A NOVEL DRIVE WITH BI DIRECTIONAL SWITCH MODULES FOR THE BLDC MOTOR WITH RESONANT AC LINK POWERED BY PHOTO VOLTAIC SOURCE WITH BATTERY STORAGE

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Abstract: A novel bi directional drive for the BLDC motor powered by a Photo Voltaic source is presented. Instead of the conventional DC rails the BLDC motor is powered by AC rails with AC voltage amplified by resonance created by an LC tank circuit. The three legs of the conventional BLDC motor drive with six switches are replaced by six bidirectional switch modules. The MPPT algorithm is implemented in the front end DC to AC converter of the H bridge type terminated on the AC side across a resonating tank circuit. A battery charging arrangement is also provided with bi directional power transaction feature. The methodology is suitable for the BLDC drive adoptable in three wheeler vehicles. The MATLAB SIMULINK model has been developed to prove the efficacy of the proposed system and it has been validated using experimental hardware setup.

Key Words: BLDC drive, Bi directional Switch modules, electrical vehicle, Photo Voltaic Power Harvesting MPPT using sliding mode control, Resonant AC linked DC to AC power converter.

1. Introduction

The present trend in the automobile industry is that electrically powered vehicles are encouraged. The electrically powered vehicles or the electric vehicles (EV) offer many distinct advantages over the internal combustion engine based vehicles, which depend on the fossil fuels. The question of availability of the fast depleting fossil fuel reserve and the effects and influence of burning them, in vehicles, towards the environment and the concern for climate change are all the discouraging factors that lead to the development of technologies for generation as well as utilization of electrical energy in vital domestic and industrial applications.

This research is oriented towards up keeping the principles of green power both in generation as well as in utilization. Photovoltaic power generation is suggested for the purpose of generation of electrical energy and the use of the BLDC motor is suggested for the core drive mechanism for the electric vehicle.

The novelty of the proposed system is that it uses an AC link bus bar for powering up the BLDC motor. The converter in the front end is a DC to AC converter with sliding mode type of MPPT incorporated. The speed control of the BLDC is carried out by PWM technique incorporated in the three leg bi directional DC drive. When real power is available in the motor shaft it can be pumped back to the AC link and then into the battery through the battery control converter.

There are three possibilities of power transaction. They are direct flow of power from the PV panel to the BLDC drive, flow of power from the battery to the BLDC drive and when the PV is generating in excess, the battery is charged. The BLDC motor can also generate power and feed it back to the battery.

The BLDC motor is driven either from the PV panel or from the battery and in either case there a set of converters. However, the focus of the work is the design of the bi directional converter that links the DC side with the BLDC motor through a resonant AC link. The peak voltage at the AC link is determined by the power available at the PV terminals. A regulating mechanism is employed to use the battery in such a manner that the AC link voltage is maintained constant irrespective of the PV availability or it is in the excess power generation mode., by accordingly discharging or charging the battery.

The resonant AC link converter system for converting DC power from the PV array to a three-phase AC load has been presented in [1-7]. The idea presented in [7] has been extended for driving the BLDC motor.

The bidirectional switching arrangements of the three leg three-phase converter makes it possible to drive the BLDC motor from an AC bus bar, even though the basic requirement for the BLDC motor's electronic commutator requires DC supply.

The PV panel feeds power into the single-phase inverter unit with feedback blocking arrangement. The inverter delivers AC output at a fixed frequency with different modulation indices depending upon the availability of solar radiation.

A quasi matrix converter algorithm is used to drive the BLDC motor and the topology can be treated as a 2×3 matrix topology. The two rows are powered from the AC link and the three columns take power to the three windings of the BLDC motor.

Fig.1. shows the basic block diagram of the proposed system.

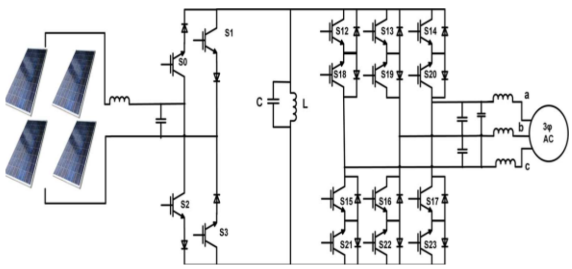

Fig.1. Block diagram of proposed system

Reengineering into the development of the mathematical models of the BLDC motor the PV panel and the battery are avoided in this discussion. The existing standard Simulink models are used. The focus is on the development of a 2×3 matrix drive for the BLDC motor where the two rows are fed with AC source.

Besides, a speed control technique, based on the fuzzy logic control scheme is adopted for the speed control of the BLDC motor to study the dynamic performance of the AC bus driven BLDC motor. The BLDC motor selected for the study is a 48 V 300 W motor typically used in electrically driven two wheelers.

The paper is organized as follows. Following this introduction a review of the BLDC motor is given in chapter 2. The 2×3 matrix converter drive is discussed in chapter 3. The open loop and the closed loop fuzzy logic based speed controller scheme for the BLDC drive are discussed in chapter 4. The MATLAB / SIMULINK based simulation and the design details of the experimental verification setup are elaborated in chapter 5. The observations and inferences are discussed in the chapter 6 followed by the conclusion.

2. Review of the BLDC Motor

The construction details of a typical BLDC motor is given in fig.2. It is a three-phase motor with the three phase windings housed in the stationary part of the motor. The rotating part carries permanent magnets.

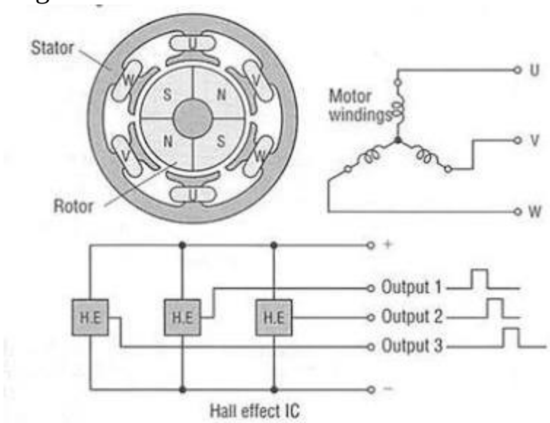

Fig.2. Construction details of BLDC

The shapes and the size of the permanent magnets are so designed that when the magnets rotate along the shaft a trapezoidal emf is induced in the stator windings of the motor. This is in contrast to the permanent magnet synchronous motor where the induced emf is a sinusoidal wave. Since there are no windings, in the rotating part, no brushes are required and as such, the motor is fit for high speed and high flame hazard applications as well.

