of the alternator structure used in the wind turbine, it is necessary to examine the conversion of wind energy to electrical energy and the factors affecting this conversion. The mechanical energy generated from a wind turbine can be expressed as follows [18]:

$$P_m = \frac{1}{2}\rho \times A \times V^3 \times C_p(\lambda, \beta) \tag{1}$$

Here, ρ, A, β, $Cp\ (\lambda, \beta)$, and V indicate the air density (average: 1.25 kg/m^3), area swept by the blades (m^2), blade pitch angle (degree), speed of the wind (m/s), and the turbine's power coefficient, respectively. The tip speed ratio λ is also expressed as [18]:

$$\lambda = \frac{\omega \times R}{V} \tag{2}$$

Here, ω indicates the rotating speed (rad/s) of the wind turbine and R indicates the blade's radius. In constant speed systems, the output power of the wind turbine is directly related to the turbine's power coefficient.

However, it is necessary to keep the turbine's output power constant at the maximum level at different wind speed values in order to obtain the maximum power from the turbines at variable wind speeds. For this purpose, the blade's pitch angle is controlled in order to obtain a higher energy conversion in wind turbines. However, power electronic converters that process the MPPT algorithms are used in small-power wind turbines. Figure 1 indicates the ratio between the turbine's output power and the rotor speed under different wind speeds [19].

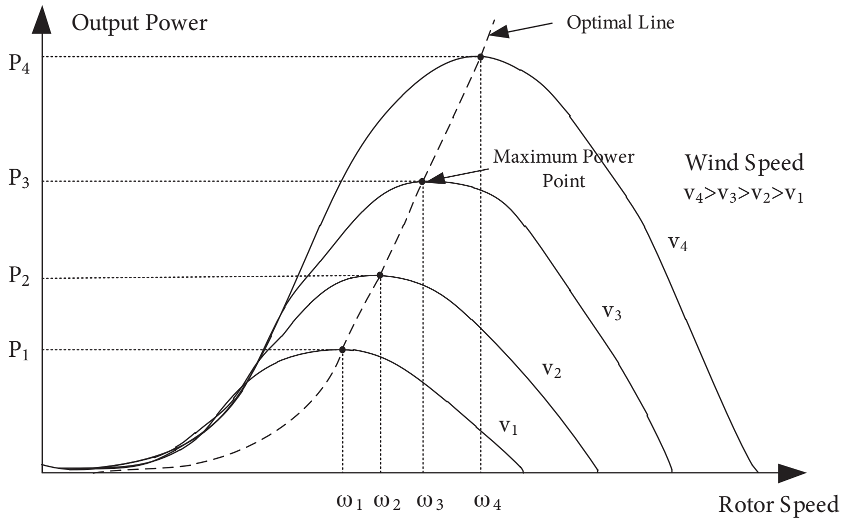

Figure 1. The ratio between the turbine's output power and the rotor speed under different wind speeds.

As seen from Figure 1, a different power point emerges for each wind speed value. However, the rotor speed should be kept at a certain point with the help of the turbine's power coefficient in order to reach the maximum power point. For the optimum wind speed, as expressed with Eq. (3), for fixed-blade and small-power turbines where the blade's inclination is not changed, the power obtained from the turbine increases in parallel with the wind speed due to the fact that blade length is also constant [18].

$$\omega_{OPT} = \frac{\lambda_{OPT} \times V}{R} \tag{3}$$

Despite that, the electronic systems connected to the turbine are overloaded when the wind speed has a changeable structure. The AC energy obtained from the turbine is converted into DC energy using a rectifier. If it is directly applied to the input of an inverter, the inverter is overloaded at the stage of performing the MPPT operation and providing a constant and maximum output power under variable current input values. In the case of using a converter after the rectifying operation for variable wind speeds, the current is kept at a constant level and the electronic equipment is protected from burdening. Furthermore, it is unavoidable to use converters in island-mode applications where the DC current is directly transmitted to the load or where the battery charge operation is performed. For this reason, the electrical energy produced by the turbine is converted into DC current in an uncontrolled rectifier. This DC current is applied to a boost converter in order to perform the MPPT operation and keep the output current at a constant level.

The electrical energy produced by the turbine is transferred to the load using different methods such as the grid interactive operation and the island-mode operation [20]. The current obtained from the turbine is confirmed in the grid interactive operation and this DC current is directly transmitted to the grid with the help of an inverter. In island-mode operation, the customers are directly fed in places without any grid. At the stage of being stored and using the system, the energy is stored by charging a battery group. The stored energy is used as needed [21]. However, in the designed system, the 3-phase AC current obtained from the turbine is converted into DC using an uncontrolled bridge rectifier. Later, the direct current obtained passes through a boost converter and is transmitted to the user by converting the current at the output of the converter into alternating current.

3. Design and implementation of the control system

In this study, a 3-phase variable-frequency AC current, which is obtained from a PMSG turbine, is converted into DC current by means of a rectifier. This DC current is applied to the DC/DC boost converter for the purpose of keeping the current at a constant level on the system's output. It also performs the MPPT operation, where the constant DC current at the converter's output is transmitted to the load or the charging unit. The block scheme of the designed system is illustrated in Figure 2. The hardware and software developed are clarified in detail in Subsections 3.1 and 3.2.

