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Torque Hysteresis Control of BLDC Drives for EV Application by using fuzzy logic controller

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Abstract— **With ever increasing oil prices and concerns for the natural environment, there is a fast growing interest in electric vehicles (EVs). However, energy storage is the weak point of the EVs that delays their progress. For this reason, a need arises to build more efficient, light weight, and compact electric propulsion systems, so as to maximize driving range per charge. There are basically two ways to achieve high power density and high efficiency drives. The first technique is to employ high-speed motors, so that motor volume and weight are greatly reduced for the same rated output power. Most adjustable speed drive systems employ a single three-phase induction motor. With such a drive system, the drive has to be shut down if any phase fails. In order to improve reliability of drive systems, six-phase induction motors fed by double current source inverters have been introduced. Such a drive requires a specially wound multiphase motor but enables the motor to continue to operate at failure of any single drive unit, although it does degrade motor performance. Compared to induction motors, permanent magnet (PM) motors have higher efficiency due to the elimination of magnetizing current and copper loss in the rotor. It has become possible because of their superior performance in terms of high efficiency, fast response, weight, precise and accurate control, high reliability, maintenance free operation, brushless construction and reduced size. This project presents a current blocking strategy of brushless DC (BLDC) motor drive to prolong the capacity voltage of batteries per charge in electric vehicle applications. The BLDC motor employs a fuzzy controller for torque hysteresis control (THC) that can offer a robust control and quick torque dynamic performance. The proposed concept is verified by using Matlab/Simulink software and the corresponding results are presented.**

Index Terms— **components; Brushless DC motor, hall effect, current controller, electric vehicle (EV) , hybrid electric vehicle (HEV), torque hysteresis controller (THC) fuzzy logic controller**

I. INTRODUCTION

Conventional dc motors are highly efficient and their characteristics make it reliable for use in many applications. However, the only drawback is that it uses commutator and brushes that require frequent maintenance and cannot be performed at dirty and explosive environment and at very high speed operating conditions [1]. When the functions of commutator and brushes were replaced by solid-state

switches, maintenance-free motor were developed. These

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types of motors are now known as brushless dc motors. Brushless dc (BLDC) motors are in fact a type of permanent magnet synchronous motors. It is driven by dc voltage and the current commutation is done by solid state switches. BLDC motor implements the basic operating principles of DC motor operation but with a difference by placing the permanent magnet in the rotor and coils in the stator. The coil windings are electrically separate from each other which allow it to be turn on and off in a sequence that creates a rotating magnetic field. The rotor position needs to be determined so that excitation of the stator field always leads the permanent magnet field to produce torque. The commutation instants are determined by the rotor position and the position of the rotor is detected either by position sensors or by sensorless techniques. The signals from Hall Effect sensors that usually used in BLDC motor need to decode to determine the shaft and energize the appropriate stator windings.

In general, the PMSM can be classified into two types depending on back-emf wave shape production, i.e. sinusoidal and trapezoidal wave shapes. The one that is operated in sinusoidal is normally referred to as permanent magnet AC motor or brushless AC motor. The latter one that produces trapezoidal back-emf wave shape is normally called as brushless DC motor (BLDC). It can be shown that the production of torque in BLDC is quite similar to that of brushed DC motor with simple control algorithm [2][3].

BLDC motors are available in many different power ratings, which vary from very small motor as used in hard disk drives to large motor used in electric vehicles. BLDC motor attracts much interest due to its high efficiency over wide torque and speed ranges, high torque & power density, compactness, high torque capability for steep slope or road conditions, high reliability and robustness for electric vehicle, low acoustic noise and offers a reasonable cost. The power circuit components that are required to convert from alternating current to direct current provide the basis for variable-speed drive, making BLDC motors well-suited for applications that require speed control over a wide operating range. The permanent magnets used in BLDC motor helps to keep the inertia low. The BLDC motor generates less heat because there is no current flow in the rotor thus allowing efficient heat dissipation from the BLDC motor's wound stator to the outer metallic housing.

In many electrical drive applications, it is desirable to achieve fast torque dynamic response as produced in brushed DC motor, whereby the torque (T_e) can be directly controlled by regulating the armature current (i_a), i.e. $T_e = K_T \times i_a$, where K_T is the constant torque. Several papers were reported to achieve this requirement, for example in [4] generates the maximum possible voltage vector that is tangential to the flux

component to have a quick change of torque dynamic and in [5] using THC method without the proposed current blocking strategy.
Ultimately, all these methods used a vector control which is complicated to be implemented.

