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Article

Enhancing the solar water pumping efficiency through Beta MPPT method-controlled drive

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Abstract: This paper presents an innovative approach to achieve efficient solar water pumping through the integration of a Photovoltaic (PV) array and a Brushless Direct Current (BLDC) motor water pumping system. The system incorporates a Voltage Source Converter (VSC) with six switches, utilized to facilitate commutation. The inherent solar radiation is harnessed by the PV array, capitalizing on its renewable nature to generate electricity. By dynamically adjusting the switching states of the six VSC switches, the speed of the BLDC motor is modulated in response to the varying levels of available solar radiation. The BLDC motor's hall sensor signals play a crucial for determining the rotor's position and they are employed to generate precise commutation signals. The control strategy integrates the Incremental Conductance (INC) Maximum Power Point Tracking (MPPT) algorithm, which initially governs the commutation signals. To enhance adaptability to rapidly changing solar irradiation conditions, the control strategy dynamically updates the commutation signals using the innovative Beta MPPT algorithm. To assess the efficiency of the proposed control strategy, a comprehensive comparison between the INC and Beta MPPT algorithms is conducted using MATLAB Simulink. The performance of the BLDC motor under these algorithms was evaluated in terms of its ability to optimize energy extraction. The graphical analysis of these algorithms, considering the temporal aspect, substantiates the identification of the superior MPPT algorithm for BLDC motor control in solar water pumping applications. This study contributes to the advancement of solar water pumping systems by introducing a novel control approach that combines PV array utilization, VSC-based commutation, and a dual-step MPPT algorithm. The results demonstrate the effectiveness of the Beta MPPT algorithm by enabling the system to respond promptly to fluctuating solar irradiation conditions, thereby enhancing the overall efficiency of the solar water pumping process.

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1. Introduction

In the face of the forthcoming global energy crisis brought on by fossil fuel depletion, researchers and entrepreneurs are turning to solar Photovoltaic (PV) technology as a pivotal solution [1]. This transition gains essential significance as the costs associated with solar photovoltaic modules, power circuits, and microprocessors continue to decrease [2, 3]. At the forefront of this technological revolution is the recognition of solar energy's potential to mitigate the looming energy catastrophe.

Solar photovoltaic modules, designed to harness the boundless energy of the sun, hold the promise of a sustainable energy source. The convergence of cost reduction and technological advancements further accelerates the feasibility of solar PV deployment. A particularly compelling application of solar PV energy is its use in autonomous water pumping systems. This versatile technology has the capacity to address a range of challenges, from preventing urban flooding to enhancing agricultural productivity and sustaining aquaculture enterprises [4].

Electric motors and other modern conveniences have greatly increased energy demand. Motors cost more than 40% of electricity [5]. A motor is necessary for a "solar PV-based energy-efficient and cost-effective water pumping system". Solar power investment is considerably reduced by reducing the number of PV modules needed to meet a specific electrical necessity. For a low-power applications considerably most of the solar PV water pumps use dc motors [6, 7]. There should be a regular maintenance for the commutator and sliding brush in order to control the efficiency of the dc motor with brushes. Unlike dc motors the PV based induction motor pumping systems are reliable, durable, and low maintenance. The Brush Less DC (BLDC) motor outperforms the induction and dc motors for solar fed water pumping. An ac motor is bigger, stronger, and consumes more energy [8]. BLDC motors also include longevity, low maintenance, a wide speed range, simple operation, and easy handling [9–12].

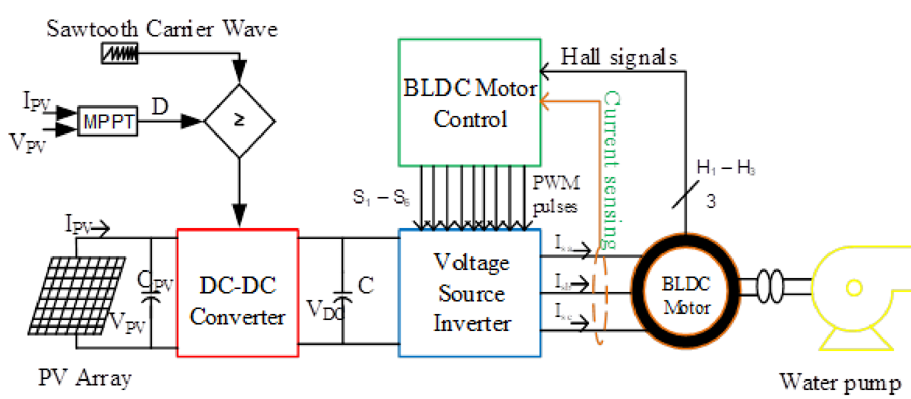

Figure 1. Current sensors based traditional BLDC motor drive.