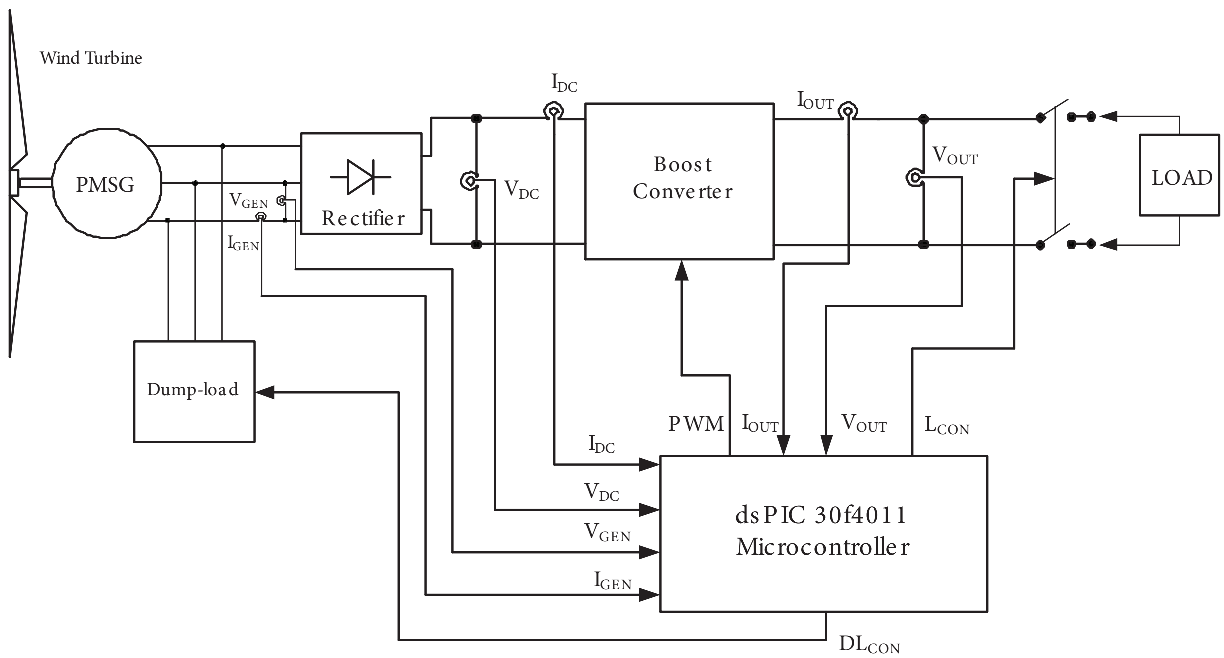

Figure 2. The block scheme of the designed system.

As seen in Figure 2, a dump load is connected in order to prevent system damage when the system faces extreme wind speed or when the input current exceeds the converter's limits. By virtue of this load, the turbine protects itself in cases of extreme wind speeds and no load situations. Moreover, a boost converter is used in the system in order to apply the converted DC energy to an inverter or a charging unit.

3.1. Hardware

During the boost converter application, the switching signal needed for the operation of the system is generated by a dsPIC 30F4011 series microcontroller. The current and the voltage values on the converter that are input during the MPPT operation are read by the controller and the system power is calculated. The ratios of the switching signal are changed according to the increase or decrease at the input current level. The output current is adjusted to always provide the maximum power according to the status of the load at the output. The block scheme belonging to the applied converter is depicted in Figure 3. The system is composed of a PMSG wind turbine, a dump load, a rectifier, a microcontroller, current and voltage sensors, a boost converter, and an insulated-gate bipolar transistor (IGBT) driver. The technical specifications of the PMSG are given in Table 1.

Table 1. Technical specifications of the PMSG.

PROVEN WT-2500 Wind turbine technical specifications		
Performance	Cut-in wind speed	2.5 m/s (5.6 mph)
	Cut-out wind speed	> 70 m/s (>155 mph)
	Rated wind speed	12 m/s (26 mph)
Rotor	Type	Downwind, self-regulating
	Number of blades	3, flexible
	Blade material	Polypropylene
	Rotor diameter	3.5
	Rated RPM	300
	Rotor thrust (kN)	5
Generator	Type	Brushless, direct drive permanent magnet (no gear box, zero maintenance)
	Output	60–400 Vac
	Rated power	2500 W
	Annual output	2500–5000 kWh, depending on the site
Rotor speed control	Above 12 m/s (25 mph) the blade pitch is automatically adjusted to maintain 300 rpm and full output up to 67 m/s (150 mph)	

In the applied system, the 3-phase variable-frequency current, which is obtained from the turbine, is passed through a sensor group and read by the microcontroller. Later, it is applied to a 3-phase uncontrolled bridge rectifier at the value of 75 A, 1200 V. The DC current obtained from the rectifier output is passed over a LEM LA-55 current sensor (a) and a LEM LV-25 voltage sensor (b), and applied to the boost converter. The current and the voltage signals taken from the (a) and (b) sensors are put into MPPT operation by the microcontroller and the V_{ref} signal is obtained. At the same time, the DC voltage read by the output voltage sensor (c) is compared with V_{out} and the error that occurs is passed through a proportional integral (PI) controller, which is commonly used in power electronics converter applications. The signal obtained from the PI output is converted into a pulse-width modulation (PWM) signal by the PWM module of the microcontroller. The PWM signal obtained is applied to the switching device in the converter over an IGBT driver. As a result, the IGBT is switched according to the PWM signal obtained from the PI controller output and the continuous operation of the system in MPPT is ensured.

In the applied boost converter, a CM75DU-24H IGBT (75 A, 1200 V) is used as a switching device and a M57959AL-01 driver is used in order to provide the switching of the IGBT. A filter capacitor is placed on the edges of the switching device in order to prevent the high-value peaks that occur during switching.

