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BLDC Motor Driven By Wind and Solar PV Array Fed Water Pumping System Employing Luo Converter

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***Abstract*—This paper proposes a simple, cost-effective, andefficient brushless dc (BLDC) motor drive by wind and solar photovoltaic (SPV) array-fed water pumping system. A luo converter is utilized to extract the maximum available power from the SPV array. The proposed control algorithm reduces the ripple and oscillationand adapts a fundamental frequency switching of the voltage source inverter (VSI), thus avoiding the power losses due to high frequency switching. No additional control or circuitry is used for speed control of the BLDC motor. The speed is controlled through a variable dc link voltage of VSI. An appropriate control of zeta converter through the incremental conductance maximum power point tracking (INC-MPPT) algorithm offers soft starting of the BLDC motor. The proposed water pumping system is designed and modeled such that the performance is not affected under dynamic conditions. The suitability of proposed system at practical operating conditions is demonstrated through simulation results using MATLAB/Simulink followed by an experimental validation.**

***Index Terms*—Brushless dc (BLDC) motor, incrementalconductance maximum power point tracking (INC-MPPT), solar photovoltaic (SPV) array, wind power, voltage-source inverter (VSI), water pump, luo converter.**

I. INTRODUCTION

THE drastic reduction in the cost of power electronic devices and annihilation of fossil fuels in near future invite to use the solar photovoltaic (SPV) and wind generated electrical energy for various applications as far as possible. The water pumping, a standalone application of the wind and SPV array-generated electricity, is receiving wide attention nowadays for irrigation in the fields, household applications, and industrial use. Although several researches have been carried out in an area of wind and SPV array-fed water pumping, combining various dc–dc convert-ers and motor drives, the luo converter in association with a permanent-magnet brushless dc (BLDC) motor is not explored precisely so far to develop such kind of system. However, the luo converter has been used in some other SPV-based applications. Moreover, a topology of wind and SPV array-fed BLDC motor-driven water pump with luo converter has been reported and its significance has been presented more or less in.

Nonetheless, an experimental validation is missing and the absence of extensive literature review and comparison with the existing topologies has concealed the technical contribution and originality of the reported work.

The merits of both BLDC motor and luo converter can con-tribute to develop an wind and SPV array-fed water pumping system possessing a potential of operating satisfactorily under dynam-ically changing atmospheric conditions. The BLDC motor has high reliability, high efficiency, high torque/inertia ratio, improved cooling, low radio frequency interference, and noise and requires practically no maintenance.

On the other Hand, a luo converter exhibits the following advantages over the conventional buck, boost, buck–boost converters, and Cuk converter when employed in SPV-based applications.

1) Belonging to a family of buck–boost converters, the luo converter may be operated either to increase or to decrease the output voltage. This property offers a bound-less region for maximum power-point tracking (MPPT) of an SPV array. The MPPT can be performed with simple buck and boost converter if MPP occurs within prescribed limits.
2) This property also facilitates the soft starting of BLDC motor unlike a boost converter which habitually steps up the voltage level at its output, not ensuring soft starting.
3) Unlike a classical buck–boost converter, the luo converter has a continuous output current. The output inductor makes the current continuous and ripples free.
4) Although consisting of same number of components as a Cuk converter, the luo converter operates as non-inverting buck–boost converter unlike an inverting buck– boost and Cuk converter. This property obviates a require-ment of associated circuits for negative voltage sensing, and hence reduces the complexity and probability of slow
down the system response.

These merits of the luo converter are favorable for proposed wind and SPV array-fed water pumping system. An incremental conduc-tance maximum power point tracking (INC-MPPT) algorithm is used to operate the luo converter such that SPV array always operates at its MPP.

The existing literature exploring SPV array-based BLDC motor-driven water pump is based on a configuration shown in Fig. 1. A zeta converter is used for MPPT of an SPV array as usual. The existing control algorithm not provides continuous supply to load and not reduces the ripple and oscillation. The additional control scheme causes increased cost and complexity, which is required to control the speed of BLDC motor. Moreover, usually a voltage-source inverter (VSI) is operated with high-frequency PWM pulses, resulting in an increased switching loss and hence the reduced efficiency.

