Design and Implementation of a Wind Turbine Emulator Using an Induction Motor and Direct Current Machine

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Abstract- The study deals with the application details and validation of a wind turbine emulator (WTE) consisting of a user interface, 1.5kW squirrel-cage induction motor (IM) and separately excited direct current machine (DCM). To this end, an induction motor and direct current machine are mechanically coupled to behave like wind turbine. Thus, by controlling the asynchronous motor over wind data, the shaft of the asynchronous motor rotates like the high turbine shaft of the wind turbine and emulates the wind turbine in the laboratory environment. The user interface includes 12 commercial wind turbines with similar characteristics. The user selects the wind data for a day, then selects the wind turbine and operates the system. The system generates reference speed information in accordance with the user's preferences. The WTE calculations are performed on a PC and 32 bit ARM cortex board, both connected on UART. The generated speed information is applied to the frequency converter via the PI control technique and the induction motor is driven according to the reference speed. The purpose of the study is the hardware implementation of a wind energy conversion system for control and online monitoring in a laboratory environment. The system will allow testing various wind data and performing efficiency analyzes at any time and will enable the testing of small-scale power converters for wind power systems.

Keywords Wind Turbine Emulator (WTE), Induction Motor (IM), DC Machine (DCM), Online Monitoring.

1. Introduction

Wind power is one of the oldest and fastest growing energy sources [1-3] amongst all renewable power sources. While wind turbines were used to generate mechanical energy in the past, nowadays they are used in electrical energy production. Wind energy is attractive for reasons such as being more powerful, infinite and efficient. In addition, it can respond significantly to meeting today's energy needs [4, 5]. This energy source is also free, environmentally friendly and promising [6, 7]. Because of these benefits as well as environmental concerns and increasing energy demand across the world [8-10], the real sector and government investments are continuously increasing. However wind energy systems are expensive to build, installations depend on historical data, and need feasibility and survey studies [11]. Besides, there are difficulties in reaching these systems for carrying out measurements especially for academic studies. Today, wind turbine emulators have become indispensable in academic and energy efficiency studies in the field of wind energy [12]. Therefore, it is possible to find wind turbine emulators acting as wind turbines [13-15] in the literature. Moreover, many studies have dealt with boosting wind turbine efficiency, test conditions [16, 17], fault detection and its impacts on the grid, maintenance cost reduction and training for research [18, 19].

2. State of Art

Various wind turbine emulator systems have been implemented in literature. In the work of [2] used a Separately–Excited DC generator. In the work of [12], design and control of a small scale WTE on Direct Current (DC) motor and Permanent Magnet Synchronous Generator (PMSG) is explained. The paper presented in [20] gives details on the implementation of a WTE using a squirrel cage IM. Ref. [21] presents the development of a wind turbine emulator which consists of an induction motor driven by a frequency inverter. The work aims to propose a hardware setup, which allows testing of wind energy systems for reliability and performance in a laboratory. The paper in [22] presents modeling and simulation of a WTE using DC motor. This WTE is coupled to a permanent magnet synchronous generator and DC motor for testing its performance. In the work of [23], the authors contribute to the development of wind turbine emulator for standalone wind energy conversion systems. WTE consists of a 2.5 kW DC motor, which drives an asynchronous generator. The LabVIEW based real-time interface has been developed to control the system. The paper presented in [24] proposes the development of a small scale wind turbine emulator workbench, which is capable of emulating wind turbines up to 1 kW and tests power electronics systems for electrical power management. In the work of [25], the authors present the implementation of WT to test its characteristics in the laboratory using separately excited DC motor. The DC motor supplied through a DC-DC converter was operated based on Fuzzy Logic (FL). The proposed system in [26] comprises wind turbine (PMSG), battery, buck-boost converter and inverter. All of these components are combined to feeding AC loads from the obtained electrical energy. The study of [27] proposed a WTE system consisting of a wind turbine connected to the grid through an induction generator and PWM controlled converter. The authors of [28] designed a separately excited DC machine that behaves as a wind turbine. It provided the required speed and torque for power generation by a self-excited induction machine. The systems can be monitored using a LabVIEW-based real-time interface.

In almost all of the mentioned studies, it is aimed to develop a system that behaves like a wind turbine. The current study has similarities in some respects, but differing from other publications, the developed user interface contains electrical and mechanical data and it allows the user to easily observe and control the system. In addition, thanks to the non-isolated (step-up) converter in the system, it allows the utilization of electrical energy obtained from the turbine in various energy management applications. The converter also allows the application of maximum power point tracking (MPPT) algorithms. Furthermore, the designed system includes a load simulator. Thus, while providing the opportunity to operate with fixed loads, the operation is also possible on resistive loads with different resistance and power values in changing durations. Load simulator can activate and deactivate loads according to a certain cycle. The load simulator can make an important contribution to the determination of MPPT efficiencies. The user interface is as simple and useful as possible. User can observe electrical and mechanical parameters from the interface, analyze graphically and control the system automatically or manually. It can also perform the comparative analysis by applying the same wind data over 12 different wind turbine models, which can be extended.

3. Simulink Model of Wind Turbine Emulator

In this section, Matlab/Simulink design of wind turbine emulator for conducting simulation studies have been explained. For this purpose, the Simulink model of the proposed wind turbine emulator system illustrated in Fig. 1 has been created. The model consists of an induction motor and driver, wind turbine and an interface to calculate the reference speed according to the wind profile, separately excited direct current machine and other control components.

