INTEGRATED SMART DRIVE: Developing Industry Ready Solution for Incommodious PMDC Motor

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***Abstract*—The development of Integrated Smart Drive systems is needed for new merging applications, such as Automotive Modular Machine Control, CNC Training Machine, PID Style Antenna Positioning Pedestal, and High-Speed Inspection Technology.**

An integrated PMDC motor and controller including a PMDC motor having a rotating Shaft with a 2 Pole permanent magnet affixed to the shaft for rotation thereby in a plane orthogonal to the axis of rotation of the shaft. An X-Y Hall Effect Sensor is carried by a controller mounted on a circuit board attached to the motor and the Hall Effect Sensor is positioned proximate the magnet with the Hall Effect Sensor producing the Sine and Cosine components of the magnetic field as the magnet is rotated by the motor shaft. The electronic controller includes software for determining the motor angle and commutation logic from the Sine and Cosine components generated by the Hall Effect Sensor response to the rotating magnetic field. A controller on the board positioned over the rotating shaft contains the highly integrated functions of internal analog digital converters, pulse Width modulation registers for driving the power amplifier, internal communication ports and all of the random excess memory and FLASH non-volatile memory that is typically required for motor control.

Keywords— PMDC Motor, Smart Electrical Drives, Hall sensor, .Net Software.

I. INTRODUCTION

THE present work relates to the field of Servo Systems which use PMDC motors for output drive and modern electronics for the system control.

PMDC-motors and controllers have a wide variety of application in industry. This combination is commonly used to accurately control the position of an output such as the table on a machine tool or the surface of a fin on a missile. Other common applications include the control of the speed of an output such as a fan or a flow metering pump. The physics and engineering of the basic motor and controller concepts are well known. As technology and industry progress, the need for greater precision and versatility at lower cost has risen. New controller and sensor technology are enabling the design of new and innovative designs to meet these objectives..

II. OBJECTIVES

The main objective of this research is to develop an integrated design methodology for the power stage of general-purpose industrial motor drives based on electrical, mechanical, considerations to achieve an optimal system design in terms of cost and performance. This paper also focuses on EMI/EMC issues and their impact on overall system. The specific goals of the project are:

- Cost optimization of front-end in the motor drive system
- Modeling and characterization of EMI emissions in the system
- EMI filter design optimization
- Development of optimization software for the whole power section.

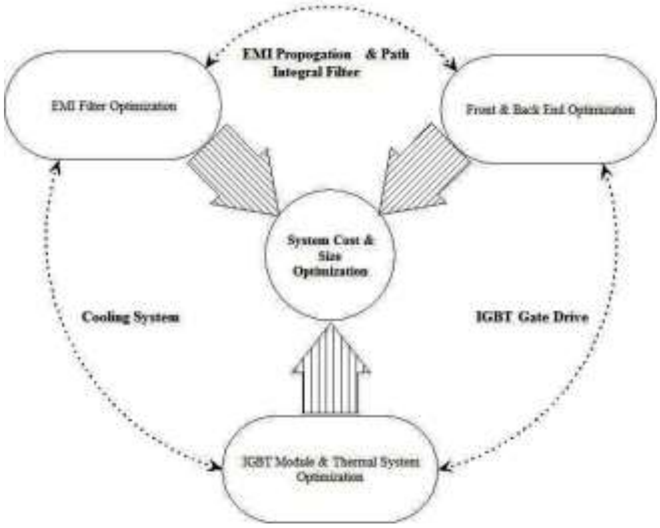

FIG 1.1 General objective block diagram

An optimization methodology has been developed for the low frequency passives considering requirements on harmonics, peak power, and thermal constraints. The optimizer for the front-end of a motor drive system has been developed and delivered. The EMI filter optimizer is being built based on the detailed modeling of the EMI sources and propagation paths.