Fig. 1. SPV-zeta converter fed BLDC motor-driven water pumping system

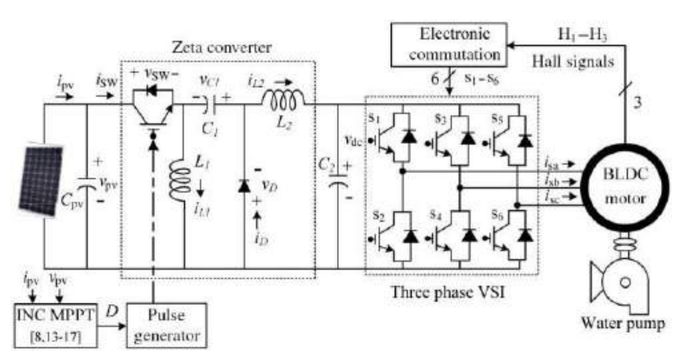
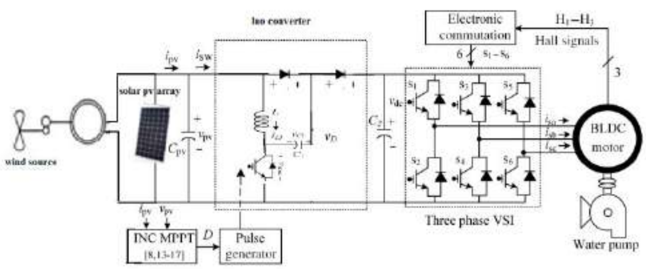


Fig. 2. Proposed wind and SPV-luo converter-fed BLDC motor drive for water pump.



other schematic of Fig. 1 remains unchanged, promising high efficiency and low cost. Contrary to it, ZSI also necessi-tates phase current and dc link voltage sensing resulting in the complex control and increased cost.

To overcome these problems and drawbacks, a simple, cost-effective, and efficient water pumping system based on wind and SPV array-fed BLDC motor is proposed, by modifying the exist-ing topology (Fig. 1) as shown in Fig. 2. A luo converter is utilized to extract the maximum power available from an SPV array, soft starting, and speed control of BLDC motor coupled to a water pump. Due to a single switch, this con-verter has very good efficiency and offers boundless region for MPPT. This converter is operated in continuous conduc-tion mode (CCM) resulting in a reduced stress on its power devices and components. Furthermore, the switching loss of VSI is reduced by adopting fundamental frequency switching resulting in an additional power saving and hence an enhanced efficiency. The phase currents as well as the dc link voltage sen-sors are completely eliminated, offering simple and economical system without scarifying its performance. The speed of BLDC motor is controlled, without any additional control, through a variable dc link voltage of VSI. Moreover, a soft starting of BLDC motor is achieved by proper initialization of MPPT algo-rithm of SPV array. These features offer an increased simplicity of proposed system.

The advantages and desirable features of both luo converter and BLDC motor drive contribute to develop a simple, efficient, cost-effective, and reliable water pumping system based on wind and solar PV energy. Simulation results using MATLAB/Simulink and experimental performances are examined to demonstrate the starting, dynamics, and steady-state behavior of proposed water pumping system subjected to practical operating condi-tions. The wind, SPV array and BLDC motor are designed such that proposed system always exhibits good performance regardless of solar irradiance level.

II. CONFIGURATION OF PROPOSED SYSTEM

The structure of proposed wind and SPV array-fed BLDC motor-driven water pumping system employing a luo converter is shown in Fig. 2. The proposed system consists of an wind and SPV array, a luo converter, a VSI, a BLDC motor, and a water pump. The BLDC motor has an inbuilt encoder. The pulse generator is used to operate the luo converter.

A step-by-step operation of proposed system is elaborated in Section III in detail.

III. OPERATION OF PROPOSED SYSTEM

The wind and SPV array generates the electrical power demanded by the motor-pump. This electrical power is fed to the motor-pump via a luo converter and a VSI. The wind and SPV array appears as a power source for the luo converter as shown in Fig. 2. Ideally, the same amount of power is transferred at the out-put of luo converter which appears as an input source for the VSI.

In practice, due to the various losses associated with a dc– dc converter, slightly less amount of power is transferred to feed the VSI. The pulse generator generates, through INC-MPPT algorithm, switching pulses for insulated gate bipolar transistor (IGBT) switch of the luo converter. The INC-MPPT algorithm uses voltage and current as feedback from SPV array and generates an optimum value of duty cycle. Further,it generates actual switching pulse by comparing the duty cycle with a high-frequency carrier wave. In this way, the maximum power extraction and hence the efficiency optimization of the SPV array is accomplished.