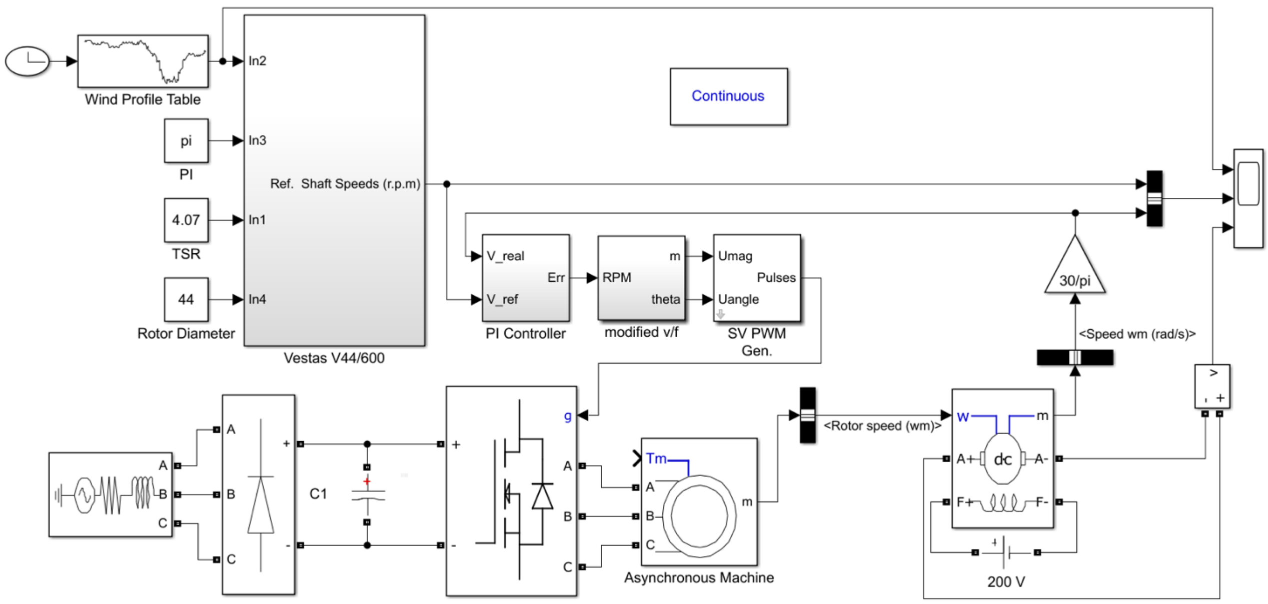

Fig. 1. Simulink model of the proposed WTE.

In the Simulink model, initially, Vestas V44-600, which is a commercial product, is used as a wind turbine. The parameters of this turbine model are given in Table 1.

Table 1. Wind turbine parameters of the used model.

Model Parameter	Parameter Value
Rated power	600 kW
Generator type	Asynchronous generator
Max. speed	1650 U/min
Rated voltage	690 V
Cut-in wind speed	4 m/s
Rated wind speed	16 m/s
Cut-out wind speed	20 m/s
Rotor diameter	44 m
Tip speed	65 m/s
Swept area	1521 m^2
Number of blades	3
Gear box ratio	1:51

In the simulation, wind data in m/s is taken from a table. The reference cycle information is produced by calculating the wind turbine parameters. The interface uses some information to produce the reference speed, the first of which is the tip speed ratio (TSR). TSR is calculated by the following equation:

$$\lambda = \frac{Tip\text{ Speed of Rotor}}{\text{Rated Wind Speed}} = \frac{wr}{v} \tag{1}$$

Wind turbine mechanical output power can be calculated by the following equation:

$$Pt = \frac{\rho A V_w^3 Cp}{2} \tag{2}$$

where, Pt is mechanical output power of wind turbine (W), ρ is air density (kg/m^3), A is swept area (m^2), Vw is wind speed (m/s), and Cp is power coefficient.

Using equation (1) and equation (4) we can obtain a reference shaft speed in rpm. This reference cycle information is then compared with the actual cycle information received from the generator shaft and applied to the PI controller. The PI controller generates a control signal based on the error value applied to the PI control block input and applies it to a controller that changes the generated signal V/f ratio. A drive that can adjust the speed of the 3-phase asynchronous motor is designed by passing through the generated signals, the space vector control, and the 3-phase full-bridge inverter. The mechanical speed information obtained from the shaft of the asynchronous motor is applied to the mechanical speed interference of the separately excited direct current machine. This direct current machine, induced with constant current, produces a voltage that changes in direct proportion with the mechanical speed information. DC machine armature output voltage is calculated by the following equation:

$$E = \frac{Zn\phi}{60} \tag{3}$$

where, E is armature output voltage (V), Z is armature wire count, n is armature shaft speed (rpm), and ϕ is Polar flux (Weber)

Fig. 2 shows the wind profile data applied to the WTE input.

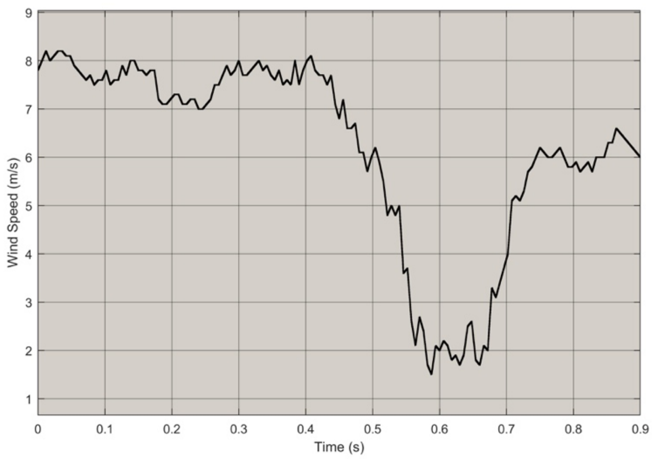

Fig. 2. The wind profile data applied to the WTE input.

4. Structure of Wind Turbine Emulator

The wind turbine emulator is the part that will act as a wind turbine and provide energy to the system by using the wind data.

This section consists of the following components:

- User interface.
- Serial port communication unit.
- 0-10 V/ 4-20 mA analog signal converter unit.
- Motor driver unit (inverter/frequency converter).
- Induction motor.
- Separately excited direct current generator.
- Separate excitation circuit.
- Optical-incremental encoder.

The wind emulator consists of an asynchronous motor and DC generator. This system has been designed in order to create the rotational effect that occurs on the high speed shaft as a result of the wind striking the turbine blades. Fig. 3 shows the proposed WTE configuration.

