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Sensorless control of BLDC motor based on Hysteresis comparator with PI control for speed regulation

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Abstract— Now a days, road vehicles and medical applications are more equipped with permanent magnet synchronous motors. Particularly interesting are brushless dc (BLDC) motors, which, due to their inherently sensorless operation, are considered as viable candidates in large scale production industries such as the automotive one. Within this trend, this paper deals with the synthesis and implementation of a novel sensorless control strategy dedicated to the control of BLDC motor drives. Compared with the most recent and highly performed strategy, the proposed one offers improved reliability due to the achievement of balanced switching frequencies of the inverter upper and lower insulated-gate bipolar transistors, on one hand, and the reduction in the average value of the motor common mode voltage, on the other hand. Furthermore, the torque ripple is significantly damped during sector-to-sector commutations using a three-level hysteresis torque controller. An experientially based comparative study of the most recent and highly performed sensorless control strategy from one side and the closed loop speed control is achieved by using PI controller. This project is implemented in matlab simulation.

Keywords- BLDC motor, Sensorless control, PI control, Hysteresis comparator, Hysteresis current controller.

I. INTRODUCTION

During several decades, electrical ac machines have been designed accounting for the fact that they will be connected to the network. This has led to the well-known conventional ac machines (induction and dc-excited synchronous machines) in which the stator windings are sinusoidally distributed in slots around the air gap to couple optimally with the sinusoidal supply. Starting from the 1980s, the emergence of power electronic converters has removed the need for such a concept as the basis for ac machine design. A new approach based on the principle that the best machine design is the one that simply produces the optimum match between the ac electrical machine and the power electronic converter has led to the so-called "converter-fed machines" (CFMs). A typical example of CFMs is the brushless dc (BLDC) machine. With its trapezoidally shaped back electromotive forces (EMFs), such a machine has to be fed by 120◦ rectangular currents leading to a six-sequence operation, in order to produce a ripple-free torque. In recent years, variable speed drives equipped with BLDC motors have been extensively integrated in various applications, particularly in automotive industry utilities. BLDC motors are characterized by a high power factor, high efficiency, and simple sensorless control strategies, which represent a crucial cost benefit for different large-scale production industries. Dealing with BLDC motor control strategies, it is quite commonly believed that they are based on the current and torque control approaches. Among the most popular strategies is a generalized harmonic injection to find out optimal current waveforms minimizing the torque ripple. However, since the torque is not directly controlled, its fast dynamic could not be achieved. Furthermore, the implementation of such strategies requires expensive position sensors. In hysteresis current controllers are used to drive BLDC motors. However, the proposed control strategy requires several transformations in order to synthesize the *abc* frame optimum reference currents, which complicates the control scheme without an effective direct control of the torque. Among the control strategies that exhibit a high torque dynamic, one can distinguish the sensorless torque control. SLC strategies have been extensively implemented in induction machine drives. They allow a direct control of the electromagnetic torque and the stator flux through the application of suitable combinations of the inverter control signals. Since then, many DTC strategies founded on analytical basis have been developed so far, considering conventional and unconventional topologies of the inverter in the stator. Such a strategy exhibits a vector selection table simply reduced to the torque control with a two phase conduction mode during sequences and three-phase conduction mode during sector-to-sector commutations. Although a notable attenuation of the torque ripple has been gained using this strategy, it has been noticed that it yields unbalanced switching frequencies of the inverter upper and lower insulated gate bipolar transistors (IGBTs), on one hand, and a relatively high average value of the common-mode voltage (CMV) of the BLDC motor, on the other hand. These limitations compromise the drive reliability. CMV creates significant common mode conducted currents in motor drives. These currents contribute to many unwanted problems such as coupling to nearby systems creating electromagnetic interference, damaging the machine bearings and the bearing lubrification, and heating the conduit carrying the armature conductors. This paper proposes an improved DTC strategy that enables the eradication of the previously depicted limitations, considering both clockwise and counterclockwise rotations. Moreover, a further attenuation of the torque ripple during sector-to-sector commutations has been gained due to the implementation of a three-level torque controller.

II. SENSORLESS OPERATION

The stator flux is not orthogonal to the rotor flux generated by the permanent-magnet at the beginning of the start-up point if the conventional alignment method is used. Thus, the initial motor torque can't obtain the maximum value at this time. Also, the stator winding incurs a high uncontrollable current by means of the fixed dc power supply and motor parameters. This might damage the stator winding of the motor if the active time for aligning a rotor position is too long.

