

## Design and Implementation of Low Cost Four Switch Inverter for Brushless Motor Drive with Active Power Factor Correction

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**Abstract:** This Research paper proposes a low cost four switch three phase inverter (FSTPI) fed brushless DC (BLDC) motor drive for Active power factor correction for residential applications without environmental issues. This proposed system is simplified the topological structure of the conventional six switch three phase inverter (SSTPI) and includes an active power factor correction in front end rectifier which results in sinusoidal input current and it closed to unity power factor. In this project a new structure of four switch three phase inverter with reduced number of switches for system is introduced. This system consists of single phase rectifier and four switch three phase inverter. This proposed inverter fed BLDC motor used in Sensorless control schemes. To improve sensorless control performance, six commutation modes based on direct current controlled PWM scheme is implemented to produced the desire Torque-Speed characteristics. This four switch three phase inverter is achieved by the reduction of switches, low cost control and saving of hall sensor. The design and implementation of low cost four switch inverter for Brushless motor drive with active power factor correction have been conducted successfully and valediction of the proposed sesorless control for four switch three phase inverter fed BLDC motor drive is developed and analysed using both MATLAB/SIMULINK and hardware results are verified out successfully.

**Key words:** BLDC Motor • Power Factor Correction • Four Switch Three Phase Inverter (FSTPI) • Sensorless control • Direct current control

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### INTRODUCTION

The Permanent Magnet Brushless DC (PMBLDC) (without pollution and vibration) motor is gaining popularity being used in computer, aerospace, military, automotive, industrial and household products because of its high torque, compactness and high efficiency. The Brushless DC (BLDC) motor is inherently electronically controlled and requires rotor position information for proper commutations of current. The BLDC motor has advantages of the DC motor such as simple control, high torque, high efficiency and compactness. Also, brush maintenance is no longer required and many problems resulting from mechanical wear of brushes and commentators are improved by changing the position of rotor and stator in DC motor. Variable speed inverter fed AC motor drives are

employing a pulse width modulation (PWM) are being used for various purposes in consumer products and industrial applications. However, cost minimization can be achieved by reduction of the inverter configuration employing a topological approach and control approach. In the topological approach, minimum number of switches is required in inverter circuit. From the control approach point of view control algorithms are designing and implementing for inverter to produce the desired speed-torque characteristics. Among the implements, the three phase inverters have only four switches, the main features of these inverter are reduction of switches and conduction losses. Until now, reduced components have been applied in AC induction motor drives, however now a day the BLDC motor drives are using due to its high power factor, high torque, simple control and lower maintenance. The four switches three phase inverter

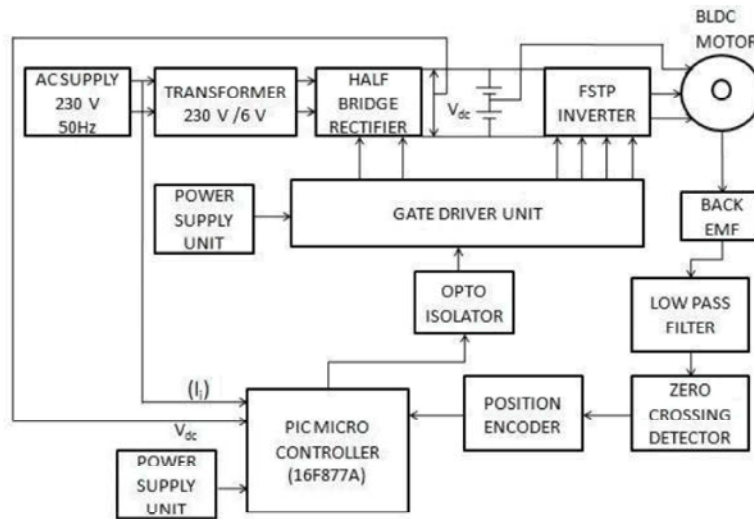


Fig. 1: Block Diagram of Proposed Research

(FSTPI) used in six commutation modes based on current control and senseless control schemes. In these BLDC drive configuration, it employs a single-phase to three phase converter using only six IGBT switches shown in Figure 1. This converter has been already employed in variable-speed induction motor drives. This configuration includes a half bridge active rectifier structure at front end that provides the Dc link with an active input current shaping feature. Moreover, the front end rectifier allows bidirectional power flows between the DC link and the Ac supply. Since the MOSFET switches can operate at high frequency, advance PWM techniques for inverter control can be used. Therefore, the proposed converter can be controlled to draw sinusoidal input current at power factor close to unity and to simultaneously deliver high-quality output current to the motor [1].

## MATERIALS AND METHODS

Figure 1 shows block diagram of proposed Research system. The block diagram mainly consist of a PIC-microcontroller (PIC16F877) for power factor calculation, FSTP Inverter, driver circuit, opto-isolator, zero crossing detection, low pass filter and BLDC motor. The ac voltage, typically 230V is connected to a transformer, which steps that ac voltage down the supply voltage (0-230V) to (0-6V) to the level of the desired dc output. The single phase AC supply is fed to rectifier to obtain DC voltage; this DC voltage is provided with a capacitor filter. The FSTPI outputs phases are a, b, c. Two phases 'a' and 'b' are connected to the two legs of

the inverter, while the third phase 'c' is connected to the centre point of the dc-link capacitors, C1 and C2. A regulator circuit removes the ripples and also remains the same dc value even if the input dc voltage varies, or the load connected to the output dc voltage changes. The pulse generator is used to generating the triggering pulse and given to the driver circuit. The driver circuit is used to amplify the triggering pulse and given to the DC to AC converter. A BLDC has a rotor with permanent magnets and a stator with windings, which are connected to the control electronics. The control electronics replace the function of the commutator and energize the proper winding. The FSTPI is converting the DC to AC. It is working PWM control strategy in using the hysteresis current control. The triggering units provide the required pulses to the power MOSFET. The values of each block are adjusted according to the need of drive system. The generated codes are loaded to the PIC microcontroller. The sensor less output is fed to the processor through the ADC. The generated error signal is fed to the PI controller in the processor. Based on the output of PI controller, the processor generated the required controlled pulses for FSTPI to control the speed of the BLDC motor [2].

**Objective of the Research:** In modern electrical machines industry productions the brushless direct current (BLDC) motors are rapidly gaining popularity. BLDC motors are used in industries such as Appliances, HVAC industry, medical, electric traction, road vehicles, aircrafts, military equipment, hard disk drive.

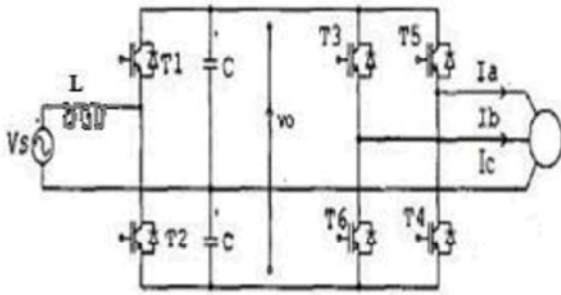


Fig. 2: Circuit Diagram of Proposed Research FSTPI System without natural defects

Motivated by these observations, the objective of this Research is:

- Modeling and analysis of the PMBLDC motor
- FSTPI fed BLDC motor drive system is implemented through prototype model
- Direct current controlling of the PMBLDC motor using PI controller

**Permanent Magnet Brushless DC Motor:** Permanent magnet Brushless Direct Current (PMBLDC) motors are one of the motor types rapidly gaining popularity. PMBLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are Better speed versus torque characteristics, High dynamic response, High efficiency, Long operating life, Noiseless operation, Higher speed ranges. In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors [3].

### AC and DC Power Supplies

**Direct Current (DC) Motor:** DC applied to both the stator and the rotor (via brushes and commutator), or else a permanent magnet stator. A BLDC motor has switched DC fed to the stator and a permanent magnet rotor. Synchronous (or stepping) motor (AC): AC in one, DC in the other (i.e., rotor or stator). If it has a permanent-magnet rotor, it is much like a BLDC motor. Induction motor (AC): AC in both stator and rotor (mentioned for completeness). Although BLDC motors are practically identical to permanent magnet AC motors, the controller

implementation is what makes them DC. While AC motors feed sinusoidal current simultaneously to each of the legs (with an equal phase distribution), DC controllers only approximate this by feeding full positive and negative voltage to two of the legs at a time. The major advantage of this is that both the logic controllers and battery power sources also operate on DC, such as in computers and electric cars. In addition, the approximated sine wave leaves one leg driven at all times, allowing for back-EMF-based sensorless feedback. A motor can be optimized for AC (i.e. vector control) or it can be optimized for DC (i.e. block commutation). A motor which is optimized for block commutation will typically generate trapezoidal EMF. One can easily observe the shape of the EMF by connecting the motor wires (at least two of them) to an oscilloscope and then hand-cranking/spinning the shaft. PMBLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic fields generated by the rotor rotate at the same frequency. PMBLDC motors do not experience the “slip” that is normally seen in induction motors. PMBLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. This application notefocuses on 3-phase motors. The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery. Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner [4].

Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles as shown in Figure 3. There are two types of stator windings variants: trapezoidal and sinusoidal motors. This differentiation is made on the basis of the interconnection of coils in the stator windings to give the different types of back Electromotive Force (EMF). The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery as shown in Figure 4. Traditionally, the stator resembles that of an induction motor; however, the windings are in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings is constructed with numerous coils interconnected to form a winding.

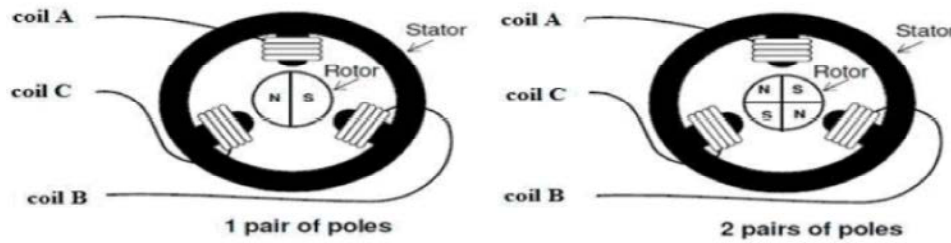


Fig. 3: Three Phase Three Coil BLDC Motor Stator and Rotor

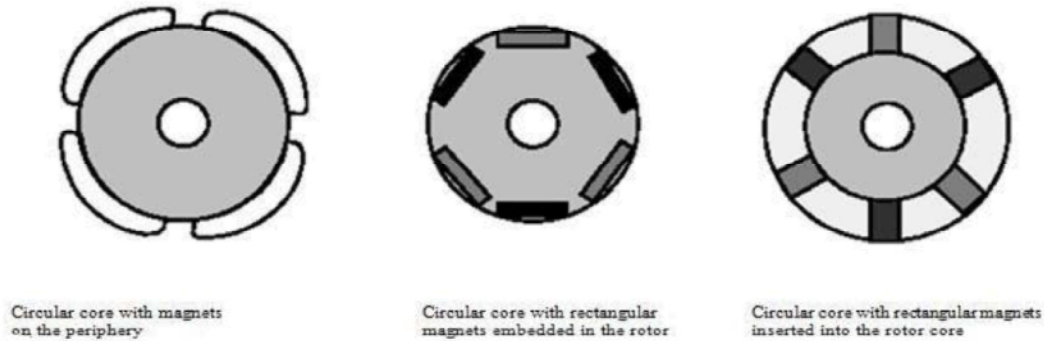


Fig. 4: Rotor of a PMLDC Motor

One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles. The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles. Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables the rotor to compress further for the same torque. Also, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets.

A PMLDC which is a kind of three-phase synchronous motor with permanent magnets (PMs) on the rotor and trapezoidal back EMF waveform operates on electronic commutation accomplished by solid state switches using PWM technique. It is powered through a three-phase voltage source inverter (VSI) which is fed from single-phase AC supply using a half bridge rectifier followed by smoothening DC link capacitor. The PMLDCM drive, fed from a single-phase AC mains through a halfbridge rectifier followed by a DC link capacitor, suffers from power quality (PQ) disturbances

such as poor power factor (PF), increased total harmonic distortion (THD) of current at input AC mains. It is mainly due to uncontrolled charging of the DC link capacitor which results in a pulsed current waveform having a peak value higher than the amplitude of the fundamental input current at AC mains [5].

**Mathematical Modelling:** Brushless DC Motors are permanent magnet motors where the function of commutator and brushes were implemented by solid state switches. BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. Because of the special structure of the motor, it produces a trapezoidal back electromotive force (EMF) and motor current generate a pulsating torque.

A three phase BLDC motor equation can be represented as:

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + M_{ab} \frac{di_b}{dt} + M_{ac} \frac{di_c}{dt} + e_a \quad (2.1)$$

$$V_b = R_b i_b + L_b \frac{di_b}{dt} + M_{ba} \frac{di_a}{dt} + M_{bc} \frac{di_c}{dt} + e_b \quad (2.2)$$

$$V_c = R_c i_c + L_c \frac{di_c}{dt} + M_{ca} \frac{di_a}{dt} + M_{cb} \frac{di_b}{dt} + e_c \quad (2.3)$$

where,

R- Stator resistance per phase.

L- Stator inductance per phase

M- Mutual inductance between the phases.

$i_a, i_b, i_c$ - Stator current per phase.

$v_a, v_b, v_c$ - are the respective phase voltage of the winding.

The stator self inductances are independent of the rotor position, hence:

$$L_a=L_b=L_c=L \tag{2.4}$$

And the mutual inductances will have the form:

$$M_{ab}=M_{ac}=M_{ba}=M_{bc}=M_{ca}=M_{cb}=M \tag{2.5}$$

Assuming three phase balanced system, all the phase resistances are equal:

$$R_a=R_b=R_c=R \tag{2.6}$$

Rearranging the above equations:

$$V_a = Ri_a + L \frac{di_a}{dt} + M \frac{di_b}{dt} + M \frac{di_c}{dt} + e_a \tag{2.7}$$

$$V_b = Ri_b + L \frac{di_b}{dt} + M \frac{di_a}{dt} + M \frac{di_c}{dt} + e_b \tag{2.8}$$

$$V_c = Ri_c + L \frac{di_c}{dt} + M \frac{di_a}{dt} + M \frac{di_b}{dt} + e_c \tag{2.9}$$

Neglecting mutual inductance:

$$V_a = Ri_a + L \frac{di_a}{dt} + e_a \tag{2.10}$$

$$V_b = Ri_b + L \frac{di_b}{dt} + e_b \tag{2.11}$$

$$V_c = Ri_c + L \frac{di_c}{dt} + e_c \tag{2.12}$$

When a BLDC motor rotates, each winding generates a voltage known as back Electromotive Force or back EMF, which opposes the main voltage supplied to the windings according to Lenz's Law. The polarity of this back EMF is in opposite direction of the energized voltage. Back EMF depends mainly on three

factors: Angular velocity of the rotor, Magnetic field generated by rotor magnets, The number of turns in the stator windings. The three phase currents are controlled to take a quasi-square waveform in order to synchronize with the trapezoidal back EMF to produce the constant torque.

The instantaneous back EMF in BLDC is written as:

$$e_a = f_a(\theta)K_e\omega \tag{2.13}$$

$$e_b = f_b(\theta)K_e\omega \tag{2.14}$$

$$e_c = f_c(\theta)K_e\omega \tag{2.15}$$

The respective back EMF in the windings is represented by the below equation.

$$e_a = \begin{cases} (6E/\pi)\theta & (0 < \theta < \pi/6) \\ E & (\pi/6 < \theta < 5\pi/6) \\ -(6E/\pi)\theta + 6E & (5\pi/6 < \theta < 7\pi/6) \\ -E & (7\pi/6 < \theta < 11\pi/6) \\ (6E/\pi)\theta + 2E & (11\pi/6 < \theta < 2\pi) \end{cases} \tag{2.16}$$

$$e_b = \begin{cases} -E & (0 < \theta < \pi/2) \\ -(6E/\pi)\theta - 4E & (\pi/2 < \theta < 5\pi/6) \\ E & (5\pi/6 < \theta < 9\pi/6) \\ -(6E/\pi)\theta + 10E & (9\pi/6 < \theta < 11\pi/6) \\ E & (11\pi/6 < \theta < 2\pi) \end{cases} \tag{2.16}$$

$$e_c = \begin{cases} E & (0 < \theta < \pi/6) \\ -(6E/\pi)\theta + 2E & (\pi/6 < \theta < \pi/2) \\ -E & (\pi/2 < \theta < 7\pi/6) \\ -(6E/\pi)\theta - 8E & (7\pi/6 < \theta < 9\pi/6) \\ E & (9\pi/6 < \theta < 2\pi) \end{cases} \tag{2.17}$$

**Torque Generation:** The Torque is the product of the theoretical motor constant  $K_t$ , the supplied current. In a single pole system, usable torque is only produced for 1/3 of the rotation. To produce useful torque throughout the rotation of the stator, additional coils, or "phases" are added to the fixed stator. The developed torque by each phase is the product of the motor constant  $K_t$  and current  $I$ .