Figs. 1 and 2 demonstrates "conventional BLDC motor drives for PV water pumping" [13, 14]. Fig. 1(a) shows a dc-dc converter performing "maximum power point tracking (MPPT)" [15–21]. Motor control requires two-phase current sensing [8]. Fig. 1(b) shows a standard arrangement that also eliminates phase

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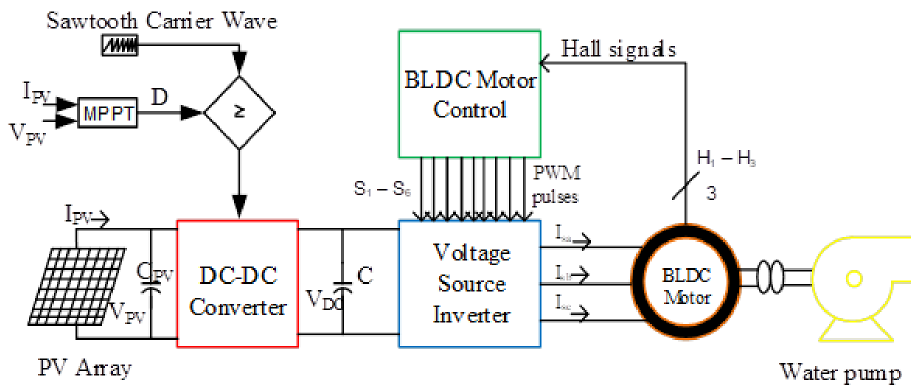

Figure 2. Non-current sensors based traditional BLDC motor drive.

current sensors. As usual, a dc-dc converter optimises PV array working power, BLDC motor-pump speed control and system soft starting. The Voltage Source Inverter (VSI) is used to regulate the speed of DC bus voltage. However, the VSI is fundamentally used as the frequency functioning unit where a big dc capacitor is required. The Z-source network substitutes the dc-dc conversion [14] by claiming to be a single-stage solution. Monitoring dc bus voltage and motor phase currents is required. Another step towards fewer sensors is position sensor-free BLDC motor driving, described in [22] and [23]. Such utility models assume two-stage power conversion.

An intermediate dc-dc converter maximises the PV array's maximum power point in the standard topologies like two-stage solar energy conversion systems. Power converters reduce efficiency, size, and cost. This article presents a single-stage PV fed system that excludes the dc-dc phase. The same VSI controls motor speed and solar PV array capacity. The typical design in Fig. 2 offers numerous advantages, including gentle starting and there is no BLDC motor phase current sensing. Peak PV array is used as the power controller for the BLDC motor's speed. Pulse with modulation (PWM) switching of VSI permits the use of a low-valued capacitor at the dc connection instead of bulkier. Single-stage PV systems for induction motor-driven water pumps have been proposed [7]. Furthermore, the existing literature has not highlighted the design of BLDC motor integrated with PV system for efficiency improvements. The BLDC motors in solar PV water pumping systems offer simplicity, cost-effectiveness, and small size.

- A solar water pumping system using BLDC motors converts electricity more efficiently than an induction motor-driven system. Excitation losses reduce induction motor efficiency under light load condition. BLDC motors provide less water in bad weather due to its magnetic excitation.
- With the better efficient way, the BLDC motor lowers the PV array size and installation costs and require fewer solar modules when compared to induction motors.
- The BLDC motors have high power factor by which the maximum load on VSI is reduced. By this feature the price of PV pumping system is low.
- The BLDC motor uses more dc bus voltage when compared to induction motor since it is rectangular in structure, which results in lower voltage for VSI switching device and dc bus capacitor voltage.
- Unlike induction motors, BLDC motors' maximum speed is unaffected by power supply frequency. BLDC motors may have a greater rated speed, which increases capacity while reducing bulk. Space-saving solar photovoltaic (PV) water pumping system.
- BLDC motor speed control is simpler than induction motor speed control. The recommended control does not need VSI and phase current monitoring like induction motor speed control [5, 24–26]

promotes two VSI's. Therefore, the recommended control simplifies, costs less, and compacts the solar photovoltaic (PV) water pumping system.

The study's design starts with a PV array and BLDC motor-pump combination to ensure reliability in all-weather situations. The Proposed a MATLAB simulated model able to analyse the system's dynamic and steady state capabilities. It operates effectively under defined conditions, notably in MPPT with PV array operation, without losing its capabilities.

The BLDC motor-water pumping system in Fig. 1 converts solar PV energy in one step. The BLDC motor-pump is powered by solar PV-connected VSI system. The solar reverse current is blocked by a series diode. A modest dc-link capacitor connects the solar system to the BLDC drive-pump. PV system is optimised by incremental conductance (INC) MPPT. This technology uses the voltage and current of a PV array as feedback signals to find the perfect duty ratio, which is the same as the maximum power of a PV array. Three Hall sensors on the motors control how the electricity flows.

2. Proposed system

A water pump's performance depends on the solar PV array and BLDC drive. BLDC motors supply the water pump. Table 1 lists BLDC motor specifications. We ensure system performance is unaffected by quick weather changes by carefully choosing the PV array, dc-link capacitor, and BLDC drive.