The conventional start-up method reveals some unexpected drawbacks that might degrade the performance of the BLDC motor. To overcome these restrictions, a simple start-up method not only to achieve the maximum starting motor torque but also to control the stator current is proposed. Unlike the case in the conventional method where only two stator windings are excited, all three stator windings are energized in the case of the proposed start-up scheme by using a specific initial voltage vector *Vi*(1,0,0). As the rotor is located between voltage vector *V1* and *V2* , the voltage vector *V3* is orthogonal to *Vi*. It is chosen as the next applied voltage vector in order to achieve maximum starting motor torque at start-up. It should be noted that the amplitude of the stator current for alignment of the rotor position can be easily adjusted by modulating the pulse width of the switching devices. It depicts the three-phase current responses of the BLDC motor, when turning on switch *A+* and modulating the pulse-width of the two switches *B-* and *C-* at the same time.

The duty cycles of PWM signals when a switching period *Ts* is 100μsec. Obviously, the magnitude of the stator current can be easily governed by adjusting the duty cycle, which can be decided by considering the initial torque required at alignment. This method can prevent a surge of current that may damage the motor as in the case of utilizing the conventional method, and also it is robust with motor parameter changes. The motor may rotate reversely during alignment according to the rotor position before alignment. However, as a maximum reverse rotating angle is only 90 mechanical degrees, it does not have the influence on operation. After aligning the rotor position, the start-up procedure is considered for accelerating the BLDC motor from standstill up to a specific speed, 3000rpm which is a minimum speed at maximum torque application. As the sensorless scheme is not self-starting, the motor should be started and can be brought to a certain speed at which the zero-crossing point of the back-EMF can be detected.

The *I-f* starting method, where the current is specified and maintained constant during accelerating the motor, is proposed at the back-EMF based sensorless control of a permanent-magnet synchronous motor. The *v/f* starting method is used at this paper, which is suitable for the BLDC motor drive. The open loop starting based on *v/f* control is accomplished by producing the rotating electric field with a specific relationship to the reference voltage in terms of a rotor speed. As the frequency is gradually increased, the rotor speed also increases. The magnitude of a reference voltage is adjusted as proportional to the rotor speed. A phase angle can be obtained from integrating the rotor speed and the pulse width of the gating signals is modulated with the reference voltage magnitude. The six PWM signals with 60° phase displacement are generated corresponding to the phase angle without any rotor position information. When the rotor speed reaches at 3000rpm, the back-EMF can be sensed to provide the rotor position information and the system is switched to the sensorless control.

This project presents a sensorless control based on a hysteresis comparator of terminal voltage and a potential start-up method with a high starting torque application. As the maximum commutation phase lag is significantly reduced from -13° to -3° by adjusting both the resistance ratio and the output voltage level of the hysteresis comparator, the commutation signal is nearly in phase with the back-EMF. If a peak of ripple voltage in the terminal voltage is within the hysteresis band +1V regardless of magnitude of the terminal voltage, it can prevent multiple output transitions at a hysteresis comparator by high frequency ripples in the terminal voltage. After aligning the rotor position for achieving the maximum starting torque, the BLDC motor accelerates from a standstill up to a nominal speed within 1.2sec. The magnitude of the stator current for aligning the rotor position can be easily controlled by modulating the pulse width of specific switching devices. Through the experimental results, it can be seen that the proposed sensorless and start-up techniques are ideally suited for the automotive fuel pump application. Brushless dc motor is one kind of permanent magnet synchronous motor, having permanent magnets on the rotor and trapezoidal shape back EMF. The BLDC motor employs a dc power supply switched to the stator phase windings of the motor by power devices, the switching sequence being determined from the rotor position. The phase current of BLDC motor, in typically rectangular shape, is synchronized with the back EMF to produce constant torque at a constant speed. The mechanical commutator of the brush dc motor is replaced by electronic switches, which supply current to the motor windings as a function of the rotor position. This kind of ac motor is called brushless dc motor, since its performance is similar to the traditional dc motor with commutators. These brushless dc motors are generally controlled using a three-phase inverter, requiring a rotor position sensor for starting and for providing the proper commutation sequence to control the inverter. These position sensors can be Hall sensors, resolvers, or absolute position sensors. Those sensors will increase the cost and the size of the motor, and a special mechanical arrangement needs to be made for mounting the sensors. These sensors, particularly Hall sensors, are temperature sensitive, limiting the operation of the motor to below about 75oC. On the other hand, they could reduce the system reliability because of the components and wiring. In some applications, it even may not be possible to mount any position sensor on the motor. Therefore, sensorless control of BLDC motor has been receiving great interest in recent years.