This paper presents the current control method implemented in THC motor drive. The simulation of THC for BLDC motor drive system is developed using 'Matlab/Simulink'. The simulation circuit includes all realistic components of the drive system. A comparative study associated with hysteresis and PWM techniques in current controllers has been made. By comparing these techniques, hysteresis current controller is chosen considering its easy implementation, quick response, maximum current limit and insensitive to load parameter variations.

II. CONSTRUCTION OF BLDC MOTOR

BLDC motor is a synchronous type of motor 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. BLDC motor has two primary pats which is rotor (rotating part), stator (stationary part) and permanent magnet of the rotor. There are two basic rotor designs which is inner rotor and the other one is outer rotor.

For the inner rotor design, the stator winding surround the rotor and are fixed at motor housing. The advantages of the design are the ability to dissipate heat thus directly impacts its ability to generate torque and its lower inertia. 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. The advantage of this design is relatively low cogging torque. The winding slots are built into the stator and changing 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.

There are two types of back-emf that a BLDC motor can generate which are trapezoidal and sinusoidal waveforms [6]. The back-emf is determined by the manner in which windings are placed in the stator, either concentrated or distributed windings. Concentrated windings produce a trapezoidal back-emf while distributed windings result in a sinusoidal back-emf.

For the permanent magnet rotor, there are also two designs which are practiced. The first design place the permanent magnet onto the surface of the rotor. By placing the magnet onto the rotor reduces the manufacturing time but during high speed condition there is possibilities that the magnet might fly off the rotor. For the other design the magnets are inserted beneath the surface of the rotor. This practice requires additional machining of the rotor to create the slots for the magnets which in the end increased the manufacturing time and cost. However, the advantage is that the motor can be operated at very high speed conditions without the danger of magnet failure.

The three phase BLDC motor is operated in a two-phases-on fashion which is mean the two phases that produce the highest torque are energized while the third phase is off, see Figure 1. The two phases are energized depends on the rotor position. The signals from the position sensors produce a three digit number that changes every 60 degree (electrical degrees). Current commutation is done by a six-step inverter.

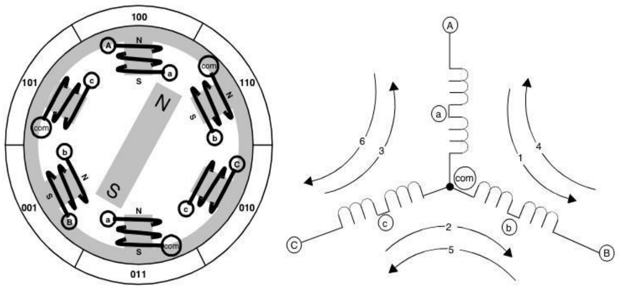


Fig 1. BLDC motor cross section and phase energizing sequence.

The power electronic converter is necessary to operate the BLDC machine. The converter is a three phase DC to AC converter and it consists of six solid state semiconductor switches as shown in Figure 2. Mosfets and IGBT are the most common types of switches used. In lower power application, mosfets are preferred over IGBT. 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].

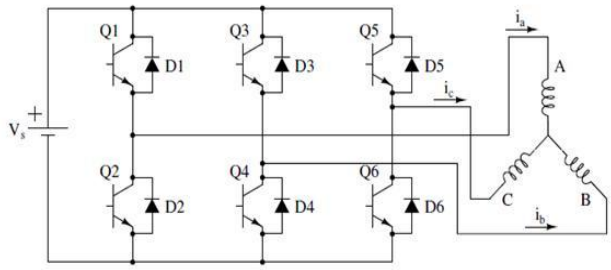


Fig 2. Three-Phase DC to AC inverter.

III. MODELLING OF BLDC MACHINES

Mathematical modeling of a BLDC motor can be derived similar to DC machines where there are two equivalent circuits, i.e electrical and mechanical equations. Figure 3 shows the basic blocks of BLDC motor that contains three phase stator circuit and mechanical part. The main difference compare to DC machines is the construction of the machine where it has three phase windings at the stator (with n number of poles) and the rotor equipped with permanent magnet which is positioned at the center of the motor by the bearing. The rotor is not electrically connected to the stator thus preventing arcing phenomena which cause carbon to be produce hence making insulation failure.