High-speed pumps, servomotors, air borne applications are where BLDC motor finds its place. The availability of high-density magnetic materials has made it possible to develop high power BLDC motors with comparatively small size and weight.

While the BLDC motors unlike the conventional DC motors do not have brushes, they have position monitoring systems usually built around Hall Effect sensors. Three such hall effect sensor units are mounted conveniently over the stationary part of the BLDC motor so that the angular shift of the BLDC motor can be estimated as to which of the possible six sectors with 60 degrees sweep the motor shaft is currently passing through. This information is required to appropriately energize the selected two coils of the motor.

2.1 The electronic commutator

The BLDC motor is a DC motor and the electronic converter used to drive the BLDC motor is just an electronic commutator that is usually powered from a DC bus bar. The electronic commutator is a three-leg half-bridge arrangement with six power electronic switches. The switches may be IGBTs or MOSFETs depending upon the operating voltage, current and the switching frequency.

In this work instead of the conventional half bridge arrangement with six numbers of unidirectional power electronic switches each unidirectional switch is replaced by a bidirectional power electronic switching module realized with two power electronic switches. The arrangement is as shown in fig.3.

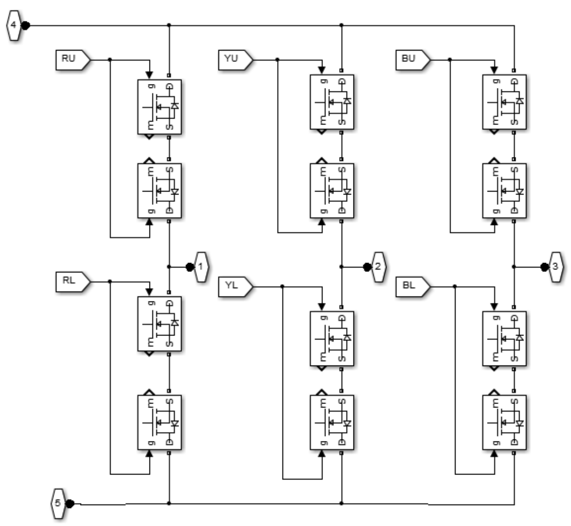

Fig.3. Bidirectional power switching module

2.2 The position sensing mechanism

The position sensing mechanism is an essential component of the BLDC motor. In the rotation of the shaft it traverses 360 degrees in one revolution. The 360 degree space is divided into 6 sectors each with a sweep of 60 degrees. As the motor shaft passes through each of these six sectors, two select windings are to be energized with the appropriate direction of current flow. In order that the process of energizing the coils of the motor is carried out in the right timing, the position of the motor is to be known. The Hall Effect sensor is used for this purpose. Three Hall Effect sensors are mounted on a stationary bracket in front of a rotating cam mounted on the shaft. As the rotating cam passes in front of these three sensors a three bit binary pattern is produced. The three-bit binary pattern represents the current position of the shaft of the BLDC motor.

The three bits of the Hall Effect sensor are used in the switching pulse generation system to generate the switching pulses with appropriate timing relevant for controlling the six switches of the electronic commutator.

In small BLDC motors, however, the Hall Effect sensor may be absent and the timing signals will be derived externally by electronic circuits by processing the back emf separated from the terminal voltages observed across the three phase windings of the BLDC motor.

The Hall Sensor output and the switching table pattern for a BLDC motor is given in Table 1.

Table 1 Hall effect sensor output and switching pattern

Hall sensors			Switches					
H1	H2	H3	S1	S2	S3	S4	S5	S6
1	0	1	0	1	1	0	0	0
0	0	1	0	1	0	0	1	0
0	1	1	0	0	0	1	1	0
0	1	0	1	0	0	1	0	0
1	1	0	1	0	0	0	0	1
1	0	0	0	0	1	0	0	1

2.3 The torque producing mechanism of the BLDC

The BLDC motor is a DC motor. It has two flux producing components viz. the 120 degrees phase shifted three phase windings in place of the armature and the permanent magnetic poles producing the field flux in place of the field winding of a conventional DC motor.

Of the three armature windings only two are energized at a time. They may be reversed also. With the selection of each set of two windings from among the available three windings and by reversing the direction of current in these windings there are six different combinations. These six combinations work at the appropriate period when the permanent magnetic poles just pass by these windings.

Due to the flow of currents through the windings, a flux is produced. The interaction between flux produced by the magnetic poles and the flux produced by the current carrying coil pair a torque is produced and the torque works along the tangent of the rotating circular shaft.

To start with, the motor is in a state of equilibrium at rest. When energized, the production of the torque causes the equilibrium to be disturbed and the motor starts run in search of new equilibrium state. In the new equilibrium state the motor runs at a steady speed drawing a steady current and the torque produced is just sufficient to keep the motor at the current running speed of the motor.

The transient period is in between the initial state of rest and the final steady operation. Fig.4. shows the waveforms pertaining to the BLDC motor during the transient and the steady state.