The VSI, converting dc output from a luo converter into ac, feeds the BLDC motor to drive a water pump coupled to its shaft. The VSI is operated in fundamental frequency switching through an electronic commutation of BLDC motor assisted by its built-in encoder. The high frequency switching losses are thereby eliminated, contributing in an increased efficiency of proposed water pumping system.

IV. DESIGN OF PROPOSED SYSTEM

Various operating stages shown in Fig. 2 are properly designed to develop an effective water pumping system, capa-ble of operating under uncertain conditions. A BLDC motor of 2.89-kW power rating and an SPV array of 3.4-kW peak power capacity under standard test conditions (STC) are selected to design the proposed system. The detailed designs of various stages such as wind and SPV array, luo converter, and water pump are described as follows.

A. Design of wind

All renewable energy (except tidal and geothermal power), ultimately comes from the sun. The earth receives 1.74 x 10^{17} watts of power (per hour) from the sun. About one or 2 percent of this energy is converted to wind energy (which is about 50-100 times more than the energy converted to biomass by all plants on earth. Differential heating of the earth's surface and atmosphere induces vertical and horizontal air currents that are affected by the earth's rotation and contours of the land WIND. Winds are influenced by the ground surface at altitudes up to meters. Wind is slowed by the surface roughness and obstacles. When dealing with wind energy, we are concerned with surface winds. A wind turbine obtains its power input by converting the force of the wind into a torque (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed. The kinetic energy of a moving body is proportional to its mass (or weight). The kinetic energy in the wind thus depends on the density of the air, i.e. its mass per unit of volume. In other words, the "heavier" the air, the more energy is received by the turbine.at 15° Celsius air weighs about 1.225 kg per cubic meter, but the density decreases slightly with increasing humidity. A typical 600 kW wind turbine has a rotor diameter of 43-44 meters, i.e. a rotor area of some 1,500 square meters. The rotor area determines how much energy a wind turbine is able to harvest from the wind. Since the rotor area increases with the square of the rotor diameter, a turbine which is twice as large will receive 2^2 = 2 x 2 = four timesas much energy.

B. Design of SPV Array

As per above discussion, the practical converters are asso-ciated with various power losses. In addition, the performance of BLDC motor-pump is influenced by associated mechanical and electrical losses. To compensate these losses, the size of SPV array is selected with slightly more peak power capac-ity to ensure the satisfactory operation regardless of power losses. Therefore, the SPV array of peak power capacity of P_{mpp}= 3.4kW under STC (STC:1000 W/m^2,25°C,AM 1.5), slightly more than demanded by the motor-pump is selected and its parameters are designed accordingly. SolarWorld make Sunmodule Plus SW 280 mono SPV

TABLE I
SPECIFICATIONS OF SUNMODULE PLUS SW 280 MONO SPV MODULE

Peak power, P_m (W)	280
Open circuit voltage, V_o (V)	39.5
Voltage at MPP, V_m (V)	31.2
Short circuit current, I_s (A)	9.71
Current at MPP, I_m (A)	9.07
Number of cells connected in series, N_{ss}	60

module is selected to design the SPV array of an appropriate size. Electrical specifications of this module are listed in Table I and numbers of modules required to connect in series/parallel are estimated by selecting the voltage of SPV array at MPP under STC as V_{mpp}= 187.2V.

The current of SPV array at MPP I_{mpp} is estimated as

$$I_{mpp} = P_{mpp}/V_{mpp} = 3400/187.2 = 18.16\text{A}. \quad (1)$$

The numbers of modules required to connect in series are as follows:

$$N_s = V_{mpp}/V_m = 187.2/31.2 = 6. \quad (2)$$

The numbers of modules required to connect in parallel are as follows:

$$N_p = I_{mpp}/I_m = 18.16/9.07 = 2. \quad (3)$$

Connecting six modules in series, having two strings in parallel, an SPV array of required size is designed for the proposed system.

B. Design of luo Converter

The luo converter is the next stage to the SPV array. Its design consists of an estimation of various components such as input inductor L_1, output inductor L_2, and intermediate capac itor C_1. These components are designed such that the zeta converter always operates in CCM resulting in reduced stress on its components and devices. An estimation of the duty cycle D initiates the design of luo converter which is estimated as

$$D = \frac{V_{dc}}{V_{dc}+V_{mpp}} = \frac{200}{200+187.2} = 0.52 \quad (4)$$

where V_{dc} is an average value of output voltage of the luo converter (dc link voltage of VSI) equal to the dc voltage rating of the BLDC motor.

