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# Direct Torque Control of BLDC Drives for Electrical Vehicle Application

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***Abstract*-Brushless DC (BLDC) motors are commonly used for several industrial applications because of their small size, high torque and high efficiency . This paper presents a Direct torque Control of brushless DC (BLDC) drive by using Hysteresis current control technique to extend the voltage capacity of batteries per charge in electric vehicle applications. In the conventional current control method, the current is still drawn from the batteries even when the motor is turned off. To avoid that leakage current, it is fed to zero crossing detector. By using Hysteresis comparator it produces high switching frequency, which produces ripple torque. But in this technique only current control is possible. The proposed method reduces the Torque ripple by controlling the inverter switching instants and high switching frequency by using direct torque control. The modeling, simulation and control of the BLDC motor is done by using the MATLAB/SIMULINK.***
***Keywords:-Brushless DC(BLDC)motor, Hysteresis controller , Electric vehicle (EV),Buck Converter(step down),Current Source Inverter(CSI), Zero Crossing Detector.***

## I. INTRODUCTION

Electric Vehicle (EV) is an emerging technology in the modern world because of the fact that it mitigates environmental pollutions and at the same time increases fuel efficiency of the vehicles. Battery-powered electric vehicles are one of the solutions proposed to tackle the energy disaster and global warming. However, the high initial cost, short driving range, long charging (refueling) time, and reduced passenger and cargo space have proved the limitation of battery-powered EVs. The efficiency of the battery is very important, because the electric motor uses the excess power of the engine to charge battery. If the engine generates more power than the driver then it provides additional power to assist the driving. BLDC drives are widely used for driving purpose.

BLDC motor is traditionally defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform shape. BLDC motors do not use brushes for commutation, instead, they are electronically commu-tated. The current commutation is done by solid state switches, which eliminates brush maintenance and sparking associated with them.

BLDC motors are one of the motor type's fast gaining the interest of the researchers. This motor attracts much interest due to its better speed, high dynamic response, high efficiency, long operating life, noiseless operation and power density, compactness, high torque potential for steep slope or road conditions, high reliability, robust-ness for electric vehicle and offers a reasonable cost.

BLDC motors are used in industries such as Industrial Automation equipment and Instrumentation, Appliances, Automotive, Aircraft, Consumer, Medical. BLDC motors are available many different power ratings, which differ from very small motor as used in hard disk drives to large motor used in electric vehicles.

## II. CONSTRUCTION OF BLDC MOTOR

In construction point of view BLDC motor has two main parts one is the stator (stationary part) and rotor (rotating part) in which the magnetic field generated by stator and rotor rotates at the same frequency, hence eliminating the slip which is normally seen in induction machine. The stator has armature windings on stator and rotor has permanent magnets.

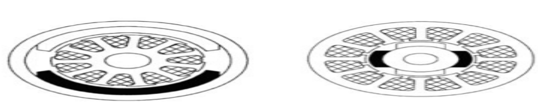


Fig 1. Outer Rotor and Inner Rotors

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BLDC motors have lifelong excitation from permanent magnets mounted on rotor surface. There are two basic rotor designs inner rotor design and outer rotor design as shown in fig 1. For the outer rotor design, the winding are located in the core of the motor. The rotor magnets surround the stator windings and acts as an insulator, reducing the rate of heat dissipation from the motor. This design operates at lower duty cycles or at lower rated current and it is used in low speed motors. The benefit of this design is relatively low cogging torque.

For the inner rotor design, the stator winding surround the rotor and is fixed at motor housing. The advantage of the design is the ability to dissipate heat thus directly impacts its ability to generate torque and its lower inertia and these are used in high speed applications.

Stator accommodates a 3-ϕ windings and the no of stator slots is chosen depending on the rotor poles, winding configuration, phase number. A fractional slots/pole design is preferred to minimize cogging torque. The winding slots are built into the stator and rotating magnetic field is provided by the current polarity changes in the slot windings. The change of current polarity must be in accordance to the rotor magnetic field, which requires the position of the rotor. Hall Effect sensors are fixed on the stator to provide this information. Solid state switches are used for current commutation which eliminates the need of brushes.