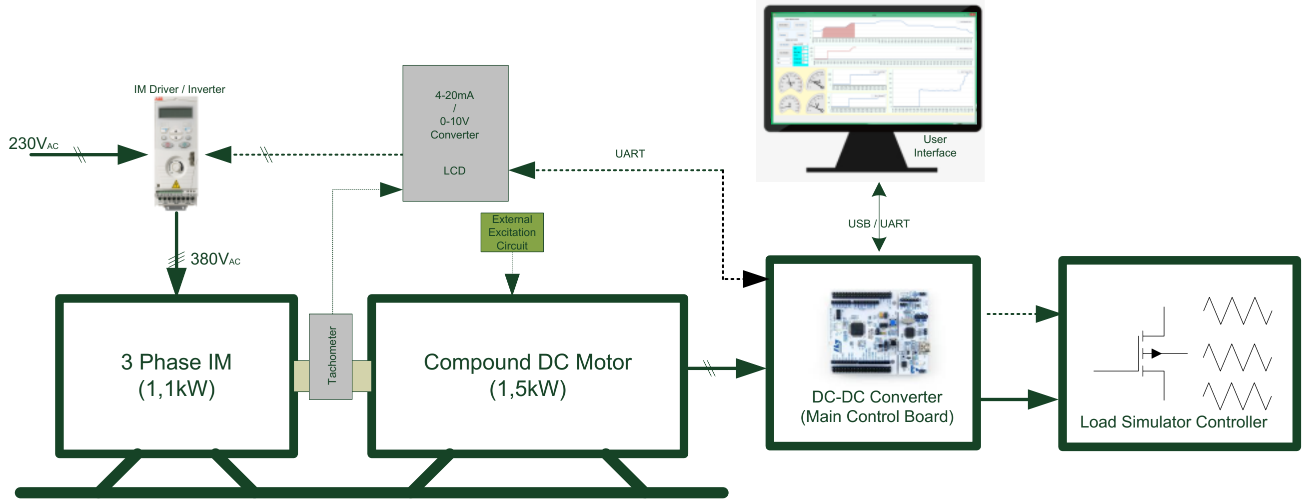

Fig. 3. The proposed WTE configuration.

In this context, a system has been designed consisting of a user interface and an electronic control board. The user interface calculates and generates a control signal according to the wind data and wind turbine type selected by the user. The generated control signal is applied to the frequency converter that will drive the motor. Thus, the rotation speed of the shaft of the asynchronous motor and the rotation speed of the high speed shaft in the wind turbines are obtained.

4.1. Design of User Interface

This is the part, in which the user can select wind data, provide automatic or manual control of the system, monitor and analyze the system's behavior with graphical or other visuals. This part is designed on Microsoft Visual Studio platform. The user interface is given in Fig. 4.

Fig. 4. The developed user interface.

The user interface includes:

- Manual and automatic control menus.
- Generator speed graph versus wind speed.
- Generator speed indicator in rpm.
- Generator current, voltage and power indicators.
- Generator current, voltage and power graphs.
- Load simulator control stage

Wind turbine emulator consists of 12 wind turbine models with similar characteristics from 12 different companies and parameters of these turbines were recorded for allowing the users to emulate the system automatically. Fig. 5

shows the selected wind turbine parameters, operating speed and the date of the data to be operated.

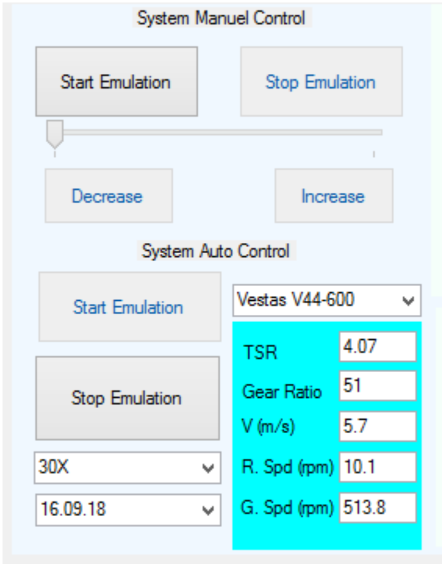

Fig. 5. Wind turbine, date selection and control options.

The user firstly chooses the desired date to emulate, chooses the speed of emulation and the type of wind turbine to be emulated. The emulation starts at a speed in regard to the corresponding wind data for the chosen date. Turbine models and brands registered in the system are:

- AN Bonus 600
- BWU 43-600
- DeWind D4 48_600
- Ecotecnia ECO 44_600
- Gemesa G42-600
- Goldwind S43_600
- Vestas V44-600
- Made Endesa AE-45-600
- Jacobs 48/600-600
- Elecon T600-48-600
- IWT V42-600
- Micon M 1500-600

Although the blade diameters of these turbine models vary slightly, their power is close to each other. The power of the generators in the interface is the same and they all have a gearbox, but the conversion rates differ among themselves. In addition, the generator types used in wind turbines are mostly asynchronous generator and are similar to each other. Apart from these, the parameters commonly used from the selected turbines are;

- Normal production wind speed (Rated Wind Speed)
- Lower limit of commissioning (Cut-in Wind Speed)
- High level of trip (Cut-out Wind Speed)
- Wing/rotor diameter (Diameter)
- Tip Speed
- TSR Ratio
- Gearbox conversion rate (Gearbox Ratio)
- Parameters such as Generator Type.

As a result of utilization of these parameters, the calculation of the high speed shaft (generator shaft) of a wind turbine is calculated using equation (4).

$$Ns = \frac{60 * Vw * TSR}{\pi * D} * \eta \tag{4}$$

where, Ns is generator speed (rpm), Vw is wind speed (m/s), TSR is tip speed ratio value of the wind turbine, D is wing diameter of wind turbine (m), and η is the conversion rate of the gearbox within the wind turbine. Moreover, the user interface also includes a load simulator consisting of resistive loads. The load simulator consists of load groups with powers ranging from 0.5 to 1.5kW. These loads are activated or deactivated in a certain sequence and time cycle according to the user's request. This unit is particularly useful in the unstable energy application of maximum power point tracking and converter structures. In Fig. 6, there is a section where the load order and time of the load simulator can be selected.