This project develops the brushless dc (BLDC) motor sensorless control system. The sensorless techniques that are based on a hysteresis comparator and a potential start-up method with a high starting torque are suggested. The hysteresis comparator is used to compensate for the phase delay of the back EMFs due to a low-pass filter (LPF) and also prevent multiple output transitions from noise or ripple in the terminal voltages. The rotor position is aligned at standstill for maximum starting torque without an additional sensor and any information of motor parameters. Also, the stator current can be easily adjusted by modulating the pulse width of the switching devices during alignment. The input DC voltage is given to the voltage source inverter, this inverter will convert the DC voltage into AC voltage. To produce the back emf initially sinusoidal V/F control PWM technique is applied to the BLDC motor, so the motor will start like a Induction motor this emf will sense by using the voltage sensor and this voltage is fed to the hysteresis comparator. From the hysteresis comparator we can identify which winding should be energized initially, this comparator will compare the emfs of two phase and produce the PWM pulses, these pulses is fed to the inverter so the inverter fed the voltage to the motor but from the voltage sensor it will get trapezoidal back emf from these we cannot identify the amplitude for that this trapezoidal back emf is given to the low

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pass filter it will give the sinusoidal back emf. The hysteresis current controller will compare the actual motor current and reference current waveform; the current controller will produce difference as PWM pulses. This pulse is given to the voltage source inverter. The inverter will fed the voltage to the motor so that stator current will decreased.

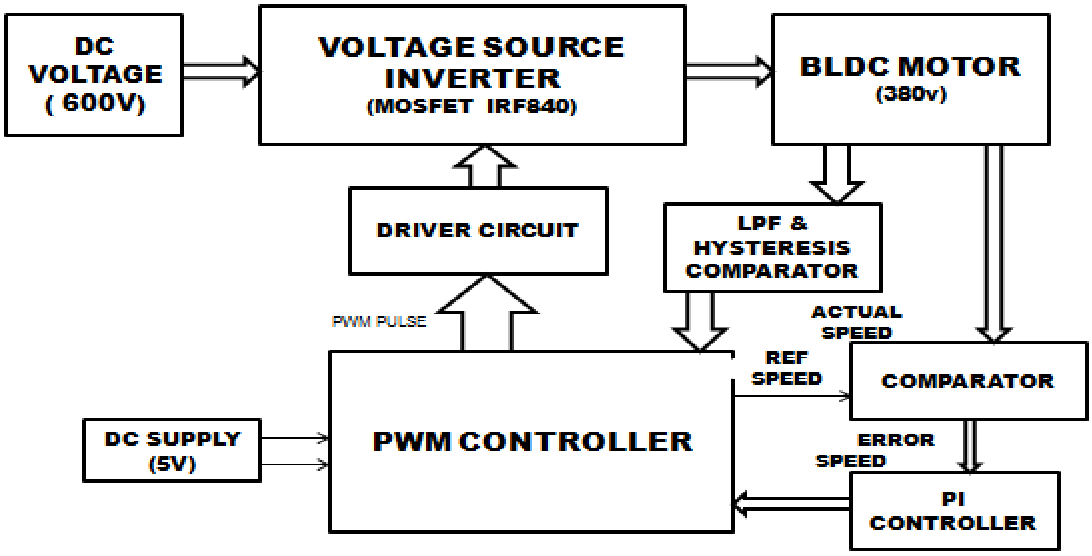
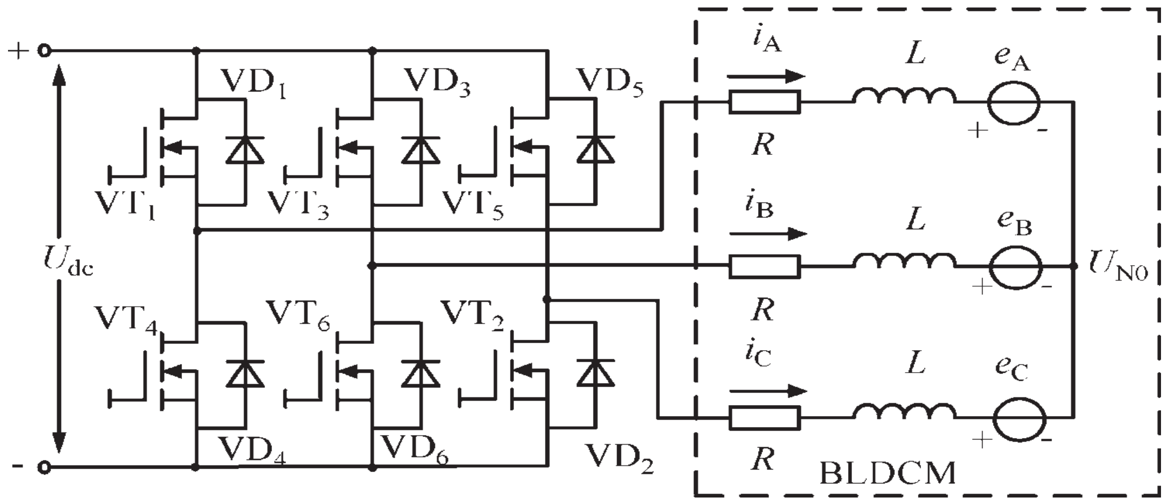


