International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391

Steer-by-Wire System Modified with Field Oriented Control of Motors

Baiju Karun[1], Viswas Eldo[2], Revathy Rajan[3], Riya Jose[4], Princy Mary Thomas[5]

[1, 2, 3, 4, 5] Department of Electronics and Communication Engineering, Muthoot Institute of Technology and Science, Kerala India

Abstract: ***Conventional power steering systems use an engine accessory belt to drive the pump, providing pressurized fluid that operates a piston in the power steering gear or actuator to assist the driver. The aim of steer-by-wire technology is to completely do away with as many mechanical components as possible. Completely replacing conventional steering systems with steer-by-wire holds several advantages. In this paper we propose a steer-by-wire system modified with Field oriented control of motors. This system has two sections-Steering wheel section and Road wheel section. Two motors are used in each section for the torque required in a power steering. The control of these motors to turn the wheels of two sections is the main function of the microcontroller. Controlling methods used for motors are usually sinusoidal method and trapezoidal method but they have certain disadvantages. Therefore we have selected Field Oriented Control (FOC) for motor controlling which provides high efficiency, low noise, low torque ripple and good torque control over a wide speed range.***

Keywords: Steer-by-wire, Field Oriented Control, Commutation, Brushless DC motor

1. Introduction

A steering system is a system which decides the path to be followed by a car or any other vehicle as directed by the driver. In a Steer-by-Wire technology, replacement of mechanical components (steering shaft, column, gear reduction mechanism, etc.) is done with wires. The complete replacement of conventional steering system with steer-by-wire holds several advantages such as the absence of steering column simplifies the car interior design, allows much better space utilization in the engine compartment, less likely that the impact of a frontal crash will force the steering wheel to intrude into the driver's survival space. Also, there are larger spaces at disposal within the compartment and since it is possible to place the input devices more rationally, the cruising comfort is more enhanced. Other than that due to the non-use of the polluting oils, environmental pollution is also eliminated in these vehicles. A Steer-By-Wire system excludes the physical connection between the steering wheel and the wheels of a car and instead uses electrically controlled motors, to change the direction of the wheels and to provide feedback to the driver. In this paper, a steer-by-wire system modified with Field oriented control scheme is discussed and how it is more efficient than other controlling techniques.

2. Steer-by-Wire System

The steer-by-wire system consists of two main parts:
1. Steering Wheel Section
2. Road Wheel Section

The Steering Wheel section consists of a Steering Wheel, a Steering Wheel Motor, Steering Wheel Angle Sensor and Steering Wheel Controller. Steering wheel controller senses the steering wheel position, which is transmitted to Road Wheel Controller through CAN interface every 250ms. Steering Wheel Module receives the actual Road Wheel position and torque through CAN interface, which is used to turn the Steering wheel to the position corresponding to the actual position of the Wheels. The Road Wheel section contains the wheels, the rack and pinion, a road wheel actuator, pinion angle sensor and road wheel controller. Road Wheel Controller uses the steering wheel position and vehicle speed, received through CAN interface, to turn the road wheel motor to required position corresponding to steering wheel position. Figure (1) shows the system components.

3. Motor Selection

A Brushless DC motor or BLDC motor is the type which is most suitable for applications that require high reliability, high efficiency, more torque per weight etc. Commutator helps in achieving unidirectional torque in a typical dc motor. Commutators and brush arrangement are not present in a brushless dc motor. Here an integrated inverter or switching circuit is used to achieve torque that is unidirectional. Hence these motors are, sometimes, also referred as 'electronically commutated motors'.

We require two motors in a Steer-by-Wire system. One motor is for the steering wheel and another one for the road wheel. Electrical motors are of different types, such as stepper motors, servo motors, and permanent magnet motors etc. There are a lot of choices, from which we have to select a motor that is most acceptable for our application. Even if conventional dc motors are highly efficient and due to their characteristics we can use them as servomotors, their main drawback is that they need a commutator and brushes which are subject to wear and tear and it requires constant maintenance. When solid-state switches were used to employ the functions of commutator and brushes, maintenance-free motors were realized. These motors are now known as brushless dc motors. We need two motors, one for road wheel section and other in the steering wheel section and for this; we have selected brushless DC motor. A brushed DC motor requires periodic maintenance since brushes require

