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# Photovoltaic Fed Brushless DC Motor Aided Water Pumping System

**N.K. Rayaguru* and S. Sekar***

***Abstract :*** This paper emphasize on developing a Photovoltaic (PV) fed brushless DC motor (BLDC) driven water pumping system which could render its application to irrigation. The BLDC motor drive has an edge over the conventional induction motor in efficiency and high pulling torque. The planned system will essentially consists of PV panel of 200 Watts, a Maximum Power Point Tracking controller, a three phase inverter and a Brushless DC (BLDC) motor with pumping system. The suggested system is simulated in MATLAB/Simulink and then it is being realized as a hardware prototype.
***Keywords :*** Photovoltaic, Maximum Power Point Tracking, Brushless DC Motor, Pumping, Induction Motor, Incremental Conductance.

## 1. INTRODUCTION

It is pragmatic statement that now nearly 1.2 billion people around the globe could not be connected through electric grid [1] . Distributed power sources like Photovoltaic system and Wind energy conversion system plays a huge role in alleviating growing energy demand .India's power sector has a pragmatic target of achieving 10 GW power production through solar photovoltaic system [2-3]. For irrigational system grid connected water pump sets are predominantly used which adds huge burden to the utility which is already hampered by power shortage issues. Diesel generators on the other hand can be used as a standalone system but the drawbacks like fuel cost , transportation difficulty, contamination of lands due to spills are inevitable[4]. Since its inception 1978 ,PV fed water pumping system has developed drastically in various technical facets[5]. A typical PV water pumping system serves for the following purposes (*i*) Solves the problem where pumping is not possible due to grid unavailability and (*ii*) aids in reducing the gap between power production and demand. The static PV water pumping system can be built in a large manner depending on the irrigational area and size of the pump motor. This paper suggests a e pumping system which will be very handy to utilize the unused clogged water for irrigational purpose. A. The BLDC pumping system necessarily consists of PV panel, a MPPT conditioner, battery system and brushless dc motor with compressor arrangement. Since PV source is intermittent in nature a Maximum Power Point Tracker (MPPT) is used to improve the power delivering capacity of PV panels[6] .There are numerous MPPT algorithms in PV market and this work prefers usage of Incremental Conductance (INC) MPPT algorithm as it is simple and effective to implement [7-8]. The usage of batteries is optional and depends on the applications the pumping system deals with. Batteries generally incur high cost and complexity in maintenance but if pumping is to be done in even in off sun shine period then usage of batteries is a mandatory. Induction motors are the usual customers in water pumping application but it has its own drawback of lesser efficiency and exhibit poor torque performance [9]. On the other hand BLDC machine, a new era motor which is getting used in new age electrical drives system and therefore this paper involves a BLDC machine for pumping [10].

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## 2. BLDC AND INDUCTION MOTOR MODELING

The equivalent circuit of the induction motor [11] is as shown in Fig 1.

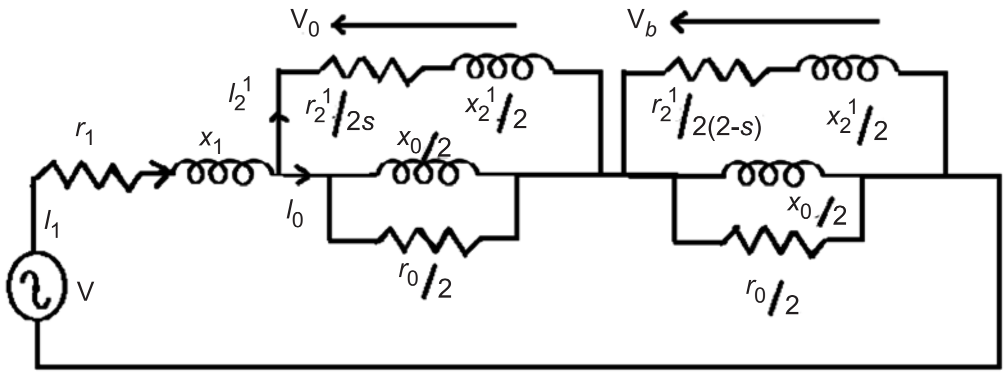


**Figure 1: Equivalent circuit of the induction motor**

Current flowing through the stator is expressed as

$$I_1 = \frac{V - V_0}{r_1 + jx_1} \tag{1}$$

If the rotor current referred to stator is taken as $I_2$ then the iron-loss and magnetizing component of no-load current can be expressed as

$$I_0 = I - I_2^1 \tag{2}$$

Output voltage can be obtained from the expression

$$V_0 = \frac{jr_0 x_0}{4*\left(\frac{r_1}{2} + j\frac{x_0}{2}\right)} I_0 \tag{3}$$

It can be rewritten as

$$V_0 = I_0 * \left\{ \frac{r_0}{2} - \frac{\left(\frac{r_0}{2}\right)^2}{\left(\frac{r_0}{2} + j\frac{x_0}{2}\right)} \right\} \tag{4}$$

Voltage across the inductor $x_2^1/2$ is expressed as

$$V_0 - I_2^1 * \left(\frac{r_2^1}{s}\right) \tag{5}$$

Torque developed by the motor is given by *s*

$$T = (I_2^1)2 * \frac{\left(\frac{r_2^1}{s}\right)}{2\pi n_s} \tag{6}$$

The load balance equation is given by the equation

$$T = j\frac{d\omega}{dt} + B\omega + T_L \tag{7}$$

By using the above set of equations, model for single phase induction motor was obtained.