Fig 1. Block diagram of Sensorless BLDC motor

Sensor less control by using a hysteresis comparator method for consists of the LPFs for suppressing the high switching frequency ripples, hysteresis comparators for generating three-phase commutation signals, and a gating signals generator for generating six PWM signals. After sensing the three-phase terminal voltages, each of the three-phase terminal voltages is fed into an LPF to suppress the high switching frequency ripple or noise. As only two phases of the BLDC motor are energized at any time, the back-EMF can be measured from its terminal voltage in the period of an open phase (60°). During the two-phase conduction period (120°), the only difference between the back-EMF and its terminal voltage is a stator impedance voltage drop, which may be considerably small compared with the dc voltage source



. Fig 2. Circuit diagram of Sensorless BLDC motor

Therefore, the waveform of the terminal voltage is nearly the same as that of the back-EMF. The terminal voltages can be used to detect the commutation points of the BLDC motor instead of the back-EMFs at the proposed sensorless control. As the rotor speed increases, the percentage contribution of the phase lag to the overall period increases. The lag will disturb current alignment with the back-EMF and will cause serious problems for commutation at high speed. The phase lag in commutation can produce significant pulsating torques in such drive which may cause oscillations of the rotor speed, and generate extra copper losses. In this paper, the cut-off frequency of the LPF is determined on 2.5 kHz by considering both the phase lag and harmonic distribution of the back-EMF. The hysteresis comparator is used to compensate for the phase lag of the back-EMFs due to the LPF in order to determine the proper commutation sequence of the inverter according to the rotor position. Also, it can prevent multiple output transitions by high frequency ripples in the terminal voltages.

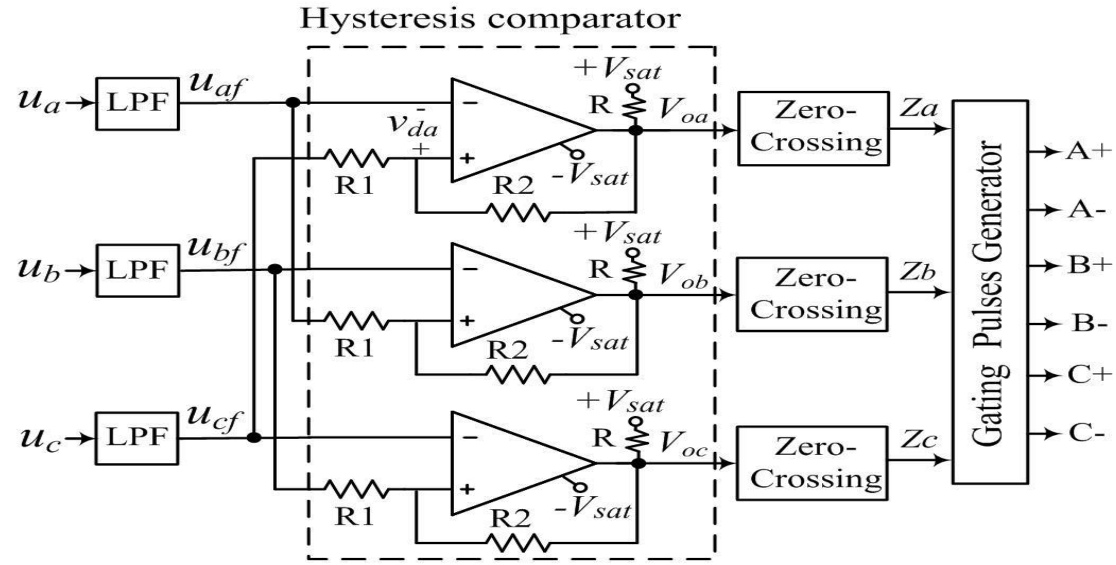


Fig 3. Hysteresis comparator

The outputs of the three-phase hysteresis comparators become three commutation signals (*Za*, *Zb*, *Zc*), and then six gating signals can be generated through some logic equations. The filtered a-phase terminal voltage is applied to the inverting input, and the filtered c-phase terminal voltage is applied via *R1* to the non-inverting input.