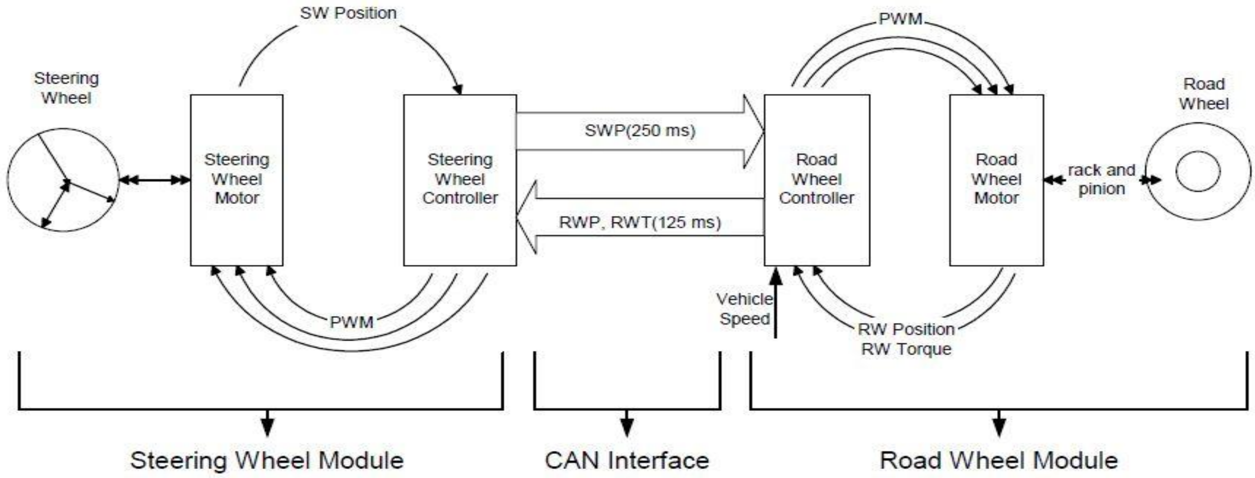

Figure 1: Steer-by-Wire system

subsequent replacement due to mechanical wear. Also, as brushes transfer current to the commutator, sparking occurs. Due to the above reasons, brushes limit the maximum speed and a number of poles the armature can have. These all drawbacks are removed in a brushless DC motor. For switching stator magnets to keep the motor running an electronic control circuit is used in a brushless DC motor. This makes a BLDC motor potentially less rugged. It consists of a rotor which is a rotating permanent magnet. It is surrounded by three stator windings having equivalent space between them, which are fixed. From each winding, current flow occurs and this produces a magnetic field vector. This field sums with the fields from the other windings. A magnetic field of arbitrary direction and magnitude can be produced by the stator by controlling currents in the three windings. Then, torque is produced due to the attraction or repulsion between this net stator field and the magnetic field of the rotor. So there are many advantages for BLDC motor over brushed motors, they are: increased efficiency, reliability, longer lifetime, no sparking and less noise, more torque per weight etc.

4. Commutation Techniques

Commutation is defined as the process of switching current in the phases so as to generate motion. Commutator is already present in the case of brushed motors and therefore commutation process is easy to understand since brushes contact the commutator and switch the current as the motor moves. Since moving contacting parts are absent in a brushless motor, commutation becomes more reliable. However, the electronics required to control the current in the motor is complex. The commutation methods change with the change in the application of the motor, but the important fact is to understand the commutation process and the merits and demerits of each of the commutation methods. The types of commutation techniques discussed here are: Sinusoidal, Trapezoidal and Field Oriented Control commutation techniques.