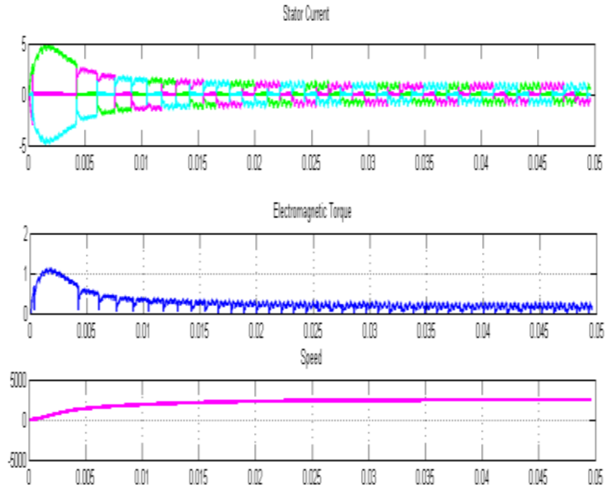

Fig.4. Stator voltage current and speed during steady state and transient period

2.4 The Resonant AC link

In this research, instead of a DC power supply the BLDC motor is driven using an AC power supply. The AC power supply is derived across the resonant tank circuit formed at the AC terminals of a H bridge inverter. The Inverter is powered from a DC source available from a PV panel.

The DC electric power from the PV panel is inverted by the H bridge inverter with blocking diodes D1, D2, D3 and D4 as shown in fig.5.

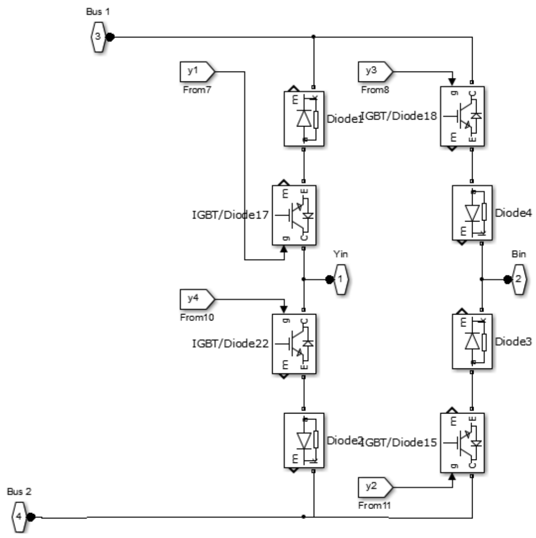

Fig.5. H bridge inverter with blocking diodes

The inverter is switched at a high frequency as shown in fig.6. The square wave switching pulses turn ON and OFF the cross arms of the inverter at the resonant frequency of the tank circuit in the AC link.

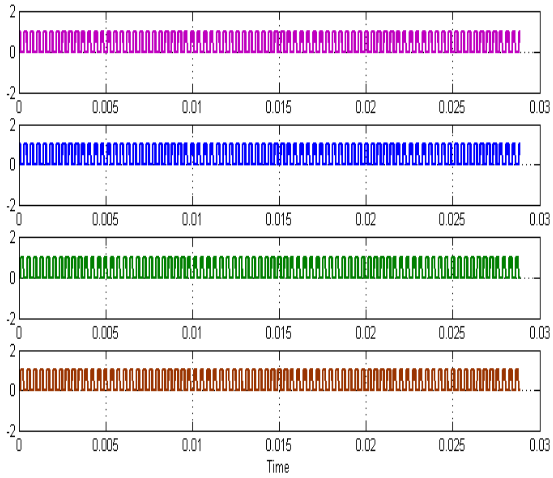

Fig.6. Switching states

The waveforms of the AC link current and the voltage across the AC link are shown in fig.7. The resulting high frequency AC link voltage is used for driving the BLDC motor.

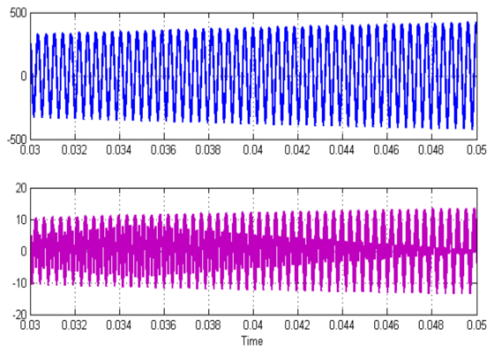

Fig.7. Voltage and current across AC link

3. The 2×3 Matrix converter

The BLDC motor is driven by the AC source and the power to the coils of the BLDC motor are routed through the 2×3 matrix converter. The two rows of the matrix arrangement get the AC power and the three columns of the matrix drive the coils of the BLDC motor.

There are in total six switching modules. Each module can either be turned ON or OFF independently. All the upper and lower switching modules can be turned ON simultaneously. These two cases are called the Null states. No two switching modules in the same leg will be turned ON. Since there are six switching modules there can be basically 2^6 = 64 switching combinations are possible. But eliminating the cases of combinations not allowed for a matrix converter there will be only eight different combinations allowed and these combinations are conveniently denoted as switching