The equivalent circuit of the BLDC motor [12] is shown in Fig. 2.

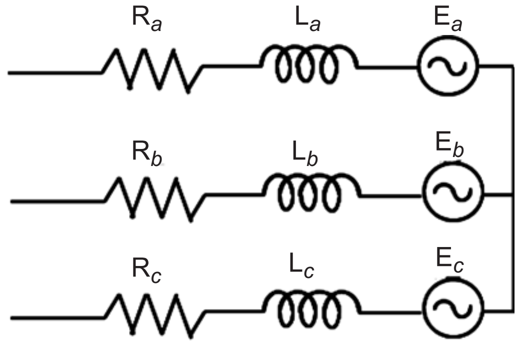


**Figure 2: Equivalent circuit of BLDC**

The voltage equations of the BLDC motor are as follows:

$$V_a = R_a i_a + \frac{d}{dt}(L_{aa} i_a + L_{ab} i_b + L_{ac} i_c) + \frac{d}{dt}\lambda_{ar}(\theta) \quad (8)$$

$$V_b = R_b i_b + \frac{d}{dt}(L_{ba} i_a + L_{bb} i_b + L_{bc} i_c) + \frac{d}{dt}\lambda_{br}(\theta) \quad (9)$$

$$V_c = R_c i_c + \frac{d}{dt}(L_{ca} i_a + L_{cb} i_b + L_{cc} i_c) + \frac{d}{dt}\lambda_{cr}(\theta) \quad (10)$$

The electromagnetic torque is given as

$$T_c = \frac{e_a i_a + e_b i_b + e_c i_b}{\omega_r} \quad (11)$$

The equation of motion is given as

$$\frac{d\omega_r}{dt} = \frac{T_e + T_L + B\omega_r}{J} \quad (12)$$

The electrical rotor speed and position are related by

$$\frac{d\theta_r}{dt} = \frac{p}{2}\omega_r \quad (13)$$

## 3. SYSTEM DESCRIPTION

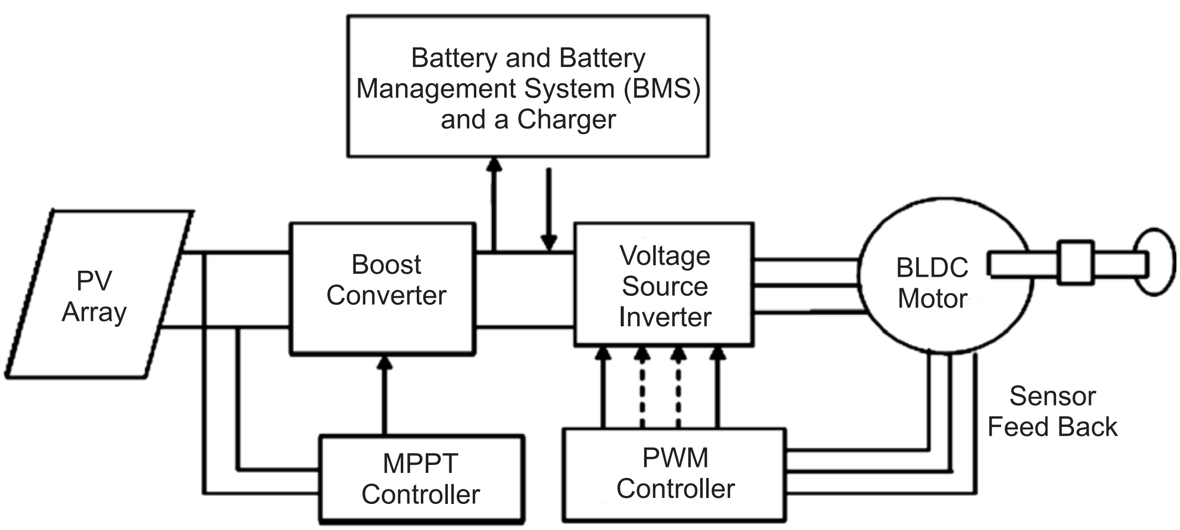


**Figure 3: Block Diagram of a Photovoltaic Water Pumping System**

The block diagram of the proposed system is depicted in Fig. 3.The system essentially consists of a PV array, *dc-dc* converter and VSI embedded driver and BLDC machine.

- The PV source is normally intermittent in nature therefore a MPPT system is indispensable. A MPPT system is built through DC-DC converter which makes the voltage level suitable for the inverter and battery. The power produced is stored in the battery when it is not required by the load. The battery pack is charged by CC-CV algorithm using a charger with BMS (for monitoring and balancing and the baatery setup may optional too.The inverter output is given to the Brushless DC (BLDC) Motor which is further used for pumping mechanism. BLDC motor has other advantages like higher efficiency and also it can operate at maximum torque from zero to base rpm. The controller will have automatic shutdown circuitry to trip the supply if there is any faut in the HV side with an additional interlock system to avoid accidents while operating and servicing the system.