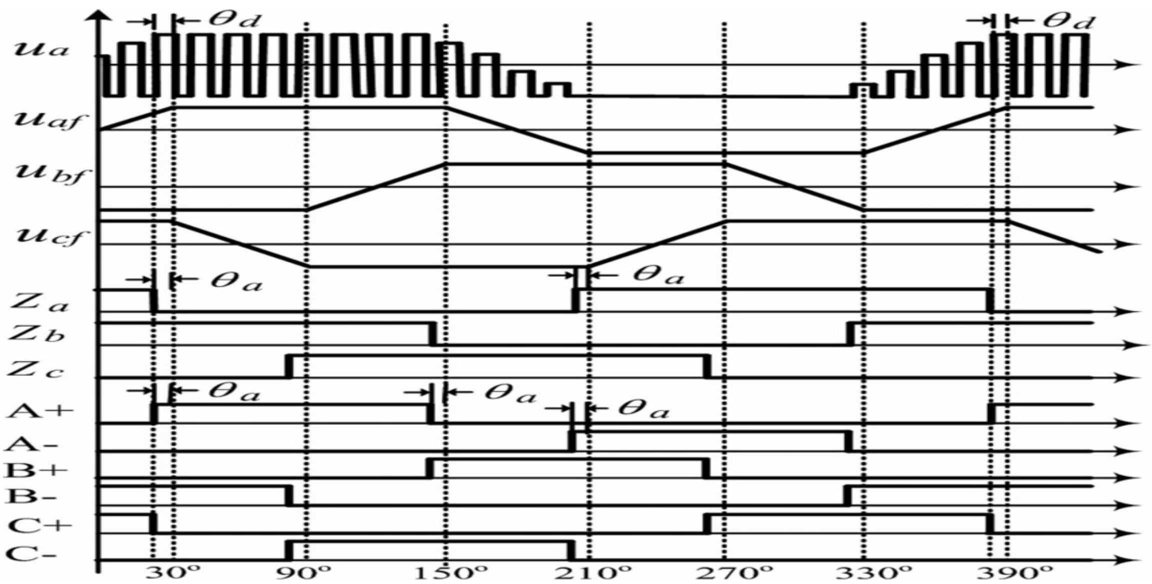


Fig 4. Hysteresis comparator output

A differential voltage of a-phase hysteresis comparator. In the BLDC motor, only two phases of the three-phase stator windings are excited at any time by utilizing alternative six excited voltage vectors *V1* and *V6*. That is why the current can flow into only two of the three windings and commutated every 60° of electrical angle. At standstill, the initial rotor position is aligned into one of six positions that are determined by the six excited voltage vectors to energize two phases of the BLDC motor. As it is well known, the deviation of these voltage vectors is every 60° of electrical angle.

Hysteresis-band PWM is basically an instantaneous feedback current control method of PWM where the actual current continually tracks the command current within a hysteresis band. Hysteresis control schemes are based on a nonlinear feedback loop with two level hysteresis comparators. The switching signals are produced directly when the error exceeds an assigned tolerance band. The following figure shows the operation principle of the hysteresis modulation/control scheme.