### *A. Operation of BLDC*

The fundamental working principle of BLDC motor is same as that of a conventional DC Motor with the permanent magnets placed in the rotor and coils in the stator. Having the armature windings on stator helps the conduction of heat from the windings. As the winding is absent on rotor, the rotor copper losses are negligible. The coil windings are electrically separate from each other which allows them to turn on and off in a sequence that creates a rotating magnetic field. The rotor position is to be determined so that excitation of the stator field always leads to the generation of torque. The rotor is not electrically connected to the stator thus preventing arcing phenomena which cause carbon to be produce hence making insulation failure.

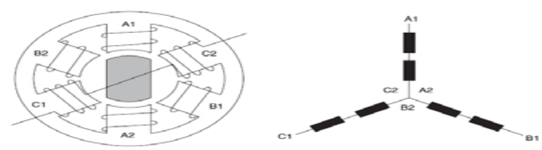


Fig 2. BLDC motor cross section and phase energizing sequence

Here the commutation instants are determined by the rotor position and the position of the rotor is detected either by position sensors or by sensor less techniques. For this mostly we are using two types of sensors they are Hall Effect sensors and Optical position sensors. These sensors are placed on shaft. The signals from these sensors that generally used in BLDC motor drive to energize the appropriate stator windings. The permanent magnets used in BLDC motor it helps to keep the inertia low. The back e.m.f amplitude of the BLDC is proportional to the rotor speed.

TABLE II. Hall Signals and Phase Sequence

| **Switching sequence** | **Seq. no** | **Position sensors** | | | **Switch closed** | | **Phase current** | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $H_1$ | $H_2$ | $H_3$ | | | **A** | **B** | **C** |
| **$0^0$-$60^0$** | 0 | 1 | 0 | 0 | $Q_1$ | $Q_4$ | + | - | Off |
| **$60^0$-$120^0$** | 1 | 1 | 1 | 0 | $Q_1$ | $Q_6$ | + | Off | - |
| **$120^0$-$180^0$** | 2 | 0 | 1 | 0 | $Q_3$ | $Q_6$ | Off | + | - |
| **$180^0$-$240^0$** | 3 | 0 | 1 | 1 | $Q_3$ | $Q_2$ | - | + | off |
| **$240^0$-$300^0$** | 4 | 0 | 0 | 1 | $Q_5$ | $Q_2$ | - | off | + |
| **$300^0$-$360^0$** | 5 | 1 | 0 | 1 | $Q_5$ | $Q_4$ | off | - | + |

The air gap flux-density wave form is essentially square wave, w.r.t the rotor position. Because of firing the back e.m.f waveform takes on trapezoidal shape. The back e.m.f induced in each phase are similar in shape and are displaced by $120^0$ w.r.t each other. By injecting rectangular current pulses in each phase that coincides with the crest of the back e.m.f wave form in that phase, it is possible to obtain almost constant torque from the BLDC motor.

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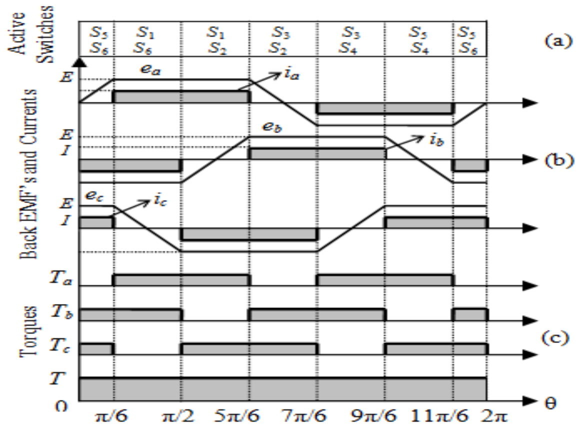


Fig 3. Three phase Back E.M.F and Torque wave forms

The amplitude of the phase back e.m.f is proportional to the rotor speed, which is given by

$E = k\phi\, \omega_m$ (1) Where k = a constant depends on the no.of turns in each phase, $\phi$ = permanent magnate flux, ωm = mechanical speed.