## A. Investigation on PV array

PV chararcteristics are influenced by irradiation and temperature, higher the irraditation higher will the power output and the temperature will have a negative impact on the PV power output. As the temperature increases, the open circuit voltage of the PV panel decreases.

**Table 1**

**Electrical characteristics of solar panel**

| *SW 250 mono / Version 2.0 and 2.5 Frame* | | |
|---|---|---|
| Maximum power SW 250 A | $P_{max}$ | 250 W |
| Open circuit voltage | $V_{oc}$ | 37.8 V |
| Maximum power point voltage | $V_{mpp}$ | 31.1 V |
| Short circuit current | $I_{sc}$ | 8.28 |
| Maximum power point current | $I_{mpp}$ | 8.05 A |

Table 1 presents the spsecifications of a 250 W PV panel . The selection of PV panel /Array can be determined depending upon the load and application . Solar cells are either connected in series or parallel. The output voltage developed then would be a minute value of around 0.5V to 0.7V Such designed unit is called a PV panel and these panels are in turn arranged in series and parallel to form PV array. A photovoltaic cell has its equivalent circuit shown in Fig 4.

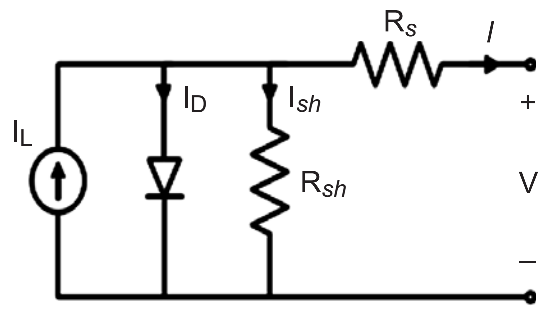


**Figure 4: PV cell Equivalent Circuit**

Mathematical Model of a PV system

$$I = I_{pv} - I_d - \frac{V + IR_s}{R_{sh}} \tag{14}$$

By substituting the value for $I_d$

$$I = I_{pv} - I_o \exp \frac{q(V + IR_S)}{kT_C i} - 1 - \frac{(V + IR_S)}{R_{Sh}} \quad (14)$$

The model includes the temperature dependence of photo-current, $I_{pv}$ and saturation current of the diode, $I_o$. Using the equations [1-2], a mathematically modelled PV system is created in Matlab/Simulink environment. We can infer from the mathematical model that the PV characteristics are non-linear in nature, and that its peak power varies with sun's radiation and temperature. Fig.5 represent the output characteristics of a PV model.

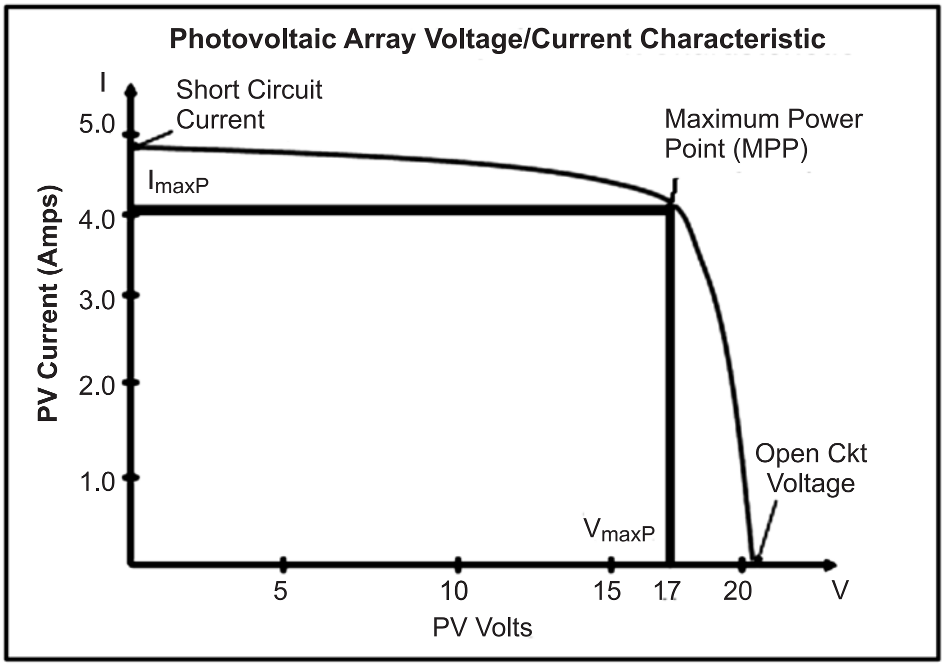


**Figure 5: output characteristics of a PV model.**

## B. INC MPPT Technique

Maximum Power Point Tracking is an intelligent power extraction method which makes sure that PV panel delivers maximum available power for the given point of time. Maximum available power of the PV system changes with respect to ambient temperature and irradiation and as a result a MPPT set up in a PV system is indispensable . Incremental conductance is an eminent algorithm which works in the principle of changing the operating voltage with respect to peak availbale power . A Flow Chart of the INC algorithm is shown in Fig 6. The MPPT algorithm is deployed in controller which exerts a duty cylce (control signal ) to a DC-DC converter to achieve the operating voltage of a PV panel at which maximum power occurs. In this work a boost converter (step-up converter) is used , the choice of converter depends on load employed for particular applications.

