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Torque Responses of Brushless DC Motor by Internal Model Control Controller

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Abstract

Brushless DC motors are employed in each little scale and large-scale industrial applications that are involving great speed and torques. They are utilized in servo, actuation, positioning, and completely different speed applications wherever the precise movement of control and stable operations are necessary for the producing method. The implementation of those motors is incredibly tough and even to attain the precise speed and force responses. The performance characteristics i.e. speed and torque of a BLDC Motor will be investigated at load torque by using PID and IMC controllers. Each of the force responses of the PID controller and IMC Controller are compared. IMC controller provides the most effective performance to scale back the ripples by employing a PID controller that is studied by using SIMULINK/MATLAB.

Keywords: *Brushless Direct Current motors, Torque responses, PID (Proportional plus Integral plus Derivative) controller, IMC (Internal Model Control) controller.*

I. INTRODUCTION

A Brushless Direct Current motor is also called as electronically commutated or synchronous Direct Current motor. These motors are driven either by using DC or an inverter or switching power supply that produces electricity in the form of alternating current to run every phase of motor by the usage of Closed loop controller. The control of speed and torque of BLDC motors can be done by giving current signals through the controller. BLDC motors are widely utilized in aeronautics, electric vehicles, robotics, food and chemical industries. By using microprocessor or microcontroller computers or analogue or digital circuits, BLDC motors are used in software sectors. In the applications like automobile industries and domestic appliances [1], different systems of speed driving have been used. In order to reduce the wastage of energy usage in different devices, using of eco-friendly electronic devices are developed. The Brushless DC motor is an extremely non-linear motor and it gives trouble to confirm a mathematical model. The force production in BLDC motors are categorised into three main sources. They are cogging force, reluctance force and mutual force. The interconnection between the rotor's permanent magnet and coils of stator are used to develop cogging torque in the motors which is self-employed of stator current excitation. When there is a change in some part of inductance with respect to relevance placement, a reluctance force is produced. The mutual coupling between current coils of stator's winding and field of the rotor forms mutual force. The benefits of Brushless DC motors are great dynamic feedback, soundless operation etc., As they have lack of electrical and friction losses and high-speed ranges their operating life is more and are also more efficient than compared to remaining motors [3]. BLDC motors are used in various applications like transport, heating and ventilation, industrial and model engineering. Mechanical commutators and brushes are used to attain communication by using stator magnet DC motors. The rotor can be rotated by developing the field of stator coils. The rotating position can be detected by using commutating signal in Hall impact detectors [4]. Therefore, permanent magnets are used rather than coil in BLDC motors. The controlling of Brushless DC motors speed can be controlled by using Proportional-Integral-Derivative controller as they have the simple structure and performance. The parameters of PID controller are modified simply that are not required to change the hardware effects of BLDC motors. The PID controller performance depends on the model accuracy and parameters of the system. PID controller are essentially used to acquire stability of a system to scale back steady-state error and to urge higher performance of the system. IMC controller states that controlling is being attained by giving the system either with implicitly or express the method to be controlled. IMC controller are used in industrial applications with multivariable processes with complex dynamics. They are not used commonly in process control as detailed analytical models are difficult to obtain and even in maintenance as process changes had a need to change the model.

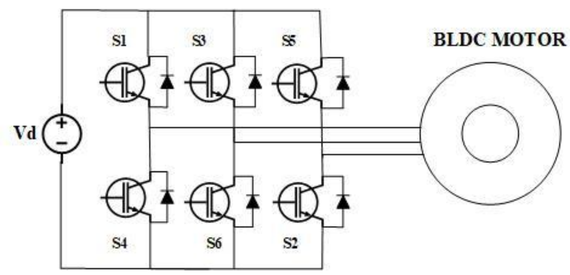

Fig.1. Voltage Source Inverter BLDC Motor

II. MATHEMATICAL MODELLING OF BRUSHLESS DIRECT CURRENT MOTOR

The Brushless DC motor have construction similar to permanent magnet synchronous machine. Variations in the dynamic characteristics can be found as the rotor are been mounted by the permanent magnets. The modelling of Brushless DC motor armature winding is explained below [2]. By applying Kirchhoff's law to the Three-Phase BLDC machine, we get

$$V_A = i_A R_A + L_A \frac{di_a}{dt} + M_{AB}\frac{di_b}{dt} + M_{AC}\frac{di_c}{dt} + e_A \qquad (1)$$

$$V_B = i_B R_B + L_B \frac{di_b}{dt} + M_{BA}\frac{di_a}{dt} + M_{BC}\frac{di_c}{dt} + e_B \qquad (2)$$

$$V_C = i_C R_C + L_C \frac{di_c}{dt} + M_{CB}\frac{di_b}{dt} + M_{CA}\frac{di_a}{dt} + e_C \qquad (3)$$