The sum of the torques is:

$$T_a+T_b+T_c \tag{2.19}$$

Assumption made is all the phases are perfect symmetry

$$K_t(\text{motor})= K_t(a)+K_t(b)+K_t(c) \tag{2.20}$$

At any given angle, the applied torque as measured on the rotor shaft is (2.23). The key to effective torque and speed control of a BLDC motor is based on relatively simple torque and back EMF equations [6, 7], which are similar to those of the DC motor. The generated electromagnetic torque is given by:

$$T_e = [e_a i_a + e_b i_b + e_c i_c] / \omega \quad (2.21)$$

The electromagnetic torque is also related with motor constant and the product of the current with the electrical rotor position which is given as:

$$T_e = K_t \{f_a(\theta) i_a + f_b(\theta) i_b + f_c(\theta) i_c\} \quad (2.22)$$

The equation of motion for simple system is,

$$J d^2\omega/dt + B\omega = T_e - T_l \quad (2.23)$$

where T is the load torque, J is motor inertia, B is damping coefficient. For a BLDC motor which its magnet length is 180 electrical degrees, the ideal phase currents to produce a relative smooth torque pulsation are rectangular waveforms with 120 degree phase differences.. Since the produced torque is linearly proportional to one of the phase current at each time, torque can be achieved by a direct current control. The relation between angular velocity and angular position (electrical) is given by;

$$d\theta/dt = (P/2) * \omega \quad (2.24)$$

where,

P is numbers of Poles

**Single Phase Rectifier:** A rectifier changes alternating current into direct current. This process is called rectification. The three main types of rectifier are the half-wave, full-wave and bridge. A rectifier is the opposite of an inverter, which changes direct current into alternating current. The first building block in the dc power supply is the half wave rectifier. The purpose of the half wave rectifier is to create a rectified ac output from a sinusoidal ac input signal. It does this by using the nonlinear conductivity characteristics of IGBT to direct the path of the current. When used in its most common application, for conversion of an alternating current (AC) input into direct current (DC) output, it is known as rectifier [8]. A rectifier provides half-wave rectification from a two-wire AC input, resulting in lower cost and weight as compared

to a rectifier with a 3-wire input from a transformer with a center-tapped secondary winding. The essential feature of a diode bridge is that the polarity of the output is the same regardless of the polarity at the input.

**Power Factor Correction:** Many loads are highly inductive, such as lightly loaded motors and illumination transformers and ballasts. You may want to correct the power factor by adding parallel capacitors. You can also add series capacitors to "remove" the effect of leakage inductance that limits the output current. The current flow through the circuit is increased by the reactive component. Normally, loads are represented by a series combination of a resistance and a purely imaginary reactance. For this explanation, it is easier to contemplate it as an equivalent parallel combination. The diagram below illustrates a partially reactive load being fed from a real system with some finite resistance in the conductors, etc. A figure of merit using the relative ratio of the real power over the apparent power is the power factor of the Converter ( $P_F$ ):

$$P_F = P_R / P_A \quad (3.1)$$

The power factor is maximized at unity when the real power and apparent power are equal.

The benefits in maximizing PF are summarized. More power can be delivered through the Converter to the loads at the same AC outlet rating.

$$\text{Output power} = \epsilon V_{rms} I_{rms} PF \quad (3.2)$$

where,  $\epsilon$  = Efficiency of the Converter.

The available outlet power is maximized for output power for PF of unity. In three phase with neutral AC supply configuration, lowering the harmonic content of the AC current in each phase reduces the harmonic current that must be carried by the neutral conductor. Reducing the harmonic losses of the Utility line reactive elements such as Transformers, Motors, Capacitors and Reactors. Reduce conducted and radiated electronic noise pollution. To derive maximum power factor it is necessary to correct the distorted current. Methods to "shape" the current waveform can be categorized into passive Power Factor Correction (PFC) and active Power Factor Correction. As the name implies, passive PFC uses passive elements in networks which the current waveform is "shaped" or filtered to remove the unwanted harmonics. The passive PFC networks can be very effective in

increasing the PF of the capacitive input filter converters. However these passive PFC networks must operate at the AC line frequency which dictates the bulky physical size and weight of the passive elements. This disadvantage must be balanced against the appeal of the relative simplicity of the passive PFC networks. An alternative to passive PFC networks is to use active circuits to reshape the current waveform. The active circuit consist of a power converter operating at frequencies several orders of magnitude higher than the AC line frequency. The physical size and weight of the reactive elements used in the active PFC converter is much reduced compared to its counter parts in the passive PFC networks. The active PFC converter can also achieve near unity PF with very reasonable reactive element values.

**Passive Power Factor Correction:** Passive power factor correction networks employs passive filters to "shape" or filter the input line current. Two popular passive PF correction filter networks are Inductive Input Filter, Resonant Input Filter. The governing equations and maximum achievable power factor for each network are implemented. The inductive input filter, depicted, differ with the capacitor input filter by an additional inductor. The sinusoidal line source and the full bridge connected rectifiers are replaced by an equivalent absolute value sinusoidal source for analysis. Unlike the capacitor input filter, where the capacitor voltage charges to the peak amplitude of the input voltage, the inductor input filter averages the full wave rectified voltage over a period that is half the period of the line source. The extent of PF correction achieved by the inductive input filter is a function of the inductor value,  $L$  and the output load of the filter,  $R$ . The inductor serves as the energy storage element filling in the discontinuous sections of the current pulses and resulting in a more continuous waveform. However, the inductive input filter cannot produce unity power factor since the inductor current will never become an in phase sinusoidal waveform. This can be explained by considering an infinite inductor as a constant current source regardless the amplitude of the input voltage. Therefore even with an infinite inductance the current waveform will not be related to the applied voltage by a scalar constant. When the resonant frequency of the filter is tuned to the line frequency, only line frequency current component is allowed to pass through the filter. For the ideal case of zero DC resistance, the input current can be shaped into a sinusoidal waveform and resulting in power factor of unity.

**Active Power Factor Correction:** Besides using passive networks, active power conversion circuits can be employed as PF correction converters. Passive PF correction networks filter and shape the current waveform to remove the unwanted harmonics. The active PFC converters accomplish the same by modulating the current extracted from the power line at the switching frequency of the converter. The converter is placed between the capacitive input filter and the power line to shape the line current into a more desirable waveform. Compared to the passive PFC networks, the PFC [6-14] converter can achieve the same or higher PF with much lower inductance value. The consequence of high frequency input current modulation effectively multiplies the actual inductor value in the convertor reflected into the AC line. The single phase fixed frequency AC input is rectified by the front-end switches T1 and T2. The switches T1 and T2 are operated based on a PWM strategy to regulate the DC link voltage and shape the input current to be sinusoidal with either in phase (in normal mode) or 180 degree out of phase (in regeneration mode) the AC input voltage.

**Four Switch Three Phase Inverter (FSTPI):** The Modelling of the four switch three phase BLDC motor drive system is based on some assumptions [3]. All the stator phase windings have equal resistance per phase and constant self and mutual inductances. Power semiconductor devices are ideal, Iron losses are negligible and the motor is unsaturated. It contains two capacitors instead of two switches and the phase c is out of control because it is connected to the midpoint of the series capacitor. The phase c voltage cannot hold at zero, it makes distortion in other phases. The same problem is inherited by the four-switch mode and it causes the produced voltage vectors to be limited and asymmetric, which were well known as asymmetric voltage vectors. The operation of four switch BLDC motor contains six modes of operation [15].

With respect to the circuit of figure 5 the FSTPI circuit consists of S1, S2, S3 and S4 four IGBT switches and split capacitors C1 and C2. The single phase AC supply is fed to rectifier to obtain DC voltage; this DC voltage is provided with a capacitor filter. The FSTPI outputs phases a, b, c. Two phases 'a' and 'b' are connected to the two legs of the inverter, while the third phase 'c' is connected to the centre point of the dc-link capacitors, C1 and C2. The four power switches are denoted by the binary variables S1 to S4, where the binary