2.1. Design of solar PV array

Within the realm of harnessing solar energy to power the BLDC drive-pump system, meticulous sizing and configuration of the Photovoltaic (PV) array emerge as critical undertakings. Under standard atmospheric conditions—ambient temperature of 25°C and solar irradiance of 1000 W/m²—a 4 kW PV array is envisaged, precisely tailored to the specifications of the BLDC drive-pump system. This selected PV array is strategically dimensioned to account for power losses incurred by both the Voltage Source Inverter (VSI) and the drive-pump. The aim is to ensure that ample operational power is available to propel the system at its rated parameters. A minimum of 36 series-connected PV modules are identified as an optimal configuration, aligning harmoniously with the energy needs of the system. The starting point in this intricate design journey is the open-circuit voltage of solar cells at ambient conditions—ranging from 0.5 to 0.6 V [27]. By employing meticulous calculations, a module open-circuit voltage of 19.8 V is derived, effectively factoring in the ambient temperature and pressure conditions [28]. The heart of optimal energy conversion is lies in the module voltage, which sits at 71%-78% of the open-circuit voltage at the Maximum Power Point (MPP). To facilitate the operational requirements of the specified BLDC motor-pump, a 310 V direct current (DC) link at the VSI is necessitated. Achieving this entails harnessing the MPP voltage of the PV array—310 V. Calculations demonstrate that approximately 20 series-connected modules are requisite

Table 1. BLDC motor specifications.

Speed (N)	3000 rpm
Power (P_m)	3.45 kW
Inertia (J)	20.8 kg·cm^2
Voltage constant	78 V/k rpm
Torque constant	0.74 Nm/A
Number of poles (P)	6
Inductance (L)	2.8 mH
Resistance (R)	0.92 Ohm

Table 2. Solar PV array design.

MPP Power	4 kW
Current at MPP	12.9 A
Voltage at MPP	310 V
Open circuit voltage (V_{OC})	396 V
Short circuit current (I_{SC})	14.4 A
Parallel connected modules (N_P)	3
Series connected modules (N_S)	20

to realize this target voltage. This pivotal configuration sets the stage for achieving the desired output—4 kW, 310 V, and 12.9 A—at the MPPT of the PV array. Intricate interplay unfolds as three parallel modules contribute to designing the PV array's MPPT current, summing up to 4.3 A. Most short-circuit current is 78%–92% [28]. The design nuances carefully leverage the characteristics of module-specific short-circuit current, approximating it to 4.8 A. A grand total of 60 modules, elegantly connected in series (20) and parallel (3), culminate in a harmonious symphony—yielding 4 kW, 310 V, and 12.9 A, at the MPPT (as shown in table 2).

2.2. DC-link capacitor design

The compact PV array employs a wired dc-link capacitor within the Voltage Source Inverter (VSI) configuration. This capacitor functions by conducting ripple current which is denoted as i_C, and i_s determined as the difference between the photovoltaic (PV) array current (i_{pv}) and the direct current (dc) current (i_{dc}). The switching frequency (f_{SW}) of the system is contingent upon various factors, including component dimensions, system responsiveness, conversion efficiency and susceptibility to noise interference. Consequently, these variables are influenced by the chosen switching frequency. A higher switching frequency leads to a reduction in the size of the dc link capacitor due to increased compactness. This enhances transient responsiveness and helps steer clear of regions prone to noise disturbances.

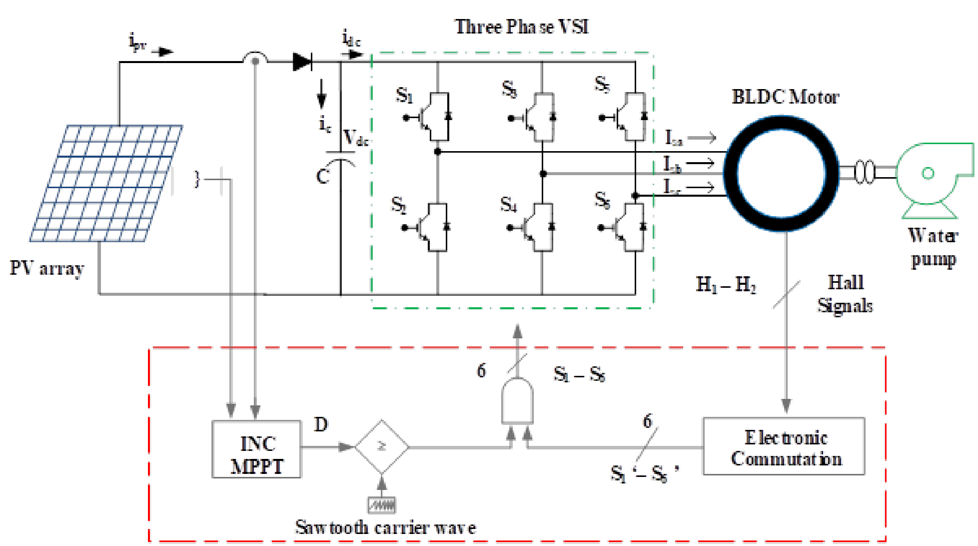

Figure 3. Solar photovoltaic (PV) energy conversion for use in a single stage water pumping system.