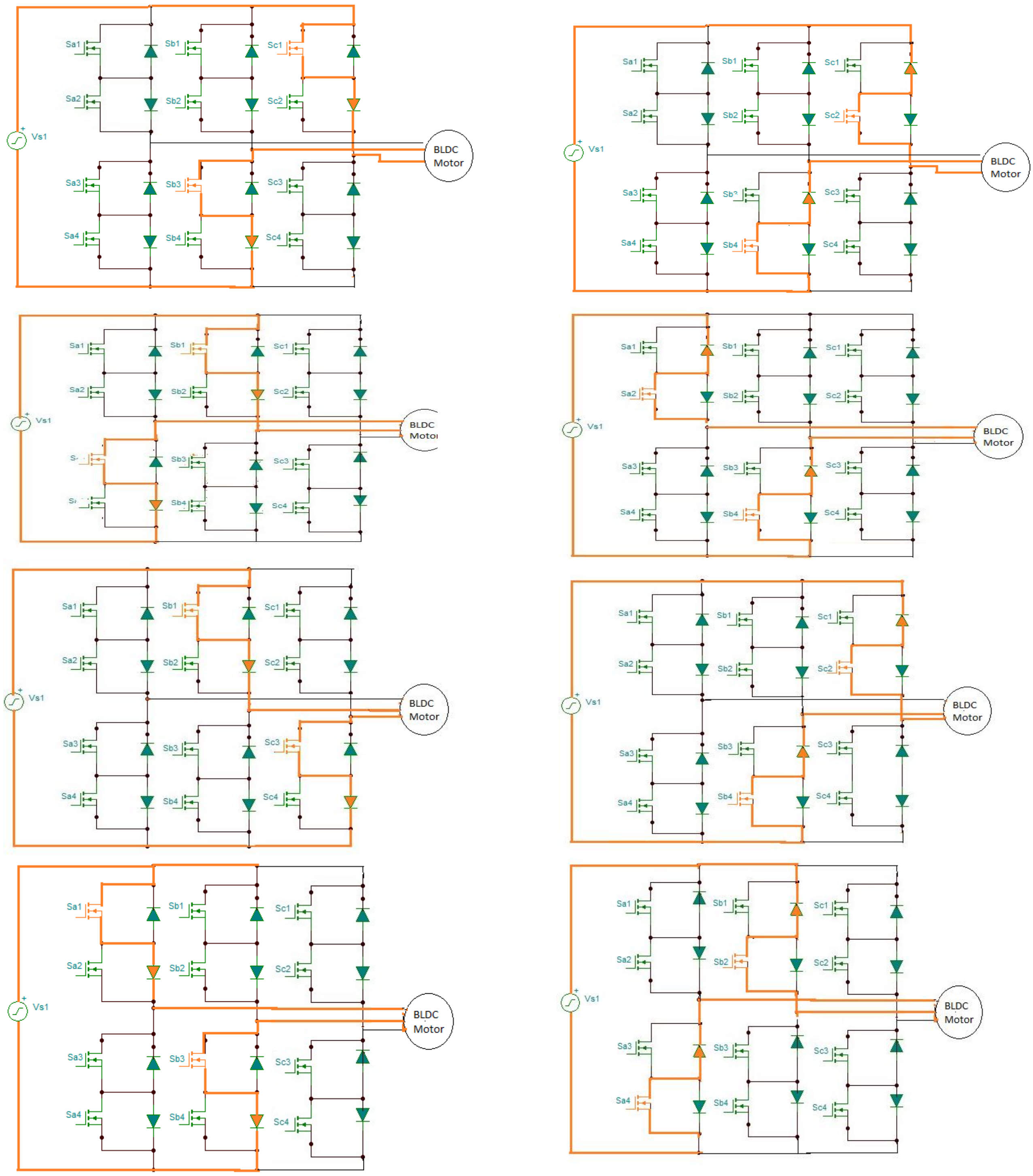

Fig.8. Operation states for single phase to three-phase matrix converter

vectors. Other than the Null switching vectors, there will be only six active switching vectors.

These six vectors will be activated as dictated by the Hall Effect sensor signals. Since the source of operation is AC even during the period for which an active vector is selected depending upon the polarity of the operating source of the direct and the complementary switching vectors will be activated. Fig.8. shows the operation states for single phase to three phase matrix converter

3.1 The zero crossing detector

The three coils of the BLDC motor are energized in pairs. For the first 180 degrees of shaft rotation, during every 60 degrees two coils are selected.

During the next 180 degrees the same order of the coils will be selected but with reversal of current flow.

In a conventional three-phase half bridge circuit, this is possible with the basic six unidirectional switches but with the AC source on the operating bus bar during every 60 degrees segment, the selected switches and the complementary switches for the selected set will be turned ON alternatively.

Thus, it is necessary to inform the control unit the polarity of the AC source prevailing at the AC bus bar. For this purpose, a zero crossing detector is used. The zero crossing detector (ZCD) generates logic 1 when the AC link is one direction, with the upper rail of the AC link at the positive polarity and the ZCD will produce logic zero output when the lower rail is positive.

4. The open and closed loop speed control

In the case of a BLDC motor there can possibly be two different methods of speed control.

a. The DC link voltage controlled speed control.

b. PWM based current controlled speed control.

Since the field flux is produced by permanent magnets the field control technique as used in the conventional DC motor is not possible in the case of the BLDC motor. The only possibility is the armature control method. In this method, there are two degrees of freedom. Speed can be controlled either by changing the DC link voltage controlled from the previous inverter stage or by controlling the current through the coils by implementing PWM in the electronic commutator bridge of power electronic switches.

In this work, both the cases of control through PWM at the electronic commutator as well as control at the AC link voltage level are discussed.

4.1 The open loop control

In applications like the electric vehicle, the speed control is always of the open loop type without any intermediate automatic control system using feedback. Every time the user wants to increase or decrease the speed, the user will act as a control element to manually accelerate or decelerate the motor.

The two schemes of speed control are,

a. Control of the AC link voltage.

b. Control of the coil current through PWM with fixed AC voltage source.

4.2 Control of the AC link voltage

The control of the AC link voltage can be used as a means of controlling the speed of the BLDC motor driven with constant modulation index maintained at the electronic commutator switching stage.

The control of the AC link voltage can be implemented by changing the modulation index at the front end inverter powered by the PV panel or any standard DC source.

The magnitude of the peak value of the fundamental component of the output of the inverter is given by Equation 1.

$$V_1 = \frac{4V_{dc}M}{\pi} \tag{1}$$

The waveforms pertaining to the variations of modulation index, in the case of single pulse modulation, along with the variations in the amplitude of the resulting fundamental component are shown in fig.9.and fig.10.