A boost converter uses the property of an inductor to resist changes in current for its operation. A schematic of a boost power stage is shown in Fig.7. Let the switch be on for a time period $T_{on}$ and off for period $T_{off}$. During the duty period, the inductor charges itself and during the off state, it discharges across the load. The equations corresponding to this are given below.

$$\Delta I_{L_{on}} = \frac{1}{L}\int_0^{DT} V_i \, dt = \frac{DT}{L} V_i \quad (16)$$

$$\Delta I_{L_{off}} = \int_{DT}^{T} \frac{(V_i - V_0)}{L} \, dt = \frac{(V_i - V_0)(1 - D)}{L} T \quad (17)$$

$$V_i - V_0 - \; = \; L\frac{d_{IL}}{dt} \tag{18}$$

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} \; = \; 0 \tag{19}$$

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} \; = \; \frac{DTV_i}{L} + \frac{(V_i - V_0)(1-D)}{L}T = 0 \tag{20}$$

$$\frac{V_0}{V_i} \; = \; \frac{1}{1-D} \tag{21}$$

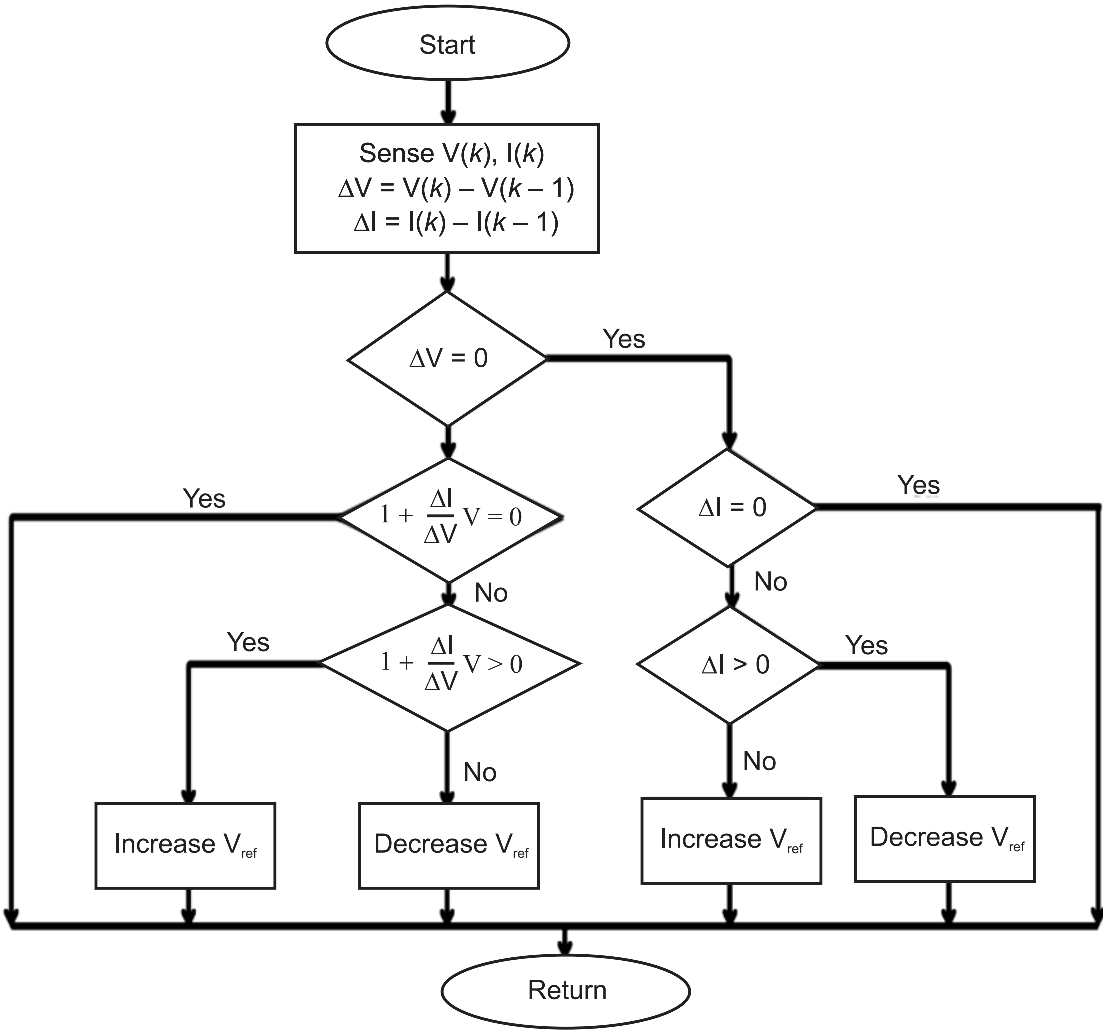


**Figure 6: Flow chart for INC MPPT**

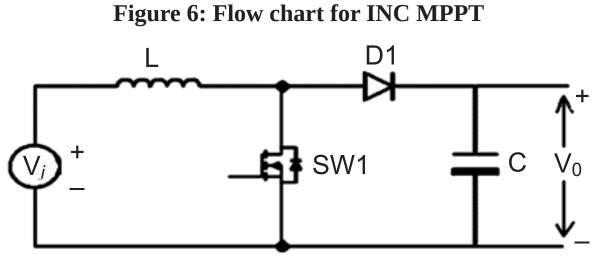


**Figure 7: Boost converter**

## C. Voltage Source Inverter fed BLDC motor

The inverter drive unit is mandatory in BLDC motor drives as the switching sequence of the inverter only pulls the permanent magnet to rotate (refer figure 8). Also, the inverter facilitates the speed control of the machine. These inverters use the SPWM technique in majority, due to its features like low THD in output voltage, low switching losses and higher output voltage for the same dc-bus voltage.