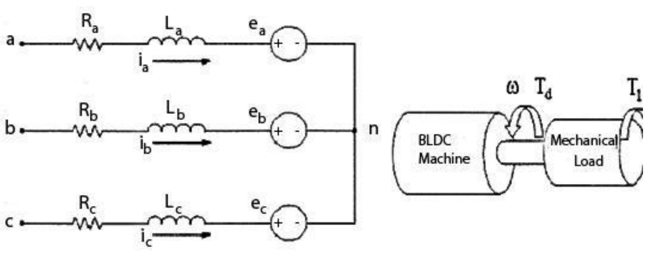


Fig 3. Three phase Brushless DC machine equivalent circuit and mechanical model.

For simplification, the electrical model is expressed for one phase of stator winding, e.g. phase *k* (*k* = *a*,*b* or *c*) as given by (1).

$$V_{kn}(t) = I_k R_k + L_k \frac{di_k}{dt}(t) + e_k(t) \quad (1)$$

where,

$v_{kn}(t)$ = instantaneous of *k*-phase voltage

$i_k(t)$ = instantaneous of *k*-phase current

$e_k(t)$ = instantaneous of *k*-phase back-emf voltage

R_k = *k*-phase resistance

L_k = *k*-phase inductance

On the other hand, the mechanical model of BLDC machine actually represents the production of torque as given by (2).

$$T_{em}(t) = J\frac{dw(t)}{dt} + Bw(t) + T_l(t) \quad (2)$$

where,

$\omega(t)$ = rotor angular velocity

B = viscous friction

J = moment of inertia

T_L = load torque

It should be noted that the production of torque is the summation of the torque produced for each phase

$$T_{em}(t) = \sum T_{em,k}(t) \quad (3)$$

The productions of torque and back-emf voltage for each phase are calculated as;

$$T_{em,k}(t) = I_k(t).k_{t,k}(\Theta) \quad (4)$$

$$e_k(t) = k_{v,k}(\Theta)\, w_e(t) \quad (5)$$

where, the torque factor $k_{T,k}(\Theta)$ can be assumed equivalent to the back-emf voltage factor $k_{V,k}(\Theta)$. The angular velocity (ω_e) is multiplication of rotor angular velocity and number of poles of the machine, i.e. ω x number of poles. For trapezoidal operated in BLDC motor, the $k_{T,k}(\Theta)$ and $k_{V,k}(\Theta)$ are not constant as opposed to the constant field operated in brushes DC motor. Given
the rotor position (Θ), these factors can be simply obtained using piece-wise normalized trapezoidal function as illustrated in Fig. 4.

From Fig. 4, it can be noticed that each phase winding is conducted in sequence for 120^0 per one cycle of period to carry either positive or negative constant current. The conduction of each phase winding is determined by the rotor position where the position can be known from hall effect sensors that provides three digitized output. The generation of three digitized outputs (i.e. H_1,H_2 and H_3) from the sensor according to the rotor position can be also described in Fig. 4

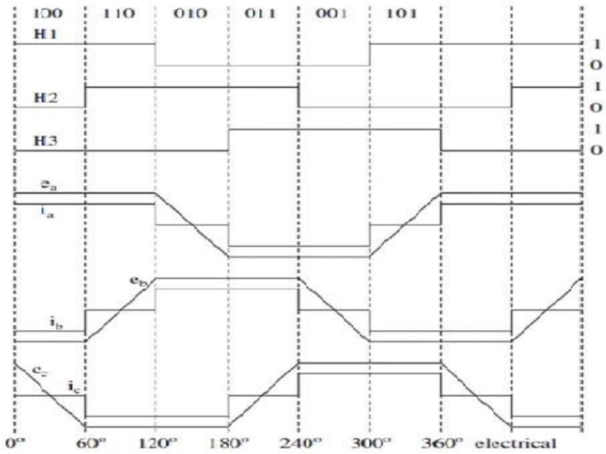


Fig 4. Three phase Brushless DC machine equivalent circuit and mechanical model.

IV. CURRENT CONTROLLER

Hysteresis control is one of the simplest closed-loop control schemes. In hysteresis control, the value of the controlled variable is forced to stay within certain limits around its reference value. For example, to control motor speed, the motor is turned off if the speed reaches a certain level above the reference speed and turned back on when the speed falls below a certain level below the reference speed. Nevertheless, due to lack of coordination among individual hysteresis controller of three phase, very high switching frequency at lower modulation index may happen [7].

The drawbacks 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 uncertain switching frequency make filtering of acoustic and electromagnetic noise become difficult. The switching method used here is the soft chopping method which is 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 chopping method. Only current control and speed control is implemented here. The reason is that if position control were 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.