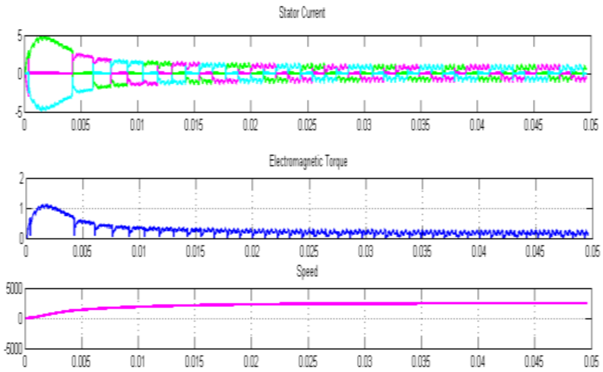

Fig.9. Stator voltage current and speed at modulation index 0.4

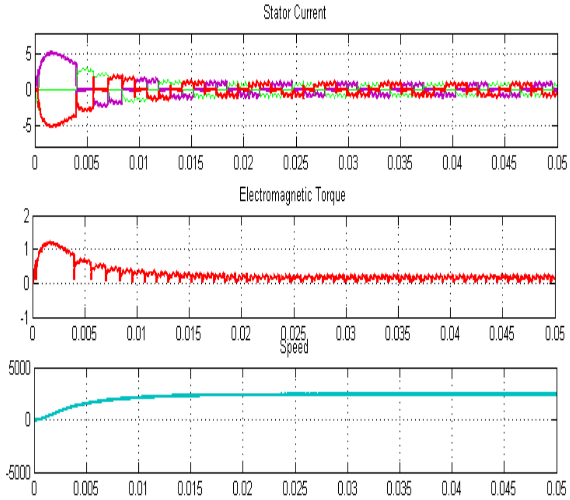

Fig.10. Stator voltage current and speed at modulation index 0.45

Therefore while keeping the frequency constant, at the resonant frequency; the modulation index can be changed to change the magnitude of the AC link voltage. Thus, the speed control of the BLDC motor can be achieved by changing the modulation index of the front-end inverter.

The relationship between the speed of the BLDC motor, with a constant load torque, and the variations in the modulation index of the inverter stage as recorded from the MATLAB SIMULINK simulation is shown in fig.9.

A direct mapping between the modulation index of the inverter and the speed of the BLDC motor is shown in fig.10. For open loop applications, in order to change the speed of the BLDC motor it is sufficient to change the modulation index of the inverter.

The variation of electromagnetic torque produced by the BLDC motor with respect to the modulation index of PWM at the three phase bridge, as recorded from the MATLAB / SIMULINK simulation is shown in fig.11.

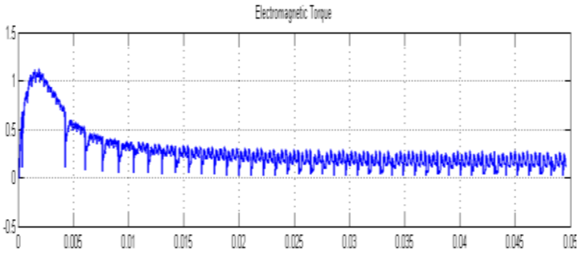

Fig11. Electromagnetic torque.

4.3 Closed loop scheme of Speed control / The Fuzzy Logic Control

A BLDC motor does not require a closed loop speed control when it is used in an electric vehicle. However in the case of industrial applications it will be necessary to have a closed loop speed control for the BLDC motor. A fuzzy logic control scheme is suggested for the speed control of the BLDC motor.

A fuzzy logic control scheme uses human experience. The fuzzy logic control scheme is a technique to deal with approximate data incorporated with human experience to ultimately arrive at results that are agreeable. Wherever the limits of error can lie within any acceptable range rather than a precise value of output is required, the FLC can be developed and put into service.

The major advantages of the FLC are that

1. It does not require a precise mathematical model of the plant to be controlled.

2. The mathematically rigorous tuning procedures as required in the PI controller design and tuning are avoided.

3. There is no usage of parameters with random nature as used in GA or PSO based control schemes.

4. Although the fuzzy logic is a technique to deal with approximate data to arrive at the agreeable results it's logical decision making principle is oriented towards the correct goal and this leads to precise results also when the data presented is precise.

Fuzzy logic considers the present and the previous error and makes a decision not just with the error but also with the rate of rise or fall error so as to arrive at the correct control parameter value so that the steady state error is close to zero.

In most cases, fuzzy logic can be developed in a manner that no overshoot is exhibited in the closed loop control scheme.

There are several steps in the implementation of a fuzzy logic control system. They are

1. Scaling
2. Normalizing
3. Segmentation
4. Fuzzification
5. Inference
6. Defuzzification
7. Denormalization

MATLAB offers a convenient platform to carry out the steps involved in the design of the Fuzzy Controller. Also MATLAB offers a library of membership functions.

4.4 The Control strategy adopted

In this work two different cases of control are verified. In the first case the speed command is changed with a fixed load on the motor. In this case the modulation index of the front end inverter is the manipulated variable.

In the second case the motor is changed without any change in the speed command. With mechanical disturbance to the load on the motor the speed gets disturbed and the modulation index of the PWM used in the three leg electronic commutator is manipulated. Thus there are two FLCs and depending upon the situation the appropriate controller comes into action.

5. The MATLAB / SIMULINK Based Simulations and Experimental Validation Setup

The details of construction, operation and the performance of the experimental setup constructed to validate the proposed system are discussed in this chapter. The experimental setup consists of three important sections. They are,

a. The PV panel and a boost converter.
b. The battery and the inverter driving the resonant AC link and

c. The Three leg electronic commutator with bidirectional switches.

5.1 The PV panel and the boost converter

The main source of electrical power is the PV panel. The PV panel collects the solar power and transforms it into electric current to charge a battery. In between the battery and the PV panel is a single switched generic boost converter. Maximum Power Point Technique of the Sliding Mode type is implemented in the boost converter. The battery is charged with the appropriate charging current as regulated by the boost converter in accordance with the MPPT requirements.

When the solar insolation is more the battery is charged with more current and with reduced insolation the charging current is reduced. The details of the PV panel are shown in Table 2. The nominal operating voltage of the PV panel is around 18V and the terminal voltage of the battery is 24 V.

Table 2. PV panel Characteristics

Parameters	Value
Maximum Power (P_{max})	80 W
Voltage at Pmax (V_{mp})	17.5 V
Current at Pmax (I_{mp})	4.75A
Open-circuit voltage (V_{oc})	22.2 V
Short-circuit current (I_{sc})	5.5A

The main switch of the boost converter is the typical IRF 540 MOSFET. The main inductor is of 500 Micro Henry and the switching frequency is 20 KHz.