A VSI fed BLDC motor with rotor position sensor is shown in Fig 8. BLDC motors are slowly emerging out as most preferred motor due to its high efficient, robustness and low maintenance. Moreover for PV applications BLDC drives are more conducive due to its low voltage , high current ratings. In addition, these systems need very limited maintenance, since they operate without storage batteries and they do not pollute the environment.

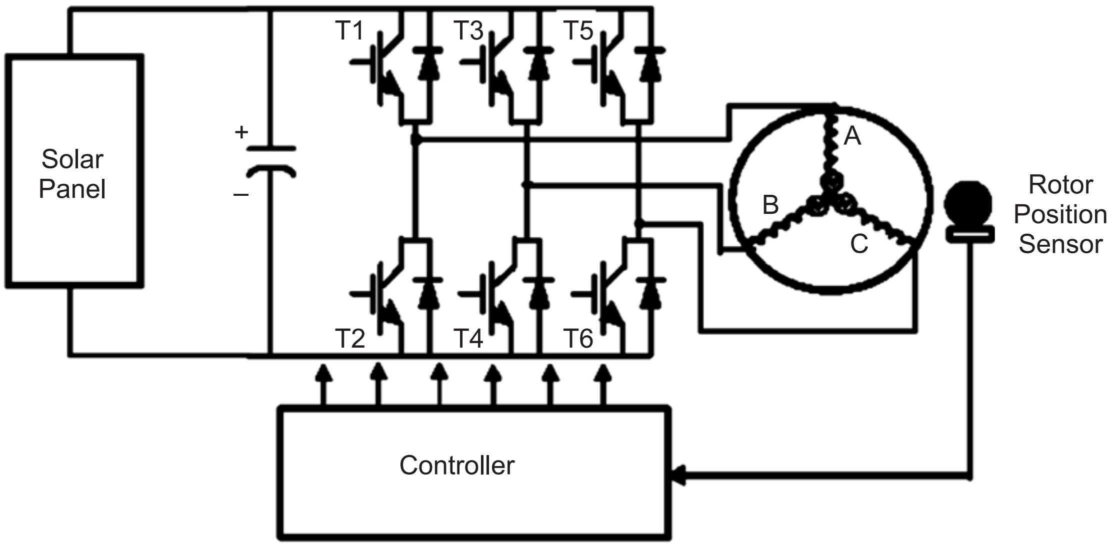


**Figure 8: VSI fed BLDC motor with rotor position sensor**

**Table 2**
**Motor switching order has been given**

| $T_1$ | $T_3$ | $T_5$ | *EEmf_a* | *Emf_b* | *Emf_c* |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | –1 | +1 |
| 0 | 1 | 0 | –1 | +1 | 0 |
| 0 | 1 | 1 | –1 | 0 | +1 |
| 1 | 0 | 0 | +1 | 0 | –1 |
| 1 | 0 | 1 | +1 | –1 | 0 |
| 1 | 1 | 0 | 0 | +1 | –1 |
| 1 | 1 | 1 | 0 | 0 | 0 |

## 4. SIMULATION RESULTS

**Table 3**
**Induction Motor and BLDC Specifications**

| *Motor Type* | *Voltage (v)* | *Speed (rpm)* | *Torque(N-m)* |
|---|---|---|---|
| Induction Motor | 230 AC | 1300 | 684 |
| BLDC motor | 70 V DC | 3000 | 10000 |

Table 3 presents the comparison table between a typical ¼ hp induction motor and BLDC machine. The simulation and hardware prototype has been developed for the same ratings. The simulation diagrams of IM drive and BLDC drive are shown in Fig 9 and Fig.10 respectively.