3.2. Software

This section examines the operations of the algorithms as well as the flowcharts belonging to the software that have been developed in order to realize MPPT and the commissioning of the dump load. In the designed system, the currents and the voltages at the input and output of the converter are read and evaluated with the help of the sensors for the MPPT operation. The current and the voltage values obtained are processed

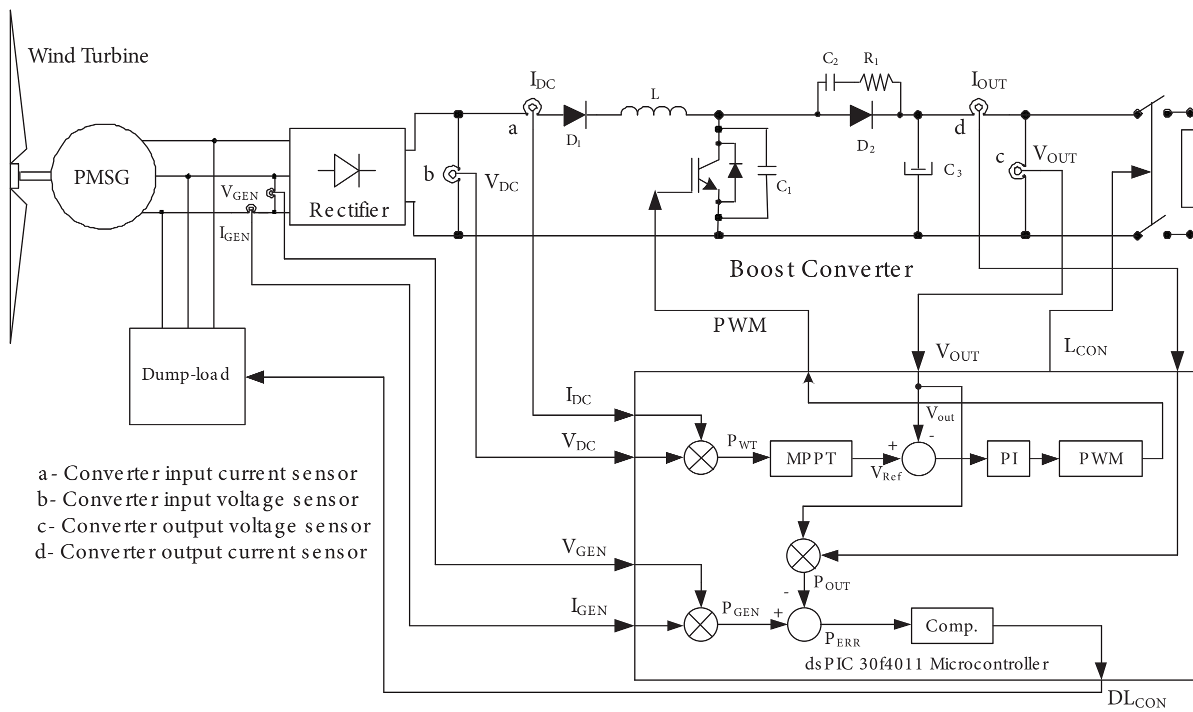

Figure 3. The application schema of the boost converter.

in the microcontroller and the switching signal needed for the converter is produced. The designed algorithm represents an integrated application of the change and supervises the algorithm and the current-controlled MPPT algorithms. The block diagram of the MPPT operation in the system is given in Figure 4.

As seen in Figure 4, if the value of the system power shows an increase compared to the previous value, it is checked whether the current input of the converter also increases. If the current value increases, the switching ratio is decreased. In contrast, this ratio is increased if the current value decreases. If there is a decrease in the power value compared to the previously calculated value, the increase in the current value is rechecked. If the current value increases, the switching value is also increased this time. Adversely, if the current value decreases, the ratio is also decreased. As a result, the system power is adjusted accordingly. If there is no increase or decrease in the power value, it is checked whether the current is equal to its previous value. The system breaks the loop if the currents are equal. In the MPPT application, the converter is protected from exceeding the maximum current value caused by the source while the PWM switching ratios are being changed. For this reason, the switching ratio of the PWM signal is limited to between 2% and 49%. Furthermore, it is undesirable for the inverter that is connected to the output of the boost converter to exceed the input current and power values. While adhering to these conditions, the transmission cutoff durations of the PWM signal that are applied to the switching device of the converter are changed in order to obtain continuous maximum power from the system. When the current generated in the turbine falls to a certain value and when the converter output current and voltage exceed the defined limits, the system gives a warning and drops the switching ratio to a certain level. In the designed software algorithm, if the turbine power increases constantly and the output current of the converter decreases, the switching signal is decreased. Thus, the output power remains at the level demanded by the load. However, if the switching signal is dropped to 2% and the power obtained from the turbine is still at high levels, this means a fast wind speed and no load state, and the system gradually engages the dump load. The engaged load is composed of 3-phases and is gradually loaded as 600-W, 1.2-kW,