III. PROBLEM DEFINITION

In recent times, approaches using machine design to influence the machine performance becoming more and more equivalently to efforts at current and hence torque control. The design of PMDC Motors by numeric methods with FEM-programs (Finite Element Method) will provides the most precise and proof results. However, calculations by FEM will be time consuming and require special, relatively complicated and expensive software. For a complete design of new type series of machines with different dimension's variants the way of using only the FEM is at present not practicable. Therefore software is necessary that can abbreviate considerably the preparation time for the following FEM-calculation. Also the dynamic operational behavior and the combination of the electric machine with other components like energy storage, converter or mechanical elements must be considered.

To meet these requirements for an effective and reliable machine design, this research work is aimed to find solutions to the above mentioned problems in terms of a new hybrid time-economic design-, calculation- and simulation procedure.

In context of the questions discussed above the OBJECTIVE of the research work is:

Elaboration of effective hybrid design program for PMDC Motors taking into account all losses in drive system, field verification and modeling of dynamic operation as well.

Application of this program to the design calculation of three different PMDC Motors destined to concrete industrial drives.

Demonstration of the correctness of proposed program by comparison of the calculation and measurement results made for three prototypes of PMDC Motors manufactured in industry.

Results of the research will evaluate from the point of view of the present above objective enable the formulation of the THESIS TO BE PROVED related to the PhD thesis:

The proposed in the research work hybrid design program for PMDC Motors enables the effective and more complex motor design from the point of view of considered drive requirements, in comparison with proposals published up to now and known by author from the bibliography.

In the proposed hybrid design program at first analytical and then field calculation methods and finally dynamic simulations will be developed. This program can perform:

Steady-state calculations like torque-, flux- and inductance characteristics, copper and core losses of the motor, converter losses and finally system efficiency. Verification of the projects by application of numerical field method (FEM). Dynamic calculations like current waveform in dependence of speed and mode of control.

FEM models will be developed as the complimentary tool in respect to the analytical models. By means of a simulation model the operational behavior of the whole drive system will be investigated during various control modes. Also sensor-less control will be researched.

- **Expected Output**

The expected output such as electric characteristic from the system will be same like normal external drive system. Mechanical movement of motor will also remain same. The main difference in traditional drive system and integrated drive system is size and cost. The expected size of driver will be as small such that we can built that drive on motor through housing. And this can be achieved in moderate cost.

Its considerable limited dimensions, it is particularly suited for space saving solutions where the space is a real constraint, such as Integrated Motor Drivers or Motor Drivers of the new generation. To include all functions and reach high-level performances a new package, named EMP, has been designed to accommodate the printed circuit board on its top, with all needed connections for a proper communication between the two parts. With this new device a motor driver designer can easily design and debug its system with an excellent level of performances and a considerably improved time to market.

The objective of high performance at a low cost is achieved by attaching the controller to the motor such that two linear and orthogonally fixed Hall Effect Sensors, packaged in a single monolithic integrated circuit and mounted on the controller board, are located proximate a 2 pole magnet that is fixed to the motors rotor shaft. As the rotor turns, the magnet rotates in a plane orthogonal to the axis of the rotor shaft and the two Hall Effect Sensors produce a Sine and a Cosine signal that is decoded in a controller to give a high resolution signal that is proportional to angular position of the motor shaft. This signal is further decoded to produce the motor state information that is necessary for brushless motor commutation. The high resolution position signal is also used for accurate positioning. This combination reduces the necessary connections between the motor assembly and the controller to only the three motor phase wires while allowing all of the advantages available to a micro-controller based controller with an electronically commutated PMDC motor and encoder quality position feedback.

The controller used for this invention is a highly integrated device that includes a microprocessor, FLASH memory for computer program and parameter storage, RAM memory for program execution, Pulse Width Modulation (PWM) drivers, analog to digital converters, and an SCI (Serial Communication Interface) port for easy serial interface to external command and sensor inputs. Within the controller the operating code closes the loops on motor commutation, current, and position, as appropriate to the programmed task. The loop closures are typically done using a classic position error amplifier with adjustable gain followed by a velocity feedback error amplifier with adjustable forward and feedback gain terms as necessary to meet stable system performance requirements. System steady state error is typically improved by use of classic lead-lag compensation. All of the loop closure computations are repeated at a very high rate to support very high bandwidth of the resulting servo control system.