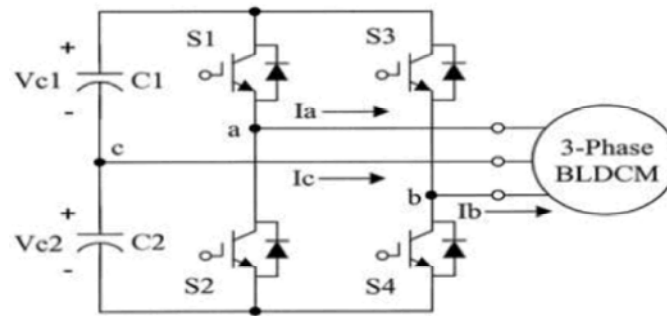


Fig. 5: Circuit Diagram of FSTPI fed BLDC Motor

'1' corresponds to an ON state and the binary '0' corresponds to an OFF state. The states of the upper switches (S1, S2) and lower switches (S3, S4) of a leg are complementary that is  $S3 = 1 - S1$  and  $S4 = 1 - S2$ . The terminal voltages  $V_{as}$ ,  $V_{bs}$  and  $V_{cs}$  of a 3-phase Y-connected Induction Motor can be expressed as the function of the states of the upper switches. Since, there is no control on the third phase, the middle point of the DC link (point C) is taken as the reference, so:

$$V_{as} = \frac{V_c}{3} (4S_3 - 2S_2 - 1) \tag{3.3}$$

$$V_{bs} = \frac{V_c}{3} (-2S_3 + 4S_2 - 1) \tag{3.4}$$

$$V_{cs} = \frac{V_c}{3} (-2S_3 - 2S_2 + 2) \tag{3.5}$$

where  $V_{as}$ ,  $V_{bs}$ ,  $V_{cs}$  are the inverter output voltages,  $V_c$  is the voltage across the dc link capacitors,  $V_{dc}$  is the voltage across the capacitors C1 and C2 ( $V_c = V_{dc} / 2$ ). In matrix form the above equations can be written as:

[ ] / ( ) [ ] / [ ]

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \frac{V_c}{3} \begin{pmatrix} 4 & -2 \\ -2 & 4 \\ -2 & -2 \end{pmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} + \frac{V_c}{3} \begin{bmatrix} -1 \\ -1 \\ 2 \end{bmatrix} \tag{3.6}$$

**Control Techniques**

**Sensorless Control Scheme:** In case of BLDC drive system utilizing hall sensors, hall sensor circuit and control are simple but these will increase the cost and the size of the motor. In some applications like as a compressor application for air conditioner, it may not be acceptable to mount any hall sensors on the stator.

Therefore, BLDC sensorless control [5] has been receiving great interest in recent years. Typically, BLDC motors are fed by a four switch three-phase inverter (FSTPI) with, what is called, electric commutation. The commutation interval for each step is 60 degrees by electrical angle. It is determined by the rotor position, which can be detected by estimated hall signals from the back EMF zero crossing. Of course, there are many other sensorless techniques [6], these techniques require more complex calculation than the back EMF method, so there are some limitation in the applications. As three-phase BLDC motor is driven with six-step 120 degree control method. That means the conduction interval of one phase is 120 degree [7]. Therefore, the Back-EMF zero-crossing detecting technique is based on the fact that only two phases of a BLDC motor are connected to the power source at one time instant so the third phase can be used to detect zero-crossing of the Back-EMF voltage. For example, when phase U and phase V are connected to the source, phase W is floating. No current is going through this phase. This conducting interval lasts 60 electrical degrees, which is called commutation step. This is described by the following conditions. In these equations, forward voltage drop of MOSFET and body diode is ignored for simplification. So if you compare terminal voltages ( $V_a$ ,  $V_b$  and  $V_c$ ) with a reference voltage by using 3 comparators, then you can detect the zero-crossing point of back EMF voltages. But the terminal voltages contain many harmonic components with several times of PWM switching frequency. So the Low Pass Filter (LPF) circuit are used to eliminate the harmonic components. And then you can detect the zero-crossing point with internal comparators. When a zero crossing is detected, several calculations start. The next commutation time is calculated by computations of the actual speed. The speed command is set according to the state of the run/stop state and the target speed



from user. The applied voltage and back-EMF are balanced so that the torque necessary to maintain rotor speed is achieved. For a BLDC motor to generate maximum and constant output torque, their phase currents should be rectangular with 120° conducting and 60° non-conducting intervals. Also at each operating mode, only two phases are conducting and the other phase remains silent. However, in the four-switch converter based on the four switching vectors, the generation of 120° conducting and a 60° non-conducting current profiles is inherently difficult. That means the conventional PWM schemes employed for four switch induction motor drives cannot be directly applied to BLDC motor drives. This led to the development of a new control scheme called Direct Current Controlled PWM scheme.

#### **Hardware Unit**

**Voltage & Current Measurement Unit:** This unit contains components for measuring the line current and voltage in order to calculate the power factor. It consists of Current transformer, Potential transformer. A current transformer is a type of "instrument transformer" that is designed to provide a current in its secondary which is accurately proportional to the current flowing in its primary. Current transformers are designed to produce either an alternating current or alternating voltage proportional to the current being measured. current transformers measure power flow and provide electrical inputs to power transformers and instruments. Current transformers produce either an alternating current or alternating voltage that is proportional to the measured current. There are two basic types of current transformers: wound and toroidal. Wound current transformers consist of an integral primary winding that is inserted in series with the conductor that carries the measured current. Toroidal or donut-shaped current transformers do not contain a primary winding. Instead, the wire that carries the current is threaded through a window in the toroidal transformer. The standards define a voltage transformer as one in which "the secondary voltage is substantially proportional to the primary voltage and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections. It means that the voltage transformer has to be as close as possible to the "ideal" transformer. In an "ideal" transformer, the secondary voltage vector is exactly opposite and equal to the primary voltage vector, when multiplied by the turn's ratio. In a "practical" transformer, errors are introduced because some current is drawn for

the magnetization of the core and because of drops in the primary and secondary windings due to leakage reactance and winding resistance. One can thus talk of a voltage error, which is the amount by which the voltage is less than the applied primary voltage and the phase error, which is the phase angle by which the reversed secondary voltage vector is displaced from the primary voltage.

**Power Circuit of Microcontroller:** Power supply is a reference to a source of electrical power. A device or system that supplies electrical or other types of energy to an output load or group of loads is called a power supply unit or PSU. The term is most commonly applied to electrical energy supplies, less often to mechanical ones and rarely to others are shown in Figure 6.

The operation of power supply circuits built using filters, rectifiers and then voltage regulators. Starting with an AC voltage, a steady DC voltage is obtained by rectifying the AC voltage, then filtering to a DC level and finally, regulating to obtain a desired fixed DC voltage. The regulation is usually obtained from an IC voltage regulator Unit, which takes a DC voltage and provides a somewhat lower DC voltage, which remains the same even if the input DC voltage varies, or the output Load connected to the DC voltage changes [15].

**Rectifier and Inverter:** In this proposed system, single phase to three phase converter using only six MOSFET (IRFZ48N) switches. This configuration includes a half bridge rectifier (at the front end) and FSTPI [10]. The half bridge rectifier provides the DC link with an active input current shaping. Moreover, the front end rectifier allows bidirectional power flows between DC link and the AC supply. The FSTPI consists of four switches and capacitors [11]. Two phases (A & B) are connected to the two legs of the inverter, while the third phase C is connected to the center point of the DC-link capacitors C1 and C2 are shown in Figure 7 & 8 & 9 [12, 13].

**Optoisolator:** There are many situations where signals and data need to be transferred from one subsystem to another within a piece of electronics equipment, or from one piece of equipment to another, without making a direct ohmic electrical connection. Often this is because the source and destination are (or may be at times) at very different voltage levels, like a microprocessor, which is operating from 5V DC but being used to control a triac that is switching 240V AC. In such situations the link