An average current flowing through the dc link of the VSI $I_{dc}$is estimated as

$$I_{dc} = P_{mpp}/V_{dc} = 3400/200 = 17\text{A}. \quad (5)$$

Then, L_1, L_2, and C_1 are estimated as [6]

$$L_1 = \frac{DV_{mpp}}{f_{sw} I_{L1}} = \frac{0.52 \times 187.2}{20\,000 \times 18.16 \times 0.06} = 4.5 \times 10^{-3} \approx 5\text{ mH} \quad (6)$$

$$L_2 = \frac{(1-D)V_{dc}}{f_{sw} I_{L2}} = \frac{(1-0.52)\times 200}{20\,000 \times 17 \times 0.06} = 4.7 \times 10^{-3} \approx 5\text{ mH} \quad (7)$$

$$C_1 = \frac{DI_{dc}}{f_{sw} V_{C1}} = \frac{0.52 \times 17}{20\,000 \times 200 \times 0.1} = 22\ \mu\text{F} \quad (8)$$

where f_{sw} is the switching frequency of IGBT switch of the luo converter; I_{L1} is the amount of permitted ripple in the current flowing through L_1, same as I_{L1}=I_{mpp}; I_{L2} is the amount of permitted ripple in the current flowing through L_2, same as I_{L2}=I_{dc}; V_{C1} is permitted ripple in the voltage across C_1, same as V_{C1}=V_{dc}.

C. Estimation of DC-Link Capacitor of VSI

A new design approach for estimation of dc-link capacitor of the VSI is presented here. This approach is based on a fact that sixth harmonic component of the supply (ac) voltage is reflected on the dc side as a dominant harmonic in the three-phase supply system. Here, the fundamental frequencies of output voltage of the VSI are estimated corresponding to the rated speed and the minimum speed of BLDC motor essentially required to pump the water. These two frequencies are further used to estimate the values of their corresponding capacitors. Out of these two estimated capacitors, larger one is selected to assure a satisfactory operation of proposed system even under the minimum solar irradiance level.

The fundamental output frequency of VSI corresponding to the rated speed of BLDC motor ω_{rated} is estimated as

$$\omega_{rated} = 2\pi f_{rated} = 2\pi \frac{N_{rated}P}{120} = 2\pi \times \frac{3000 \times 6}{120} = 942\text{ rad/s.} \quad (9)$$

The fundamental output frequency of the VSI corresponding to the minimum speed of the BLDC motor essentially required to pump the water (N= 1100 r/min)ω_{min} is estimated as

$$\omega_{min} = 2\pi f_{min} = 2\pi \frac{NP}{120} = 2\pi \times \frac{1100 \times 6}{120} = 345.57\text{ rad/s} \quad (10)$$

where f_{rated} and f_{min} are fundamental frequencies of output voltage of VSI corresponding to a rated speed and a minimum speed of BLDC motor essentially required to pump the water, respectively, in Hz; N_{rated} is rated speed of the BLDC motor; P is a number of poles in the BLDC motor.

The value of dc link capacitor of VSI at ω_{rated} is as follows:

$$C_{2,rated} = \frac{I_{dc}}{6 \times \omega_{rated} \times V_{dc}} = \frac{17}{6 \times 942 \times 200 \times 0.1} = 150.4\ \mu\text{F}. \quad (11)$$

Similarly, a value of dc link capacitor of VSI at ω_{min} is as follows:

$$C_{2,min} = \frac{I_{dc}}{6 \times \omega_{min} \times V_{dc}} = \frac{17}{6 \times 345.57 \times 200 \times 0.1} = 410\ \mu\text{F} \quad (12)$$

where V_{dc} is an amount of permitted ripple in voltage across dc-link capacitor C_2.

Finally, C_2= 410μF is selected to design the dc-link capacitor.

D. Design of Water Pump

To estimate the proportionality constant K for the selected water pump, its power–speed characteristics is used as

$$K = \frac{P}{\omega_r^3} = \frac{2.89 \times 10^3}{(2\pi \times 3000/60)^3} = 9.32 \times 10^{-5} \quad (13)$$

where P= 2.89 kW is rated power developed by the BLDC motor and ω_r is rated mechanical speed of the rotor (3000 r/min) in rad/s.

A water pump with these data is selected for proposed system.