Further enhancements will be made in the system software to improve accuracy, reduce electromagnetic emissions, allow a large range of power supply voltage, allow current limiting without a hardware sensor, greatly improve velocity accuracy, and to maximize the computational throughput.

An integrated PMDC motor and controller including a PMDC motor having a rotating shaft, an electronic controller attached to the motor and positioned over the rotating shaft, a two pole permanent magnet affixed to the shaft for rotation by the shaft in a plane orthogonal to the axis of rotation of the shaft, an X-Y Hall Effect Sensor carried by the controller and positioned proximate the magnet, the Hall Effect Sensor producing the Sine and Cosine components of the magnetic field as the magnet is rotated by the motor shaft, the electronic controller includes means for determining the motor angle and commutation logic from the sine and cosine components generated by rotation of the magnet adjacent the Hall Effect Sensor.

IV. Analogy Of System Design

- **Projected System Design**

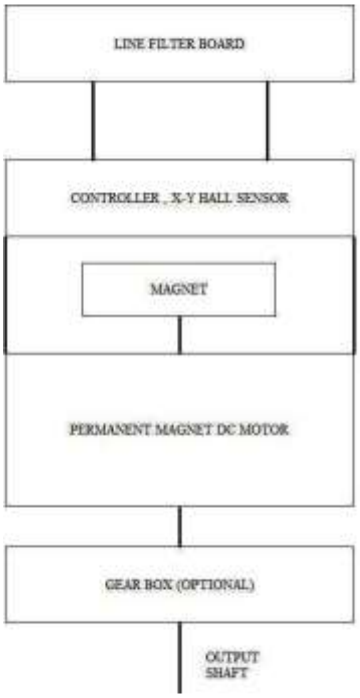

FIG. 2 Schematic block diagram of an integrated motor controller constructed in accordance with the principles of the projected research

Referring now more particularly to FIG. 2, there is illustrated in a schematic block diagram the motor and controller combination in accordance with the principles of the projected work. As is therein illustrated there is provided a brushless DC motor which includes a shaft extending from one end thereof. The shaft rotates with the rotor of the motor and has a two pole permanent magnet secured to the end of the shaft by being affixed with adhesive. The magnet is arbitrarily attached to the end of the shaft and as the shaft rotates the magnet rotates in a plane that is orthogonal to the axis of the shaft. As is also well known in the art the shaft may also extend from the motor as shown and engage a gear box which is optional.

The output shaft from the gear box may be then being attached to any desired load.

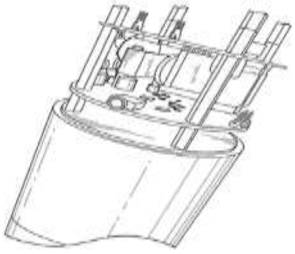

FIG. 3 Perspective view of the integrated motor and controller in accordance with the present invention with the housing for the controller removed

The controller is mounted on the circuit board as shown in FIG. 3 and includes an X-Y Hall Effect Sensor which is positioned proximate the magnet. It is preferable that the magnet be positioned as nearly as possible to the axis of rotation of the shaft and that the X-Y Hall Effect Sensor is positioned so that it is approximately 0125 to 0.025 inches displaced from the magnet. It should be noted as shown in FIG. 3 & 4 that the controller is mechanically affixed to the motor by way of the rods. Also connected to the motor is a power supply which is also mechanically affixed to the motor by the rods and which are effectively an extension of the rods.

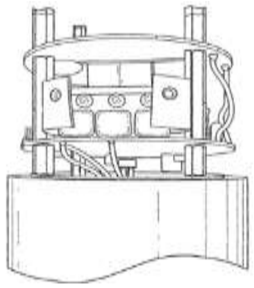

FIG. 3 Perspective view similar to FIG. 2 but illustrating the controller from a different view.