It is desirable to provide current limitation and fast torque dynamic control for many electric drive applications. 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 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. $I_{ref} = T_{e,ref}$ 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 1.

TABLE 1 Derivation of Decoded Signals based on Hall Effect Signals

Hall Eff. 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

Each phase current is controlled using a 2-level hysteresis comparator, which is responsible to produce appropriate switching status to be fed into the inverter, 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.

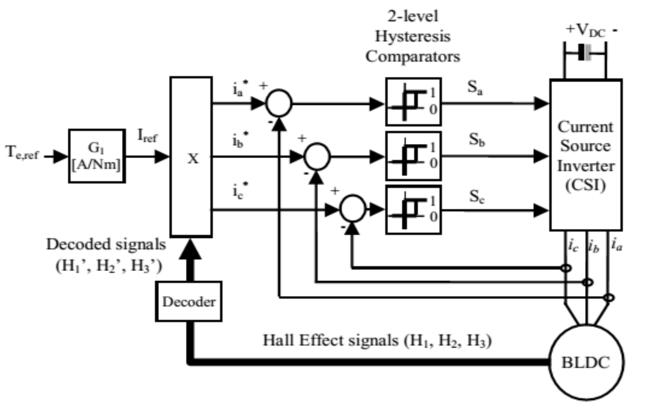


Fig 5. Structure of Optimal Current Control drive for BLDC motor.

V. PROPOSED CURRENT BLOCKING STRATEGY

This section presents a new 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. 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 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 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 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. 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, respectively. The activation to switch OFF all IGBTs/MOSFETs in current source inverter will perform if the torque production, T_e and torque demand,

$T_{e,ref}$ decrease to zero. For clearer picture, the condition of the activation is illustrated in Fig 7. Otherwise, normal switching operation to keep the current (or torque) to be regulated within the hysteresis band will perform.

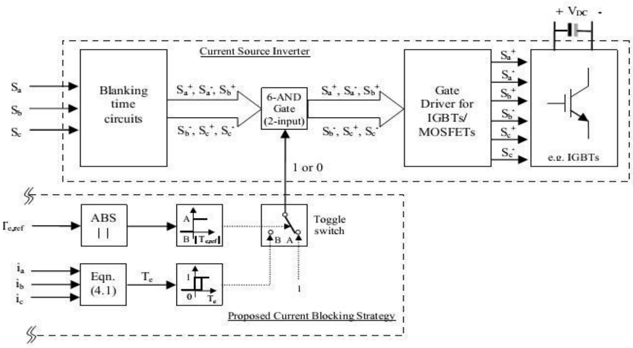


Fig 6.proposed blocking strategy based on hysteresis comparator.

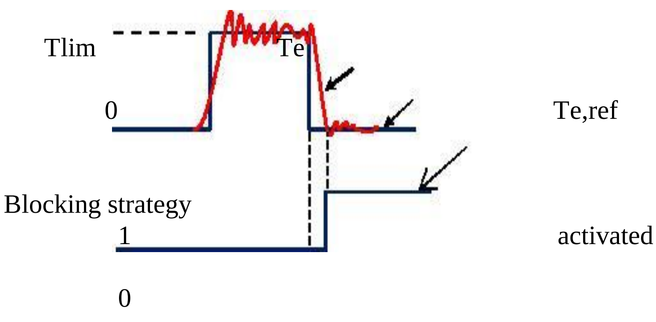


Fig 7. Blocking strategy is activated if T_e and $T_{e,ref}$ decrease to zero

VI. FUZZY LOGIC CONTROLLER:

In recent years, the number and variety of applications of Fuzzy Logic (FL) have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

To understand why use of Fuzzy Logic has grown, it must be first understood as what is meant by Fuzzy Logic.

Fuzzy Logic has two different meanings. In a narrow sense, Fuzzy Logic is a logical system, which is an extension of multivalve logic. However, in a wider sense Fuzzy Logic is almost synonymous with the theory of Fuzzy sets, a theory which relates to classes of objects with un sharp boundaries in which membership is a matter of degree. In this perspective, Fuzzy logic in its narrow sense is a branch of Fuzzy Logic. Even in its more narrow definition, Fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

VII. IMPORTANCE OF FUZZY LOGIC

Fuzzy logic is all about the relative importance of precision: use as Fuzzy Logic Toolbox software with MATLAB technical computing software as a tool for solving problems with fuzzy logic. Fuzzy logic is a fascinating area of research because it does a good job of trading off between significance and precision something that humans have been managing for a very long time.