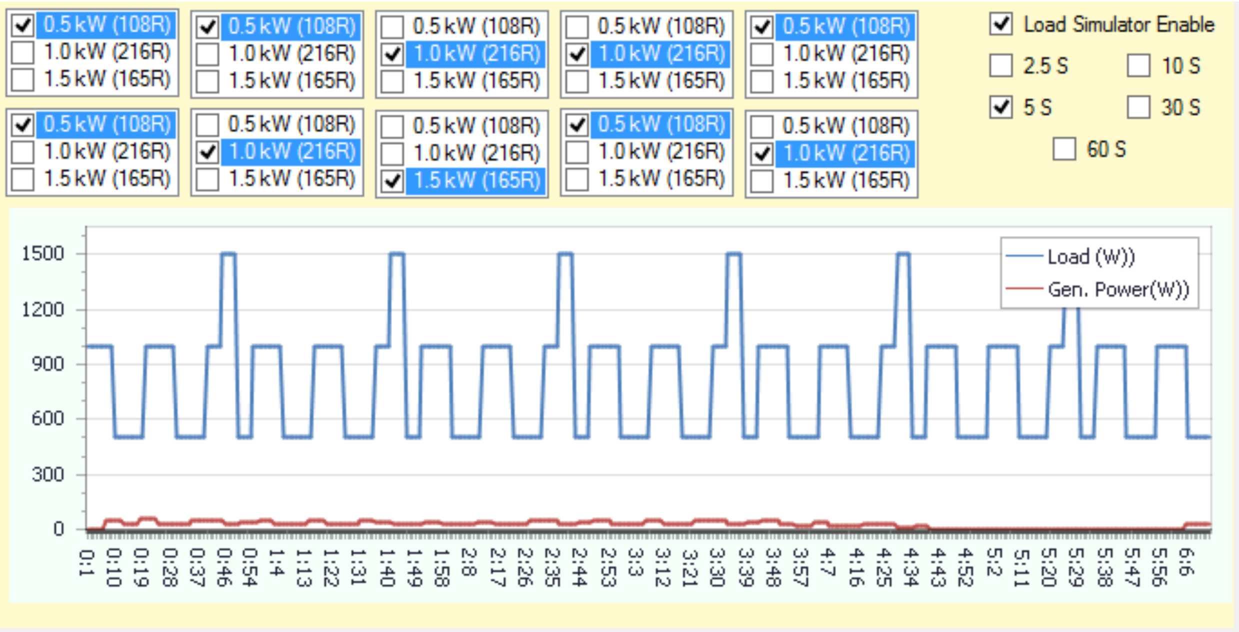

Fig. 6. Load simulator control stage in user interface.

Loads are activated in a certain order with the load simulator control board. The connection diagram of the loads is given in Fig. 7. Each resistive load is of the same value and is 108 Ohms 0.5kW.

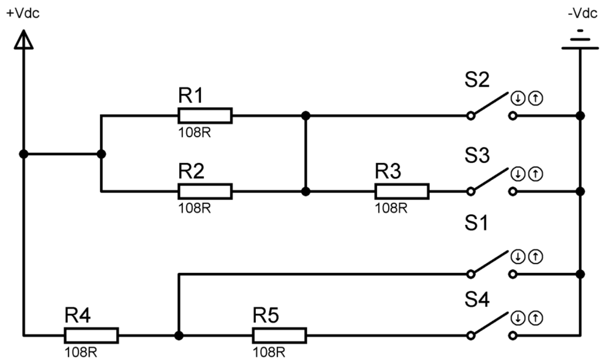

Fig. 7. Connection diagram of loads.

Activation or deactivation of loads is done by switching MOSFETs. Electric energy of direct current type obtained from the generator is transferred to the loads through this section.

4.2. Induction Motor Control Board

This unit allows the emulator system to work in harmony with the user interface. The control board contains two components. The first and the main part is the unit that has a 32-bit microcontroller on it, which communicates with the computer and controls the converter unit. The second unit is an intermediate board and is the unit between the main component and the motor driver that controls the drive of the motor. The second board unit and its components are given in Fig. 8.

Fig. 8. The mezzanine board unit that controls the drive and the components of the board.

This mezzanine board calculates the motor shaft speed from the optical incremental encoder that is connected to the shaft of the motor. Generator speed is measured every 200 milliseconds and written on the screen under the label Ns. It sends the measured value to the main control board as the actual motor shaft speed. In addition, this board generates the 4-20mA / 0-10V analog signal from the main control board that is applied externally to the motor driver to form the desired speed. This board operates PI controller for feedback control in accordance with the generation of 4-20mA analog signal. The circuit and components with Op-Amps created to produce 4-20mA signal are given in Fig. 9.

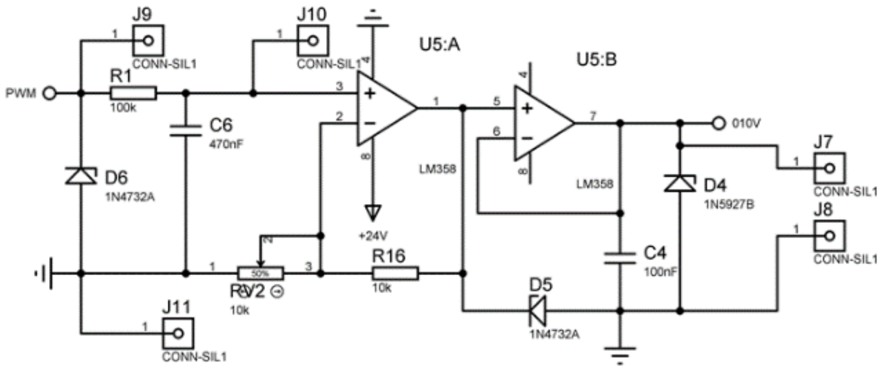

Fig. 9. 4-20mA signal generator circuit for motor driver unit.

The mezzanine board communicates with the motherboard via an optically isolated structure. Thanks to the optical isolation, system components are protected by preventing the high frequency noise created by the motor driver. Besides, this board has an 8-bit microcontroller in itself to control the character LCD required for reading information from the optical encoder, providing serial communication and printing the data on the screen. The entire circuit diagram of the designed mezzanine board is given in Fig. 10.

