BLDC Motor Power Control Techniques Appraisal

Novel current control Technique

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***Abstract*—This paper details current state of the art with respect to digital motor commutation techniques illustrates the distinct advantages and disadvantages of each technique and goes on to propose a novel current control technique aimed at increasing efficiency at high speed part load conditions.**

Keywords- BLDC motor, trapeziodal comutation, sinusoidal comutation, field oriented control, digital motor, PMSM

I. Introduction

With the development of semiconductor technology a new age for motors has begun with the introduction of the digitally commutated motor. A digital motor offers longer lifetimes, higher operating speeds and efficiencies in comparison to the traditional mechanically commutated motors.

Digital synchronous motors can be categorised into two main groups based upon the shape of their Back Electromotive Force (BEMF) [1,2] (Fig.1), one produces a trapeziodal BEMF and is reffered to as a Brushles DC Motor (BLDC) whilst the other produces a sinusoidal BEMF and is commonly refered to as a Permanent Magnet Synchronous Motor (PMSM).

Both types of digital synchronous motors can have many mechanical layouts for example, the rotor can be internal or external and the number of phases can vary from one to three [2]. However three-phase motors are the most popular and widely adopted kind.

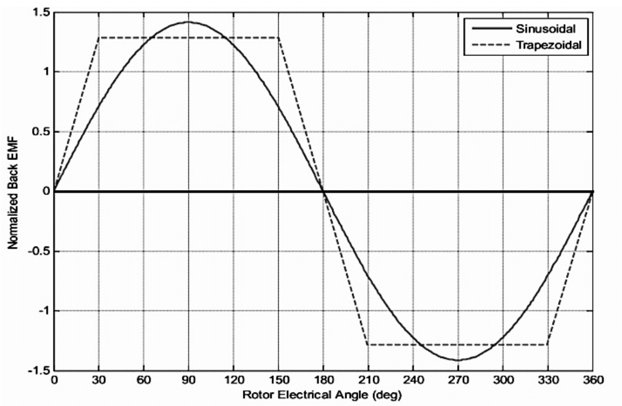

Figure 1. BLDC vs. PMSM idealized BEMF for one phase **[*1*]**

The operation and characteristics of the BLDC motor are very similar to that of a brushed DC motor, but the lack of brushes reduces the frictional losses increases the operating speed and allows the use of high level control. Due to the nature of a BLDC motor it is necessary to perform the commutation via a dedicated digital driving circuit, there are many types of BLDC driver circuits, for the most part they are bipolar (both high and low side semiconductors, aka H-bridge) 3-phase drivers (see Fig.2).

II. Commutation

Commutation refers to the process of creating a rotating magnetic field in the stator of the motor in the desired direction. There are three main ways to achieve commutation [3,4], each one a distinct set of advantages and disadvantages that will be discussed.

A. *Trapezoidal Commutation*

This is the simplest form of commutation, using the trapezoidal technique only two of the three phases are ever simultaneously powered (Fig.3). During one electrical revolution, six commutation steps take place as current can flow both ways within the inductors (Fig.3), giving rise to 6 stator flux vectors as shown in Fig.4.