5.2. The Sliding Mode Control

The sliding mode control is a control technique in which the control element of the system is switched between two positions alternately so that parameter to be governed is maintained closely about the required level.

It is probable that in any system, consisting of a switch type control element with two distinct states then, if the control element is assuming in either of the two possible positions, the system heads towards instability. However, if the switch is turned ON and OFF alternately the direction of heading towards instability is curtailed and the system parameter under consideration is stable and at the required level.

Going by an example in the case of the boost converter the switch S plays the role of the control element. It can be either turned ON or kept in the ON state or it can be turned OFF and kept in the OFF state.

While the switch is in the ON state a large current flows through the series inductor and this current is exponentially growing with its time constant decided by the R and L of the inductor. Usually the boost inductor of a boost converter has negligible resistance and as a result, the current rises very steeply. As the resulting current will eventually cross the allowable bounds, it can be treated as a state of instability.

While the switch is open and kept in the OFF state a current flows through the inductor and load. This current reaches a steady state when the inductor drops zero voltage and the full source voltage will try to reach the load. However because of the higher potential existing across the capacitor connected across the load terminals the diode D will be reverse biased and the inductor current becomes zero.

Thus the extreme cases of keeping the switch ON and OFF results in a current either tending to infinity or tending to zero. But the requirement is that an average current flow from the source to the load and this can be done only by turning ON and OFF the switch periodically at a frequency as decided by the other design factors of the circuit.

5.3. The Sliding Mode MPPT technique

In the sliding mode control for the boost converter the switch is operated at a finite switching frequency. The threshold of turning ON and turning OFF the switch is associated with the Maximum Power Point Tracking of the PV panel.

In the PV panel under consideration the open circuit voltage at a solar insolation of 1000 W/m^2 and at a temperature of 25^O C is 22.2 Volts. The terminal voltage to be maintained at the said standard insolation and temperature for maximum power delivery is 17.5 V. The ratio between the MPPT voltage and the OC voltage will be 17.5 / 22.2 = 0.788.

For insolation levels falling below the maximum of $1000w/m^2$ the open circuit voltage will be accordingly reduced but for maintain the MPPT condition the PV panel should be loaded such that the terminal voltage is just equal to the OC voltage at the current insolation level multiplied by the factor 0.788.

Therefore, the algorithm for sliding mode controlled MPPT will be as follows.

1. Turn off the switch.
2. Measure the open circuit voltage of the PV panel.
3. Turn on the switch.

4. Wait until the terminal voltage falls down to the threshold voltage (Voc×0.788).
5. Go to step 1.

The results of the MATLAB / SIMULINK simulations are depicted first. Fig.12. shows the variations of the SMC based switching pulses, the variations in insolation and the accordingly varying battery charging current.

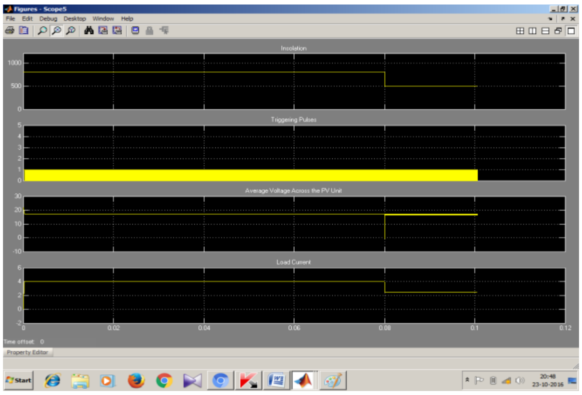

Fig.12. SMC based battery charging

It is clear that the SMC maintains a close tracking of the solar insolation and the terminal voltage of the PV panel is maintained at the optimal value in the face of changing insolation levels.

Whenever there is a change in the insolation level either higher or lower from the present value the terminal voltage slides up or down to the new PV panel terminal voltage by means of the switching action of the MOSFET in the SMC based boost converter.

The battery being a sink, there is no much change in the terminal voltage of the battery, even though the boost converter may operate above 50% duty cycle, but the charging current changes promptly as dictated by the solar insolation levels. In the whole discussion the temperature dependency of the PV panel has not been considered. With the SMC, even the changes in the generation of the PV panel by virtue of changes in temperature are accommodated, as the temperature influences the terminal voltage of the PV panel.

5.5. The Front End Inverter and Resonant Circuit

The PV charges the battery. The battery drives the front-end inverter. At the AC terminals of the inverter is the resonant tank circuit. The inverter is of the single-phase full bridge configuration with four power electronic switches. The switches are of type IRF 840. All the switches are coupled to the micro controller through opto couplers MCT 2E.

The inverter is driven by the micro controller PIC 16F877A. The inverter output frequency is maintained at 3 KHz. This frequency is the resonant frequency of the tank circuit. In order to control the amplitude of the output voltage the single pulse modulation scheme is used. Depending upon the modulation index the width of the single pulse switching signals varies and this controls the magnitude of the AC link voltage.

For measuring and accepting the set point AC link voltage two analog inputs of the PIC 16F877A are used. A potentiometer is used to adjust the average value of the set point voltage for the AC link. The actual AC link voltage is monitored using a chain of rectifier, filter and attenuator stages.

The L and C components are 3 mH and 1μF and the frequency of resonance is given by

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

$$= \frac{1}{2\pi\sqrt{0.003 * 0.000001}}$$

$$= 2907 \text{ Hz.}$$

The inverter is a single pulse width modulated inverter and it can be modulated to supply variable amplitude fundamental component sine wave with 2907 Hz.

The waveforms of the AC link voltage with different modulation indices as recorded from a DSO are shown in fig.13.

Fig.13. AC link voltage

5.6 The Hardware Realization of the Electronic Commutator

The electronic commutator usually used for a BLDC motor is of the Three-leg Bridge with bi directional power conversion feature. The switches are typically MOSFETs or IGBTs with the internal reverse diodes.