As the shaft rotates and with it magnet the Hall Effect Sensor as shown in FIG. 4 provides an output which is representative of the Y or Sine component of the magnetic field and the X or Cosine component.

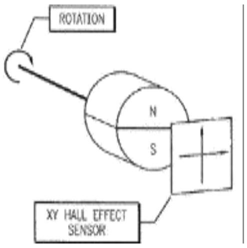

FIG 4 Schematic diagram illustrating the magnet and the X-Y Hall Effect Sensor

As shown in FIG. 5 the X-Y signals represent the projections of the rotating magnetic field on a unit circle and the inverse tangent of Y/X Will reproduce the motor angle as a value in the controller code.

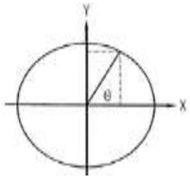

FIG. 5 Unit Circle –projection of the magnetic fiel d onto the X-Y plane for the motor angle θ

V. System Epitome

The minimal embodiment of the invention is physically shown in FIG. 1 and depicted in the block diagram of FIG. 4 This configuration has the following key elements.

An electronic controller is mechanically fixed to one end of the motor directly over the rotor shaft. The rotor shaft is fitted with a concentrically located magnet with a single North and South Pole rotating in the plane that is orthogonal to the axis of motor rotation. The controller circuit is mounted such that an XY Hall Effect Sensor, mounted on the board, is located directly over the rotating magnet. The output of the XY Hall Effect Sensor represents and Cosine components of the rotation of the magnet and thus rotor, position.

A controller on the board that contains the highly integrated functions of internal Analog to Digital converters, PWM (Pulse Width Modulation) registers for driving the power amplifier, internal communication ports, and all of the RAM (Random Access Memory) and FLASH non-volatile memory that is typically required for motor control. The software in the controller provides the command and control interfaces for the user and it computes the control algorithm that provides stable motor performance that accurately follows the external commands. The software uses the FLASH memory to store highly configurable control parameter settings that allow the system to be easily configured to perform a wide variety of servo functions.

The controller reads the X and Y linear outputs of the Hall Effect Sensor and by methods, Written in software, decodes the motor angle with reasonable accuracy (i.e. at least within 5 degrees of mechanical rotation). Based on the mechanical angle, the controller computes the electrical motor angle. From the electrical angle, the controller calculates the motor state and executes the commutation logic internally. It then directly drives the power bridge transistors that regulate the current into the appropriate motor windings. Those currents produce the rotor torque that drives the rotor in the correct direction and at the correct speed to follow the external user commands.

The derived motor angle is further integrated to give a position output that may span many motor rotations. The resulting position is used as feedback to the controller to apply torque in the direction that will reduce the error between the externally commanded position and the synthesized position.

The preferred embodiment of the invention is physically shown in FIG. 1 and is depicted in the block diagram of FIG. 6. This configuration has the following key elements which, in combination, result in a highly versatile, very simple, very reliable, and cost effective design. An electronic controller is mechanically fixed to one end of the motor directly over the rotor shaft. The rotor shaft is fitted with a concentrically located magnet with a single North and South Pole rotating in the plane that is orthogonal to the axis of motor rotation. The controller circuit is mounted such that an XY Hall Effect Sensor, mounted on the board, is located directly over the rotating magnet. The output of the XY Hall Effect Sensor represents the Sine and Cosine components of the rotation of the magnet, and thus rotor, position.