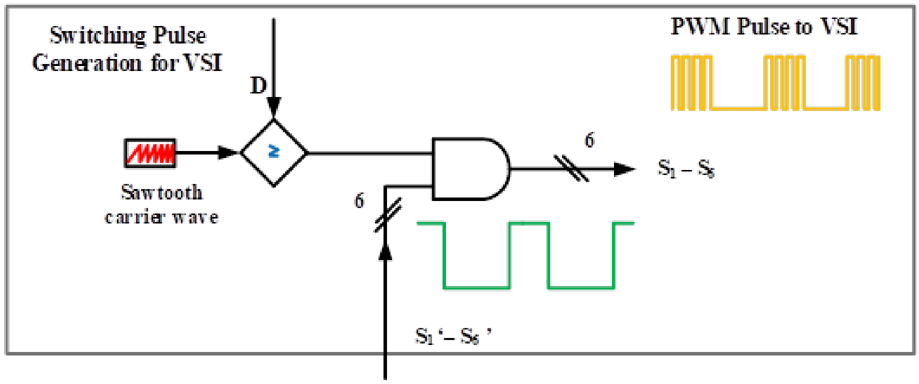

Figure 4. Control structure of the proposed water pumping system.

Nonetheless, opting for a high frequency switching mechanism within the VSI results in diminished conversion efficiency. This arises from the fact that elevated switching frequency, while maintaining constant energy which leads to amplified switching losses. After careful evaluation, a switching frequency of 10 kHz is identified as the optimal choice. This frequency strikes a balance between the advantages and drawbacks of different switching frequencies. The integration of the VSI dc link capacitor is performed as the final step, taking into account that the limitations imposed by existing network designs [13]. The operation of this system is governed by managing the operating point of the solar PV array through maximum power point tracking (MPPT), electronically commutating the Brushless DC (BLDC) motor, generating switching pulses for the VSI, and controlling the motor's speed. These components collectively regulate the proposed system, ensuring its efficient functionality.

2.3. Control approach

The proposed system controls solar PV array operating point through MPPT, BLDC motor electrical commutation, switching pulse generation for VSI and BLDC motor speed. Figs. 3, 4 illustrates the control structure of proposed water pumping system.

3. Inverter

The Boost converter takes the direct current (DC) supply and transforms it into three-phase alternating current (AC) using a three-phase inverter. This converted ac is then supplied to the stator of the Brushless Direct Current (BLDC) motor, allowing precise control of the motor's operation. In this setup, an Insulated Gate Bipolar Transistor (IGBT) based Voltage Source Inverter (VSI) is utilized to design a system that feeds the BLDC motor with a dc link charge through the converter. There are two distinct approaches to regulating this system, both of which are explained in the subsequent paragraphs. The first approach involves managing the dc supply voltage and the speed of the motor. Alternatively, the second approach employs Pulse Width Modulation (PWM) control within the operation of the three-phase inverter. Both methods are elaborated upon in the following sections.

The main role of the inverter is to facilitate the conversion of DC to AC. This ac power is crucial for properly energizing the stator coils in the BLDC motor, ensuring its seamless operation. To facilitate this, hall sensors are integrated into the motor. These hall sensors provide hall signals that are then transformed into Electromotive Forces (EMF's) for each phase. Based on this information, the inverter's switching is precisely orchestrated. This synchronization ensures the optimal functioning of the BLDC motor.

4. Speed control system

Brushless Direct Current (BLDC) motors necessitate the integration of a controller circuit to effectively manage their operation. As technology advances, the evolution of speed controllers becomes imperative to ensure optimal performance. Typically, the speed controllers fall into two categories: closed-loop and open-loop control systems. Fig. 5 and 6 illustrates the flow chart and BLDC motor speed control mechanism. In scenarios where high-precision control is paramount, closed-loop methods are employed. These methods incorporate an internal loop responsible for tuning and polarity sensing of the power supply. Concurrently, an external loop takes charge of speed regulation. Adjusting of the Direct Current (DC) bus voltage is a key mechanism for modifying motor speed. The DC supply is orchestrated based on the motor speed in revolutions per minute (rpm) and its capacity. Thereby exerting control over the entire system. Within this framework, a Proportional-Integral-Derivative (PID) controller is responsible for regulating the inverter's output voltage. Closed-loop controllers rely on sensors to meticulously control motor speed. These sensors facilitate the closed-loop mechanism by providing real-time feedback on the motor's performance, guiding the precise adjustment of control parameters.