During any $120^0$ interval, the instaneous power is converted from electrical form to mechanical form, it is given by

$P_o = \omega_m T_e = 2\, EI$ (2)

So the out put torque can be written as

$T_e = 2\, k\phi\, I = T_e = k_t\, I$ (3)

Where $k_t$ = torque constant, $T_e$ = out put toque

A BLDC motor mathematical equations can be derived similar to DC machines where there are two equivalent circuits, i.e. electrical and mechanical equations. Figure 4 shows the basic blocks of BLDC motor that contains three phase stator circuit and mechanical part.

Applying Kirchhoff's voltage law for the three phase stator loop winding circuits yields

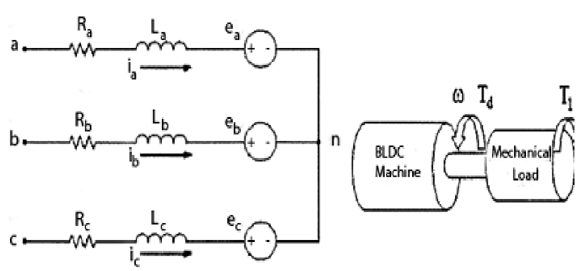


Fig 4. 3-$\phi$ Brushless DC machine equivalent circuit and mechanical model.

$$v_a = iaR_a + L_a \frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ac}\frac{di_c}{dt} + e_a \quad (4) \qquad v_b = ibR_b + L_b \frac{di_b}{dt} + M_{bc}\frac{di_a}{dt} + M_{ba}\frac{di_c}{dt} + e_b \quad (5)$$

$$v_c = icR_c + L_c \frac{di_c}{dt} + M_{ca}\frac{di_a}{dt} + M_{cb}\frac{di_b}{dt} + e_c \quad (6)$$

Where, $v_a$ = instantaneous of phase voltage

$i_a$= instantaneous of phase current

$e_a$= instantaneous of phase back-emf voltage

$R_a$= r-phase resistance

$L_a$= a-phase inductance

M= mutual inductance

The electromagnetic Torque is given by

$$T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega_m \qquad (7)$$

The discussion has concentrated on the operation of BLDC machine as a motor. It can however operate equally well as a generator in some special applications.

## III. CONVENTIONAL CONTROL SYSTEM

It is a simple method that can offer these requirements is the use of current control technique. Figure 5 shows the structure of current controller for BLDC motor. The control of current can be established by controlling the three-phase current at its reference such that

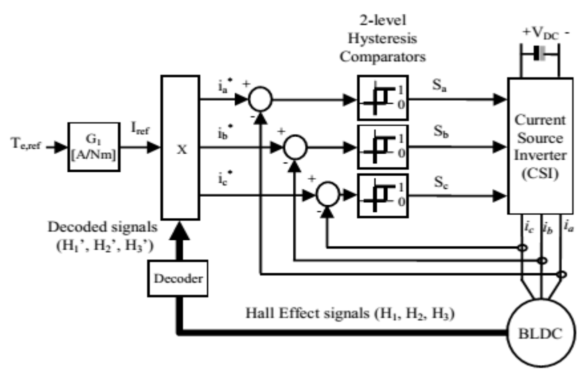


Fig 5. Structure of Conventional Current Control drive for BLDC motor.

it will satisfy the equations (4).As shown by Fig. 5, the motor currents need to be controlled satisfying to their references ($i_a$*, $i_b$*and $i_c$*). The generations of reference currents are based on the torque demand (i.e. Iref =Te,ref x $G_1$) and decoded signals ($H_1$', $H_2$' and $H_3$') which are derived from the Hall Effect signals ($H_1$, $H_2$ and $H_3$) as given in Table. I

TABLE I: Derivation of Decoded Signals based on Hall Signals

| Hall Effect signals | | | Decoded Signals | | |
|---|---|---|---|---|---|
| $H_1$ | $H_2$ | $H_3$ | $H_1$ | $H_2$ | $H_3$ |
| 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 | -1 | 0 |
| 1 | 0 | 1 | 0 | +1 | -1 |
| 1 | 1 | 0 | 0 | +1 | -1 |
| 1 | 1 | 1 | 0 | 0 | 0 |

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Each phase current is controlled using a 2-level hysteresis comparator, which is responsible to produce appropriate switching status to be fed into the inver-ter, either to increase or decrease the phase current such that its error (or current ripple) is restricted within the hysteresis band (HB).In such a way, the reference current for each phase will have the same pattern waveform with the respective decoded signals.