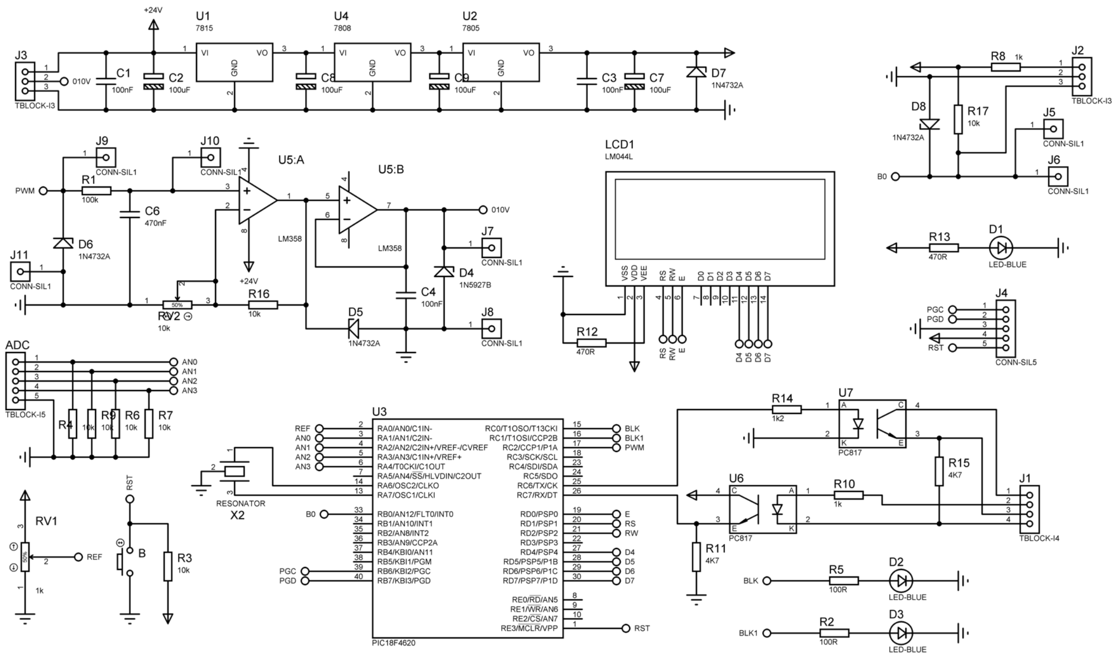

Fig. 10. The mezzanine board unit that controls the drive and the components of the board.

The mezzanine board receives the motor shaft speed information from the optical incremental encoder. The position of the designed optical incremental encoder on the body of the DC generator is given in Fig. 11.

The block diagram of the wind turbine emulator including the mezzanine board and the motor driver is given in Fig. 12.

Fig. 11. Optical incremental encoder designed to read motor shaft speed.

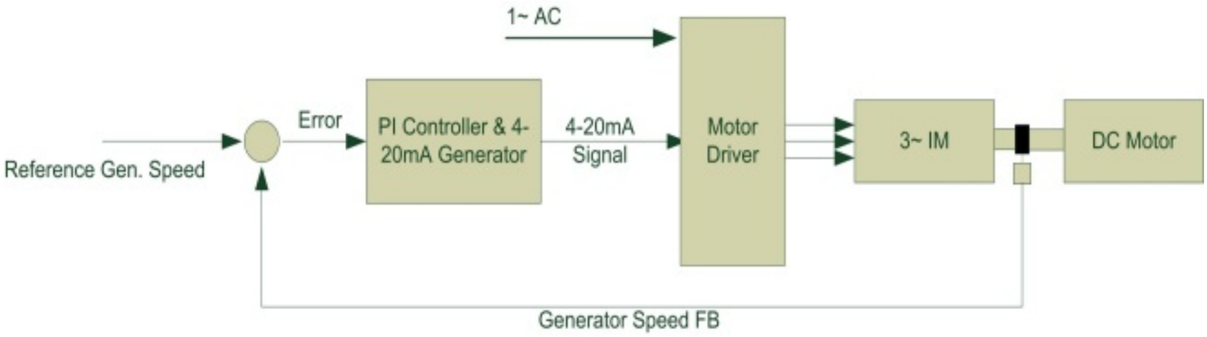

Fig. 12. The mezzanine board and motor driver for WTE.

The second component that constitutes the control board is the main control board. It is the component in the structure of a DC-DC converter that also features a 32-bit STM microcontroller on the board. This structure contains a non-isolated step-up converter. The step-up converter unit having MOSFET as a switching element allows the evaluation of the electrical energy obtained from the separately excited direct current machine for various purposes. For example, MPPT algorithms can be run on this converter. The electronic circuit diagram of the power stage of the designed converter is given in Fig. 13.

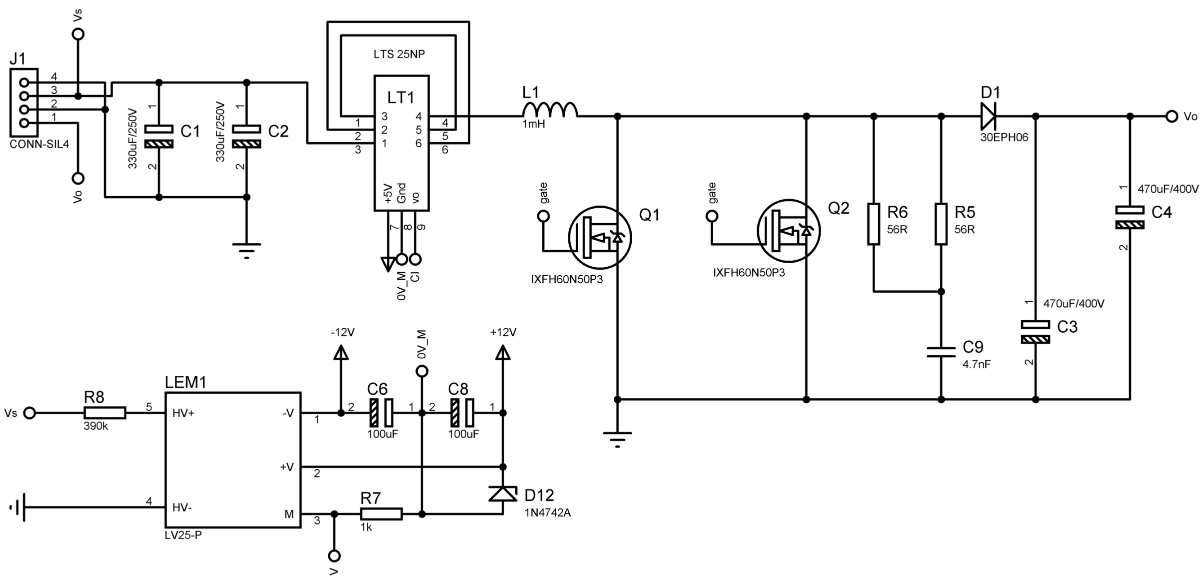

Fig. 13. The electronic circuit diagram of the power stage of the designed converter.