The switches are numbered S1, S3, and S5 in the upper arm of each leg and the corresponding lower arms carry the switches S4, S6 and S2. When the Electronic commutator is operated from an AC link then each switching module comprises of two switches connected in the anti series formation with the source terminals or the emitter terminals connected together. Fig.14. shows the circuit arrangement of the electronic commutator suitable for operation with the AC link. For each module, a common gate signal is used and there will be only 6 gate signals.

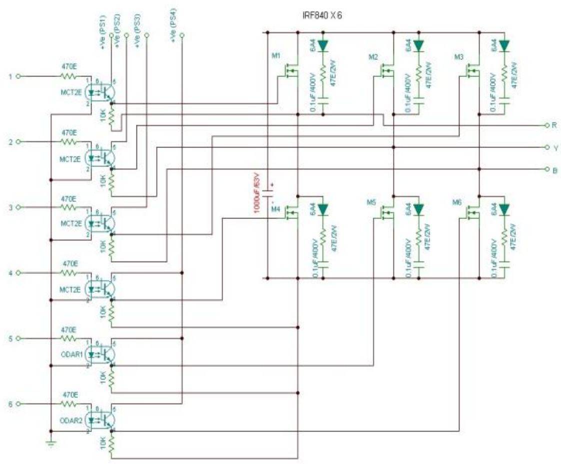

Fig.14. Electronic commutator

Normally in a BLDC drive with DC link the electronic commutator is operated as an inverter with 120 degree conduction mode. The hall sensor unit will govern the duration of active period of each switch, which is function of the speed and current position of the shaft of the motor. Within the active period of each switch, conduction is not continuous but modulated with a multiple pulse width modulation for which the modulation index will be supplied by the controller unit.

This additional PWM control is the second degree of freedom using which the motor speed can be regulated in the face of load side disturbances when the operating AC link voltage is not disturbed.

5.7. The control strategy

The BLDC motor, in certain applications may not require a closed loop speed regulation arrangement, like in the case of an electric vehicle. However, in certain cases the BLDC motor may be required to run at preset speed and be regulated at that speed.

However, there could happen source side and load side disturbances. The source side controller takes care of the AC link voltage so that the motor runs at the set speed for the given mechanical load. If any change occurs at the AC link voltage, caused by the battery voltage, then the modulation index of the front-end inverter is automatically adjusted and the AC link voltage restored to the set value.

While the AC link voltage is maintained at the set voltage level and if there is a drop in speed due to want of more driving torque, that happens with increased load then the PWM strategy of the electronic commutator bridge comes into action, the modulation index is adjusted to adjust the motor current to meet the increased load. Similarly, if the speed of the motor shoots up caused by the removal or a decrease of the mechanical load then the modulation index at the electronic commutator is reduced automatically and the motor is brought back to the set speed.

Thus, there are two degrees of freedom that takes care of source and load side disturbances. However, a strategically operated single fuzzy logic controller takes care of the situations.

5.8. Implementation of Fuzzy Logic Control

The objective of the control scheme is to regulate the speed of the BLDC motor. The Speed of the BLDC motor is a function of the AC link voltage and on the mechanical load for any given AC link voltage.

There are two manipulated parameters. The MI at the front-end inverter and that at the three leg electronic commutator. The voltage at the AC link is a continuously variable quantity and so is the motor current. The speed of the BLDC motor is the controlled parameter.

The speed of the motor and the RMS value of the AC link motor are monitored and fuzzified. First, a basic set fuzzy rule base is developed and it is as follows. M1 and M2 are the modulation indices respectively for the front-end inverter and the three leg electronic commutator.

1. If the change in speed is accompanied by change in AC voltage then adjust M1.
2. If the change in speed is not accompanied by a significant change in the AC link voltage then change M2.

The speed and the AC link voltages are continuous quantities and hence they have Universe of Discourses. The modulation indices M1 and M2 can also be varied from 0 to 1. Therefore all these four quantities can be segmentised and fuzzified and can be governed by fuzzy rules as given below.

1. If change in Vac is small and change in speed is small then change M1 by a small quantity.
2. If change in Vac is medium and change in speed is medium then change M1 in the medium range.
3. If change in Vac big and change in speed is big change M1 by a big quantity.
4. If change in Vac is small and change in speed is big then change M2 by a big quantity.

Table 3 Rule table

	Fall / Rise in Voltage across AC link					
Fall / Rise in Speed	Big F	Medium F	Small F	Big R	Medium R	Small R
Big F	M1 Big + M2 NC	M1 Med + M2 Med +	M1Small + M2 Big +	M1 BIG - M2 Big +	M1 Med - M2 Med -	M1Small- M2 Big -
Medium F	M1 Big + M2 Med -	M1 Med + M2 NC	M1Small + M2 Med +	M1 Big - M2 NC	M1 Med - M2 NC	M1Small - M2 Big -
Small F	M1 Big + M2 Big -	M1 Med + M2 Small -	M1Small + M2 NC	M1 Big - M2 NC	M1 Med - M2 Med -	M1Small - M2 NC
Big R	M1 Big + M2 Big -	M1 Med + M2 Big -	M1Small + M2 Big -	M1 Big - M2 NC	M1 Med - M2 Med -	M1Small - M2Big -
Medium R	M1 Big + M2 Med -	M1 Med + M2 NC	M1Small + M2 Med -	M1 Big - M2 Med -	M1 Med - M2 NC-	M1Smal - M2 Med -
Small R	M1 Big + M2 Small -	M1 Med + M2 Med -	M1Small + M2 Small -	M1 Big - M2 Small-	M1 Med - M2 Med -	M1Small - M2 NC

If change is Vac is small and change in speed is medium then change M2 by a medium value. These rules can be coded in the C program and then down loaded into the PIC 16F877 A.

The rules can be consolidated as shown in the table 3. The rows denote the Speed and the columns denote Vac.