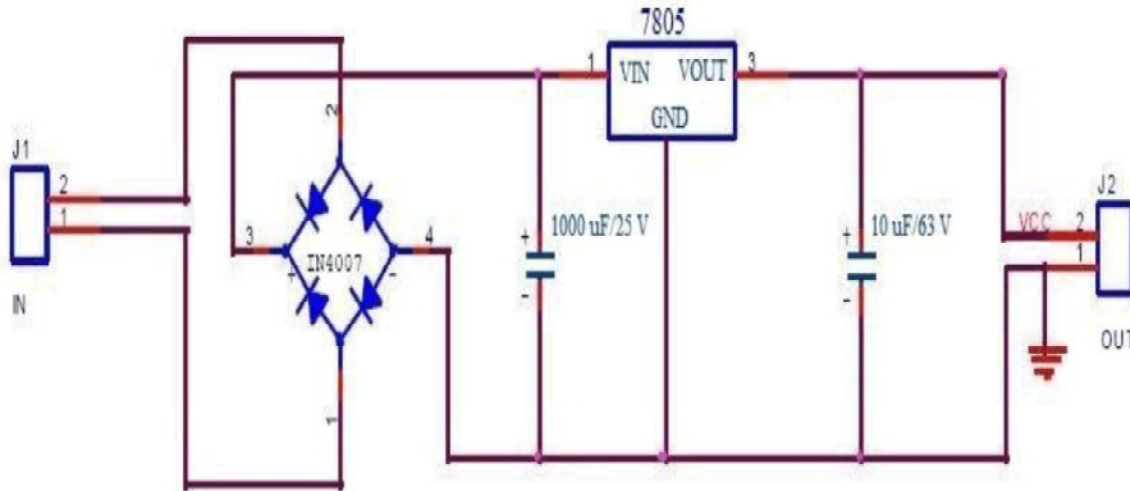


Fig. 6: Power Circuit of Microcontroller

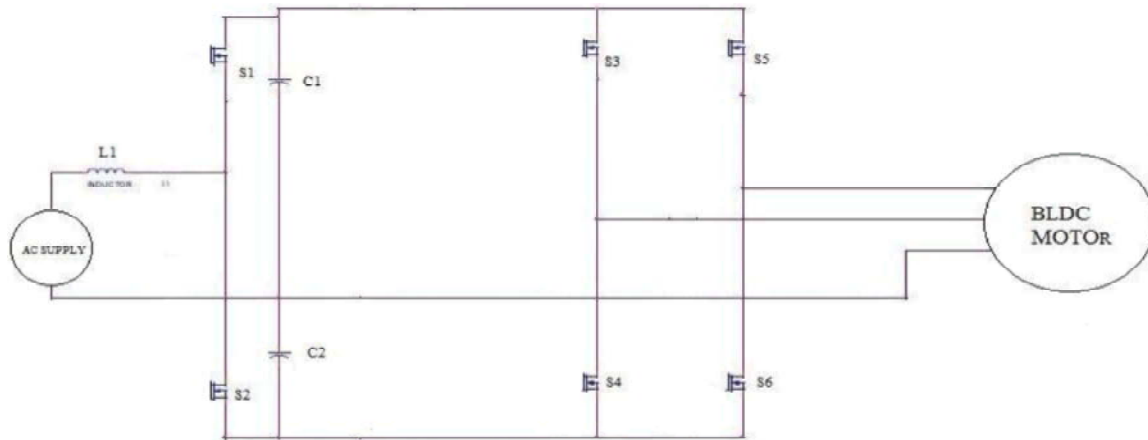


Fig. 7: Equivalent Circuit of FSTPT fed BLDC Motor

between the two must be an isolated one, to protect the microprocessor from over voltage damage. Suppose control circuit is connected to power circuit without isolation circuit the control circuit may get affect so needed to isolation circuit interface between power circuit and control circuit. Relays can of course provide this kind of isolation, but even small relays tend to be fairly bulky compared with ICs and many of today's other miniature circuit components. Because they're electro-mechanical, relays are also not as reliable and only capable of relatively low speed operation. Where small size, higher speed and greater reliability are important, a much better alternative is to use an optoisolator. These use a beam of light to transmit the signals or data across an electrical barrier and achieve excellent isolation. Optoisolator typically come in a small 6-pin or 8-pin IC package, but are essentially a

combination of two distinct devices: an optical transmitter, typically a gallium arsenide LED (light-emitting diode) and an optical receiver such as a phototransistor or light-triggered diac. The two are separated by a transparent barrier which blocks any electrical current flow between the two, but does allow the passage of light. The basic idea is shown, along with the usual circuit symbol for an optoisolator. The 6N135 optoisolator consists of a light-emitting diode and an integrated photon detector composed of a photodiode and an open-collector output transistor. Separate connections are provided for the photodiode bias and the transistor-collector output.

**Zero Crossing Detection Circuit:** As the name indicates the zero crossing detector is a device for detecting the point where the voltage crosses zero in either direction.

Driver Circuit

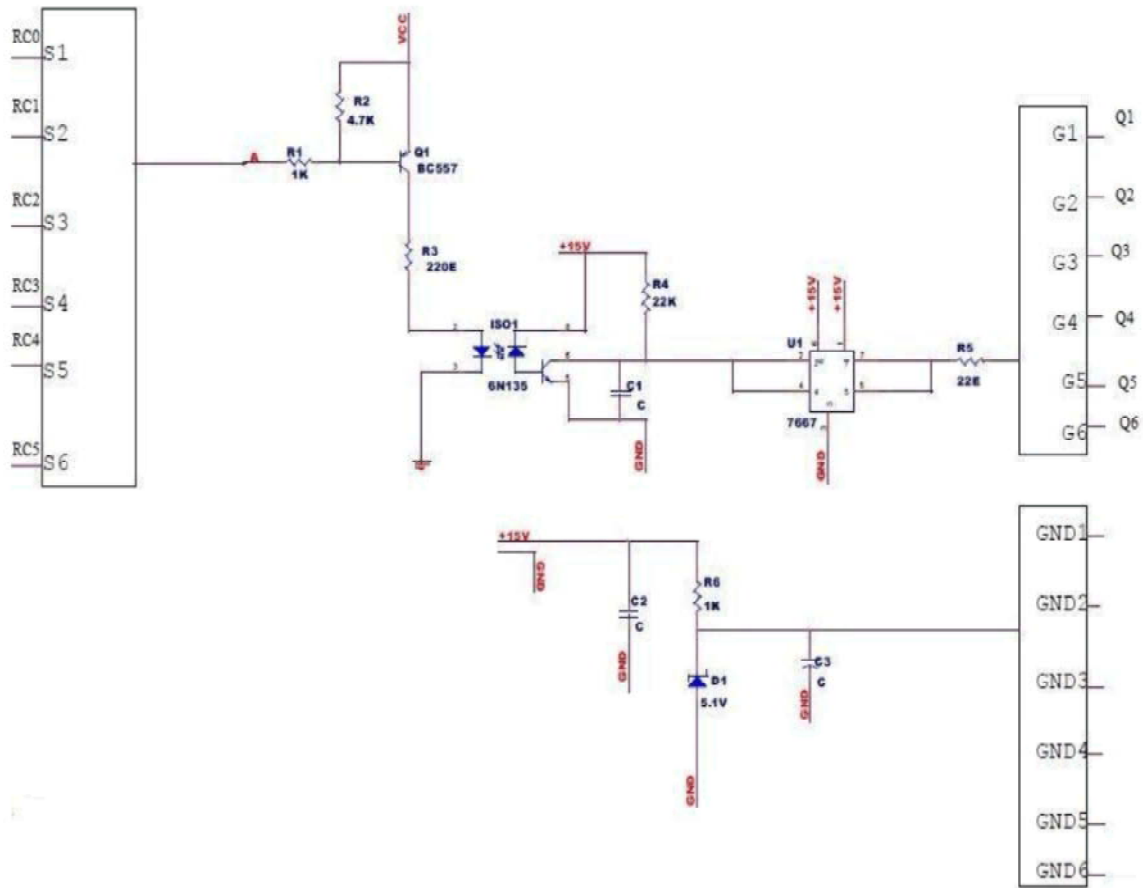


Fig. 8: Gate Drive Circuit of Proposed FSTPI System

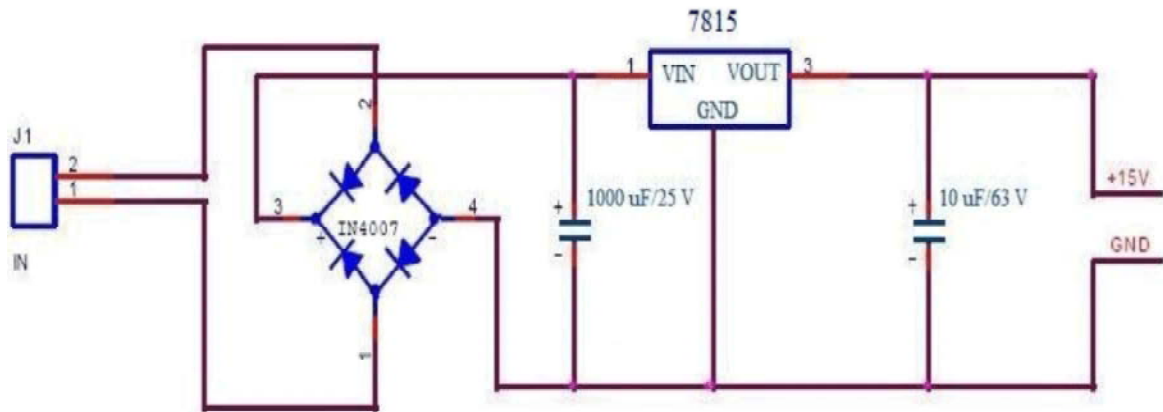


Fig. 9: Power Circuit of Driver Unit

As shown in the Figure 9 the first section is a FSTPI, which provides three phase voltages. This is applied to the op- amp comparator circuit. The zero crossing detector circuit is an important application of the op-amp comparator circuit. It can also be called as the sine to

square wave converter. Anyone of the inverting or non-inverting comparators can be used as a zero-crossing detector. The only change to be brought in is the reference voltage with which the input voltage is to be compared, must be made zero ( $V_{ref} = 0V$ ).