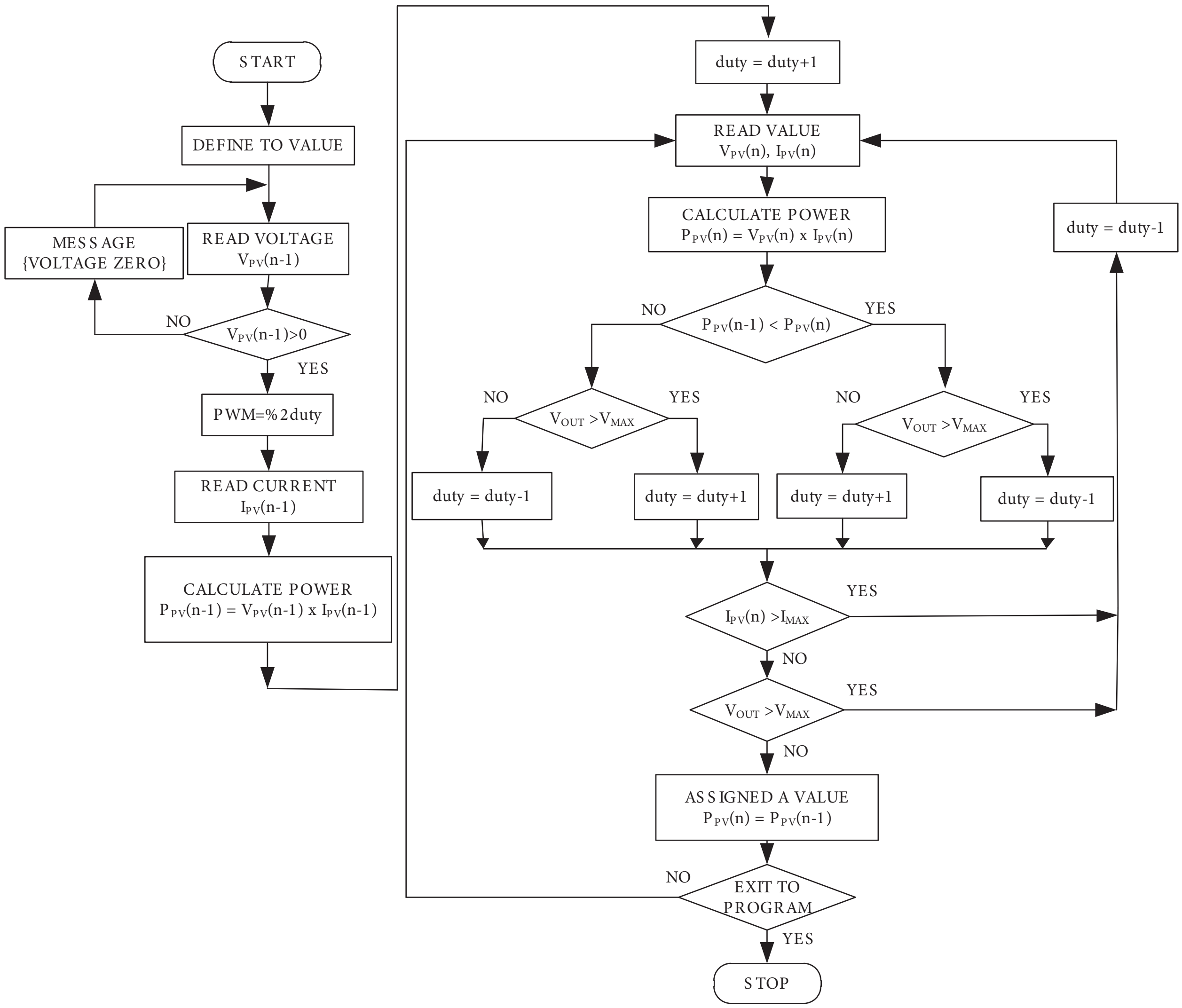

Figure 4. The flowchart of the MPPT operation.

and 1.8-kW for the 2.5-kW turbines. The block schema of the algorithm used for switching on the dump load is illustrated in Figure 5.

In cases where there is no load at the output and the turbine output power is high, an adjustable dump load is connected to the output of the wind turbine in order to prevent the system from facing extreme currents and voltages during turbine applications with variable speeds. The adjustable dump load is directly connected to the turbine output, the bridge rectifier, the converter, and the inverter. A view of the control circuit is illustrated in Figure 6.

When the turbine power is high and the converter switching rate is at 2%, this means that the converter is switched at the minimum level, the system switches on the first step of the adjustable dump load, and this step loads the wind turbine with 600-W. Next, the software waits for the determined period. The wind turbine output and converter output values are observed in this time. If there is no load demand at the converter output and turbine power is high during the waiting period, the second step of the adjustable dump load is switched on. This process is repeated by switching on the third step depending on the load and the change of wind.