In the conventional current control method, the current is still drawn from the batteries even the reference current is set to zero. As the phase current needs to be regulated IGBTs/MOSFETs in the inverter,. When the torque pedal is released ($T_{e,ref}$= 0) and once the actual motor torque is completely reduced to zero. This section presents a current blocking strategy to avoid a waste of energy from the battery (due to the current drawn) when the torque pedal is released (i.e. $T_{e,ref}$= 0) for electric vehicle applications.

This simply can be established with minor modification on the original structure of current control (shown in Fig. 5) Using hysteresis comparator as shown in Fig. 6 within the hysteresis band at around zero Amperes (A). To block the current drawn from the battery, the proposed current blocking strategy will turn OFF all. By referring to the Fig. 6, the activation of current blocking strategy requires the absolute value of torque demand, $T_{e,ref}$ and phase currents ($i_a$, $i_b$ and $i_c$) which are then fed into zero crossing detector and hysteresis comparator, respecti-vely.

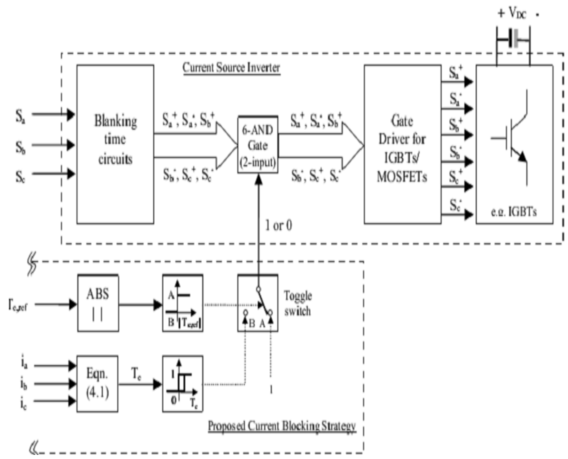


Fig 6. Conventional current blocking strategy based on hysteresis comparator

The activation to switch OFF all IGBTs/MOSFETs in current source inverter will perform if the torque produ-ction, Te and torque demand, Te,ref decrease to zero. For clearer picture, the condition of the activation is illustrated in Fig 7. Otherwise, normal switching opera-tion to keep the current (or torque) to be regulated within the hysteresis band will perform.

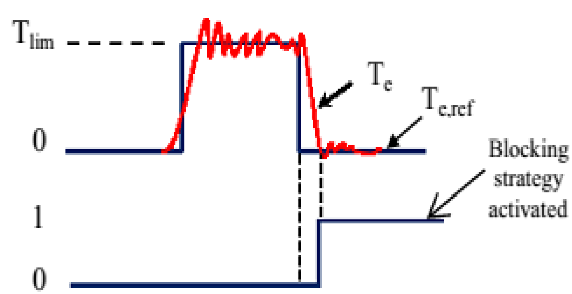


Fig 7. Blocking Strategy is Activated if Te and $T_{e,Ref}$ Decrease to

## IV. BLOCK DIAGRAM COMPONENTS

### A. Current Controller

Hysteresis control is one of the simplest closed-loop control schemes. A reference sine wave current is compa-red with the actual phase current. When the current exceeds a prescribed hysteresis band, the upper switch in the inverter bridge is turned off

 

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and the lower switch is turned on, and the current starts to decay. As the current crosses the lower band limit, the lower switch is turned off and the upper switch is turned on. The actual current is forced to track the sine reference within the hysteresis band by back and forth (or bang-bang) switching of the upper and lower switches. The inverter then essentially becomes a current source with peak-to-peak current ripple, which is controlled within the hysteresis band. In hysteresis control, the value of the controlled variable is forced to stay within certain limits around its reference value. By comparing with PWM technique, hysteresis current controller is preferred, considering its performance, fast reaction maximum current limit and insensible to load parameter variations.