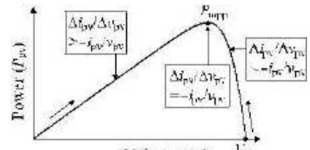


Fig. 3. Illustration of INC-MPPT with SPV array P_{pv}–v_{pv} characteristics.

TABLE II
SWITCHING STATES FOR ELECTRONIC COMMUTATION OF BLDC MOTOR

	Hall signals			Switching states					
position θ (°)	H_3	H_2	H_1	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0–60	1	0	1	1	0	0	1	0	0
60–120	0	0	1	1	0	0	0	0	1
120–180	0	1	1	0	0	1	0	0	1
180–240	0	1	0	0	1	1	0	0	0
240–300	1	1	0	0	1	0	0	1	0
300–360	1	0	0	0	0	0	1	1	0
NA	1	1	1	0	0	0	0	0	0

V. CONTROL OF PROPOSED SYSTEM

The proposed system is controlled in two stages. These two control techniques, viz., MPPT and electronic commutation, are discussed as follows.

A. INC-MPPT Algorithm

An efficient and commonly used INC-MPPT technique in various SPV array based applications is utilized in order to optimize the power available from a SPV array and to facilitate a soft starting of BLDC motor. This technique allows perturbation in either the SPV array voltage or the duty cycle. The former calls for a proportional-integral (PI) controller to generate a duty cycle for the luo converter, which increases the complexity. Hence, the direct duty cycle control is adapted in this work. The INC-MPPT algorithm determines the direction of perturbation based on the slope of P_{pv}–v_{pv} curve,

$$\frac{dP_{pv}}{dv_{pv}} = 0; \quad \text{at mpp}$$
$$\frac{dP_{pv}}{dv_{pv}} > 0; \quad \text{left of mpp} \qquad (14)$$
$$\frac{dP_{pv}}{dv_{pv}} > 0; \quad \text{right of mpp}$$

Since

$$\frac{dP_{pv}}{dv_{pv}} = \frac{d(v_{pv} * i_{pv})}{dv_{pv}} = i_{pv} + v_{pv} * \frac{di_{pv}}{dv_{pv}} \sim i_{pv} + v_{pv} * \frac{\Delta i_{pv}}{\Delta v_{pv}}. \qquad (15)$$

Therefore, (14) is rewritten as

$$\frac{\Delta i_{pv}}{\Delta v_{pv}} = -\frac{i_{pv}}{v_{pv}}; \quad \text{at mpp}$$
$$\frac{\Delta i_{pv}}{\Delta v_{pv}} > -\frac{i_{pv}}{v_{pv}}; \quad \text{left of mpp} \qquad (16)$$
$$\frac{\Delta i_{pv}}{\Delta v_{pv}} < -\frac{i_{pv}}{v_{pv}}; \quad \text{right of mpp}$$

Thus, based on the relation between INC and instantaneous conductance, the controller decides the direction of perturbation as shown in Fig. 3, and increases/decreases the duty cycle accordingly. For instance, on the right of MPP, the duty cycle is increased with a fixed perturbation size until the direction reverses. Ideally, the perturbation stops once the operating point reaches the MPP. However, in practice, operating point oscillates around the MPP.

As the perturbation size reduces, the controller takes more time to track the MPP of SPV array. An intellectual agreement between the tracking time and the perturbation size is held to fulfill the objectives of MPPT and soft starting of BLDC motor. In order to achieve soft starting, the initial value of duty cycle is set as zero. In addition, an optimum value of perturbation size ($\Delta D = 0.001$) is selected, which contributes to soft starting and also minimizes oscillations around the MPP.

B. Electronic Commutation of BLDC Motor

The BLDC motor is controlled using a VSI operated through an electronic commutation of BLDC motor. An electronic commutation of BLDC motor stands for commutating the currents flowing through its windings in a predefined sequence using a decoder logic. It symmetrically places the dc input current at the center of each phase voltage for 120°. Six switching pulses are generated as per the various possible combinations of three Hall-effect signals. These three Hall-effect signals are produced by an inbuilt encoder according to the rotor position.

A particular combination of Hall-effect signals is produced for each specific range of rotor position at an interval of 60°. The generation of six switching states with the estimation of rotor position is tabularized in Table II. It is perceptible that only two switches conduct at a time, resulting in 120° conduction mode of operation of VSI and hence the reduced conduction losses. Besides this, the electronic commutation provides fundamental frequency switching of the VSI; hence, losses associated with high-frequency PWM switching are eliminated. A motor power company make BLDC motor with inbuilt encoder is selected for proposed system and its detailed specifications are given in the Appendixes.