Where,

R is Resistance of stator of all the three phases A, B and C

L is Inductance of stator of all the three phases A, B and C

I is Current of stator of all the three phases A, B and C

V is voltage referred all the three phases A, B and C

M is mutual inductance

e is back-EMF

In this case, a 3-phase balanced system is assumed,

$$\therefore L_A = L_B = L_C = L \qquad (4)$$

$$M_{AB} = M_{AC} = M_{BA} = M_{BC} = M_{CB} = M_{CA} = M \qquad (5)$$

$$R_A = R_B = R_C = R \qquad (6)$$

Arranging equation (1), (2) and (3) according to the equations (4), (5) and (6) and neglecting mutual inductance, we will get,

$$V_A = i_A R + L\frac{di_A}{dt} + e_A \qquad (7)$$

$$V_B = i_B R + L\frac{di_B}{dt} + e_B \qquad (8)$$

$$V_C = i_C R + L\frac{di_C}{dt} + e_C \qquad (9)$$

Arranging the equations (7), (8) and (9) in vector form,

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$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} = \frac{1}{L}\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} + \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \quad (10)$$

The above equation (10) can be solved by the use of any numerical solution technique to find the values of i_A, i_B and i_C.

The equation for the generation of back EMF can be given by

$$e = Back\ EMF\ constant * Mechanical\ Rotor\ Speed * Rotor\ angle$$

$$e = k \cdot \theta \cdot w \quad (11)$$

Because, the angle difference between each rotor is 120^0 and, back-EMF is related to the function of the rotor, therefore,

$$e_A = k_e \cdot \theta_e \cdot w_r \quad (12)$$

$$e_B = k_e \cdot \left(\theta_e - \frac{2\pi}{3}\right) \cdot w_r \quad (13)$$

$$e_C = k_e \cdot \left(\theta_e + \frac{2\pi}{3}\right) \cdot w_r \quad (14)$$

Where,

w_r is rotor speed (rad/sec)

k_e is back EMF constant

Difference across winding = Supply Voltage – Back EMF Voltage

The equation for the generation of torque is given by

$$T = k_t * I \quad (15)$$

The produced torques are influenced by the permanent magnet because of the trapezoidal flux linkage. Therefore, the torque produced is

$$T_e = T_A + T_B + T_C \quad (16)$$

And here the resultant T_e can be obtained by following equations:

$$T_A = k_t * \theta_e * i_A \quad (17)$$

$$T_B = k_t * \theta_e * i_B \quad (18)$$

$$T_C = k_t * \theta_e * i_C \quad (19)$$

Where,

θ_e is Rotor Angle expressed in electrical degree

w is Rotor's Speed (rad/sec)

θ_m is Mechanical Rotor Angle

$$\theta_e = \frac{P}{2}\theta_m \quad (20)$$

The equation of the simple motion system (i.e. mechanical torque which is transferred to the motor shaft) with friction constant, load torque and inertia is

$$T_e - T_l = k_f \cdot w_m + J\frac{dw_m}{dt} \quad (21)$$

Where,

T_e is Electrical Torque

T_l is Load (Mechanical) Torque

k_f is Friction Constant

J is Rotor Inertia

III. TORQUE RESPONSES OF BLDC MOTORS

The speed control of BLDC Motors is controlled by two methods. They are

- By using PID Controller
- By using IMC Controller

1. PID CONTROLLER:

A Proportional-Integral-Derivative (PID) controller is also known as Three-time period controller which has feedback closed loop mechanism that was broadly utilized for industrial control structures and which require constantly modulated control [2], [4]. The difference between a desired setpoint (SP) and a process variable that is measured (PV) is an error value. The error value is monitored by PID controller, so as to apply the correction which is related to proportional, integral, and derivative terms.

The overall control function is

$$u(t) = K_p e(t) + K_i \int_0^t e(t')\, dt' + K_d \frac{de(t)}{dt} \qquad (22)$$

where K_p, K_i and K_d K_p, K_i and K_d are non-negative terms that denote the coefficients of the derivative, proportional and integral terms respectively.

K_p and K_d are been replaced by $\frac{K_p}{T_i}$ and $K_p T_d$ in order to get standard form to the equation. The advantage of this equation is to be understandable with a physical meaning to represent both integration time and the derivative time at the same time.