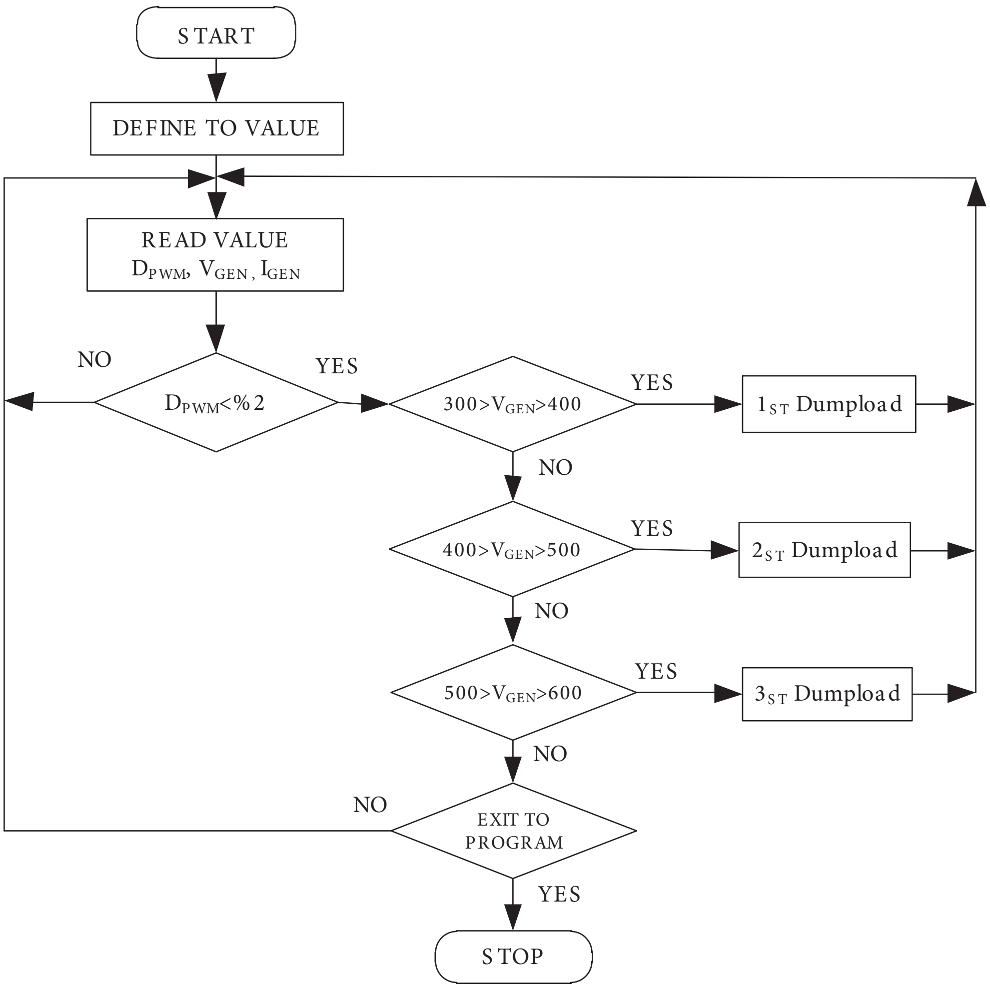

Figure 5. The block schema of the algorithm used for switching on the dump load.

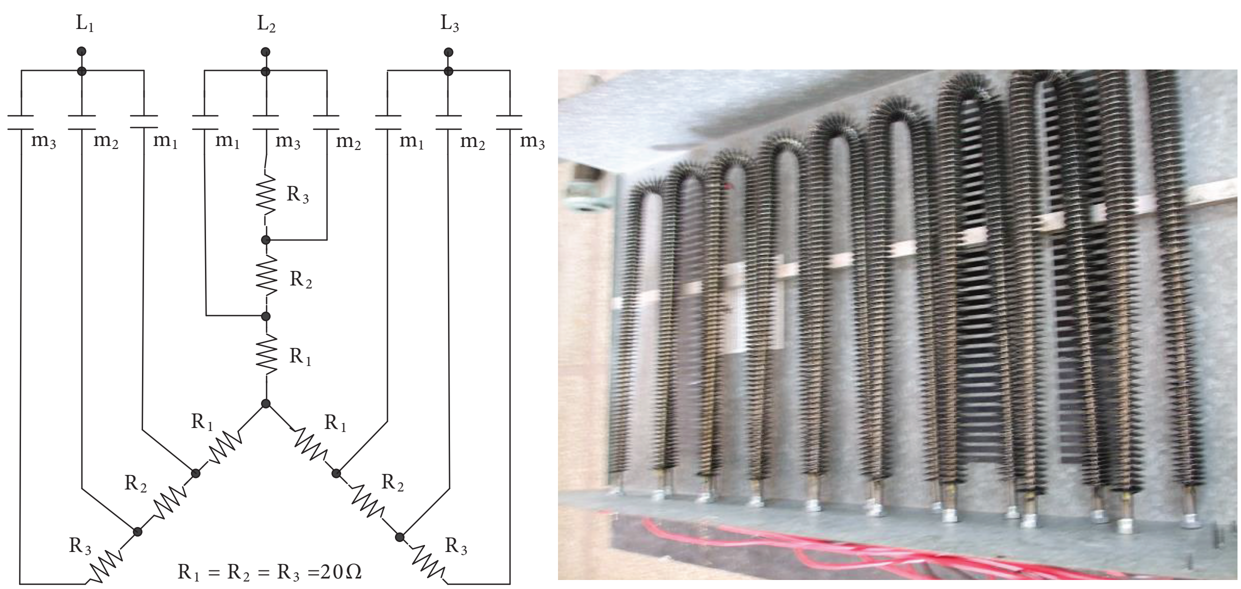

Figure 6. Adjustable dump load.

4. Experimental results

The operation efficiency and MPPT function of the proposed converter are analyzed using different input voltages and load levels. Experiments are carried out with the input voltage levels at between 96 V and 200 V, and the response of the system is investigated. The test rig of the proposed converter is depicted in Figure 7 and it includes the Fluke 43B power quality analyzer, 3-phase Fluke 434 power quality analyzer, and Tektronix 3014 oscilloscope.