In this sense, fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the concept of fuzzy logic relies on age-old skills of human reasoning.

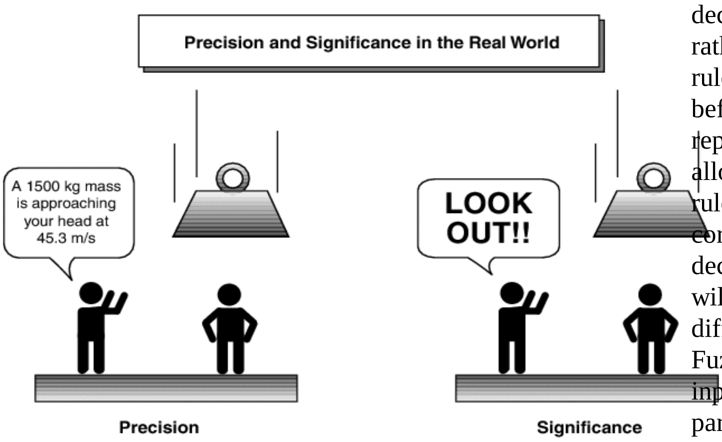


Fig Fuzzy Description

USAGE OF FUZZY LOGIC

Fuzzy logic is a convenient way to map an input space to an output space. Mapping input to output is the starting point for everything. Consider the following examples:

- With information about how good your service was at a restaurant, a fuzzy logic system can tell you what the tip should be.
- With your specification of how hot you want the water, a fuzzy logic system can adjust the faucet valve to the right setting.
- With information about how far away the subject of your photograph is, a fuzzy logic system can focus the lens for you.
- With information about how fast the car is going and how hard the motor is working, a fuzzy logic system can shift gears for you.

To determine the appropriate amount of tip requires mapping inputs to the appropriate outputs. Between the input and the output, the preceding figure shows a black box that can contain any number of things: fuzzy systems, linear systems, expert systems, neural networks, differential equations, interpolated multi dimensional lookup tables, or even a spiritual advisor, just to name a few of the possible options. Clearly the list could go on and on.

Of the dozens of ways to make the black box work, it turns out that fuzzy is often the very best way. As Lotfi Zadeh, who is considered to be the father of fuzzy logic, once remarked: "In almost every case you can build the same product without fuzzy logic, but fuzzy is faster and cheaper".

VIII. CONVENIENCE OF FUZZY LOGIC

Fuzzy logic is not a cure-all. When should you not use fuzzy logic? The safest statement is the first one made in this introduction: fuzzy logic is a convenient way to map an input space to an output space. Fuzzy logic is the codification of common sense — use common sense when you implement it and which will probably make the right decision. Many controllers, for example, do a fine job without using fuzzy logic. However, it take the time to become familiar with fuzzy logic, it can be a very powerful tool for dealing quickly and efficiently with imprecision and nonlinearity.

A. The Fuzzy Logic Concept

Fuzzy logic arose from a desire to incorporate logical reasoning and the intuitive decision making of an expert operator into an automated system [14]. The aim is to make decisions based on a number of learned or predefined rules, rather than numerical calculations. Fuzzy logic incorporates a rule-base structure in attempting to make decisions. However, before the rule-base can be used, the input data should be represented in such a way as to retain meaning, while still allowing for manipulation. Fuzzy logic is an aggregation of rules, based on the input state variables condition with a corresponding desired output. A mechanism must exist to decide on which output, or combination of different outputs, will be used since each rule could conceivably result in a different output action.

Fuzzy logic can be viewed as an alternative form of input=output mapping. Consider the input premise, x, and a particular qualification of the input x represented by Ai. Additionally, the corresponding output, y, can be qualified by expression Ci . Thus, a fuzzy logic representation of the relationship between the input x and the output y could be described by the following:

R1: IF x is A1 THEN y is C1
R2: IF x is A2 THEN y is C2
. . . .
. . . .
Rn: IF x is An THEN y is Cn

where x is the input (state variable), y is the output of the system, Ai are the different fuzzy variables used to classify the input x and Ci are the different fuzzy variables used to classify the output y. The fuzzy rule representation is linguistically based .