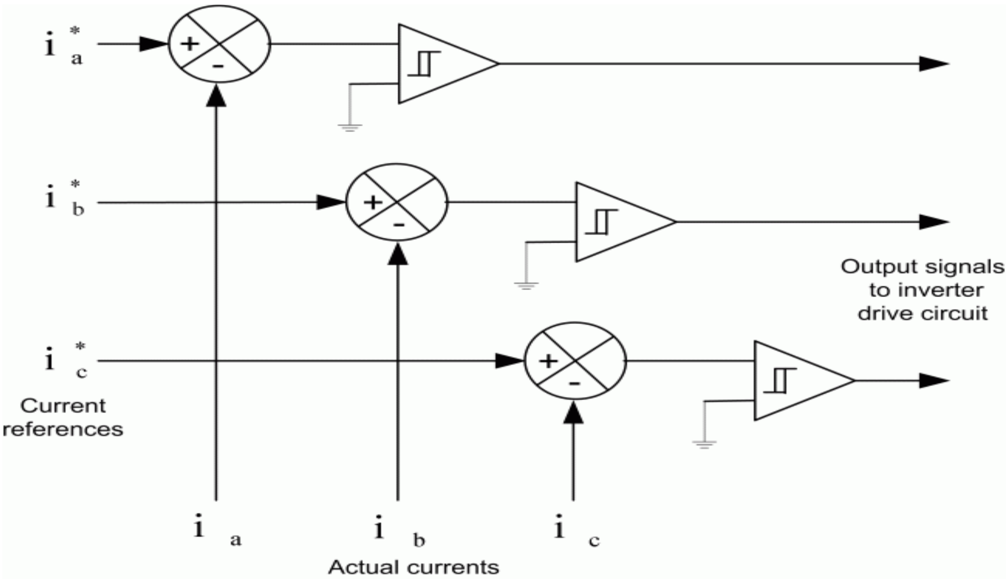


Fig 5. Hysteresis current controller

The controller generates the sinusoidal reference current of desired magnitude and frequency that is compared with the actual line current. If the current exceeds the upper limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the current crosses the lower limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. Hence, the actual current is forced to track the reference current within the hysteresis band.

The speed can be controlled in a closed loop by measuring the actual speed of the motor. The error in the set speed and actual speed is calculated. A Proportional plus Integral (P.I.) controller can be used to amplify the speed error and dynamically adjust the PWM duty cycle. For low-cost, low-resolution speed requirements, the Hall signals can be used to measure the speed feedback. A timer from the Controller can be used to count between two Hall transitions. With this count, the actual speed of the motor can be calculated. For high-resolution speed measurements, an optical encoder can be fitted onto the motor, which gives two signals with 90 degrees phase difference.

Using these signals, both speed and direction of rotation can be determined. Also, most of the encoders give a third index signal, which is one pulse per revolution. This can be used for positioning applications. Optical encoders are available with different choices of Pulse Per Revolution (PPR), ranging from hundreds to thousands. So finally the motor will run at constant speed by using PI controller.

III. SIMULATION RESULTS

To verify the feasibility of the proposed strategy, simulations are carried out.