IXFH60N50P3 600V-50A MOSFET is used as the switching element in the designed converter. MOSFETs were driven with TLP250 optical isolator and the MOSFET driver is powered from an external source. Thus, the power stage and the gate drive stage are separated from each other. The converter unit can also measure isolated current and voltage to be transferred to the user interface or to be used in MPPT algorithms. Current and voltage sensors adopted are CAS-25NP (LTS-25NP) and LV-25P from LEM, respectively. These sensor structures measure current and voltage values using the hall-effect method and generate an analog value at the output. In addition, the current sensor has an off-set magnitude value of 2.54V. This feature allows the sensor to be used in both AC and DC applications. An op-amp circuit was also installed to filter the analog value from the current sensor at a certain rate and gain. Nucleo Board STM411RE, the development board of the 32-bit STM company, collects information from sensors, operates MPPT algorithms, controls the transducers, and communicates with the computer. It also includes serial port communication unit, voltage regulators, coil forming the power stage, capacitors, additional electronic circuit elements and other components on the main control board. When all these components are put together, the main control board is formed. Fig. 14 shows the main control board.

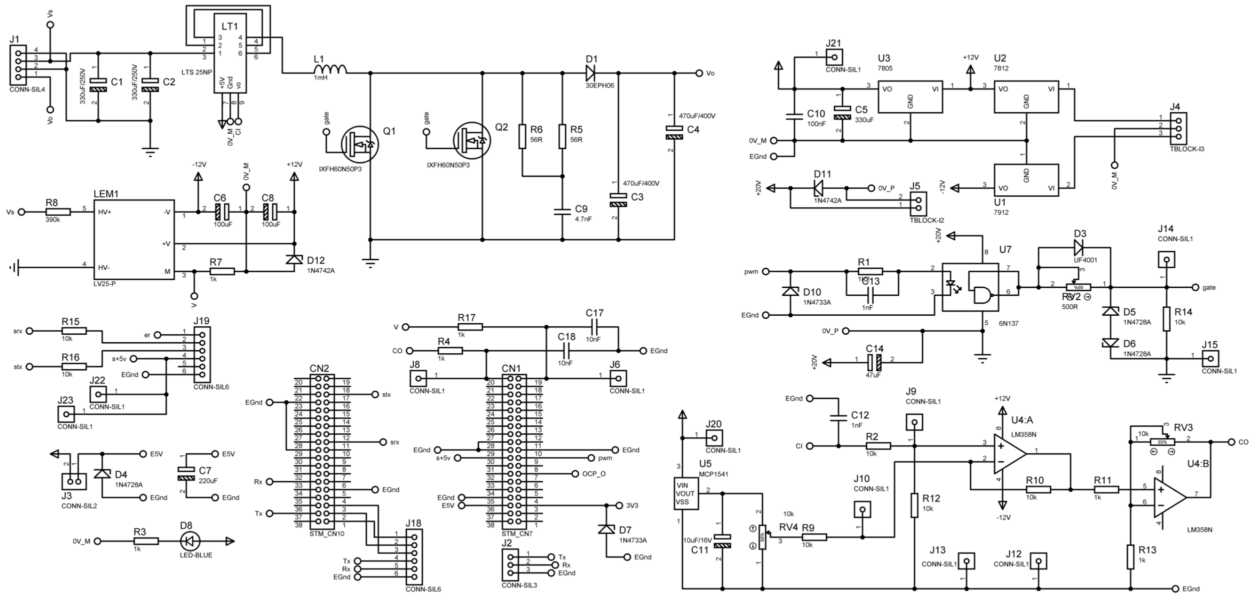

Fig. 14. The schematic of the main control board.

The PCB scheme obtained within the framework of this circuit design has been printed and applied to the copper plate. The practically implemented main control board is shown in Fig. 15.

Fig. 15. Main control board PCB application for WTE.

4.3. Induction Motor Driver Unit

This unit is a commercial product of the ACS150 series of ABB Company used in speed control of IM. The motor driver that has been used for the wind emulator is shown in Fig. 16.

The motor driver allows the speed control to be made by changing the voltage applied to the stators in regard to the constant V/f method. In addition, the motor driver has a wired remote control with analog signals such as 4-20mA or 0-10V. This driver has a power of 1.5kW and is used extensively in the market to drive 3-phase IM.

4.4. Separately Excited Direct Current Machine

This component has a separately excited DC machine structure and is coupled with 3-phase IM. It is the component that will generate electricity in regard to the speed obtained from the shaft of the induction motor. The DC machine is powered from an external source with separate excitation.

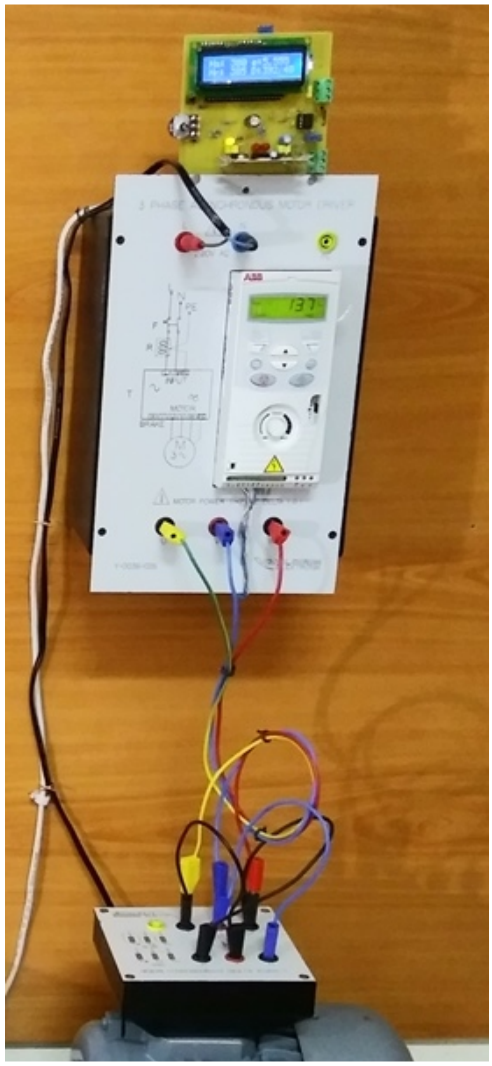

Fig. 16. The motor driver for WTE.