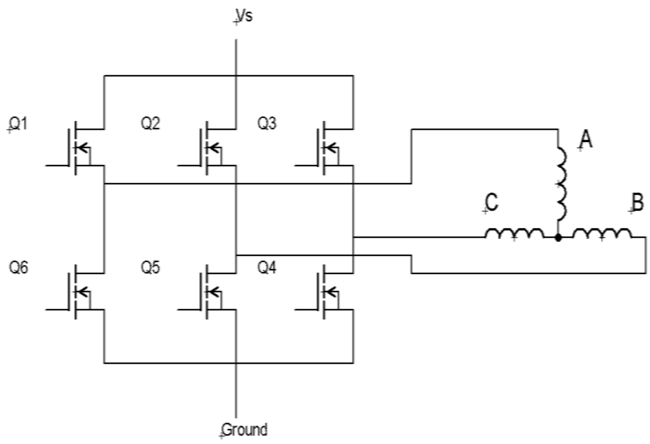

Figure 2. Three Phase Invertor and motor

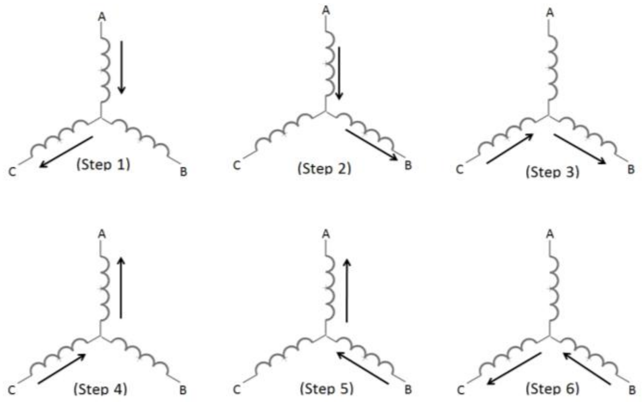

Figure 3. Current flow to produce rotating magnetic field

In order for the controller to switch to the next commutation step at the correct time the position of the rotor must be known. This can be achieved once rotation has commenced by sensing the BEMF of the unused phase, or from a standstill by reading binary outputs from just three sensors separated by 120^{o} electrical, commonly latching magnetic hall sensors [5, 6]. Once the rotor position is known it can be compared to lookup tables relating to the desired operating direction.

When trapezoidal commutation is used to drive a BLDC motor it results in constant torque due to the driving waveform (Fig.1) matching the BEMF [7] waveform of the motor in this case, current cannot penetrate a motor phase instantly leading to torque ripples every commutation step, six times per electrical revolution (Figure 5). However many applications are immune to a certain amount of torque ripple and it has little to no effect on the motors performance.

The same cannot be said when driving a PMSM with the Trapezoidal technique, torque ripple is produced from the miss matched between driving and BEMF waveforms causing less than optimal flux interaction angle. This coupled with the ripple from the commutation step produces relatively high torque ripple as shown in Fig.6.

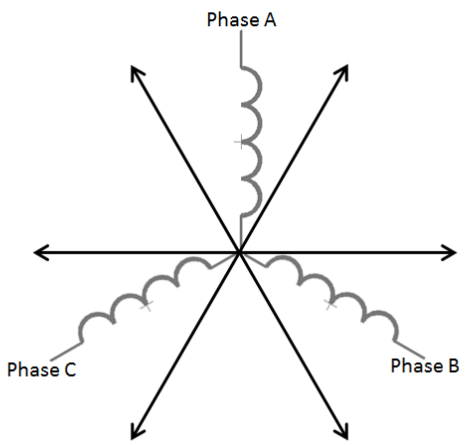

Figure 4. Stator flux vector locations, ABC = rough position sensors

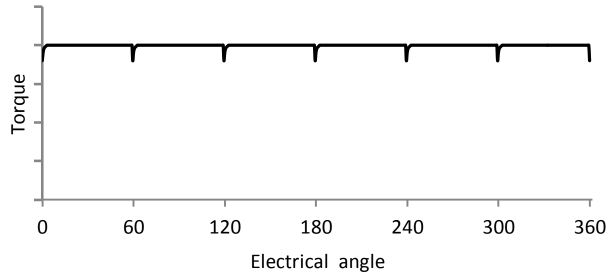

Figure 5. Trapezoidal driven BLDC torque ripple

B. Sinusoidal

Sinusoidal commutation attempts to create a rotating field that can constantly keep the flux vector interaction angle at ninety degrees to optimize efficiency and reduce torque ripple, it does this by manipulating all three phases simultaneously to produce three sine waves of the desired frequency each 120^{o} apart. This is the sinusoidal shape of this driving waveform that produces smooth ripple free torque [5]. In order to achieve a smooth sinusoidal wave the rotor position is needed to a much greater accuracy in comparison to trapezoidal techniques, this is achieved by a position sensor with a resolution much larger than the commutation step. This output from the sensor is then used to compute the desired PWM ratio at that point to create a sinusoidal waveform. If a sinusoidal waveform is used to drive a BLDC motor the torque will have ripples similar to those of a PMSM driven by a trapezoidal waveform (Fig.6). The only difference being there will be no additional ripples introduced from the commutation as it is no longer discreet steps.

Simple sinusoidal commutation does however have some drawbacks. The feedback system that controls the current to the phases tends to fail at, high operating speeds, as the speed increases the current loop controllers have to track a sinusoidal signal of high frequency, and the proportional-integral (P-I) controllers used have a limited gain and frequency response. This results in lag and gain errors in the motor currents, the slew rate of the feedback system isn't fast enough.