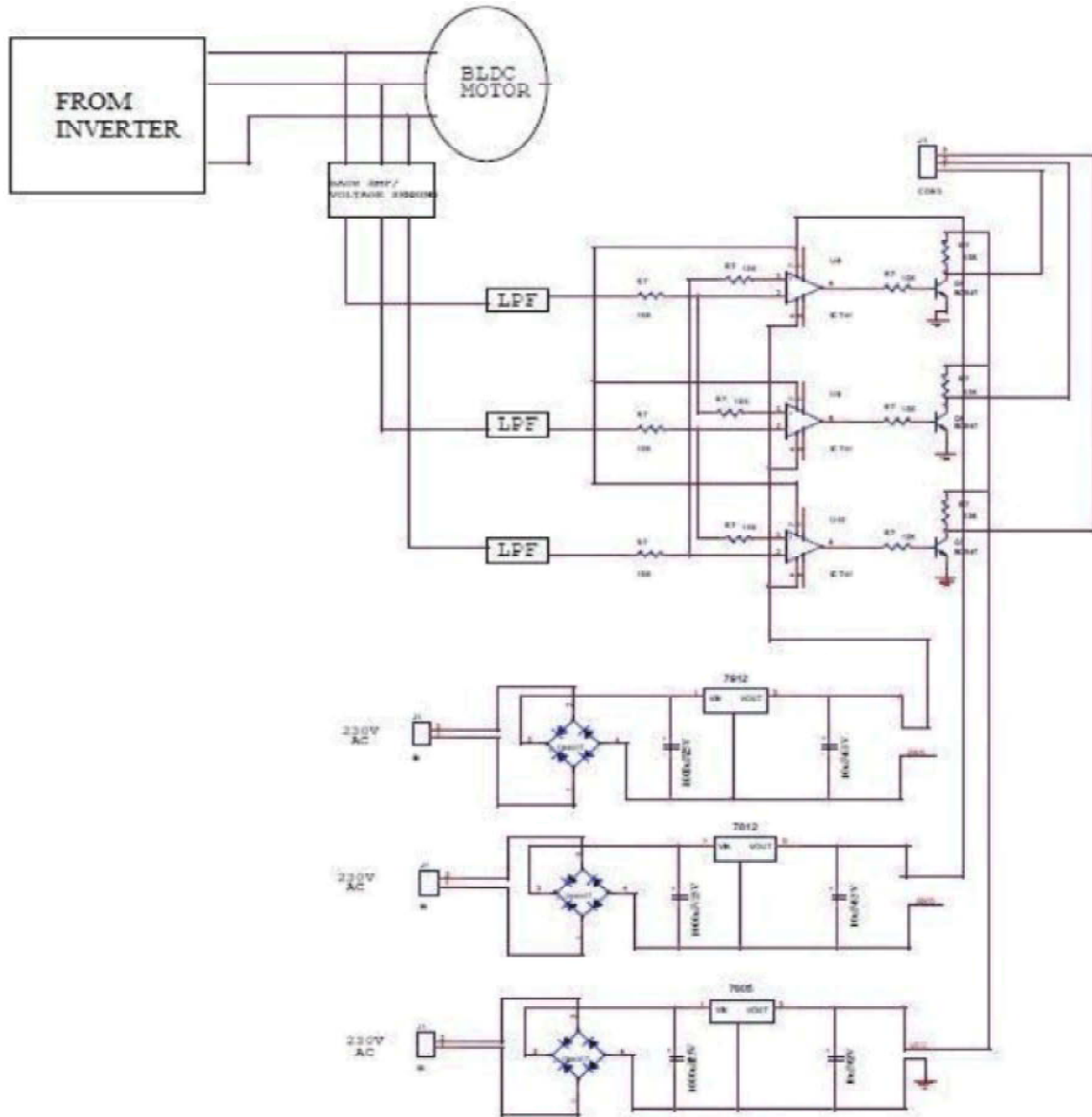


Fig. 10: Zero Crossing Detection Circuit

An input sine wave is given as  $V_{in}$ . These are shown in Figure 10 and input and output waveforms of an inverting comparator with a 0V reference voltage. The output of the op-amp comparator is applied to the base of the transistor through a base resistor, R7. This charge is available to the transistor as VCC. The transistor remains OFF until the Cut-in voltage  $V_{BE}$  is reached. During the OFF period of the transistor the output will be high and approximately equal to VCC. A zero crossing detector literally detects the transition of a signal waveform from positive and negative, ideally providing a narrow pulse that coincides exactly with the zero voltage condition.

**PIC 16F877A Microcontroller Used in Research:** The PIC 16F877A Microcontroller is the prime controller of this project. It controls the operation of various circuits associated in this project. The PIC 16F877A Microcontroller issues control signal to the MOSFET drive circuit [9]. The various features present in this PIC16F877A helps to achieve an effective control over the induction motor are shown in Figure 11.

**BLDC Motor:** A 1000 KV and 12 V Brushless outrunner motor is used for proposed FSTPI system. Are shown in Table 1.

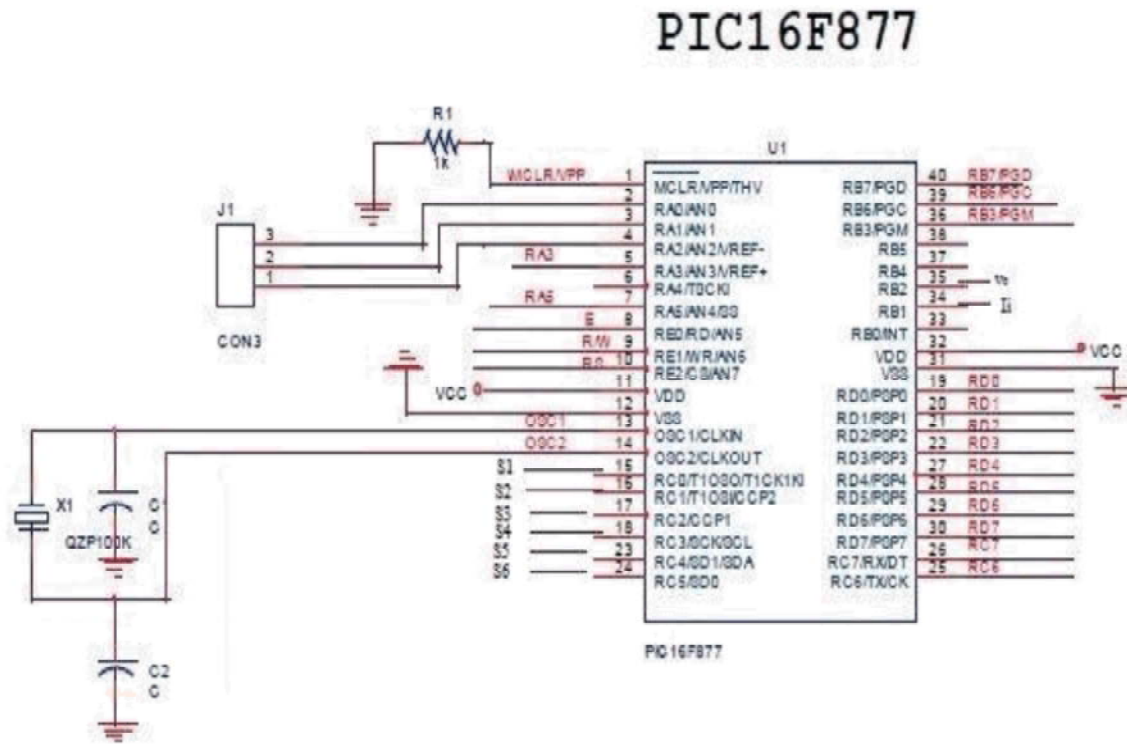


Fig. 11: PIC16F877A Microcontroller

Table 1: BLDC Motor Specifications

Variable name	Value
Number of poles	4
Number of slots	4
Rated Speed	1000 rpm
Maximum efficiency	80%
Current capacity	12 A/ 60 S
Number of cells	2-3 Li-Poly

## RESULTS AND DISCUSSION

**Simulation and Experimental Results of FSTPI System: Power Supply Unit:** Figure 12 shows the supply to the PIC16F877A microcontroller. From the result, it is found that the power supply unit provides voltage of about 5 V to the PIC microcontroller unit.

Figure 13 shows the power supply to the driver unit. From the result, it is found that the power supply unit provides voltage of about 15 V to the driver unit.

**Gate Pulse Generation of Proposed FSTPI System:** Figure 14 and Figure 15 shows the pulses to the switches S1, S2 of front end rectifier respectively. Experimentally, results are attained with pulses each of about 15 V.

Figure 16 to Figure 19 shows the gate pulses to the switches S3 to S6 of FSTP inverter respectively.

Experimentally, results are attained with pulses each of about 15 V.