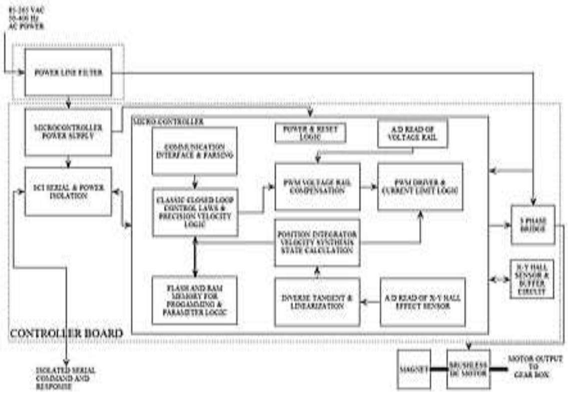

FIG 6 Block diagram of the preferred embodiment of the integrated motor controller

A controller on the board that contains the highly integrated functions of internal Analog to Digital converters, PWM (Pulse Width Modulation) registers for driving the power amplifier, internal communication ports, and all of the RAM (Random Access Memory) and FLASH non-volatile memory that is typically required for motor control.

The software in the controller provides the command and control interfaces for the user and it computes the control algorithm that provides stable motor performance that accurately follows the external commands. The software uses the FLASH memory to store changeable control parameter settings that allow the system to be easily configured to perform a wide variety of servo functions. The controller reads the X and Y linear outputs of the Hall Effect Sensor and by methods, Written in software, decodes the motor angle with reasonable accuracy (i.e. at least Within 5 degrees of mechanical rotation). Based on the mechanical angle, the controller computes the electrical motor angle.

From the electrical angle, the controller calculates the motor state and executes the commutation logic internally. It then directly drives the power bridge transistors that regulate the current into the appropriate motor windings. Those currents produce the rotor torque that drives the rotor in the correct direction and at the correct speed to follow the external user commands. The derived motor angle is further integrated to give a position output that may span many motor rotations. The resulting position is used as feedback to the controller to apply torque in the direction that will reduce the error between the externally commanded position and the synthesized position. The PWM driver performance is enhanced by the use of a unique modulation scheme that both improves efficiency and

resolution for very low duty cycles and makes the introduction of variable PWM modulation frequency easy to accomplish. The variable modulation frequency spreads the spectrum of EMI switching related electromagnetic emissions.

This feature improves the conducted emissions numbers by about 10 dB. The design implements a motor angle linearization technique that requires calibration at the time of production. The algorithm greatly improves the accuracy of Hall Effect Sensor decoded motor angle. This reduces production cost because it removes most of the tolerance criticality for concentricity of the end shaft sensor magnet With respect to the XY Hall Effect Sensor placement. It also reduces the second order contamination of the field measurements from the main motor rotor magnets.

The design further employs a simple bridge rectifier and filter circuit that is capable of accepting a Wide range of input power supply characteristics from DC to greater than 400 HZ and an input voltage range up to 265 VAC or 375 VDC.

The broad range of input supply voltage for the motor supply rail is enhanced by the use of line voltage feed forward term in the motor control algorithm. The PWM duty cycle that is calculated from the control algorithm is modified by the reciprocal of the motor rail voltage to normalize the performance of the system over a large voltage range. The use of this method eliminates the need for a difficult current feedback loop in the control calculations. A sensor-less current limiting method is used to further reduce cost and circuit complexity. The technique involves estimating the required motor PWM to achieve the real time no-load velocity. The PWM allowed is limited to the no load theoretical value plus or minus the value that is required to achieve current limit at zero speed.

Velocity control is greatly enhanced by using a method in which the motor is actually controlled as a position loop. The commanded velocity is used to setup a precise position trajectory that will require the exact commanded velocity. Because the motor will follow the position trajectory with a minimal and bounded steady state error, the velocity of the motor over a period of time, Will be as accurate as the crystal oscillator time base in the controller. The servo loop performance is enhanced by a very high speed inverse tangent function that uses a table look up method. The typical Inverse Tangent method required to get motor angle from the Hall Effect Sensors, is very math intensive and would significantly impact the processor throughput.