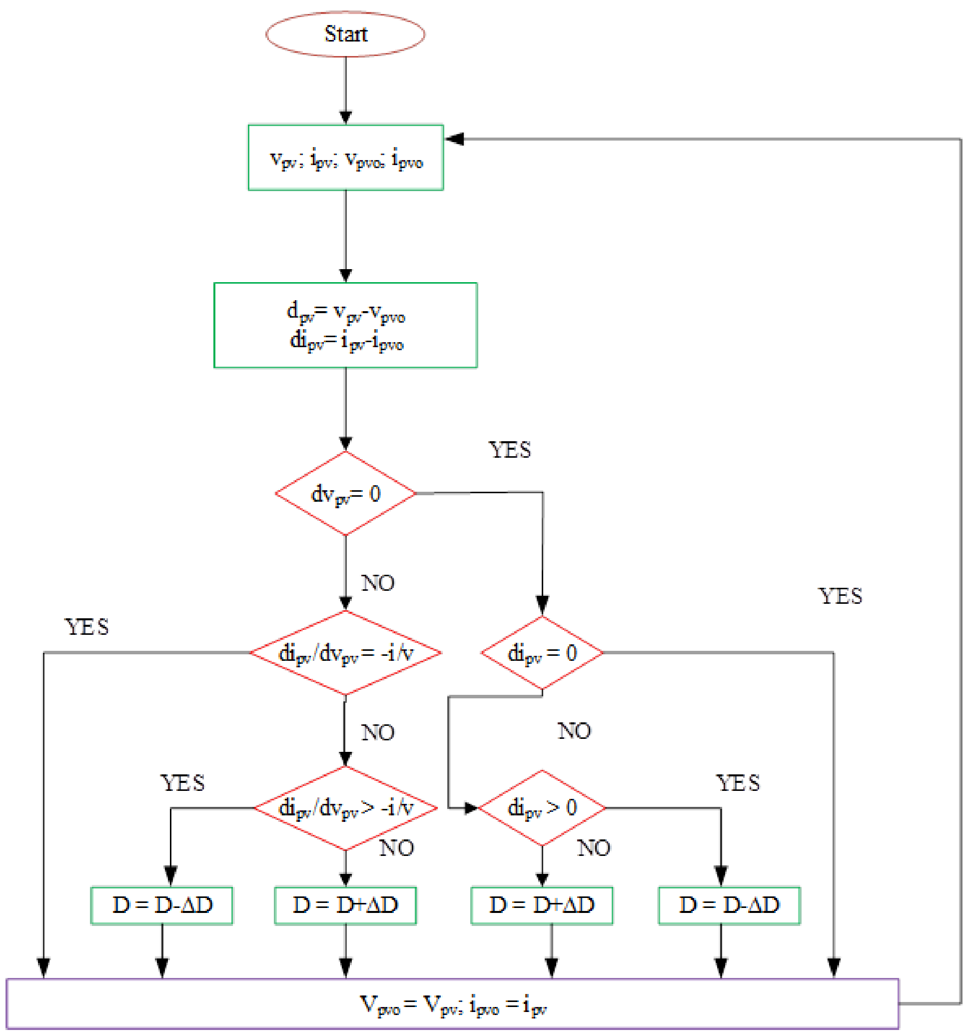

Figure 5. Flow chart of an incremental conductance MPPT algorithm.

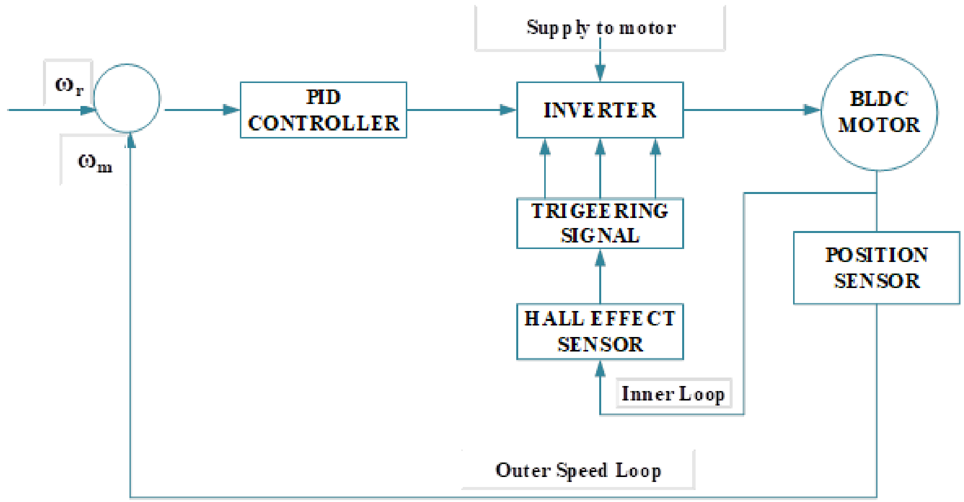

Figure 6. Speed control system.

5. BLDC motor

Appliances, automotive, aerospace, consumer, medical, automated industrial and instrumentation all employ BLDC motors. Power switches, nor brushes, commutate BLDC motors. The BLDC motor outperforms brushed DC and induction motors in several ways, providing improved speed versus torque characteristics, a higher speed range, stronger dynamic responsiveness, reduced acoustic noise, and longer life. Rotor position feedback controls current switching in BLDC motors with Hall sensors or rotary encoders provide feedback. Stator windings and rotor permanent magnets create a fairly consistent air gap flux density. This allows the stator coils to be powered by a continuous DC voltage hence the term 'brushless DC', which changes from one stator coil to the next to provide a trapezoidal AC voltage waveform.