Due to lack of coordination among individual hysteresis controllers of three phases, very high switching frequency at lower modulation index may happen [7]. The disadvantage of the hysteresis band control technique are the high and uncontrolled switching. frequencies when a narrow hysteresis band is used and large ripples when the hysteresis band is wider [8].

The uncontrolled switching frequency makes it difficult to filter the acoustic and electromagnetic noise. The switc-hing method used here is the soft chopping method in which only the upper switch is turned on and off while the lower switch is left on. This method produces less torque ripple and less switching losses than the hard chopp-ing method. Only current control is implemented here. The reason is that if position control is to be implemented in the same way as the torque and the position control, it would only be possible by constantly reversing the rotor speed so that the rotor angle would stay within the hysteresis band..

### *B. Rectifier*

Rectifier is an electronic equipment; that converts alternating current to direct current (A.C-D.C), which flows only in one direction. Many applications of rectif-iers, such as power supplies for television and computer equipment, radios, where a constant DC current (as would be produced by a battery) is required. In these applications the output of the rectifier is curved by an electronic filter (usually a capacitor) to generate a steady current.

### *C. DC/DC Converter (Buck Converter)*

A buck converter is a voltage step down and current step up converter. The basic operation of the buck converter has the current in an inductor restricted by two switches (usually a transistor and a diode).

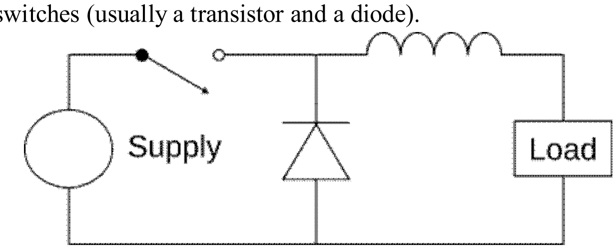


Fig 8. DC /D.C (buck) converter

In this paper, the buck converter is used for voltage step down purpose of rectified D.C. the voltage is being controlled depending on the duty ratio (D). The gate signals are generated by using current speed wave forms of the motor. This controlled voltage is fed to the battery.

Output voltage of buck converter

$$V_o = D\, V_{in} \tag{8}$$

### *D. Current Source Inverter (C.S.I)*

An inverter is an electronic device that changes direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling depend on the design of the particular device. The converter is a three phase DC to AC converter and it consists of six solid state semiconductor switches as shown in Figure 9. Mosfets and IGBT are the most common types of switches used. In lower power application, Mosfets are preferred over IGBT. The power electronic converter is necessary to operate the BLDC machine. Current commutation is done by a six-step inverter. The three phase BLDC motor is operating in a two phases-on fashion which means the two phases that produce the highest torque are energized while the third phase is off, see Figure 2. The two phases are energized depends on the rotor position. Hall Effect position sensors are most frequently used.

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The inverter is responsible for both the Electronic commutation and current regulation. The conduction of every phase winding is determined by the rotor position where the position can be known from hall effect sensors that provides three digit output that changes every 60 degree (electrical degrees).The generation of three digitized outputs (i.e. H1,H2 and H3) from the sensor according to the rotor position can be also described in Table 2.

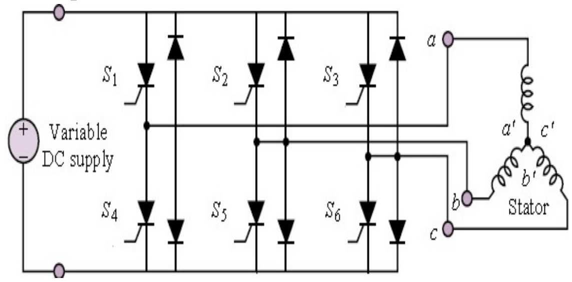


Fig 9. Three-Phase DC /AC inverter.

The power electronic inverter must be capable of applying positive, negative and zero voltage across the motor phase terminals. Each drive phase consists of one motor terminal driven high, one motor terminal driven low, and one motor terminal floating [6].

## V. PROPOSED *DIRECT TORQUE CONTROL* TOPOLOGY

In the conventional current control strategy only current will be controlled, with high ripples in torque. The Direct Torque Control scheme is extended to BLDC motor drives to minimize the Torque Ripples. The electro-magnetic torque and the stator flux linkage amplitude of the BLDC motor under 2-phase conduction mode can be controlled simultaneously.