VI. SIMULATED PERFORMANCE OF PROPOSED SYSTEM

Performance evaluation of proposed wind and SPV array-fed BLDC motor-driven water pump employing a luo converter is carried out using simulated results. The proposed system is designed, modeled, and simulated considering the random and instant variations in solar irradiance level and its suitability is demonstrated by testing the starting, steady state, and dynamic behavior as illustrated. To demonstrate the suitability of the system under dynamic condition, solar irradiance level instantly reduced from 600 to 200W/m^2 and then increased to 1000 W/m^2.

A. Performance of SPV Array

exhibits the starting and steady-state performances of SPV array at 1000 W/m^2. The MPP is properly tracked. The tracking time is intentionally increased at the starting by adapt-

v_{pv} − v_{pv}

to achieve the soft starting of BLDC motor. The low value of D causes the reduced rate of rise of dc-link voltage of VSI resulting in a smooth and soft starting of the motor. However, a negligible tracking time is required under the dynamic variation in irradiance level.

B. Performance of luo Converter

Presents the steady-state performance of luo con-verter at 1000 W/m^2. The input inductor current i_{L1}, interme-diate capacitor voltage v_{c1}, output inductor current i_{L2}, voltage stress on IGBT switch v_{SW}, current stress on IGBT switch i_{SW}, blocking voltage of the diode v_D, current through diode i_D, and dc-link voltage v_{dc} are presented. The luo converter is oper-ated in CCM. The operation of converter in this mode reduces the stress on power devices and components. These converter indices follow the variation in the weather condition and vary in proportion to the solar irradiance level, such as i_{L1}, v_{c1}, i_{L2}, and v_{dc}. The luo converter automatically changes its mode of operation from buck mode to boost modeand vice versa according to the irradiance level to optimize the output power of SPV array. A small amount of ripples in the luo converter variables are observed caused by permitting the ripples up to an extent to optimize the size of the components.

C. Performance of BLDC Motor-Pump

The starting and steady-state behaviors of the BLDC motor-pump at 1000 W/m^2. All the motor indices such as the back EMF e_a, the stator current i_{sa}, the speed N , the electromagnetic torque developed T_e, and the load torque T_L reach their corresponding rated values under steady-state condition. The soft starting along with the stable operation of motor-pump is observed and hence the successful operation of proposed system is verified. However, a small pulsation in T_e results due to the electronic commutation of the BLDC motor. As the solar irradiance level alters, all the BLDC motor-pump indices vary in proportion to the solar irradiance level. The BLDC motor always attains a higher speed

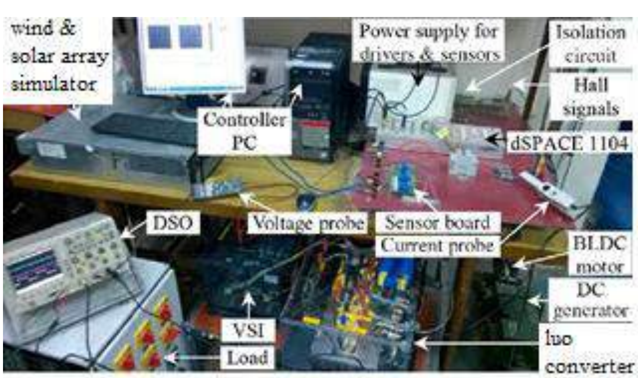


Fig. 4. Photograph of a developed prototype of the proposed system.

than 1100 r/min, a minimum speed required to pump the water at a minimum solar irradiance level of 200W/m^2. Performance of BLDC motor-pump is not deteriorated by weather conditions and it pumps the water successfully.

VII. Hardware Validation of Proposed System

ing a low value of perturbation size (ΔD= 0.001) in order

The various performances of wind and SPV array, luo converter, and BLDC motor-pump are validated on a developed prototype of the proposed system, which is presented.