Brushless DC motors revolve continuously because electronic switches commutate current. These electric switches are commonly coupled in an H-bridge structure for a single-phase BLDC motor and a three-phase bridge construction for a three-phase motor. PWM converts a DC voltage into a modulated voltage, limiting starting current, control speed and torque. Lower switching frequencies can restrict system bandwidth and may cause destructive ripple current pulses that shutdown the BLDC motor driver, whereas higher switching frequencies increase PWM losses.

6. Simulation results

MATLAB Simulink models the circuit architecture. The parameters below mimic Power system library blocks. Common Simulink library blocks are used to represent MPPT modules. PV array, BLDC motor, and six-switch IGBT VSC comprise the proposed system. PV array and BLDC motor tables.

Fig. 7. Shows the voltage, current and irradiation obtained from PV array. Voltage at a magnitude of 400 V. Current at a magnitude of 5 amps, with a ripple of 2 amps approximately and irradiation of 1000W/mt2.

Fig. 8. Shows the BLDC motor performance at constant irradiation. It obtained a speed of 4000 and above rpm, electromagnetic torque of 4 N-m and initially the transient torque is at 8 N-m later reduced and stabilized, and duty ratio is at 1.

Fig. 9 illustrates the stator current BLDC motor with a magnitude of approximately 10 amps and electromotive force obtained due to solar irradiation with a magnitude of 180V. The simulated waveforms are shown to the right side with a time duration from 1 second to 1.7 seconds.

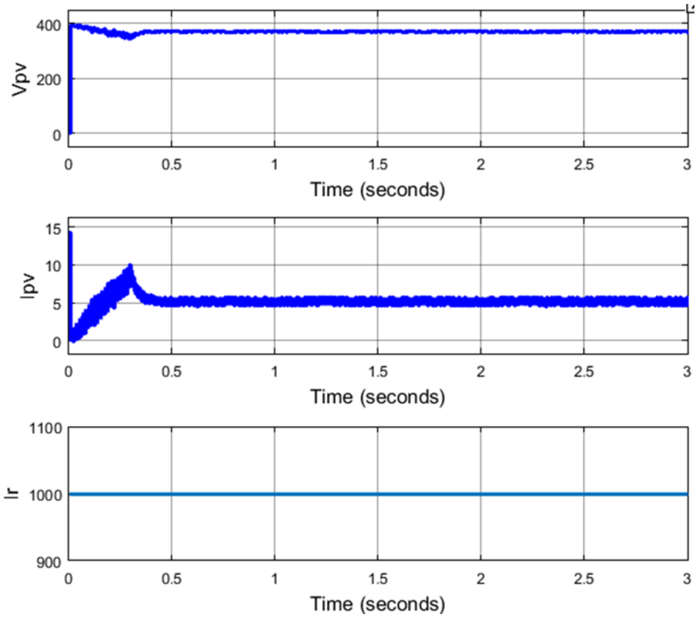

Figure 7. PV array characteristics for constant 1000W/mt2.

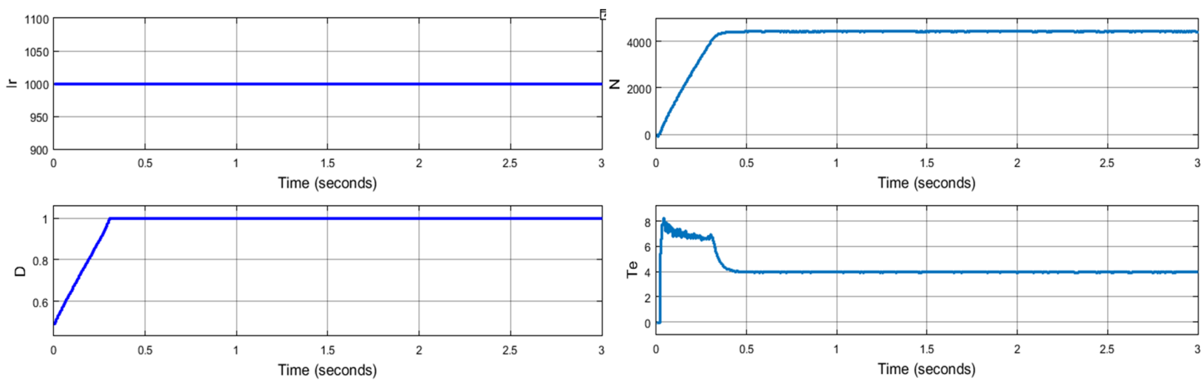

Figure 8. BLDC motor characteristics during constant solar irradiation of 1000W/mt2.