Thus, the input x is a linguistic variable that corresponds to the state variable under consideration. Furthermore, the elements Ai are fuzzy variables that describe the input x. Correspondingly, the elements Ci are the fuzzy variables used to describe the output y. In fuzzy logic control, the term ''linguistic variable'' refers to whatever state variables the system designer is interested in . Linguistic variables that are often used in control applications include Speed, Speed Error, Position, and Derivative of Position Error. The fuzzy variable is perhaps better described as a fuzzy linguistic qualifier. Thus the fuzzy qualifier performs classification
(qualification) of the linguistic variables. The fuzzy variables frequently employed include Negative Large, Positive Small and Zero. Several papers in the literature use the term ''fuzzy set'' instead of ''fuzzy variable'', however; the concept remains the same. Table 30.1 illustrates the difference between fuzzy variables and linguistic variables. Once the linguistic and fuzzy variables have been specified, the complete inference system can be defined. The fuzzy linguistic universe, U, is defined as the collection of all the fuzzy variables used to describe the linguistic variables .
i.e. the set U for a particular system could be comprised of Negative Small (NS), Zero (ZE) and Positive Small (PS). Thus, in this case the set U is equal to the set of [NS, ZE, PS]. For the system described by Eq. (30.1), the linguistic universe for the input x would be the set Ux . .A1A2 . . . An.. Similarly,
TABLE 2 .1 Fuzzy and linguistic variables

Linguistic Variables		Fuzzy Variables (Linguistic Qualifiers)	
Speed error	(SE)	Negative large	(NL)
Position error	(PE)	Zero	(ZE)
Acceleration	(AC)	Positive medium	(PM)
Derivative of position error	(DPE)	Positive very small	(PVS)
Speed	(SP)	Negative medium small	(NMS)

the linguistic universe for the output y would be the set Uy . .CaC2 . . . Cn.
The Fuzzy Inference System (FIS) The basic fuzzy inference system (FIS) can be classified as: Type 1 Fuzzy Input Fuzzy Output (FIFO)
Type 2 Fuzzy Input Crisp Output (FICO)

Type 2 differs from the first in that the crisp output values are predefined and, thus, built into the inference engine of the FIS. In contrast, type 1 produces linguistic outputs. Type 1 is more general than type 2 as it allows redefinition of the response without having to redesign the entire inference engine. One drawback is the additional step required, converting the fuzzy output of the FIS to a crisp output. Developing a FIS and applying it to a control problem involves several steps:

1. fuzzification
2. fuzzy rule evaluation (fuzzy inference engine)
3. defuzzification.

The total fuzzy inference system is a mechanism that relates the inputs to a specific output or set of outputs. First, the inputs are categorized linguistically (fuzzification), then the linguistic inputs are related to outputs (fuzzy inference) and, finally, all the different outputs are combined to produce a single output (defuzzification). Figure 30.1 shows a block diagram of the fuzzy inference system.

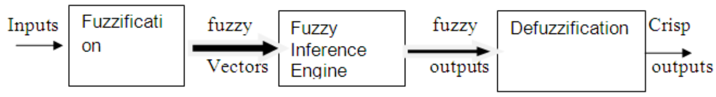


Fig Fuzzy inference system.

a) Fuzzification:

Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error between reference signal and output signal can be assigned as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive small (PS), Positive Medium (PM), Positive Big (PB). The triangular membership function is used for fuzzifications. The process of fuzzification convert numerical variable (real number) to a linguistic variable (fuzzy number).

Defuzzification:

The rules of fuzzy logic controller generate required output in a linguistic variable (Fuzzy Number), according to real world requirements; linguistic variables have to be transformed to crisp output (Real number). This selection of strategy is a compromise between accuracy and computational intensity.

IX. FUZZY LOGIC CONTROLLER

Fuzzy logic is a method of rule-based decision making used for expert systems and process control that emulates the rule-of-thumb thought process used by human beings. The basis of fuzzy logic is fuzzy set theory which was developed by Lotfi Zadeh in the 1960s. Fuzzy set theory differs from traditional Boolean (or two-valued) set theory in that partial membership in a set is allowed. Traditional Boolean set theory is two-valued in the sense that a member belongs to a set or does not and is represented by 1 or 0, respectively. Fuzzy set theory allows for partial membership, or a degree of membership, which might be any value along the continuum of 0 to 1. A linguistic term can be defined quantitatively by a type of fuzzy set known as a membership function. The membership function specifically defines degrees of membership based on a property such as temperature or pressure. With membership functions defined for controller or expert system inputs and outputs, the formulation of a rule base of IF-THEN type conditional rules is done. Such a rule base and the corresponding membership functions are employed to analyze controller inputs and determine controller outputs by the process of fuzzy logic inference. By defining such a fuzzy controller, process control can be implemented quickly and easily. Many such systems are difficult or impossible to model mathematically, which is required for the design of most traditional control algorithms. In addition, many processes that might or might not be modeled mathematically are too complex or nonlinear to be controlled with traditional strategies. However, if a control strategy can be described qualitatively by an expert, fuzzy logic can be used to define a controller that emulates the heuristic rule-of-thumb strategies of the expert. Therefore, fuzzy logic can be used to control a process that a human can control manually with expertise gained from experience. The linguistic control rules that a human expert can describe in an intuitive and general manner can be directly translated to a rule base for a fuzzy logic controller