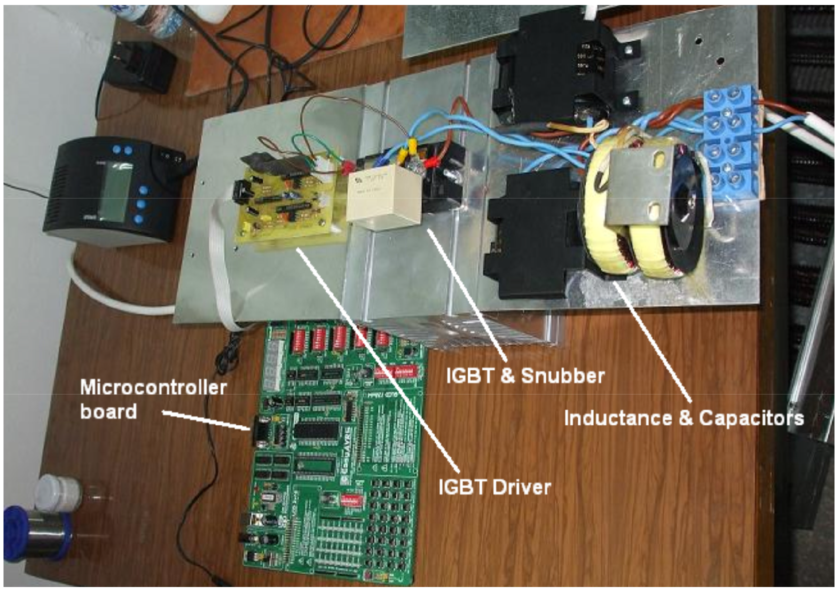

Figure 7. Photograph of the designed converter.

The maximum output voltage of the proposed 2.5-kW wind energy conversion system is 420 V and it varies according to the wind speed. The waveforms of the 3-phase output voltages of the wind turbine, including the PMSG, are given in Figure 8. These measurements are made at a wind speed of 8.1 m/s.

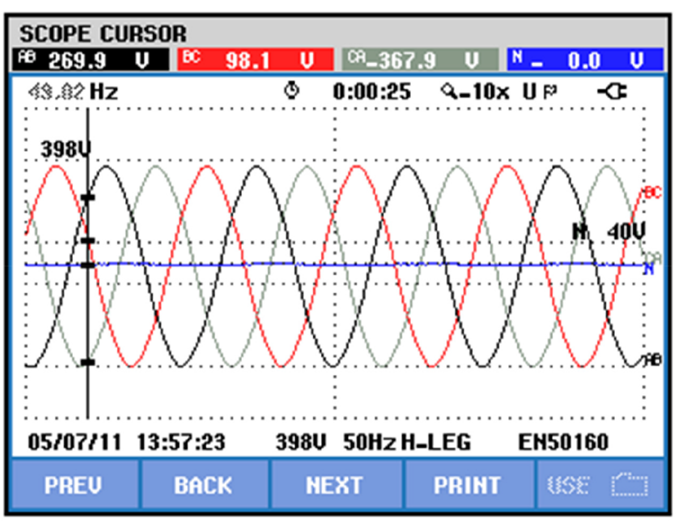

Figure 8. The output voltage waveform of the wind turbine.

One of the main objectives of the designed and implemented MPPT-controlled DC/DC boost converter and the dump load system is to achieve maximum efficiency at variable wind speed conditions. The output voltage variation of the wind turbine used in the application for a 20-min period is seen in Figure 9.

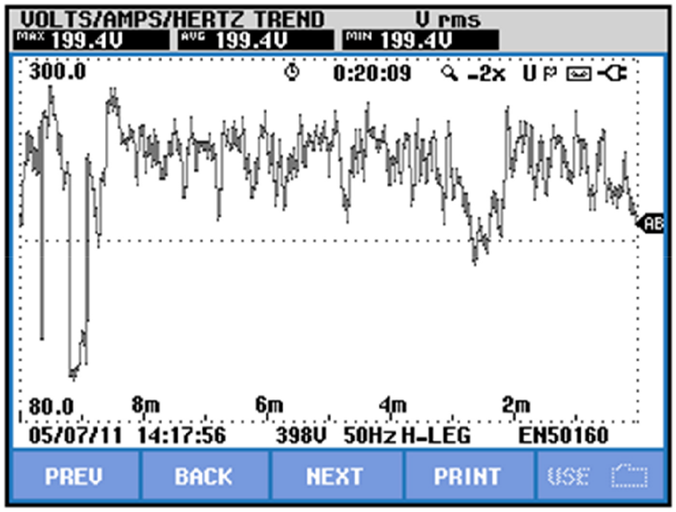

Figure 9. The output voltage image of the wind turbine under different wind speeds.

The grid connection process of the wind turbine takes quite a long time. This may cause a decrease in the system efficiency for variable wind speed conditions. The proposed converter and dump load system are designed to prevent decreases in the efficiency of the system and to protect the system components in extreme situations. In cases where the input voltage of the converter is 175 V, the output voltage and the gate signal of the IGBT for 500-W and 1000-W load levels are as shown in Figures 10a and 10b, respectively. As seen from Figures 10a and 10b, the output voltage of the converter is 280 V with a 500-W load and when the load level increases to 1000-W, the output voltage decreases to 250 V. The duty ratio of the converter is the same for both conditions.