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(t')\, dt' + T_d \frac{de(t)}{dt} \right) \qquad (23)$$

By using three rectifying terms, whose summation contains the manipulated variable (MV), the PID control plot is named. In order to calculate the Proportional-Integral-Derivative controller's yield, the summation of the three proportional, integral, and derivative terms are done [5], [8]. By communicating as the yield of the controller, the Proportional-Integral-Derivative algorithm's final form is

$$u(t) = MV(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt} \qquad (24)$$

where

$K_p K_p$ is Proportional gain which is a tuning parameter

$K_i K_i$ is Integral gain which is a tuning parameter

$K_d K_d$ is Derivative gain which is a tuning parameter

$e(t) = SP - PV(t)$ is the error

where SP is the setpoint, and PV(*t*) is the process variable),

tt is the Instantaneous time (the present),

$\tau\tau$ is the Integration's variable (takes on values from time 0 to the present tt).

Therefore, the Laplace domain of the transfer function of the PID controller is

$$L(S) = K_p + K_i/_s + K_d s \qquad (25)$$

Where s is the complex frequency.

A measurable output (PV), ideal price of desired setpoint output (SP) and input of the method (MV) are being used by controller which shows an effect on the relevant PV. Various parameters like temperature, pressure, force, position, speed and many more variable measuring parameters are used by controllers that are present in motors. The physical parameter which is equal to both fluid level or rate can be controlled by a PID controller as acts as output loop controller. The inner loop controller which is a opposite controller reads the outer loop controller's output as setpoint, flowrate or acceleration, additional fast dynamic parameter.

The inner loop which sense the offer polarity is used for the standardization whereas the regulation of speed is done by the external loop. The regulation of voltage of DC bus can be measured by speed controller of motor that regulates the system. The DC offset system whose cost relies upon the speed of motor and its ability is additionally required. The above method needs a controller. The output voltage of electrical converter is been controlled by using a PID controller. To dominant the speed of motor, an integral part of controller's control system i.e., sensor is used. The conversion of physical position and motor's condition into the electrical signal of a controller circuit is the first operation of the sensor. Electrical converter circuit is used for the conversion of DC power offset voltage to equivalent AC supply voltage as Brushless Direct Current motor needs an alternating current voltage waveform to its operation. They can be mathematically proved which defines that controller's operating frequency will be exaggerated and cascaded PID controller's exploitation decreases the time constant.

2. IMC CONTROLLER

Internal Model Control is a scientific process for system style that is being supported for the Q-

Parameterization construction. Several fashionable control techniques are developed by IMC controller. The calibration of single loop PID-type controllers can be done by preferring procedure of the IMC controller. The procedure of IMC style is sort of extensive and different [9]. It is been developed in various forms i.e., Single-Input Single Output (SISO) and Multi-Input Multi-Output (MIMO) formulations, continuous-time, and style procedures of discrete-time, unstable open-loop control system style procedures, mixed feedback-feedforward IMC design and etc.,

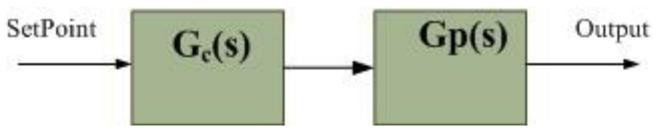

Fig. 2. Open Loop Control Strategy of Internal Model Control

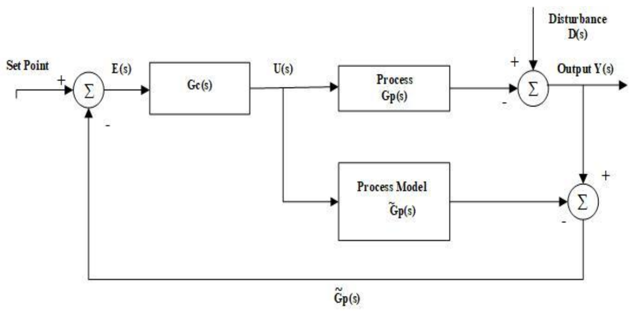

Fig. 3. Schematic Diagram of IMC scheme

In the above figure, d(s) is referred as unknown errors that influences the system. The manipulated input U(s) is acquainted with both the procedure and to its model. The procedure output, Y(s) is contrasted with the output of the model, which results a sign d(s). That is

$$\tilde{d}(s) = [G_p(s) - \tilde{G}_p(s)]U(s) \qquad (26)$$

IMC scheme has the following properties:

- Compensation of Time-Delay will be provided.
- Shaping of both the setpoint tracing and interruption rejection responses can be done by utilizing a filter.
- The controller gives offset free resolution at steady-state conditions.