Characteristics of DC machine coupled to induction motor are given in Table 2. The resistance of the separate excitation winding of the DC machine is on average around 350 ohms. Therefore, it was excited by applying approximately 0.5A with a rated excitation voltage of 200 V on average, considering the separate excitation values. The excitation circuit is not adjustable in any form but provides constant stimulation

Table 2. Characteristic values of separately excited DC machine

Armature Circuit		Excitation Circuit	
V. Arm.	200 V	V. Exc.	200 V
A. Arm.	8.5 A	A. Exc.	0.4 A
Rated Speed		1500 rpm	
Rated Power		1500 W	

5. Experimental Results Analysis

In this study, the design and implementation of a wind turbine emulator are presented. For this reason, the hardware components of the targeted wind turbine emulator are designed step by step. In the first stage of the implementation, the system is simulated in a Matlab/Simulink software environment and a model is designed for this purpose. The objective for creating the model is to shed light on the wind turbine application to be designed. WTE's behavior was observed by operating real wind data on the model. In Fig. 17, it is observed that WTE exhibits certain desired behaviors. As a turbine's power is proportional to the cube of the wind speed, operation at very low speed is not preferred. Therefore, wind turbine models are expected to be stopped below 4m/s for the purpose of reducing efficiency costs and maintenance costs. It is seen that this request is fulfilled in Fig. 17.

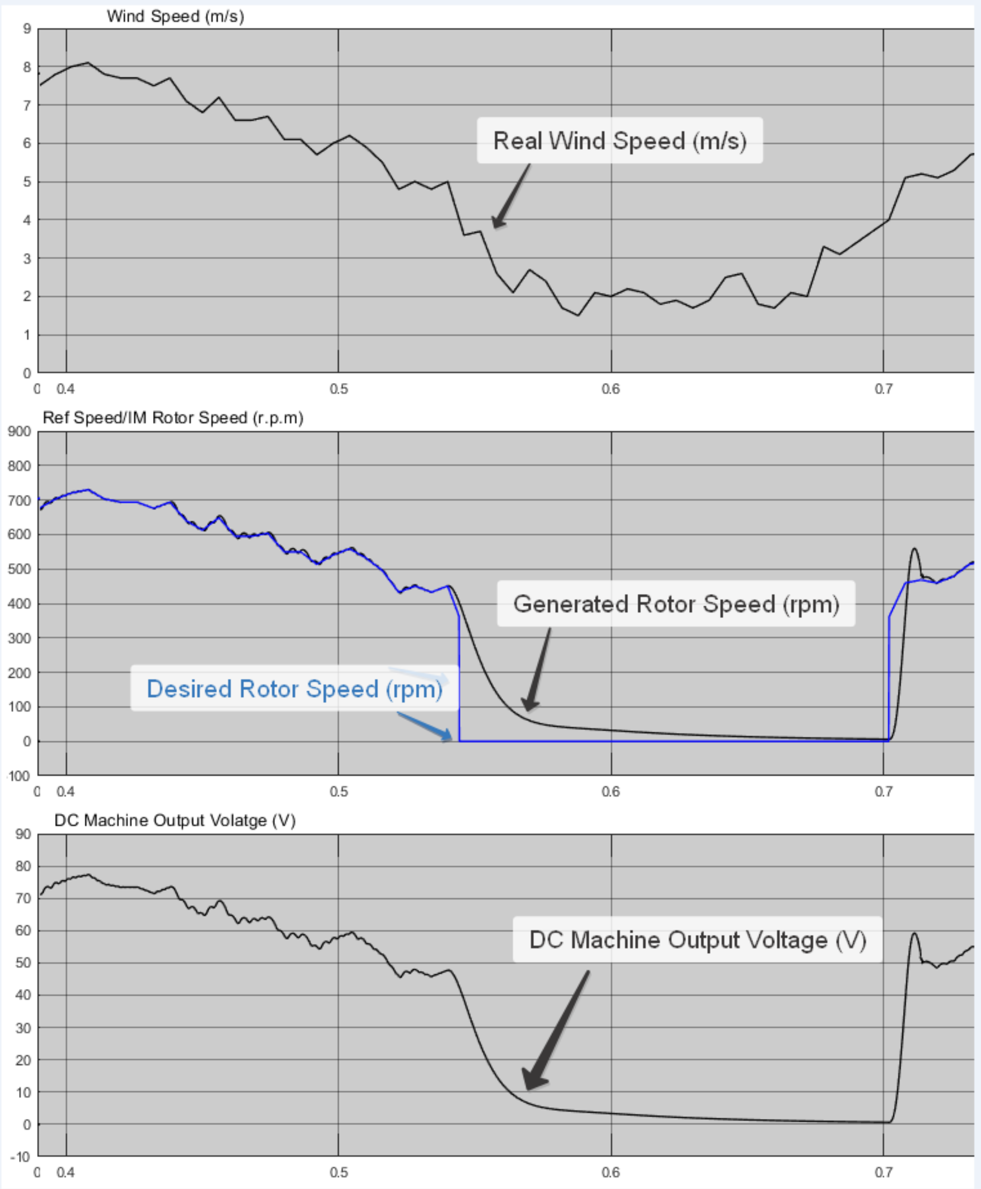

Fig. 17. Real wind speed, generated rotor speed, and DC machine output voltage characteristics demonstrating the cut-out of the system below 4 m/s.