Here we are going to reduce the ripples in torque by using direct torque control. Mainly BLDC drive has a drawback of high torque pulsation. Basically it is caused by two-components one is ripple torque and another one is commutation torque.

The main components of ripple torque are motor related and inverter related. Motor related components are produced by the non-idealities in the back e.m.f wave forms. Here Motor relates cogging torque, inverter relates ripple torque.

Ripple torque is a consequence of the interaction of the armature currents with the machine back e.m.f wave forms. Cogging torque produced by variation of reluctance caused by the stator slot openings as rotor rotates. Cogging torque can be reduced by skewing and by choosing a fractional slot/pole motor design.

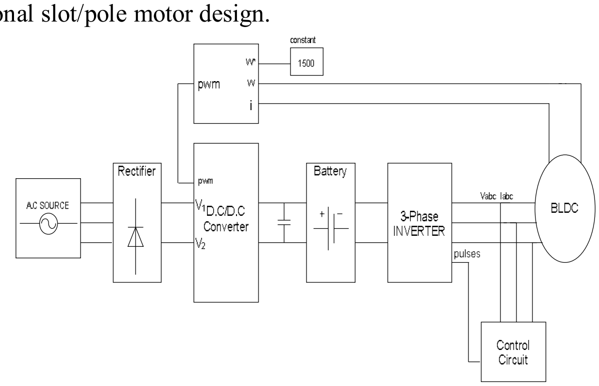


Fig 10. Block diagram of proposed system

The inverter related ripple torque components departure from the ideal rectangular current profiles due to finite inductance. The inverter related ripple torque is caused by the Hysteresis controller because which produces high switching frequency current ripple. This high frequency ripple is caused by corresponding ripple in phase current. The back e.m.f related component has high frequency; it is Six times of the electrical frequency, corresponding to the six conduction intervals in each cycle. At low speeds they can affect the performance of the drive, but at high speeds it is not a problem as it is filtered out by load inertia. This high frequency torque ripple is reduced by controlling the current and rotor position.

The second component of inverter related torque ripple is commutation torque ripple, it occurs at every commutation instant. The torque ripple generates some of the currents at ON/OFF position almost never constant during the switching instants. Here

ISSN: 2321-9653
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the current is commutated from B - phase to C – phase. The rate at which the current builds up in C – phase is greater than the rate at which decays in B – phase, which results in current ripple in A – phase and a resultant ripple in torque production. This torque ripple depends on rotor speed and source voltage. This commutation ripple component is minimized by using current sensor in each phase. Here D.C/D.C converter controls the source voltage, BLDC motor current and actual speed ($\omega_m$). Actual speed compared with reference speed ($\omega$*) and is controlled using PI controller. The PWM controller generates the switching pulses to the buck converter, which controls the source voltage.

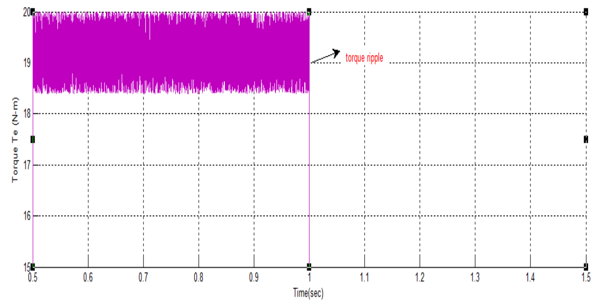


Fig 11. Ripple Torque Wave Forms

In conventional current control only current control is possible, but having large torque ripple as shown in above fig 11.(ripple is nearly 1.4 N-m).