4.1 Trapezoidal Commutation

Trapezoidal commutation is one of the simplest and easiest methods of control for brushless dc motors. In this method, the current is controlled through two motor terminals at a time, and the third terminal is electrically disconnected from the power source[1]. Digital signals are provided using three Hall devices that are embedded in the motor[4]. Using these hall devices we could measure the position of the rotor within 60-degree sectors and this information is given to the motor controller. For any given instant, the current flowing through two windings will be equal in magnitude and the current flowing through the third terminal is zero. Using this method current space vectors having one of six different directions could only be produced[4]. As the motor turns, commutation occurs at every 60 degrees of rotation of the motor, therefore, the current space vector lies within the nearest 30 degrees of the quadrature direction-thereby for each winding the current waveform is a staircase- starting from zero, then to positive current, returning to zero, and then to negative current. A current space vector is produced that would be approximating smooth rotation while it steps among six distinct directions as the rotor turns. A PI controller is used to control current. An error signal is produced by comparing the desired torque with the measured current. Then this error signal is integrated (I) which is then amplified (P) producing an output correction which tends to minimize the error. The P-I controller's output is latterly PWM modulated and is given to the output bridge. Because of this, a constant current is maintained in those windings which are presently being driven. The process of commutation is performed independently with respect to the current control. The desired pair of motor terminals which is to be driven by the output bridge is selected by the position signals from the Hall sensors present in the motor. The third terminal is not connected to the power source. The design of current sensing circuit is in such a way that the current is measured in the active winding pair and is given back to the current control loop[1]. Trapezoidal commutation proves to be efficient for many applications, but it has its own limitations. As the current space vector points only in six different directions, it is misplaced from the optimal direction by anywhere from 0 to 30 degrees. This leads to a torque ripple of about 15% (1-cos (30)) at a frequency of six times the electrical rotational speed of the motor. Since some of the winding currents is incapable to produce torque, the misplacement of the current space vector represents a loss in the efficiency. A transient is introduced to the current control loop because of the switching of active terminals. This causes an audible „click' and thus the motor becomes hard to control precisely at slow speeds.

4.2 Sinusoidal Commutation

Trapezoidal commutation proves inefficient to provide smooth and precise control of BLDC motors at low speeds. Sinusoidal control resolves this problem[5]. The motor controllers of a sinusoidally commutated brushless motor attempt to drive the three motor windings with three currents that vary smoothly and sinusoidally as the motor rotates. The relative phases of these currents are chosen in such a way that they can form a rotating smooth current space vector which lies in the quadrature direction with respect to the rotor and has a constant magnitude. Thus the torque ripple spikes of commutation associated with trapezoidal commutation are eliminated. An exact measurement of rotor position is required for developing smooth sinusoidal modulation of the motor currents as the motor rotates[5]. The Hall devices give only a rough value of the position of the rotor which is not sufficient for this purpose. As a result angle feedback from an encoder is required. In this method, we are using a separate current loop for each of the two motor winding currents. The current flowing in the third motor winding will be equal to the negative sum of the currents passing through the first two windings (Norton current law) since the motor is WYE wired and therefore it cannot be separately controlled. In order to produce a smoothly rotating current space vector which is of constant magnitude the winding currents must combine, and since the stator windings are lying 120 degrees apart from each other, currents flowing in each winding must be sinusoidal and 120-degree phase shifted. Two sinusoids are synthesized using position information from the encoder, which is phase shifted by 120 degrees from each other. These sinusoids are then multiplied by the torque command so that the amplitudes of these sinusoids are proportional to the requested torque, as desired. As a result, two sinusoidal current command signals properly phased are produced which in turn generates a rotating stator current space vector in the quadrature direction. These sinusoidal command signals are given as inputs to a pair of P-I controllers that would regulate current in the two motor windings. The current through the third winding cannot be separately controlled as it is the negative sum of the currents in the controlled two windings. This output is fed to a PWM modulator from each P-I controller and to the output bridge and then to the two motor terminals. The voltage given to the third terminal is obtained as the negative sum of the voltage signals which is applied to the first two windings, as suitable for three sinusoidal voltages each separated by 120 degrees. To an extent the actual output waveform precisely follows the sinusoidal current command signals, the resultant current space vector rotates smoothly, which is constant in magnitude and is oriented in the quadrature direction, as desired. The smoothness of control is achieved by using sinusoidal commutation which is generally unachievable with trapezoidal control. However, while it is very effective at low motor speeds, it fails to give that efficiency at high motor speeds. The reason is that as speed increases, the current loop controllers have to follow a sinusoidal signal of increasing frequency. Besides they have to overcome the back emf which increases in amplitude and frequency as speed goes high. As the P-I controllers have controllable gain and frequency response, the time-variant oscillations to the current control loop can cause phase lag and gain error in the motor currents. Greater speeds result in more errors. This changes the normal direction of the current space vector with respect to the rotor, forcing it to shift away from the quadrature direction. During this occurrence, a lesser amount of torque is generated by the given amount of current and thereby more current is required to maintain the same torque. Efficiency gets deteriorated. This degeneration continues as speed rises. The motor current phase shift crosses through 90 degrees at few peculiar points. When this develops, torque is reduced to zero. Speeds beyond this point in sinusoidal control result in a negative torque and hence it is not achievable.