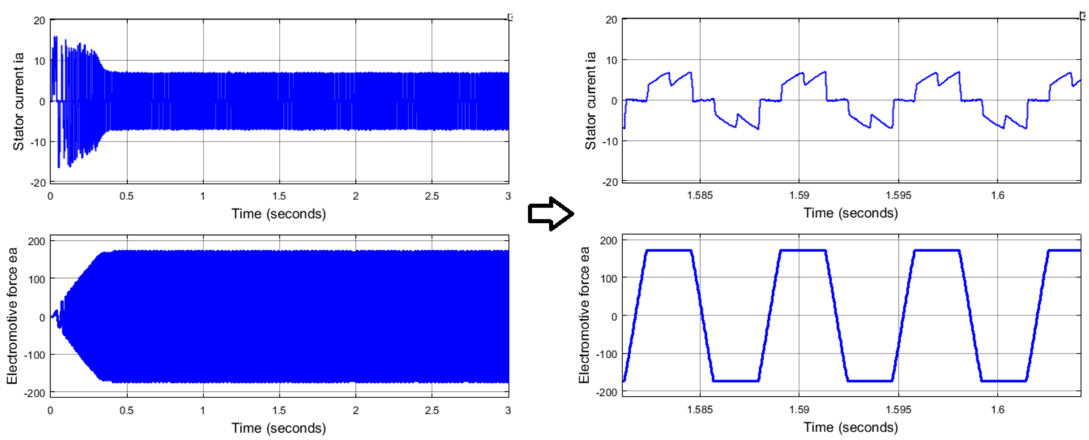

Figure 9. BLDC motor stator current and electromotive force of phase A during constant solar irradiation.

Fig. 10 illustrates the PV array characteristics during variable solar irradiation, it is plotted between the solar PV voltage (Vpv), current (Ipv) and rotor current (Ir) along the y-axis and the time(sec) is taken for all along the x-axis. The blue line shows the variation in the values. The Vph, Ipv and Ir shows the maximum values of 400,10 and 1000 respectively.

Fig. 11 shows the variations of the Ir, D, N and Te with respect to the Time(seconds). The thick blue colour lines shows the value of Ir, D and have the maximum values of the 1000 and 1 respectively. And the light blue shows the N and Te values have the maximum values of above 4000 and approximately 8.

Fig. 12 demonstrates the magnitude value of the stator current obtained is nearly 12A and the electromotive force obtained due to the BLDC motor due to variable solar radiation is 80.

Fig. 13 illustrates the relation between the speed (N) rpm and the Time (seconds), the red line shows the variation in the N Inc whereas the black line shows the variation in the value of N Beta. Both the lines reached the maximum value of nearly 4500 and the maintained similar values 0.5 sec to 2 sec from the value of 4500 to 1800 approximately.

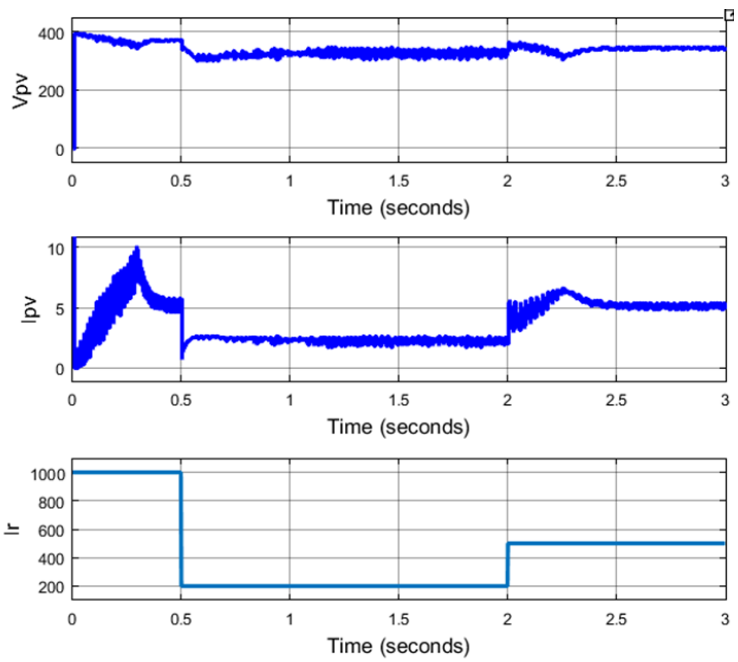

Figure 10. PV array characteristics during variable solar irradiation.

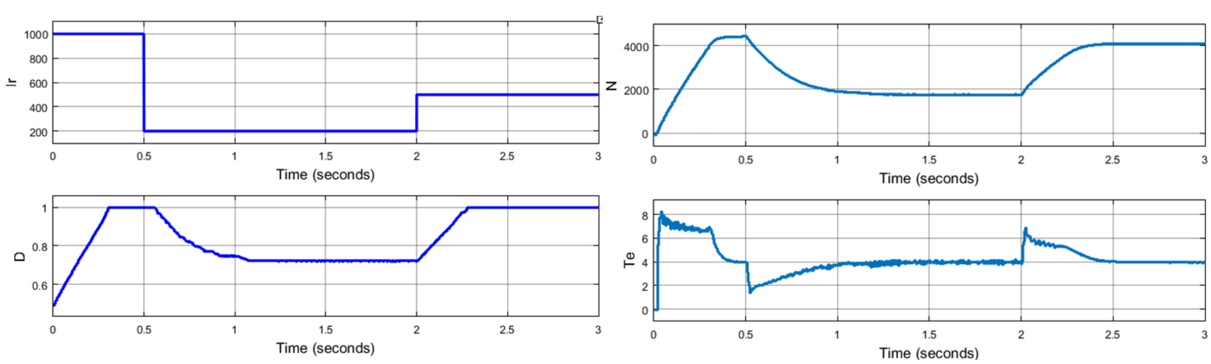

Figure 11. BLDC motor characteristics during variable solar irradiation.