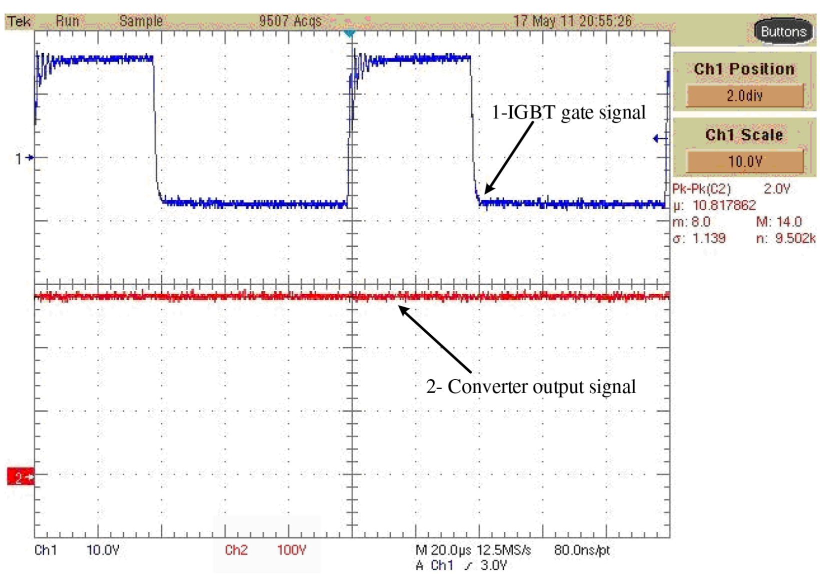

Figure 10. Output voltage and the gate signal images under different loads (a and b).

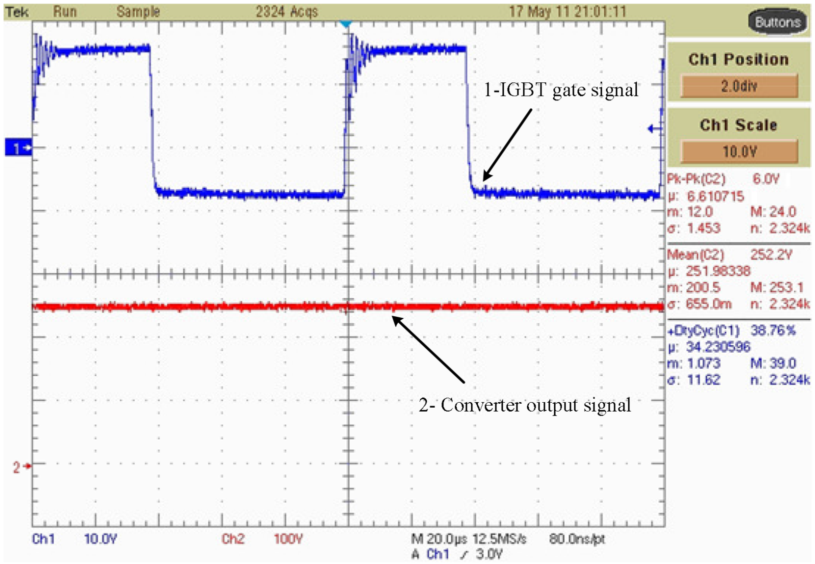

Figure 10. Continued.

The output voltage of the converter is depicted in Figure 11, where the load is stepped up from 500-W to 1000-W and stepped down from 1000-W to 500-W. The output voltage decreases with the load step and the converter increases the voltage to its reference value in 10 ms without any overshoot. The switching signal of the converter is also illustrated in Figure 11 (channel 2).

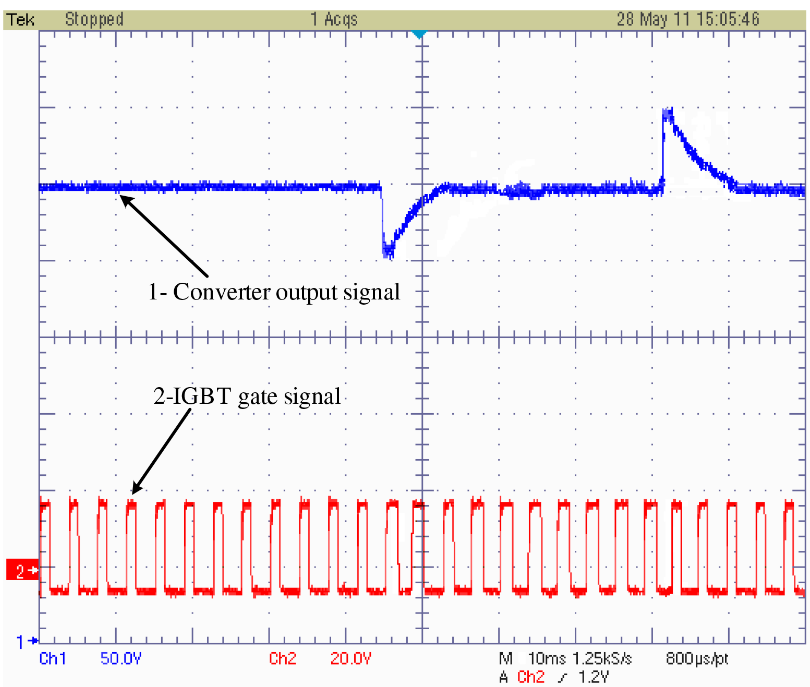

Figure 11. Output voltage and the switching signal images of the converter under different loads.

The proposed converter is tested with a 175 V input voltage level and the output voltage level of the converter is defined as 254 V. The ripple voltage of the converter output is measured as 1.83 V with a 254 V output voltage and 500-W load levels. This value is 0.72% of the output voltage level. According to IEC 61204, the ripple level of the output voltage of the power supplies must be below 1.0% and, therefore, the proposed converter fulfills this standard [22]. It is seen that considerable amounts of high-quality output voltage are obtained. The output current, voltage, and its ripples are shown in Figures 12a–12c.