## VI. SIMULATION CIRCUITS AND RESULTS

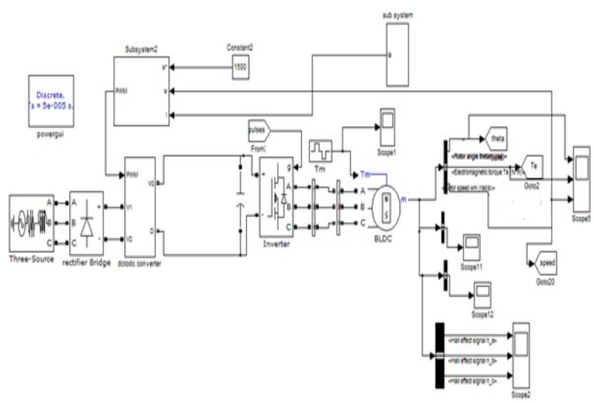


Fig 12. Simulink Block Diagram of Overall System

The above figure.12 shows simulation diagram of overall controlling system. It contains a.c source, d.c/d.c converter, inverter and BLDC drive.

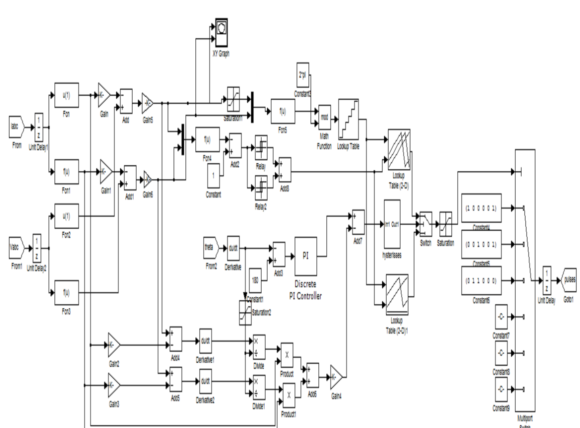

Fig 13. Simulink Circuit of Controlling Circuit

Figure13 shows the simulation diagram of inverter controlling system. It controls torque and speed by controlling current and rotor position.

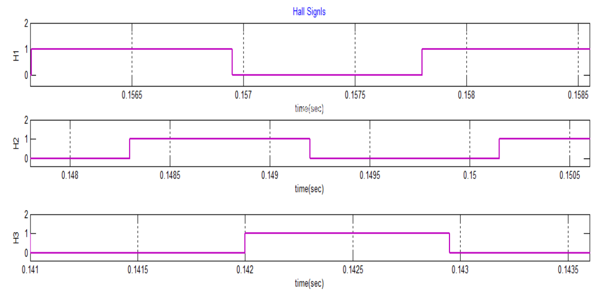


Fig 14. Hall Sensor Signals

Figure 14 shows the hall signals are generated by the leakage flux at the appropriate rotor positions

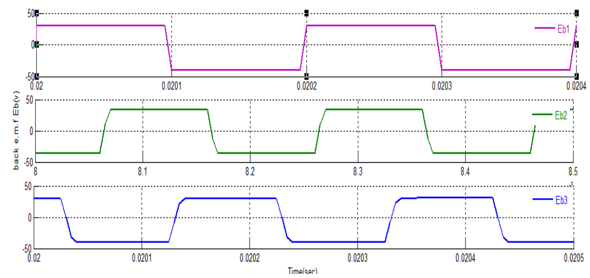


Fig 15. Back E.M.F Wave Forms

Figure 15 shows Back E.M.F wave forms. Which are displaced by 1200 w.r.t each other in a 3-phase machine.

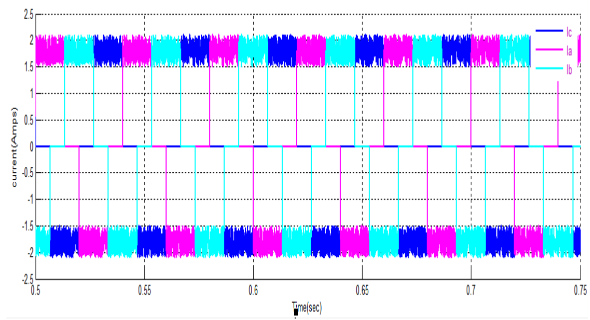


Fig 16. Motor Stator Currents

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Figure 16 shows 3-phase stator currents and the current error ripple is restricted within the predefined band gap.