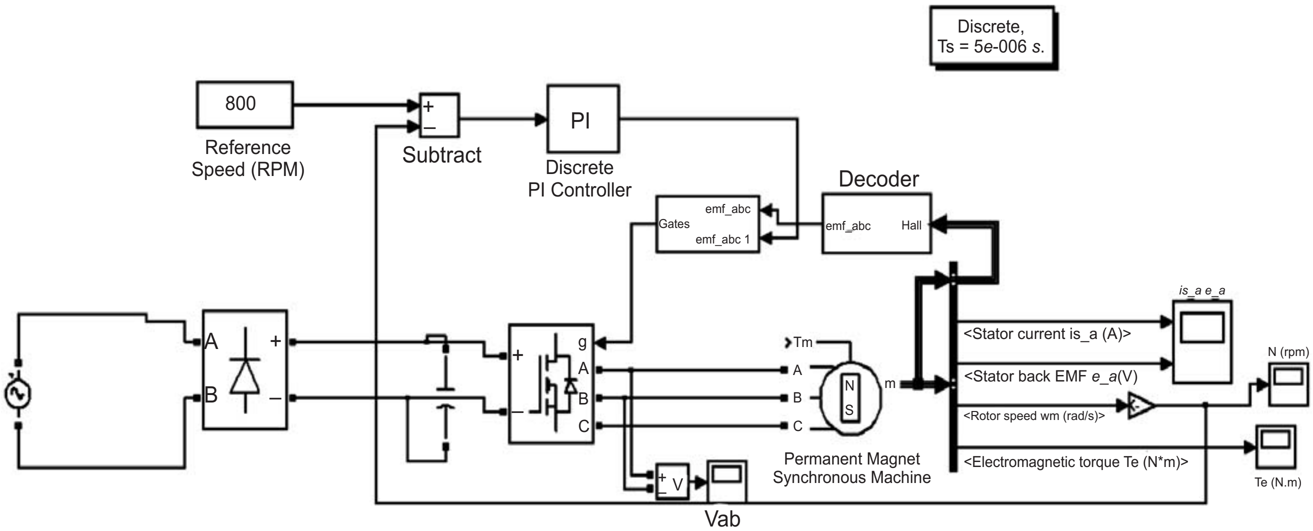


**Figure 9 : Simulink model of the closed loop system with BLDC motor**

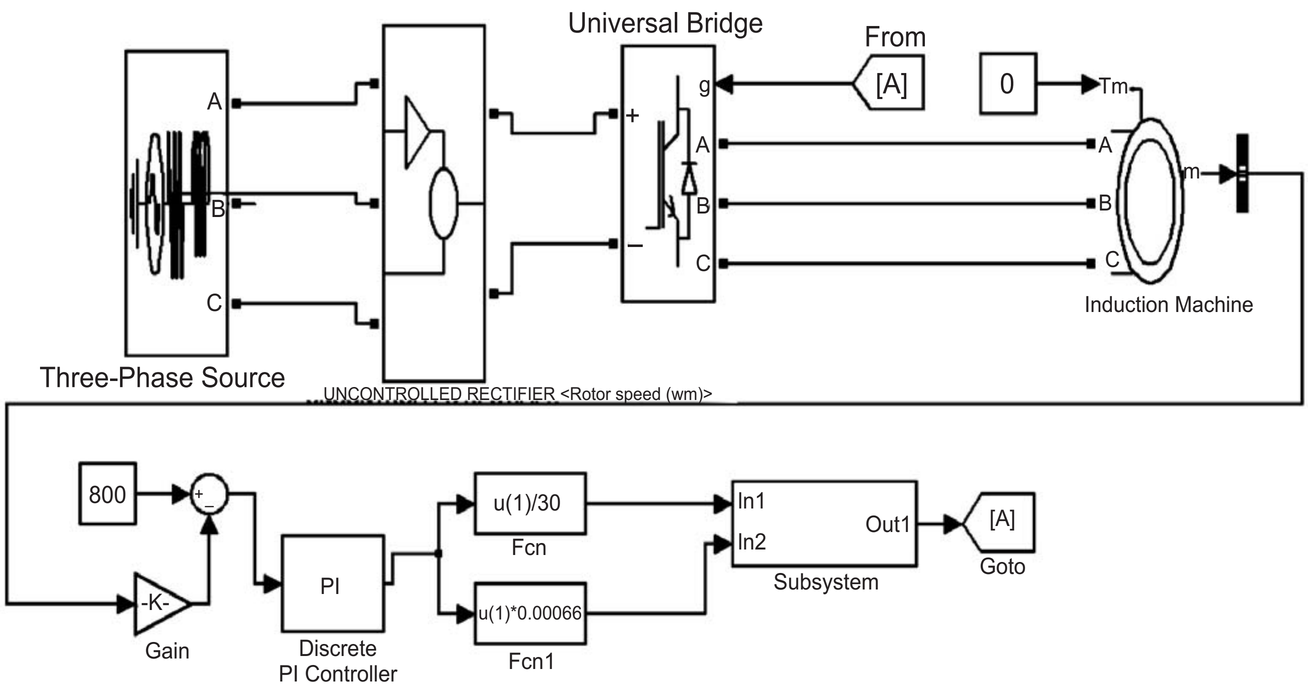


**Figure 10: Simulink model of the IH motor**

The comparisons in terms of speed and torque characteristics reveal that the BLDC machine has a clear edge over the conventional IM which is shown in Fig 11 and Fig 12 respectively.