The system constitutes an wind and SPV array simulator (AMETEK ETS 600×17DPVF), luo converter, VSI (SEMIKRON MD B6CI600/415-35F), real-time DSP controller (dSPACE 1104) to per-form MPPT and electronic commutation, BLDC motor (Motor Power Company make) coupled with a dc generator (Benn make) and resistive load bank. A volumetric pump is realized by driving a dc generator feeding a resistive load. Thus, this motor-generator-load set becomes analogous to a volumetric pump, possessing proportional relationship between torque and speed. Because of the rating constraints, experiments are carried out with a 1-HP, 2000-r/min BLDC motor fed by a 900-Wp PV array. A voltage sensor (LV-25P) and a current sensor (LA-55P) are used for MPPT control. To provide the isolation between real-time controller and gate drivers, the optocouplers (6N136) are used. Detailed specifications of wind and SPV array, luo converter, and BLDC motor used for test are given in the Appendixes. Experimental performance of proposed system is analyzed in the following sections.

A. Performance of SPV Array

The performance of developed system is tested for solar irradiance level varying from 400 to 1000 W/m^2. The recorded p_{pv} − $v_{pv}$and i_{pv} − v_{pv}characteristics, at 1000 and 400 W/m^2 verify excellent performance of MPPT. A tracking efficiency for both irradiance levels is observed more than 99%.

B. Steady-State Performance at 1000 W/m^2

The steady-state performances of SPV array, luo converter, and BLDC motor-pump at 1000 W/m^2 are validated using the recorded waveforms and elaborated in the following sections.

1) Performance of SPV Array: The recorded waveforms ofvarious SPV array indices v_{pv}, i_{pv}, p_{pv} along with the duty ratio *D*. These indices correspond to MPP.
The operation of luo converter in boost mode is observed at

D = 0.52.. Furthermore,represents another set of the indice$_W$, i_{SW}, v_D, and i_D. These indices justify the operation ofconverter in CCM and limited stress on its power devices. The peak voltage and peak current of the switch are

2) observed as 400 V and 13.7 A, respectively. Similarly, the peak voltage and peak current of the diode are observed as 500 V and 14 A, respectively. The IGBT and diode operate in a complementary fashion.

*3) Performance of BLDC Motor: E*xhibits the recorded waveforms of stator currents of all three phases i_{sa}, i_{sb}, $i_{sc}$and speed N . The BLDC motor indices reach theirrated values of 2000 r/min and 3.6 A. A 1-HP (746 W) motor draws 900 W from PV array, offering 83% system efficiency.

C. Dynamic Performance of Proposed System

To demonstrate the satisfactory performance of system under dynamically varying atmospheric condition, the solar irradi-ance is varied from 400 to 1000 W/m^2. The recorded wave-forms, are

i_{pv}, v_{dc}, i_{sa}, and N . It is clearly observed that the MPP is tracked accurately. The luo converter quickly changes its mode of operation following the variation in.

D. Starting Performance of Proposed System

The soft starting of BLDC motor at both solar irradiances of 1000 and 400 W/m^2, is validated using recorded waveforms of i_{pv}, v_{dc}, $i_{sa}$and N . The initial duty ratio is set at 0.1 to startthe motor. All these indices reach their steady-state values at MPP of SPV array. The motor attains 1150 r/min at 400 W/m^2 a sufficient speed to pump the water.

E. Efficiency Estimation of Proposed System

The experimental measurements are considered to estimate the efficiency of the proposed water pumping system. Table III and Estimated efficiency of the wind and SPV array-fed BLDC motor-pump, subjected to the random variation in solar insolation level, where P_{pv}, P_m, and η are, respectively, the maximum power available from the SPV array, mechani-cal power output of the BLDC motor, and efficiency. Hence, this efficiency includes the efficiency of INC-MPPT algorithm, luo converter, VSI, and BLDC motor. A very good efficiency of 83% is obtained at the standard solar insolation level of 1000 W/m^2, whereas it is 71% even at 400 W/m^2.

VIII. Conclusion

The wind and SPV array-luo converter-fed VSI–BLDC motor-pump has been proposed and its suitability has been demonstrated through simulated results and experimental validation. The proposed system has been designed and modeled appropriately to accomplish the desired objectives and validated to examine various performances under starting, dynamic, and steady-state conditions. The performance evaluation has justified the combination of luo converter and BLDC motor for wind and SPV array-based water pumping. The system under study has shown various desired functions such as maximum power extraction of the SPV array, soft starting of BLDC motor, fundamental frequency switching of VSI resulting in a reduced switching losses, speed control of BLDC motor without any additional control, and an elimination of phase current and dc-link voltage sensing, resulting in the reduced cost and complexity. The proposed system has operated successfully even under minimum solar irradiance.

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