IV. RESULTS AND DISCUSSION

The simulation model of Brushless DC motor (BLDCM) Drive which is based on both PID Controller and IMC Controller in a Closed Loop system has been simulated by using Simulink/MATLAB. The test specifications of the Brushless DC which are taken for simulating method are investigated.

Due to different loading conditions, motor will run according to that industrial applications in which speed and torque should meet according to the conditions. In this scheme, ripples and disturbances are created by which there will be variations in speed and torque responses. When the Load torque is applied at 0.5sec of 20n-m and there will be change in stator current and torque waveforms where the magnitude of those parameters raises which results are discussed below.

The below results are stator current responses of Brushless DC motor drive with PID Controller in which the load torque is give at 0.5sec.

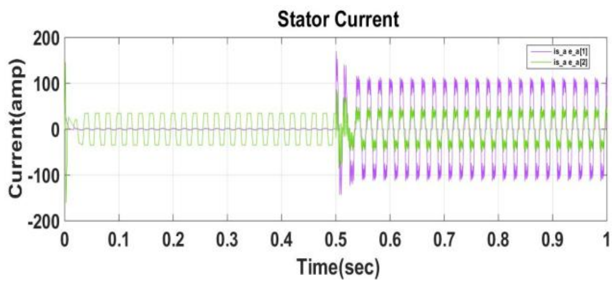

Fig. 4.a. Stator Current of Brushless DC Motors with PID Controller

The below results are electromagnetic torque responses of Brushless DC motor with PID Controller in which the load torque is give at 0.5sec.

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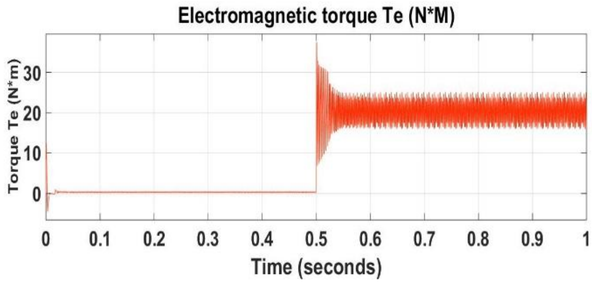

Fig. 4.b. Torque Responses of BLDC Motors at Load Torque with PID Controller

The below results are stator current responses of Brushless DC motor drive with IMC Controller in which the load torque is give at 0.5sec.

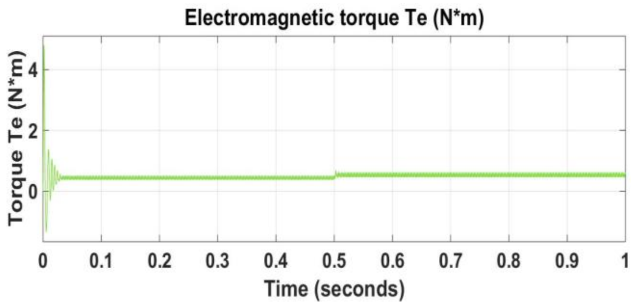

Fig. 5.b. Torque Responses of BLDC Motors at Load Torque with IMC Controller

V. CONCLUSION

The project describes the speed controller for the BLDC motor drive in a closed loop system. Two control strategies namely PID control and IMC are presented for the drive. Design of Internal Model Control (IMC) is presented. It can be observed that IMC controller is giving faster response when compared to PID controller in transient's parameters. So, we can say that the Internal Model Control (IMC) will be better when related to Proportional-Integral-Derivative (PID) controller as it had the interruption non-acceptance ability and can also had ability to withstand the load variations.

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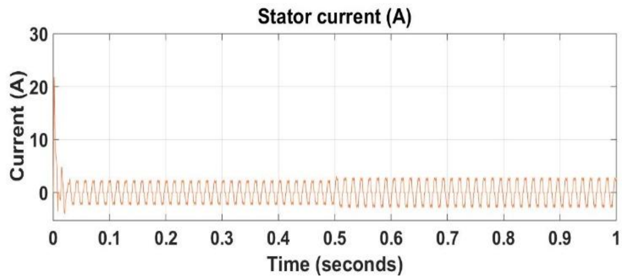

Fig. 5.a. Stator Current of BLDC Motors with IMC Controller

The below results are electromagnetic torque responses of Brushless DC motor with IMC Controller in which the load torque is give at 0.5sec.

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