4.3 Field Oriented Control

Field Oriented Control is an important technology for motor control, especially for the permanent magnets motors. FOC provides an effective way of controlling a synchronous motor in variable speed drive applications that have varying loads, and can also improve the power efficiency of an AC induction motor, especially at lower speeds[1]. Some designers have mistakenly considered FOC can be used only with AC motors because of this reason. It is true that BLDC motors present today offer 96% efficiency even without FOC, but the advantages offered by FOC is minimal torque ripple, thereby resulting in smoother motor performance and quiet operation. The introduction of FOC to a BLDC motor does not require any hardware change on the motor side thus making it cost effective. The only requirement is an MCU with suitable MIPS in order to support FOC processing within the motor control loop. FOC is one of the methods used in varying frequency drives or varying speed drives for controlling the torque (and thus the speed) of three-phase AC electric motors through controlling the current[5]. Using FOC, the torque and the flux can be controlled independently. The response produced with FOC is faster and dynamic. The torque ripple is minimized almost to zero and the motor can be controlled efficiently at low and high

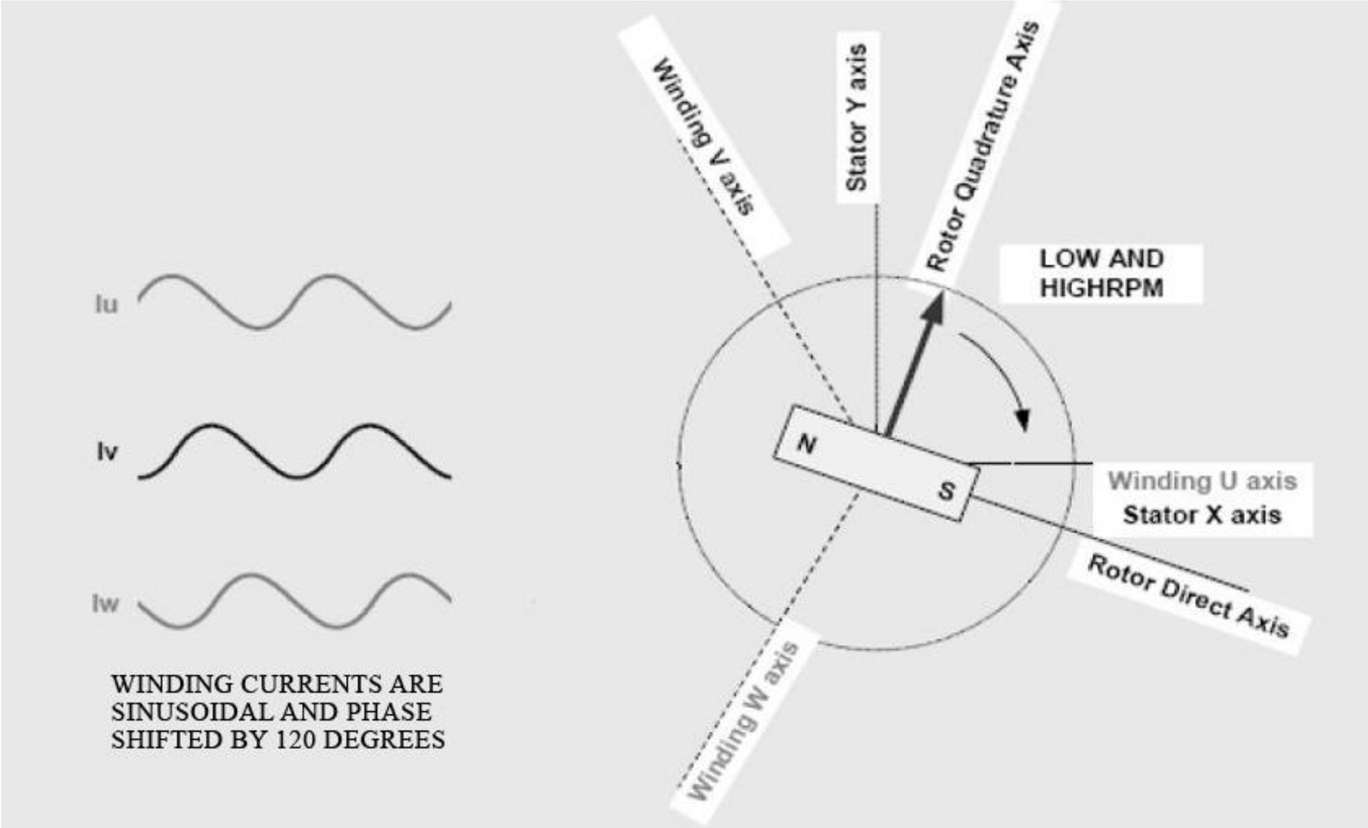

Figure 2: FOC control of motor

speeds. An induction motor can produce the maximum torque when the stator and the rotor magnetic fields are being orthogonal to each other. In FOC, the stator currents are being measured and varied in such a way that the angle between the stator and rotor flux is 90 degrees to produce the maximum torque. Through FOC technique our goal is to maintain the rotor and stator flux in quadrature by having the stator and rotor flux orthogonal to each other. This control method is computationally intensive.

Why FOC?

The traditional motor control for BLDC motors was Scalar Control or the Six-Step Commutation. It was based on the Hall Sensor or Sensor less inputs and has a dynamic response. It energizes a pair of windings only when the motor reaches the successive position and thereby the commutation moves to the next step. Hall sensors determine the position of the rotor and then the motor is commutated accordingly in case of Sensored motor control. One important merit of scalar control is that it is easy to implement. Modification of scalar control methods uses the back EMF to decide the position of the rotor. But the response produced by this method is not sufficient in applications where the load varies dynamically within a cycle[7]. These dynamic load changes can be handled only by advanced methods such as FOC. Steer-by-Wire has been already implemented using trapezoidal control. This has now been modified with field oriented control for motor control.FOC Control solves the limitations of other control techniques by decoupling the effect of torque and magnetizing flux. With decoupled control of magnetization, the torque-producing component of the stator flux can be considered as independent torque control. With decoupled control, the magnetization can be maintained at the proper level, and the torque can be controlled to regulate the speed at low speeds.FOC