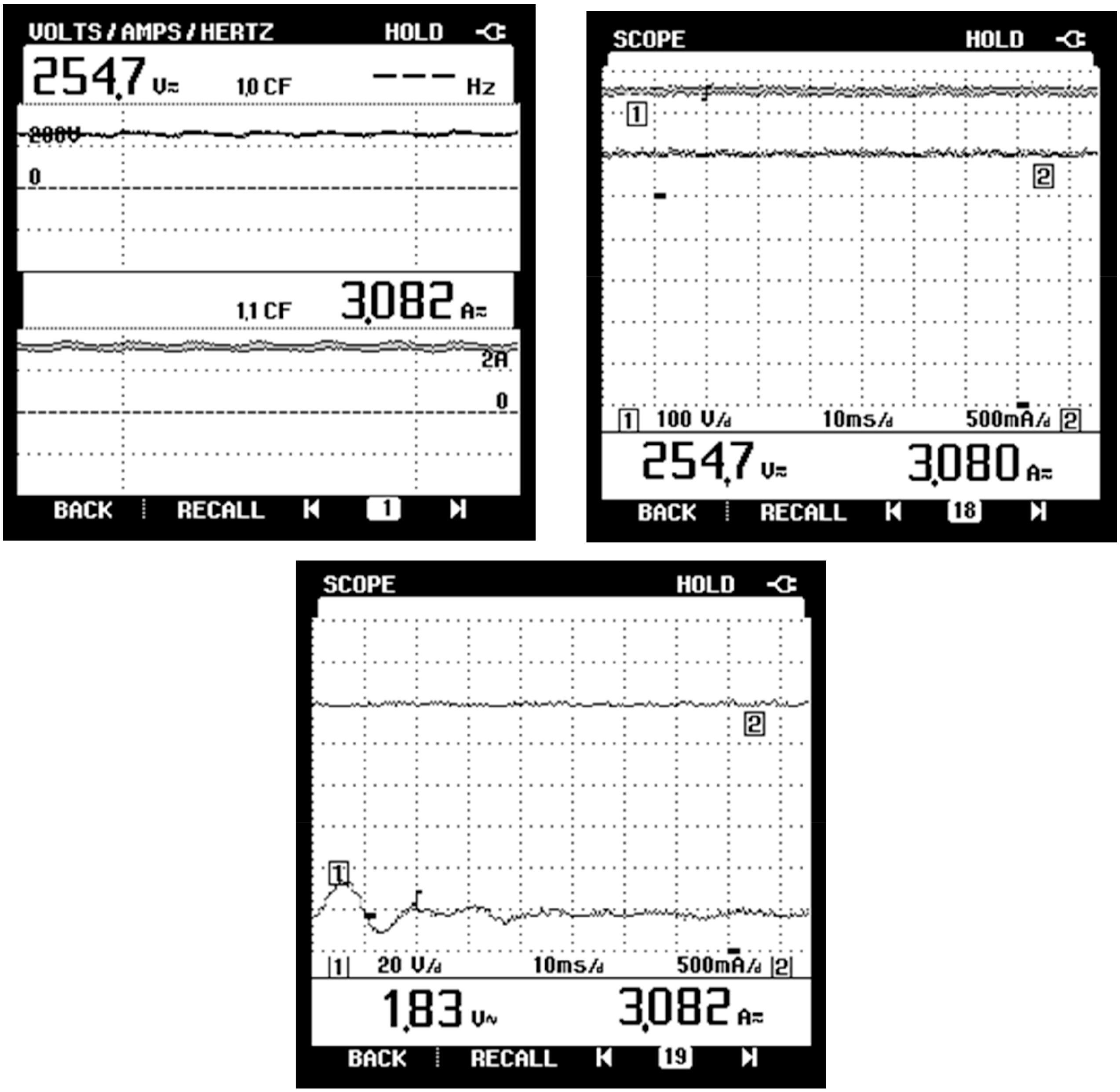

Figure 12. Current (a), voltage (b), and voltage ripple (c) of the designed converter.

The PMSG is tested with and without the proposed system for the same average wind speed (7.3 m/s) condition and the produced energy amount is measured and given in Table 2, where it is seen that the produced energy amount is increased from 13.078 kWh to 17.665 kWh. It is also seen that the proposed system improves the energy conversion efficiency of the wind energy conversion system (35%).

Table 2. Performance of the proposed MPPT converter.

	Without converter	With converter
Measurement day	13/03/2011	21/03/2011
Average wind speed	7.3 m/s	7.3 m/s
Daily energy production	13.078 kWh	17.665 kWh

5. Conclusion

In this study, a dsPIC-controlled DC/DC boost converter and a wind turbine control system that tracks the maximum power point are proposed for wind energy systems. Electrical energy generated from wind turbines with a PMSG is transferred to the load by means of the proposed system. The proposed system tracks the maximum power of the PMSG. The P&O method is used as a MPPT algorithm. Therefore, the energy conversion efficiency of the wind turbine is increased at the rate of 35%. Moreover, the output voltage quality is improved and a high-quality output voltage is obtained. Generally, the rate of the AC ripple is not evaluated by others, but this value is important to emphasize the quality of the converter output voltage. The output voltage ripple of the proposed converter is achieved as 0.72%, within the limits of IEC 61204 ($0.72\% < 1\%$). The proposed system also has protection capability. The wind turbine is protected by controlling the dump loads against the overvoltages in high wind speed conditions. Dump load groups are switched on according to the wind generator output voltage step by step. As a result, a fast, economical, and reliable system that can also be used in other wind energy conversion systems is achieved.

During an experimental study, some difficulties with meteorological conditions such as changes in the wind direction and speed can be faced. Measurement of the local wind conditions is especially crucial. When the wind speed is slower than expected, the energy yield will fall. Sometimes, this situation may be caused by measurement problems. Furthermore, trees, buildings, and tower height also represent obstacles for measurements.

Acknowledgment

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