**FSTPI System with BLDC Motor:** Figure 20 and Figure 21 shows the simulation and experimental results of supply voltage and current of the proposed FSTPI system with PFC respectively. This proposed converter draws near sinusoidal current with power factor close to unity [15].

**Advantages of Power Factor Correction:** The main advantages of the Power Factor Correction are, The electrical load on the Utility is reduced, thereby allowing the Utility to supply the surplus power to other consumers, without increasing its generation capacity [1]. Most of the Utilities impose low power factor penalties. By correcting the power factor, this penalty can be avoided.

Figure 22 shows the simulation results of the FSTPI. From the result, the value of maximum output voltage of the FSTPI fed BLDC motor drive system is about 40 V.

Figure 23 shows the experimental results of the FSTPI. From the result, the value of maximum output voltage of the FSTPI fed BLDC motor drive system is about 12 V.

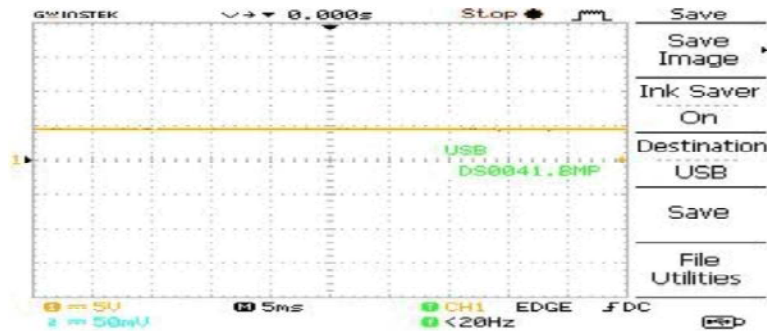


Fig. 12: Power Supply to PIC16F877A Microcontroller

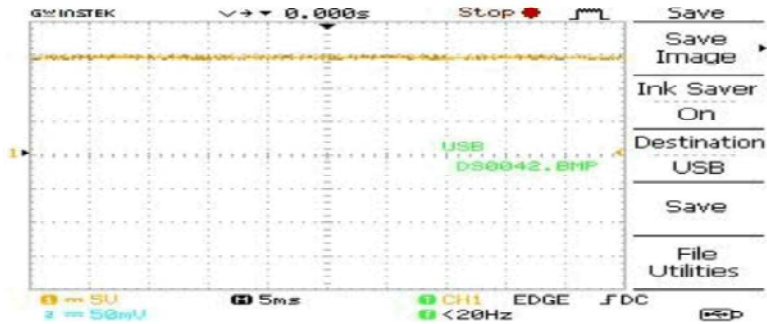


Fig. 13: Power Supply to Driver Unit

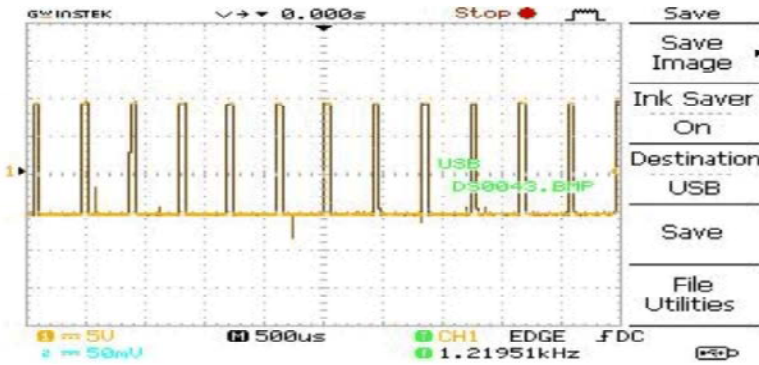


Fig. 14: Gate Pulse to Rectifier Switch S1



Fig. 15: Gate Pulse to Rectifier Switch S2

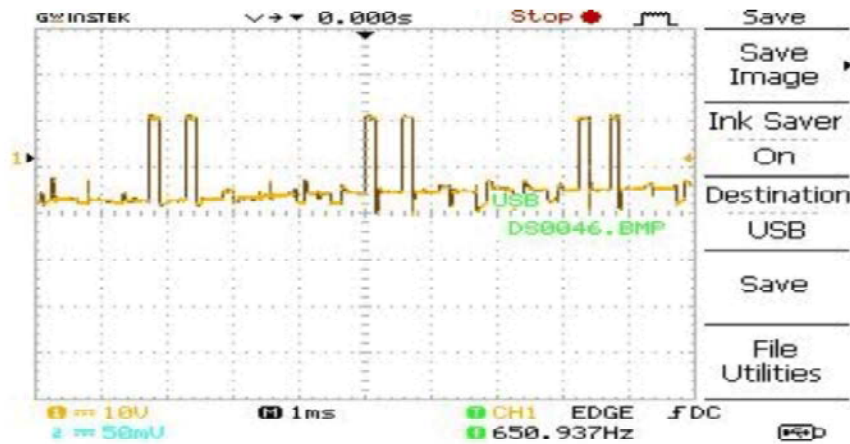


Fig. 16: Gate Pulse to FSTPI Switch S3



Fig. 17: Gate Pulse to FSTPI Switch S4



Fig. 18: Gate Pulse to FSTPI Switch S5



Fig. 19: Gate Pulse to FSTPI Switch S6

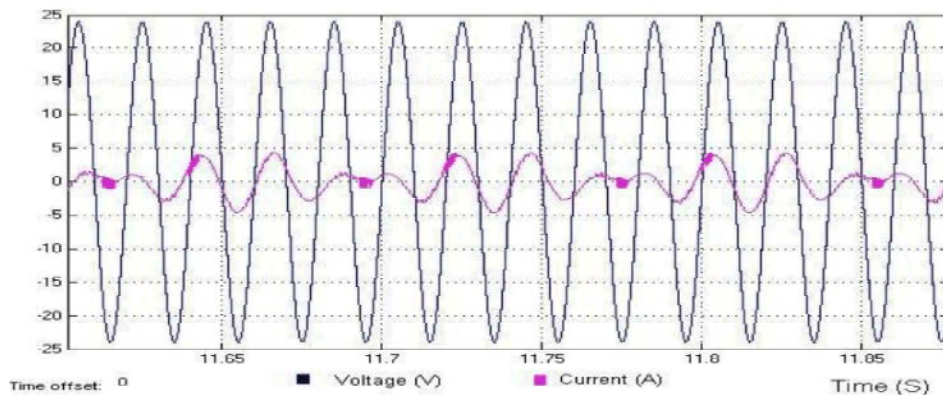


Fig. 20: In simulation - Input Voltage and Current with PFC

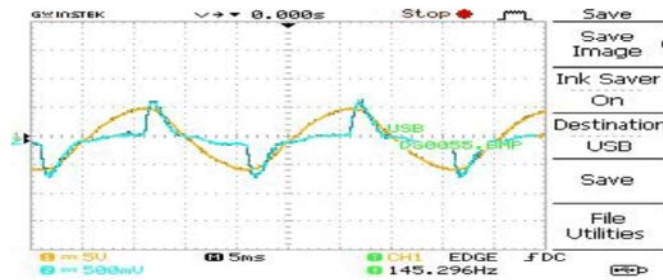


Fig. 21: In hardware - Input Voltage and Current with PFC

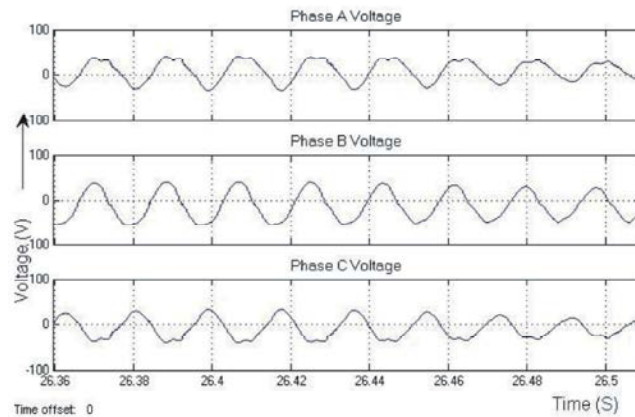


Fig. 22: In simulation - Output Voltage of FSTPI



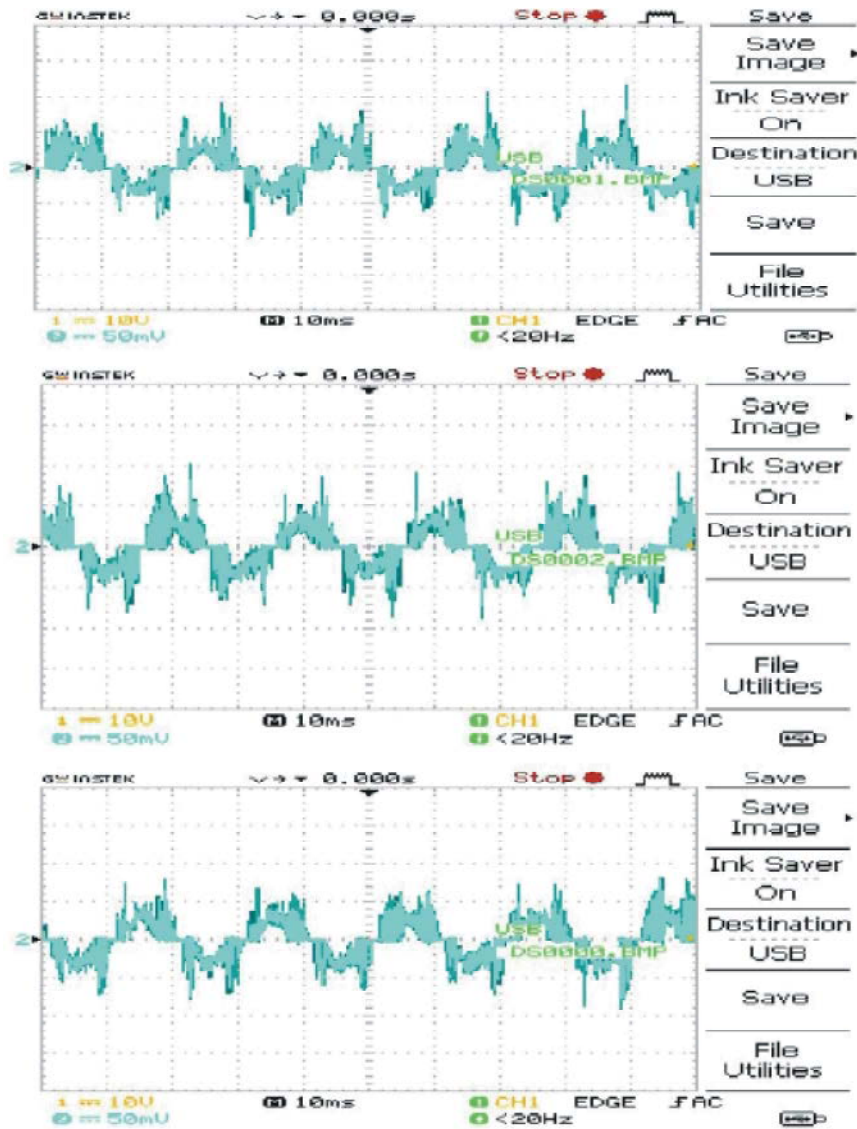


Fig. 23: In hardware - Output Voltage of FSTPI

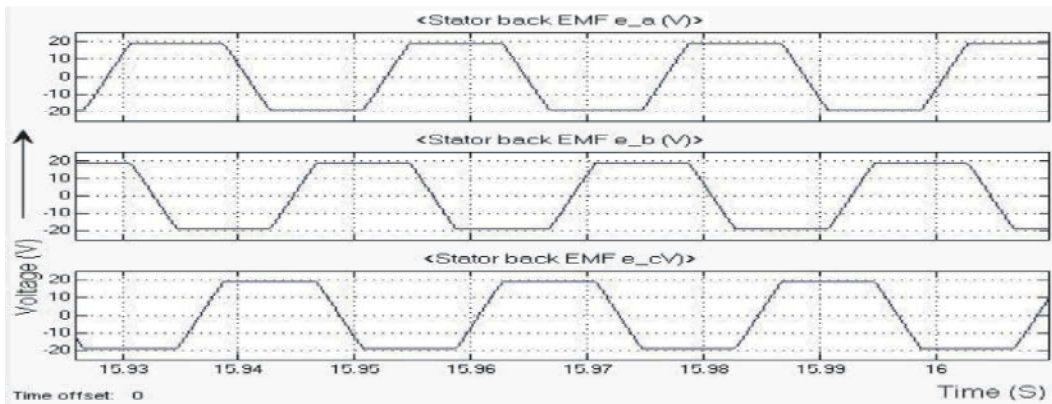


Fig. 24: In simulation - Back EMF of BLDC Motor

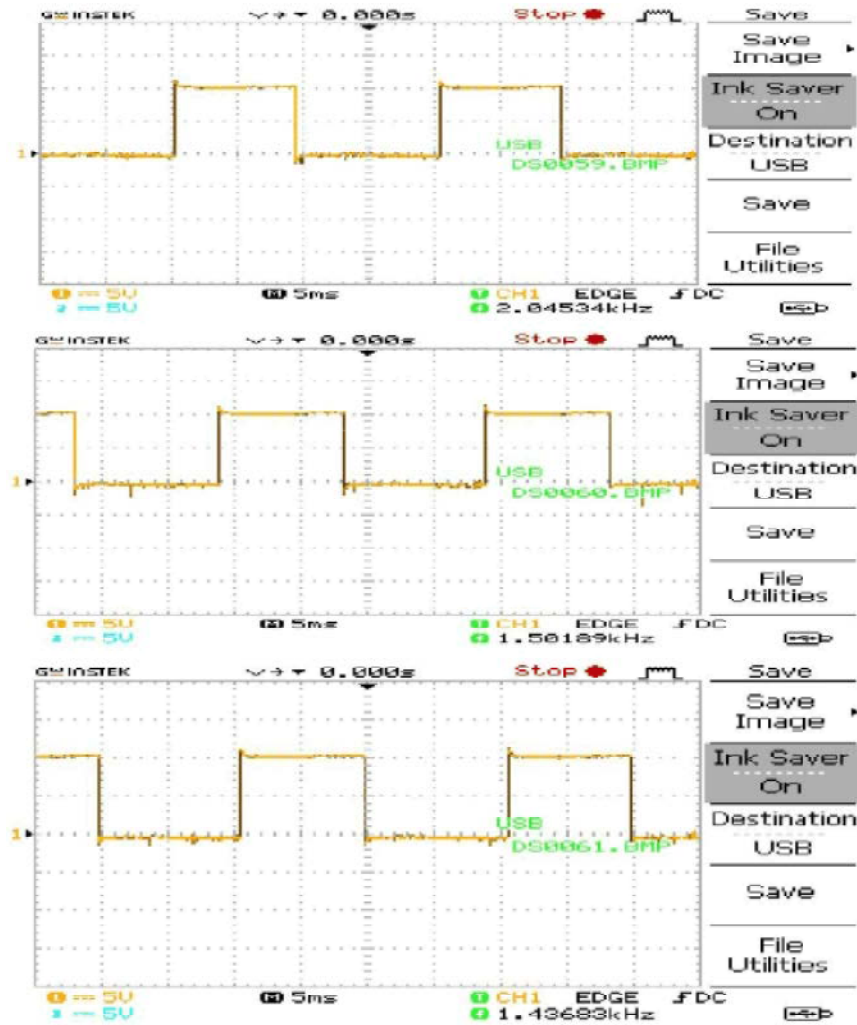


Fig. 25: In hardware - Back EMF of BLDC Motor