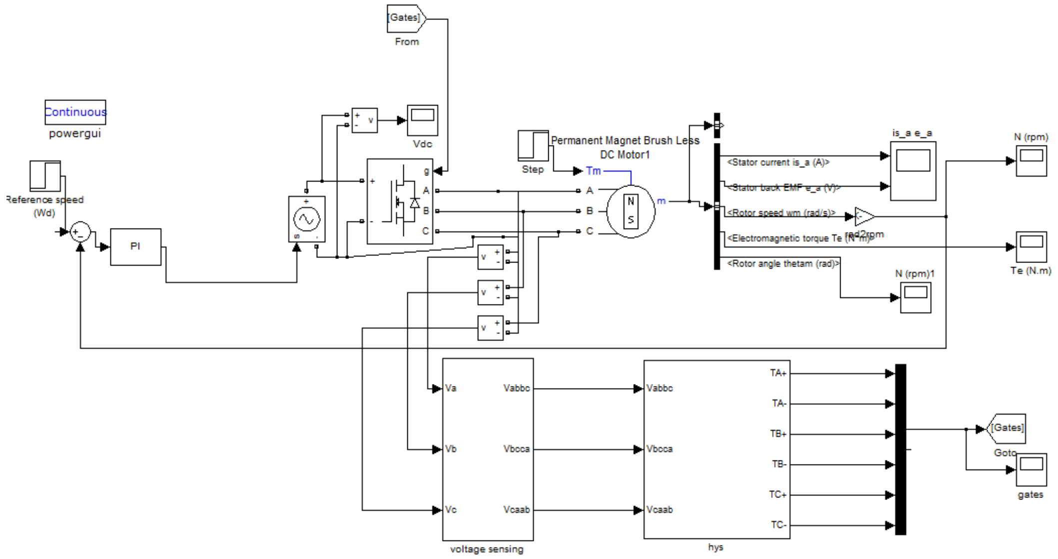


Fig.6. Proposed system Simulink diagram

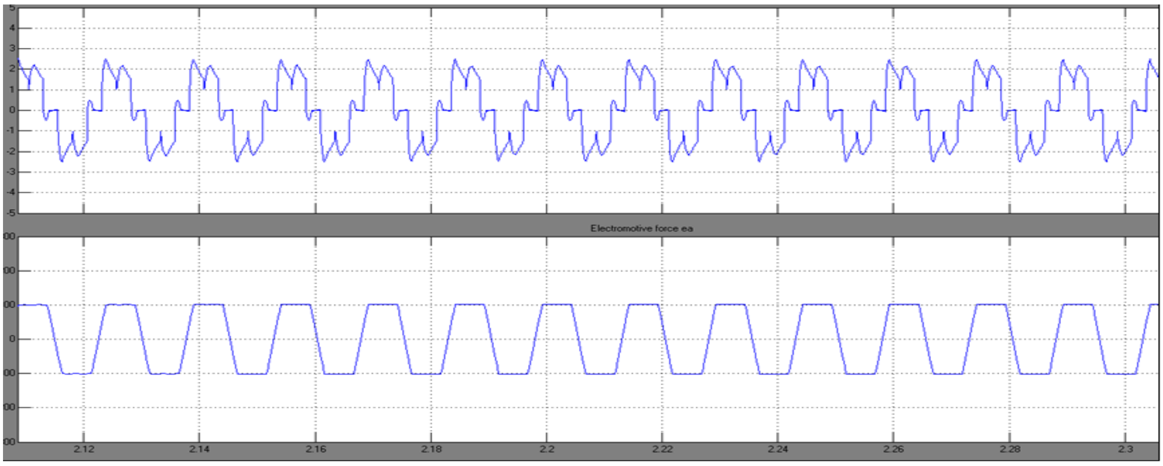


Fig.7. Three phase voltage source inverter output and back emf waveform of BLDC motor