X. SIMULATION AND ITS RESULTS

The simulations of the current blocking strategy were performed using MATLAB/Simulink. The typical waveforms in current control are shown by simulation results as shown in Fig. 8. It can be observed that the motor current for each phase is controlled at its reference (the reference is not shown in the figure). By applying the hysteresis controller, the current error ripple is restricted within pre-defined band gap (HB). The current references are determined by the torque demand (at its limit) and decoded signals. For clearer picture, the related waveforms of Hall Effect signals and decoded signal (as decoded in Table 1) are also depicted in Fig. 8.

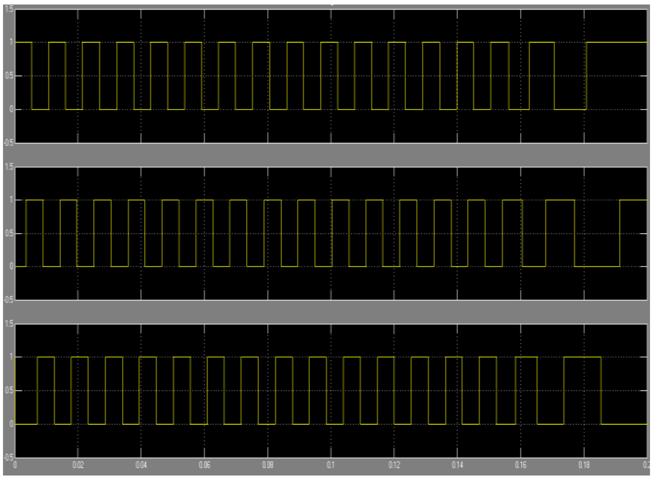
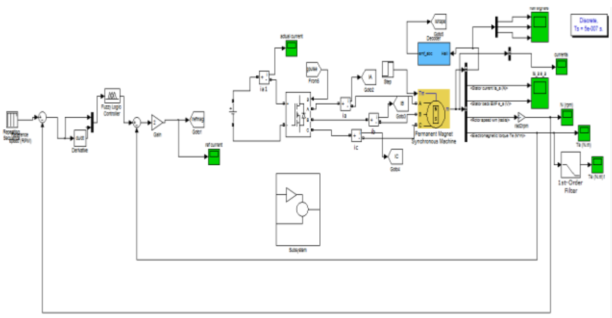
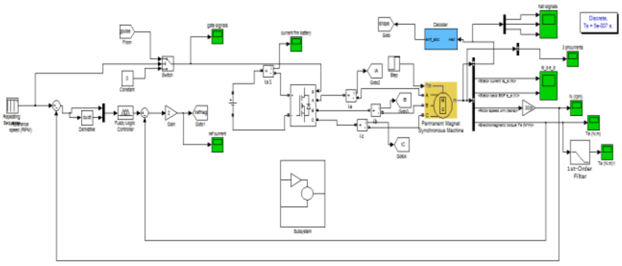


Fig 8. Motor currents are controlled such that follow their references which are generated according to the hall effect signals (Time/div=0.5s/div).

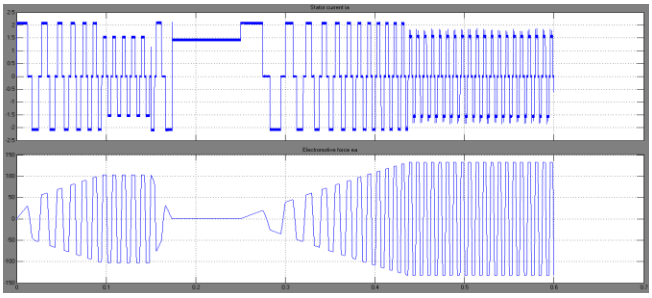
Figure 9 shows the simulation results of output torque, speed and current waveforms for THC without current blocking strategy and THC with the proposed current blocking strategy. It can be clearly seen that, the current drawn from the batteries is almost zero when the reference torque is suddenly decreased to zero in the case of THC with the proposed strategy. In both cases the current from the batteries is required to produce appropriate torque either to accelerate or decelerate the motor