## 5. HARDWARE RESULTS

The hardware setup for induction motor pumping is shown in Fig. 13. A PV panel of 250 W with a MPPT controller is used to drive the motor with an inverter set up. On the other hand a BLDC machine with a inverter drive circuit is presented in Fig.14. The BLDC machine is facilitated with a shaft which is compatible with a compressor drive. A belt driven compressor is so apt for this pumping application and the speed of the motor is adjusted by adjusting the PWM pulses of the inverter. Thus the brushed D.C motor should never be used for operations that demand long life and reliability. A low cost BLDC which generally used for a walker machine has been taken for this particular prototype work and this can be also designed technically competent once the production goes in mass. Fig 14 shows the pivotal point and core thrust of this work where the whole system is made.

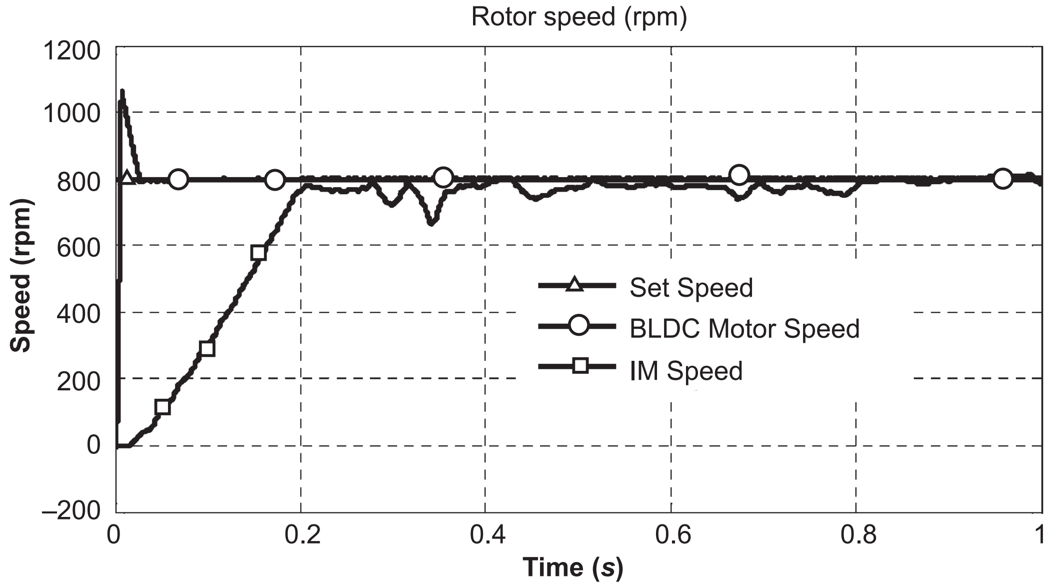