Examining these graphs, it can be seen that the 1st graph is the wind profile in m/s applied to the wind turbine emulator. In the 2nd graph, the engine shaft is the actual speed information compared to the reference speed information. Finally, the lowermost graph shows the output voltage of the direct current machine. Both simulations in Simulink environment and studies in real environment behave in accordance with the characteristics of selected generator structures ensuring that the selected wind turbine stops energy production below (Cut-in wind speed) 4m/s. In the second stage, as a result of the experiences obtained from the simulation environment, physical realization stage of WTE has been started. Initially, IM and separately excited direct current machine are coupled. Here, while the IM represents the high speed shaft of the wind turbine, the separately excited direct current machine acts as a generator. IM is controlled by a frequency converter that can change the voltage so as to keep V/f ratio constant. In this way, the rotational movement in the high speed shaft is obtained. In the overall experimental laboratory setup of the WTE system shown in Fig. 18, the IM and separately excited DC machine can also be seen. In the third stage, an interface has been designed to enable control and monitor the system. This interface is designed as Windows Form Application (WFA) in Microsoft Visual Studio platform. The interface detailed in Section 4.1 contains electrical and mechanical parameters. Electrical and mechanical parameters were obtained as a result of 12 bit ADC conversion. Errors affecting the system operation may result from ADC resolution and sampling time, as well as from the PI control block. For this reason, the ADC resolution has been selected as 12 bits and the sampling rate is 50 samples per second. Although WTE system reference cycle information is updated once per second, system feedback is received 50 times per second and an electronic low-pass filter is applied. In this way, electrical and mechanical data are measured and kept under constant control. In addition, the control cycle of the load simulator and the order of change of loads can be selected from this interface and their behaviour can be observed. Finally, for the system to allow the realization of various energy management and MPPT applications, another component has been added. That is a load simulator that enables testing the system for varying loads. With this component, in total 5 resistive loads in discrete power values namely 500W, 1000W and 1500W have been installed with serial/parallel connections. All components of the wind turbine emulator were brought together to ensure a smooth operation of the system. With the designed system, a small scale wind turbine was designed that acts as a wind turbine in a laboratory environment using the previously recorded wind data. Thanks to the employed DC-DC converter, WTE is suitable for the evaluation of energy efficiency or MPPT techniques realizations. In addition, it is possible to try various methods on the system thanks to the separately excited DC machine. Moreover, energy conversion can be accomplished to convert the DC type of energy to AC by means of inverter applications. The current study emphasized the design and application aspects of the system and these applications are left for future research. The experimental setup of the WTE system and its components are shown in Fig. 18.

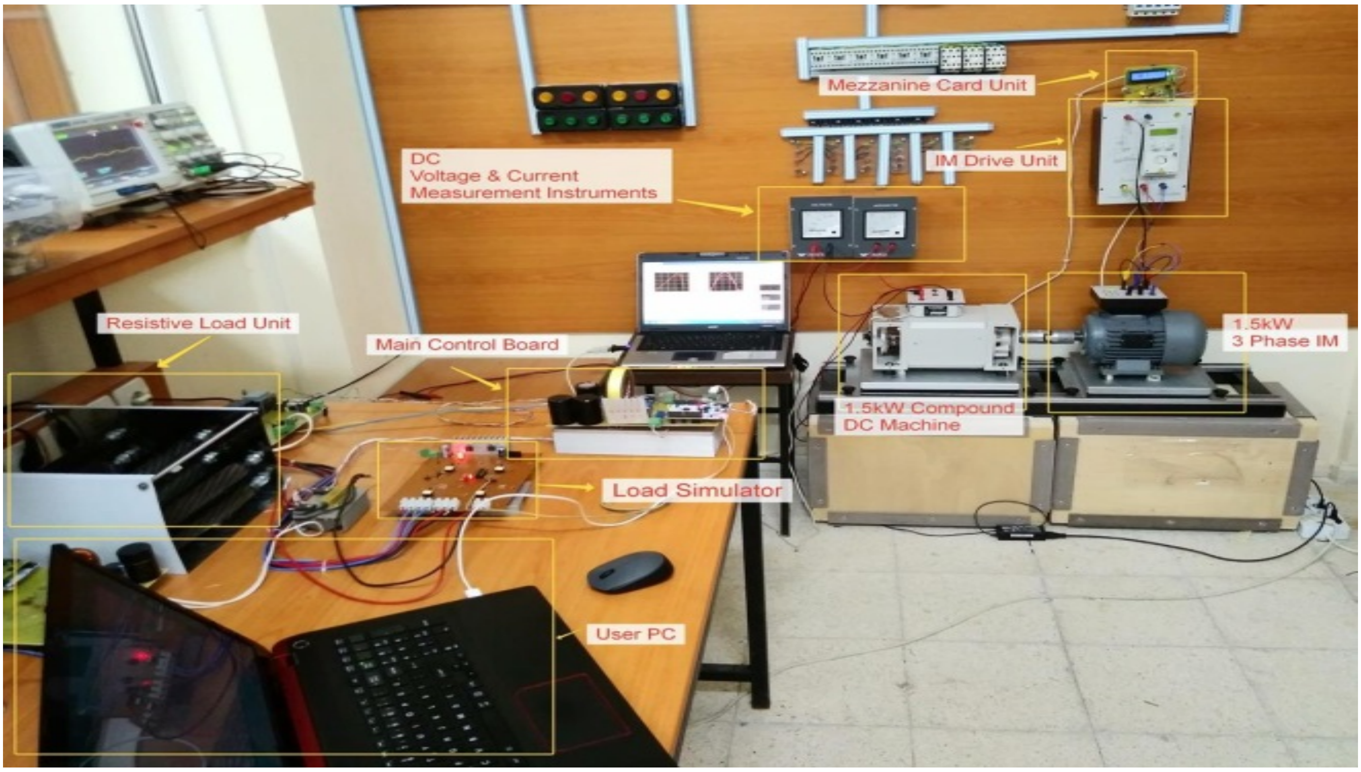

Fig. 18. The experimental setup of the designed WTE system and its components.

6. Conclusion

This paper proposes experimental realization of wind turbine emulator system that can act as a wind turbine by using wind data obtained from different sources. The intended wind turbine emulator is low-cost and has an easy-to-use interface. In cases where it is difficult to reach the wind turbines physically and the desired wind power cannot be provided, the proposed system as an accessible emulator for emulating wind turbines in the laboratory environment can be a very essential tool. Another purpose of the study is to carry out academic and educational experiments on wind turbines available at all times. For this purpose, a model has been created in Matlab/Simulink environment and simulation studies have been made on this model. The physical implementation phase of the aimed system has been started exploiting the experiences and design parameters obtained from the simulation environment.

The study was accomplished in two major stages. The first stage involved the design of the user interface enabling online monitoring, whereas the second stage involved the experimental implementation of the power stage, the driver and related components. The interface is connected to the control board via USB/RS232. Afterwards, all components were combined to ensure a smooth operation, and a very beneficial laboratory test system was established.

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