A basic requirement of any servo system is that it must have accurate and timely information relating to measured position and velocity of the plant. In this case the plant is the motor and the output is the rotor shaft. The commanded values of position and velocity are compared to the measured values to close a loop which results in the mechanical output following the signal command. This invention uses a single reliable and robust XY Hall Effect Sensor to get all of the necessary system state information to produce a high performance servo system. Because this single sensor does not require wiring between the motor and the controller (it does require close physical proximity) the resulting system has only three electrical Wires (FIG. 3) between the motor and the controller.

As shown in FIGS. 1, 2 and 3 the electronic controller is mechanically fixed to one end of the motor directly over the rotor shaft. The rotor shaft is fined with a concentrically located magnet with a single North and South Pole (2 pole magnet). The sensor magnet rotates in the plane that is orthogonal to the axis of motor rotation as shown in FIG. 4.

The controller circuit is mounted such that an X-Y Hall Effect Sensor, mounted on the board, is located directly over the rotating magnet at a critical distance that maximizes the analog X and Y outputs while not allowing the field to saturate the two sensors. As the motor rotor and the sensor magnet rotate, the magnetic field around the sensor magnet rotates, painting a magnetic unit circle as shown in FIG. 5. The X-Y Hall Effect Sensor is directly exposed to this rotating field and is designed to detect two orthogonal components of the field which are referred to as the X and Y outputs. The outputs from this monolithic integrated circuit are analog voltages centered about 1/2 of the chip power supply voltage and whose magnitude is directly proportional to the component of the field strength that is in the sensors orientation. The analog signals are subsequently read into the controller for processing.

Because the X and Y signals represent the projections of the rotating magnetic field on the unit circle, the inverse tangent of Y / X Will reproduce the motor angle as a value in the controller code. This function is depicted in FIG. 7. The circuit is insensitive to the exact placement of the magnet relative to the sensor because the ratio of Y/X removes the absolute magnitude of the signal from the equation. This makes the sensor very robust and easy to assemble. The exact location of the board is not very sensitive while the general proximity of the board to the motor and sensor magnet is critical to the functionality of the system.

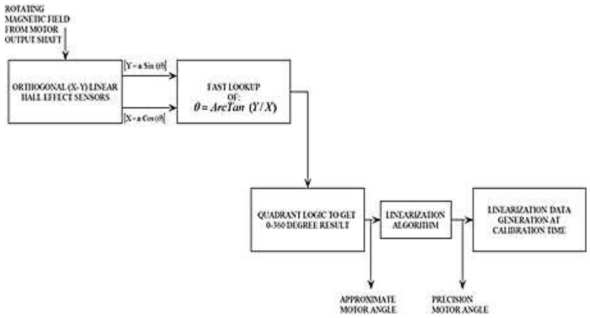

FIG 7 Diagram illustrating the termination of the motor angle from the Hall Effect Sensor data

As seen in FIG. 8, the resulting angle is used to synthesize the motor state, the servo position, and the servo velocity. The servo velocity is simply the difference between the present position and a past position. The time delay from present to the past value that is used is adjustable to allow an optimal tradeoff between phase lag in the result and signal to noise ratio. Longer delays increase the signal to noise ratio at the expense of greater phase lag. The servo position is simply the integral of the motor position. Both the velocity and the position integral algorithms require some special consider action at the rollover of the motor angle between 360 and 0 degrees.

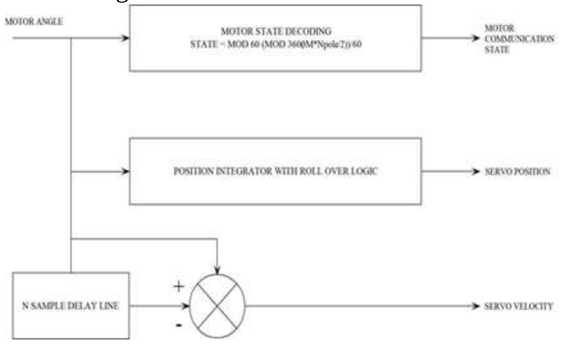

FIG 8 Diagram illustrating extraction of the motor state servo position and servo velocity from motor angle

VI. Virtual System Design

In the proposed Topology a boost converter is used to boost the input voltage which is fed to a voltage source inverter (VSI), the PMDC motor is given its supply from this VSI. A Speed Controller and a Voltage Controller is used in the motor side and the input side respectively. Both Controllers are realized using Proportional Integral (PI) controller.