**Figure 11: Comparison of speed waveforms between IM and BLDC**

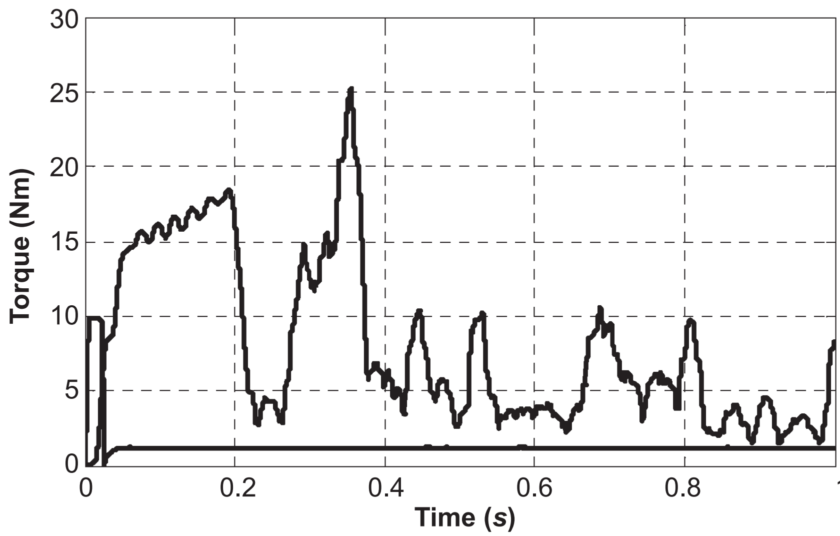


**Figure 12: comparison of torque waveforms**

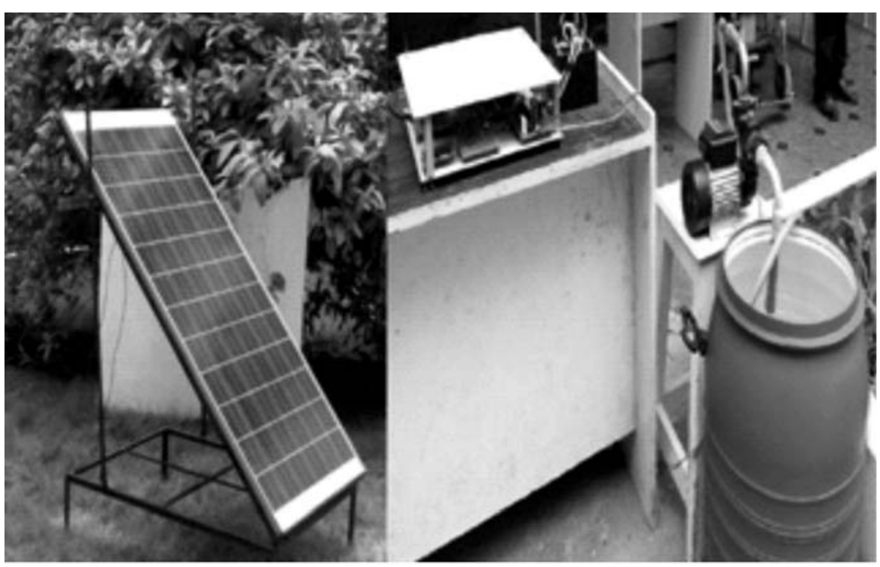

**Figure 13: Hardware setup of Induction Motor Pumping**

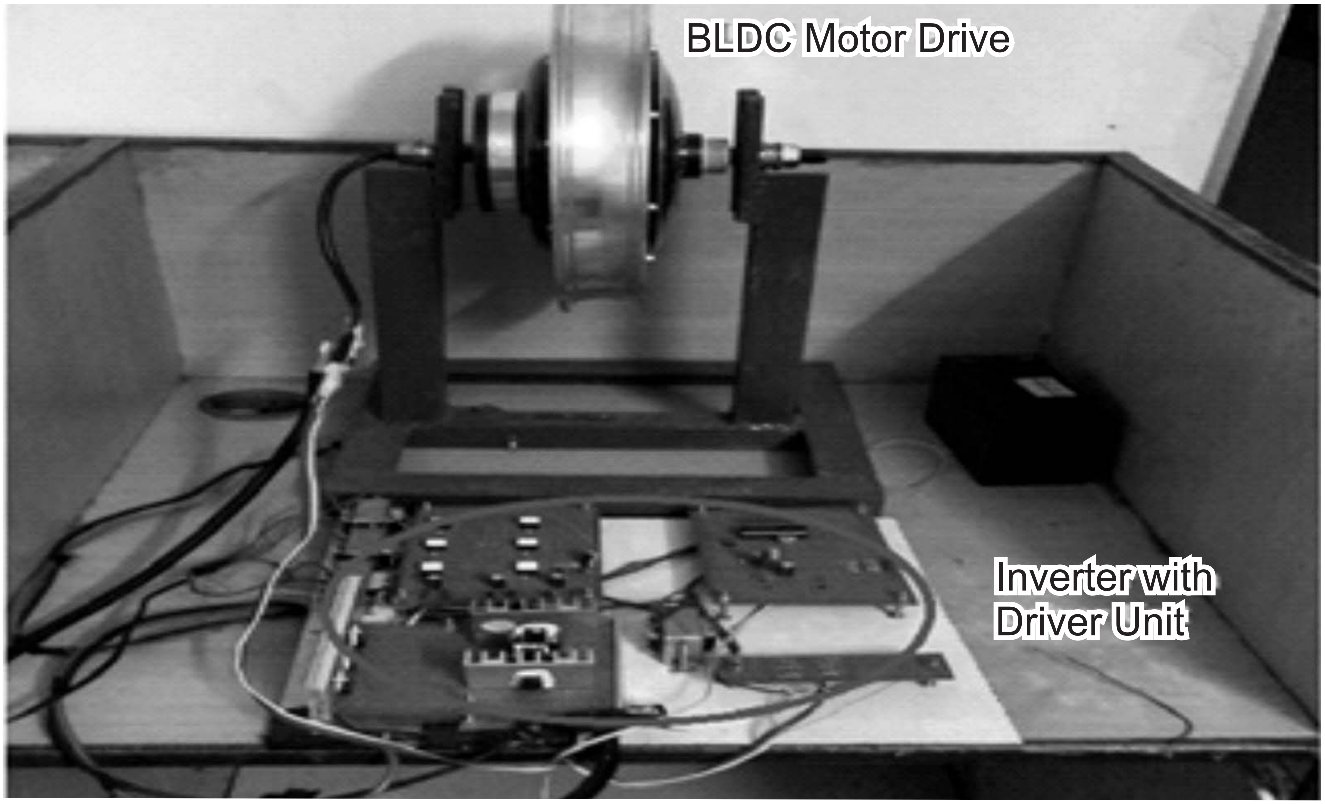


**Figure 14: Hardware setup of BLDC motor**

## 6. VI CONCLUSION

The developed mathematical model and simulation results presents that the BLDC motor when used for pumping application has a clear edge over its Induction motor fed pumping counterpart. The efficiency of a BLDC pumping system is too high that a prudent compromise on the economy aspect could be done. With much emphasis given on usages of renewable sources and increased awareness on energy conservation and effective consumption usage of high efficiency brushless DC motor will become the main stream in the field of the electrical appliance in near future.

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