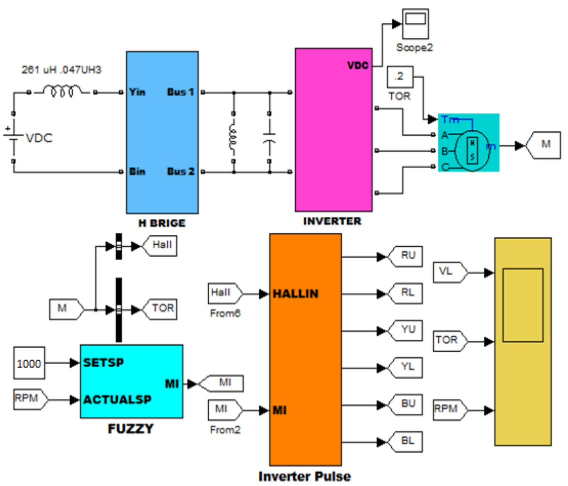

Fig.15. Control system block diagram of BLDC powered from AC link using fuzzy controller

The implementation of the fuzzy logic technique for the speed control of the BLDC motor is done in MATLAB Simulink platform. Fig.15. shows the control system block diagram of BLDC powered from AC-link using fuzzy controller. The alternate lookup table selection scheme based on zero crossing of AC-link and the fuzzy logic controller sub system for the AC link drive are shown in fig.16 and fig.17 respectively.

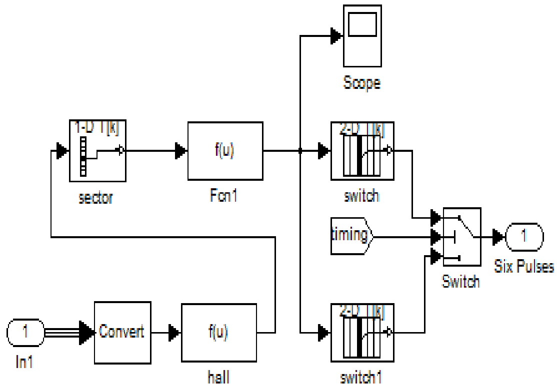

Fig.16. The alternate lookup table selection scheme based on Zero crossing of AC link

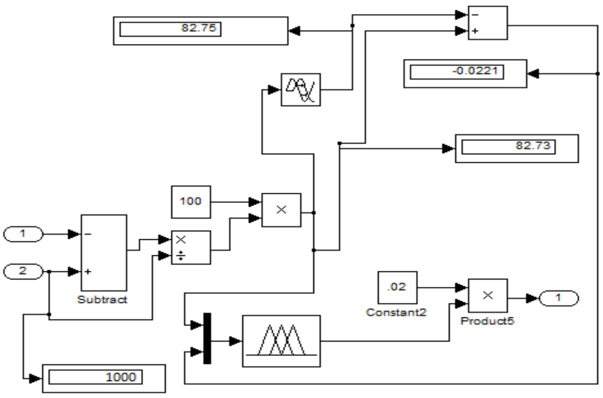

Fig.17. The fuzzy logic controller sub system for the AC link drive

6. Experimental Observations and Inferences

The observations, inferences along with the results based conclusions are discussed in this chapter.

6.1. Results of experimental Verification

The complete hardware to validate the proposed idea was constructed and tested. All the relevant waveforms with open loop and closed loop has been recorded and presented.

Fig.18. Experimental setup

The experimental setup was constructed and the waveforms were observed using a RIGOL 4 channel Digital Storage Oscilloscope. The various waveforms are recorded and presented in this chapter.

Fig.19. AC voltage

Fig.19. gives the waveform of the AC voltage at the resonant AC link realized across the tank circuit comprising of the L and the C.

Fig.20. BLDC input voltage

With the BLDC motor in operation, the line voltages across terminals of the BLDC motor are shown in fig.20. The measurement has been carried out with a 1:10 Probe.

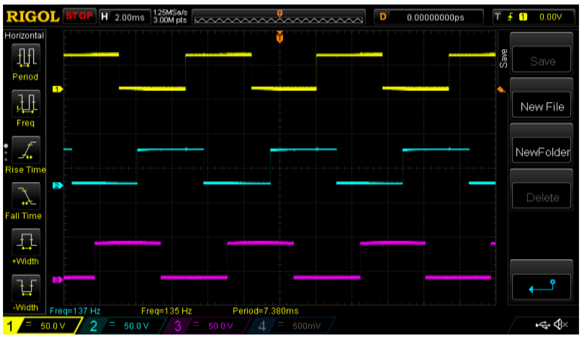

Fig.21. Hall sensor output

The Hall sensor signals measured across the three external pull up resistors used for the three Hall sensor output terminals are shown in fig.21. The Hall sensor outputs were pulled up to 5 volts since the operating voltage of the PIC micro Controller 16F877A is 5 Volts.

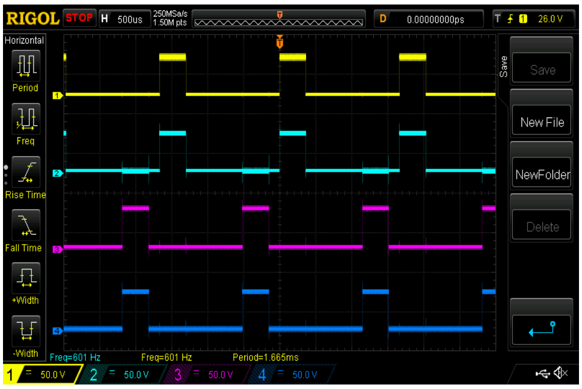

Fig.22. Inverter gate pulse

The resonant AC link is powered from the front-end inverter. For this inverter gating pulses are to be applied with a 180-degree phase delay for the cross arm switches. The first two signals are meant to switch on devices 1 and 2 while the lower two signals switch on devices 3 and 4.

Fig.23. Stator currents for phases RYB

Conclusion

The results reveal that the proposed scheme of operation of the BLDC motor with speed regulation in two degree of freedom is quite promising. The advantages of the proposed scheme are operational flexibility and small size of the source side inverter with high frequency AC link.

The combined two degrees of freedom controller incorporated in a coon FLC is also proved to have been effective in the simulation and experimental verification setup.

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