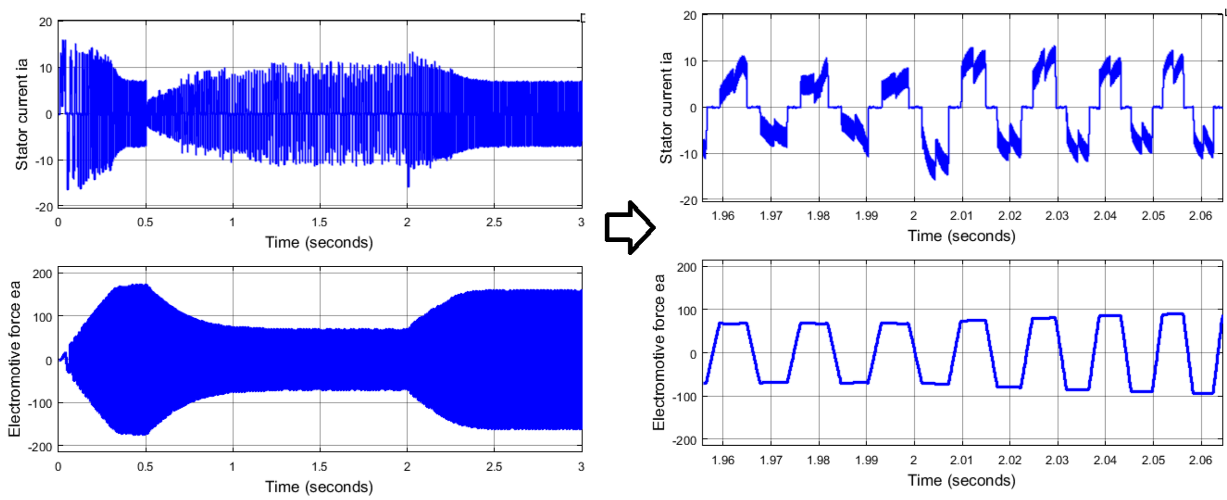

Figure 12. BLDC motor stator current and electromotive force of phase A during variable solar irradiation.

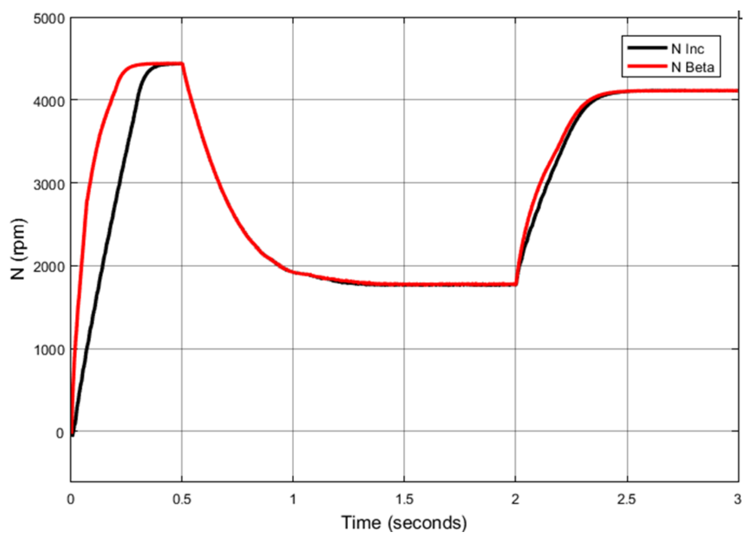

Figure 13. BLDC motor speed comparison of INC and Beta MPPT algorithm.

7. Conclusion

The integration of a Photovoltaic (PV) array with a Brushless Direct Current (BLDC) motor is has been through six switches as an Insulated Gate Bipolar Transistor (IGBT) Voltage Source Converter (VSC). The design and modeling of this integrated system have been simulated, and graphical representations exhibit the properties of both the PV array and the BLDC motor across various operational scenarios. The graphical illustrations clearly demonstrate the dependency of BLDC motor speed on the available solar energy. As solar energy fluctuates, the BLDC motor speed exhibits corresponding variations. Specifically, reduced solar irradiation leads to a decrease in the PV array's output, which in turn results in a reduction in the BLDC motor's speed. The enhancement of machine performance is achieved by revising the Incremental Conductance (INC) Maximum Power Point Tracking (MPPT) algorithm to the Beta MPPT algorithm. This adjustment is reflected in the speed settling time of the BLDC motor. In particular, the use of the Beta MPPT algorithm leads to an increase in speed settling time, contributing to improved overall performance. Under the INC MPPT algorithm, the BLDC motor's speed stabilizes within 0.4 seconds.

However, with the implementation of the Beta MPPT method, this settling time is significantly reduced to 0.2 seconds. Consequently, the Beta MPPT algorithm serves to enhance the machine's performance within the defined operating parameters. This is substantiated through meticulous parametric analyses and graphical comparisons, all of which pertain to a BLDC motor water pumping system powered by a PV array.

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