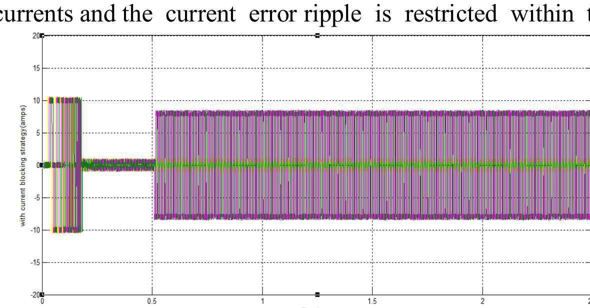


Fig.17. blocking strategy Motor leakage Currents

Above fig.17 wave forms shows leakage current of the motor. Current ripple is reduced small amount compared to current control 1A to 0.8 A.

 

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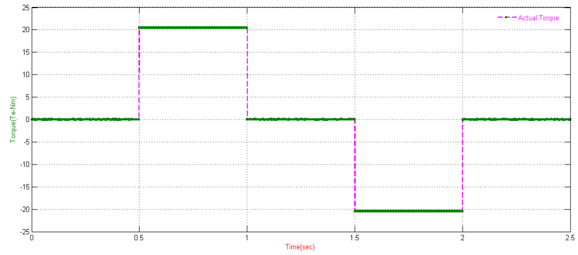


Fig.18(a). Torque wave forms

The above figure shows reduced ripple torque waveforms.

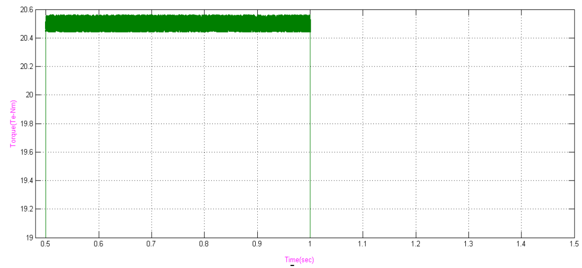


Fig18(b). Torque Wave Forms

The above figure shows reduced ripple torque waveforms (ripple is reduced from 1.4 N-m to 0.12 N-m).

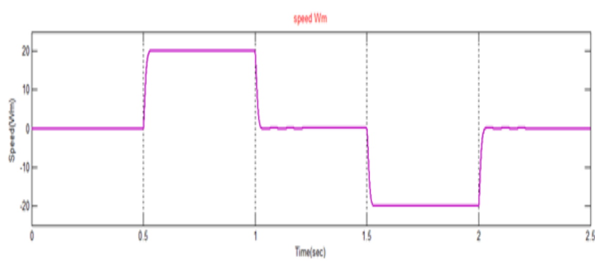


Fig 19.Speed Wave Forms

Above figures 18 & 19 shows Torque and speed wave forms, these are in positive and negative. It can be observed as the speed and torque decreases (during motor braking) the frequency of the current waveforms decreases and as the speed and torque increase (during motor acceleration) the frequency of the current waveforms increases. By the operation of a BLDC motor it can however work as generator. The polarity of Torque can be reversed by simply reversing the polarity of phase current waveforms w.r.t back e.m.f. waveforms. In regenerative breaking it is used an advantage, in vehicle population. For example special arrangements are needed in the power converter to allow the energy returned by the machine, as conventional diode bridge rectifiers are unable to feed back to the A.C. supply. In automobile applications this situation is considerably simplified by using the battery as a source.

TABLE 2: Performance Comparison

| | **Without Blocking Strategy** | **Current control** | **Direct Torque control** |
|---|---|---|---|
| **Torque Ripple** | 1.6 N-m | 1.4 N-m | 0.12 N-m |
| **Current Ripple** | 4.9 A | 1 A | 0.8 A |

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## VII. CONCLUSION

This paper presents simulation results of a Direct Torque Control of brushless DC (BLDC) drive by using Hysteresis current control technique to extend the voltage capacity of batteries per charge in electric vehicle applications. In the conventional current control method, the current is still drawn from the batteries even when the motor is turned off. To avoid that leakage current, it is fed to zero crossing detector. By using Hysteresis comparator it produces high switching frequency, which produces ripple torque. But in this technique only current control is possible. The proposed method reduces the Torque ripple by controlling the inverter switching instants and high switching frequency by using Direct Torque control. The simulations of the direct torque control were performed using MATLAB/Simulink.

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