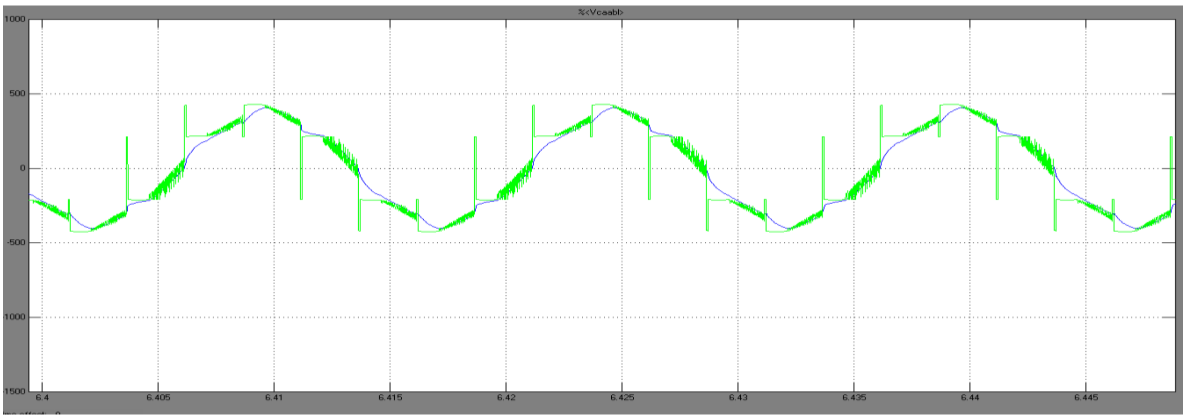


Fig.8. Back emf waveform before and after filter

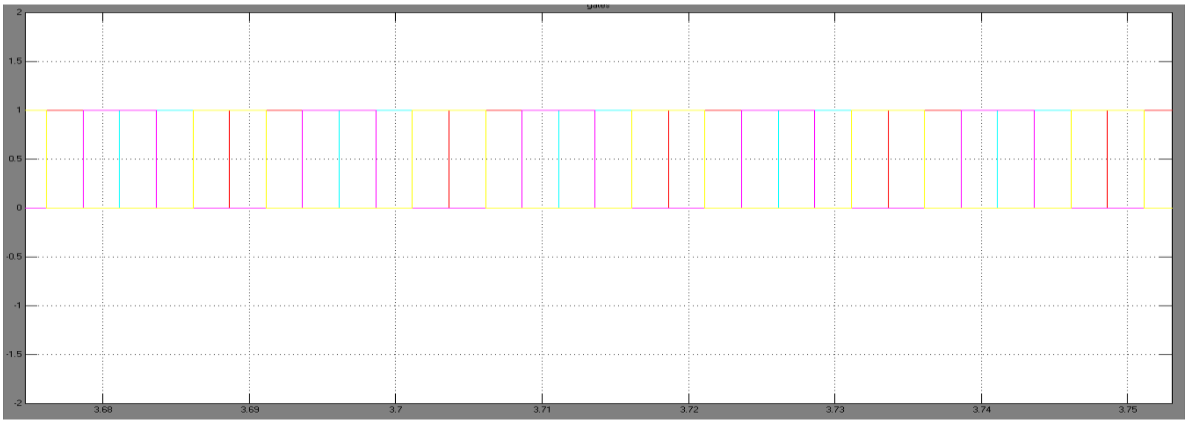


Fig.9. Gate pulses to the inverter

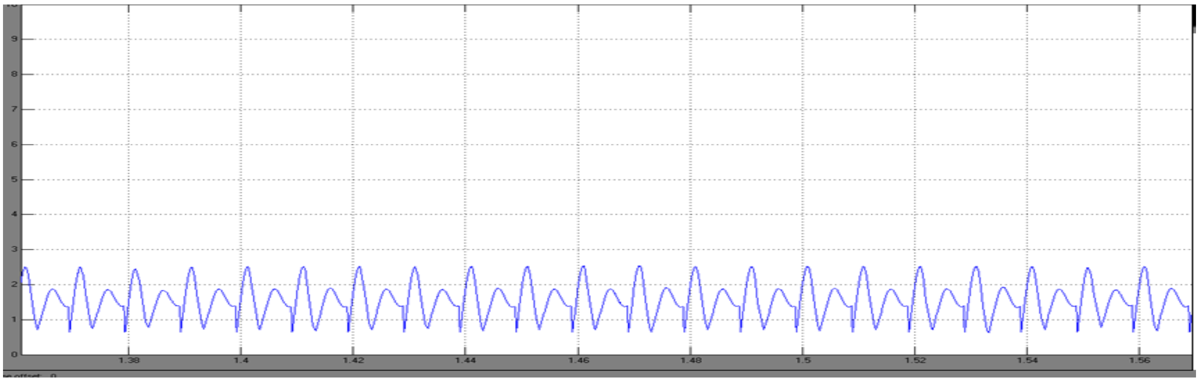


Fig.10. Torque waveform of the BLDC motor

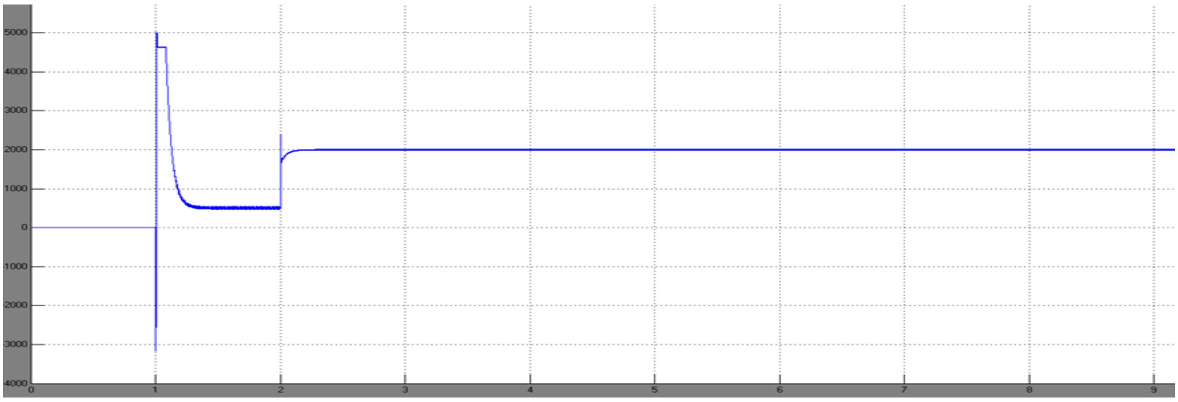


Fig.11. Speed waveform using PI controller

IV. CONCLUSIONS

This project presents a sensorless control based on a hysteresis comparator of terminal voltage and a potential start-up method with a high starting torque for an automotive fuel pump application. As the maximum commutation phase lag is significantly reduced from -13°to -3°by adjusting both the resistance ratio and the output voltage level of the hysteresis comparator, The commutation signal is nearly in phase with the back-EMF It can prevent multiple output transitions at a hysteresis comparator by high frequency ripples in the terminal voltage. The hysteresis current controller was reduced the stator current ripples. The closed loop speed control is achieved by using PI controller.

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