Fig. 26: In simulation - Rotor Speed of BLDC Motor



Fig. 27: In hardware - Rotor Speed of BLDC Motor



Fig. 28: Hardware Model of FSTPI System with PFC Correction

Figure 24 and Figure 25 shows simulation and experimental results of back

**EMF of BLDC Motor Respectively:** Figure 26 and Figure 27 shows simulation and experimental results of back EMF of BLDC motor respectively.

Figure 28 shows the Hardware model of the FSTPI fed BLDC system. The entire system is assembled in a single board and the necessary output voltage is attained. The entire unit is tested in research laboratory.

### CONCLUSION

The Brushless DC motors and drives have grown significantly in recent years in the commercial applications. Sensorless BLDC drives are very preferable for compact, low cost, low maintenance and high reliability system. The power factor correction of three

phases FSTPI fed BLDC motor is analyzed. Design of FSTPI, zero crossing detection, power factor correction is implemented. Then the PFC is necessary to increase the utilization efficiency of the AC power and to minimize harmonic pollution of the AC lines and hence the line current becomes sinusoidal in shape and will be in same phase with the voltage. The back EMF compensating and direct current controlling for BLDC motor drives is proposed and analyzed. In this direct back EMF sensing scheme avoids motor neural point as the reference for the zero crossing detection. In this scheme based the zero crossing points of three phase voltage. The direct back EMF sensing is developed and the circuit is integrated with a standard low cost 8-bit microcontroller to be a dedicated BLDC sensorless drive controller. The proposed Research work for the future research, development of IGBT based FSTPI for higher power levels. And the FPGA based sensorless control scheme

for FSTPI BLDC motor drive is implemented. This design of BLDC motor is not standardized yet. Optimized design of the BLDC motor that achieves high speed with lower cost is desirable.

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