can provide smooth motion at slow speeds as well as effective operation at high speeds. Sinusoidal commutation can only produce smooth motion at small speeds, and it proves to be ineffective at higher speeds. Trapezoidal commutation can be relatively effective at high speeds, but it can lead to torque ripple at lower speeds. Field Oriented Control provides the best of both streams. The primal problem of sinusoidal control is that it tries to control the time varying motor currents. This cannot be fulfilled at higher speeds and frequencies owing to the limited bandwidth of PI controllers.FOC proves to be the solution for this problem through controlling the current space vector in the d-q reference frame of the rotor[1]. Ideally, the current space vector is fixed (magnitude and direction) with respect to the rotor, irrespective of rotation. For the current space vector in the d-q reference frame is stationary, the P-I controllers operate on dc, rather than ac signals. This could provide isolation to the controllers from the time varying winding currents and voltages, and thus it eliminates the limitation of controller frequency response and phase shift on motor torque and speed. Using Field Oriented Control, the quality of the current control remains unaltered by the speed of rotation of the motor. In FOC, motor voltages and currents are handled in the d-q reference frame of the rotor which meant that the measured motor currents are mathematically transformed from the three-phase stationary reference frame of the stator windings to the two-axis rotating d-q reference frame, before giving for processing to the PI controllers. Similarly, the voltages provided to the motor terminals are mathematically transformed from the d-q reference frame of the rotor to the three phase reference frame of the stator before they can be used for PWM output. To perform these transformations we require the fast math capacity of a DSP or high-performance processor, which is the heart of Field Oriented Control. Even though these reference frame transformations can be performed in one step, these can be best described as a double step process. First of all, the motor currents are converted from the 120-degree physical frame of the stator windings to a fixed orthogonal reference frame which is then transformed to the rotating frame of the rotor. This process is then reversed to transform voltage signals from the P-I controllers which are in the d-q frame of reference to the stationary terminals of the stator windings. Once the motor control currents are transformed to the d-q reference frame, then the control becomes somewhat easy. We are using two P-I controllers for this; first is for the direct current component and the second one for quadrature current. The input which is given to the PI controller for the direct current component is zero input. This drives the direct current component to be zero and thereby forcing the current space vector to be laid in the quadrature direction. Thus the torque efficiency of the system is maximized since only the quadrature current component can produce the useful torque. The other P-I controller operates on the quadrature current and the input given is the requested torque. This allows the quadrature current to follow the desired torque[6].