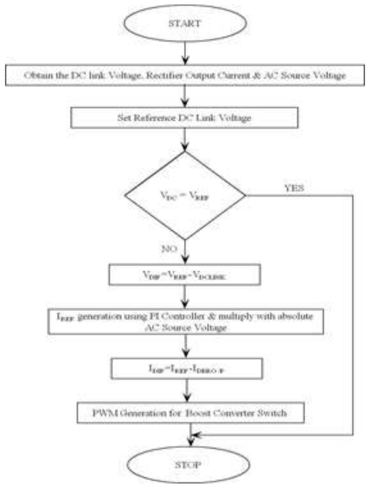

FIG 9 Control Flow chart for Voltage Controller

PMDC motors are generally powered by a conventional three-phase voltage source inverter (VSI) or current source inverter (CSI) which is controlled using rotor position. The rotor position can be sensed using Hall sensors, resolvers, or optical encoders. These position sensors increase cost, size and complexity of control thereby reducing the reliability and acceptability of these drives. Due to the high cost of the motor and controller, very few commercial applications of PMDC motors have been reported. Recently some additional applications of PMDC motors have been reported in electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to environmental concerns of vehicular emissions. PMDC motors have been found more suitable for EVs/HEVs and other low power applications, due to high power density, reduced volume, high torque, high efficiency, easy to control, simple hardware and software and low maintenance. Due to ease of control in PMDC motors, they are preferred for numerous applications in low power and variable speed drives.

For the Voltage Controller, the DC link voltage is sensed and compared with the reference DC link voltage. The error voltage is passed through a PI Controller, and multiplied with a unit template of absolute input voltage so as to generate the reference current signal. This signal is compared with sensed converter current which gives the modulating wave for the PWM. This current error is the modulating signal and a triangular wave is taken as the carrier signal so as to generate the PWM gate pulses for turning on/off the Boost converter switch. The flowchart for Voltage Controller is shown in Fig 9.

The control of PMDC motors can be accomplished by control algorithms using conventional six pulse inverters which can be either VSI or CSI. The control of these inverters for PMDC motors needs rotor position information only at the commutation points, for example, every 60° electrical in the three phases; therefore comparatively simple controller is required for commutation and control. The rotor position is sensed using Hall Effect sensors. The speed of the motor is measured and is compared with the reference speed. The error signal is passed through a PI controller to give a reference signal. This reference signal is compared with the Boost converter output current so as to give modulating signal for PWM. This signal is compared with triangular carrier signal to generate the PWM pulses for turning on/off the VSI switches. The flowchart for Speed Controller is given in Fig 10.

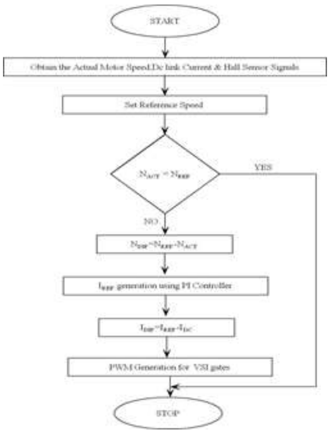

FIG 10 Flow chart for Speed Controller

VII. Conclusion

The said topology for quality improvement in PMDC motor drives is designed and their performance will be simulated to provide in depth understanding on various aspects of these drives. The performance of this topology will evaluated through simulation for validation of their designs. The topology will be used as this is the best option for applications having rated DC voltage higher than single phase supply RMS voltage. The PMDC motor drives incorporating different electronic circuitry can be a milestone towards the widespread application of these drives.

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