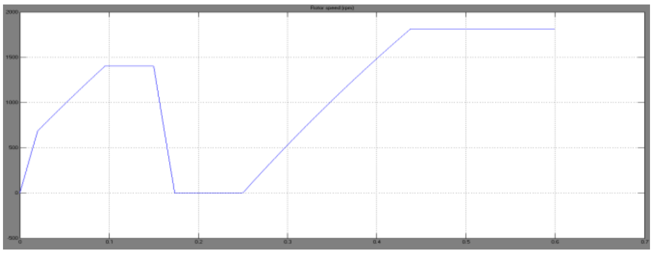
(a) THC without current blocking strategy with fuzzy logic controller



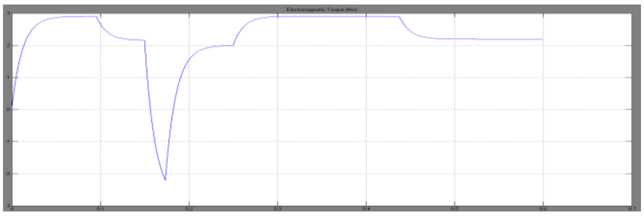
(b) THC with current blocking strategy with fuzzy logic controller



Waveform of current and emf

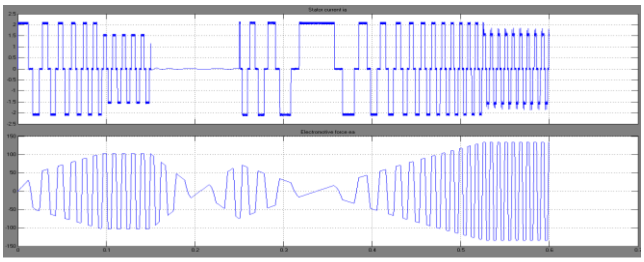


Waveform of speed

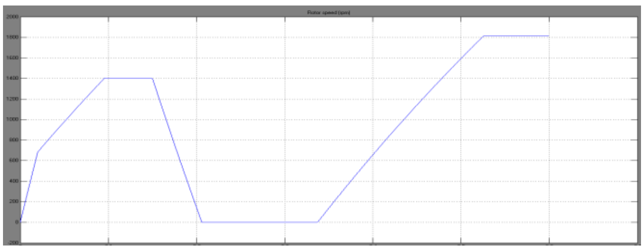


Waveform 0f torque

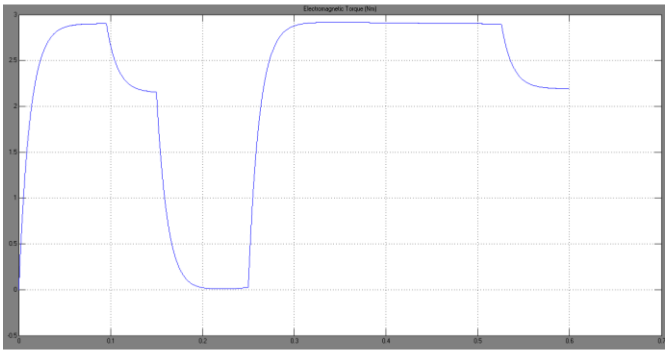
Fig 9 (a) THC without current blocking strategy



Waveform of current and emf



Waveform of speed



Waveform of torque

Fig 9.(b) THC with current blocking strategy.

TABLE 2 Control and Motor Parameters Values

Control System	
Hysteresis band	0.2 A
Sampling time	50 μs
BLDC Motor	
Stator resistance	0.2 Ω
Stator inductance	8.5 Mh
Flux linkage established by magnets	0.175 V.s
Torque constant	1.4 Nm/A
Moment of inertia	0.04 Kg.m²
Friction factor	0.005 Nms
Pole pairs	4

XI. CONCLUSIONS

This project presented the modelling and experimental result of THC for BLDC motor. The current controller has been applied to a BLDC drive and the results shows that the current ripple stays within the hysteresis band as defined by the controller. The proposed current blocking strategy shows that the energy wastage from the batteries is prevented such that it can prolong the capacity of voltage battery and it also showed that the hysteresis controller by using fuzzy logic controller can offer inherent current protection/limitation and robustness in controlling the motor torque.

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