5. Conclusion

Field Oriented Control has a lot of advantages when compared with Trapezoidal and sinusoidal control. FOC helps us to get around the limitations by decoupling the effect of the torque and the magnetizing flux. The torque-producing component of the stator flux can now be thought of as independent torque control since we have a decoupled control of magnetization. Also, with this decoupled control, even at low speeds, we can maintain the magnetization at the proper level, and the torque can be controlled to regulate the speed. At small speeds, FOC provides smooth motion. It also gives an effective operation at higher speeds. So it overcomes the limitations of sinusoidal commutation which can only produce smooth motion at slow speeds and is inefficient at high speeds. Also, when compared with Trapezoidal commutation which leads to torque ripple at slow speeds, FOC works more efficiently. Hence Field Oriented Control can be the best control when compared with the other two[5]. So, in a Steer-by-Wire system, for the efficient control of the road wheel motor and steering wheel motor, Field Oriented Control is more suitable than the existing Trapezoidal system.

References

[1] B PavanKumar and Krishnan C.M.C.“Comparitive Study of Different Control Algorithms on Brushless DC Motors,” presented at the International Conference on Power and Energy Systems:Towards Sustainable Energy,Bienna,2016.

[2] Salih Baris Ozturk and Hamid A. Toliyat," Direct Torque and Indirect Flux Control of Brushless DC Motor,"*IEEE/ASME Trans.Mechatronics, vol. 16, no. 2,pp 351-360, April 2011*.

[3] Fatih Korkmaz, smail Topaloglu and Hayati Mamur."MODIFIED DIRECT TORQUE CONTROL FOR BLDC MOTOR DRIVES."*International Journal of Control Theory and Computer Modeling (IJCTCM),*vol 6,*no.3,* July 2016.

[4] Bilal Akin and Manish Bhardwaj, **“** Trapezoidal Control of BLDC Motors Using Hall Effect Sensors" *Texas Instruments Application Report,* SPRABQ6–July 2013.

[5] www.copleycontrols.com/Motion/pdf/Field-Oriented-Control.pdf

[6] Renesas, “*Motor Control Algorithms,”* http://america.renesas.com (Renesas Technology–Motor Control)

[7] Jiancheng Fang, Haitao Li, and Bangcheng Han,” Torque Ripple Reduction in BLDC Torque Motor With Non ideal Back EMF”, *IEEE Transactions on Power Electronics , Vol , 27, NO , 11, November 2012.*

[8] Peter, D. and Gerhard, R., "Electric Power Steering - The First Step on the Way to “Steer by Wire”," SAE Technical Paper 1999-01-0401, 1999, doi:10.4271/1999-01-0401

[9] P. Yih and J. C. Gerdes, "Modification of vehicle handling characteristics via Steer-by-Wire," *IEEE Transactions on Control Systems Technology*, vol. 13, no. 6, pp. 965–976, Nov. 2005

[10] M. Bertoluzzo, G. Buja, R. Menis and G. Sulligoi, "Approach to steer-by-wire system design," *2005 IEEE International Conference on Industrial Technology*, Hong Kong, 2005, pp. 443-447. doi: 10.1109/ICIT.2005.1600679