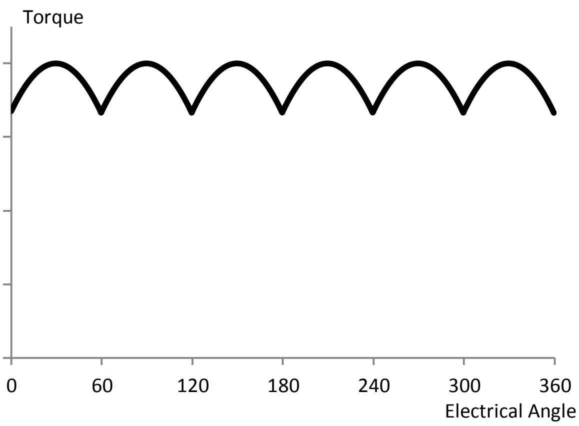

Figure 6. PMSM trapezoidal driven

B. *Field Oriented Control (FOC)*

FOC is an advanced type of sinusoidal driving technique, with the difference being the control system to generate the driving waveforms is relatively complex and as such is considered a high end commutation technique due to its large processing requirements. On the plus side it offers high efficiency over a wide operating range whilst giving precise control over torque and speed.

It moves the feedback loop from a time and speed dependent system into a two co-ordinate time invariant system. This removes the previous bandwidth limitations of the controller, because it is now seen as a DC system from the controller's point of view, with separate processors taking care of transforming between the two reference systems.

This is achieved by utilizing two transforms, the first step is performing a Clarke transform [8], that gives a two variable representation of the three phase, followed by performing a Park transform on the new two variable representation to move it from a stationary reference frame to a rotating and proceeds to use these new DC values to compute the error signal for the PI controller.

That is it takes the flux positions of the rotor and stator and transforms them into easy to compute DC components Iq(torque) and Id(magnetising). For maximum efficiency two PI control loops are used to equate Id to zero and Iq equal to the desired current to control torque.

C. *Commutation Summary*

As previously mentioned each commutation technique has associated benefits and drawbacks and there is no golden solution to every problem. Table-1 outlines the major advantages and disadvantages of each that should be considered when selecting a commutation technique, assuming the commutation technique is being applied to the correct motor.

Table 1. Commutation summary

Technique	Trapezoidal	Sinusoidal	FOC
Power density	High power density	Low power density	Low power density
Start-up power	High starting torque, but lots of ripple	Lower but smooth starting torque	Lower starting torque
Power delivery	High torque ripple	Smooth	Smooth
Speed control	Excellent	Excellent	Excellent
High speed performance	Good	Poor	Excellent
Position sensing	Hall (simple)	Encoder/resolver	Encoder and current sensor
Controller complexity	Low	Medium	High

III. POWER CONTROLL

The previous section discussed the method in which the rotating field is generated, to control torque it is necessary to control the current input into the motor because the two are directly linked [9]. There are three methods commonly implemented to achieve this current control.

A. *Pulse Amplitude Modulation (PAM)*

PAM can be used to control the current for all three of the aforementioned commutation techniques, the applied voltage across the motor is reduces by controlling the bus voltage. This is one of the simplest methods of current control.

B. *Pulse Width Modulation (PWM)*

The motor controller is connected to the full rated bus voltage and instead controls the current through the motor by altering the duty cycle driving the three phase H-bridge. There are two types of switching strategies when considering PWM control, hard chopping where both the high and low switches are controlled by PWM and soft chopping in which the lower switches continuously conduct and only the top fed with PWM [10].

Hard chopping has the advantage of easier control as it only needs to handle three input signals and relies on simple logic components to ensure that a phase is never shorted but does come with the disadvantage of increased torque ripple and increased switching losses.

In comparison soft chopping requires six input signals to independently control each switch increasing the level of control over the system and reducing torque ripple and reducing switching losses by a factor of two when compared to hard chopping due to the lower switches constantly conducing (Fig.7).

PWM is already implemented in sinusoidal and FOC commutation to generate the three phase input waveforms, to control the current going to the motor the ratio of pulses remains constant but the average duty cycle is reduced.

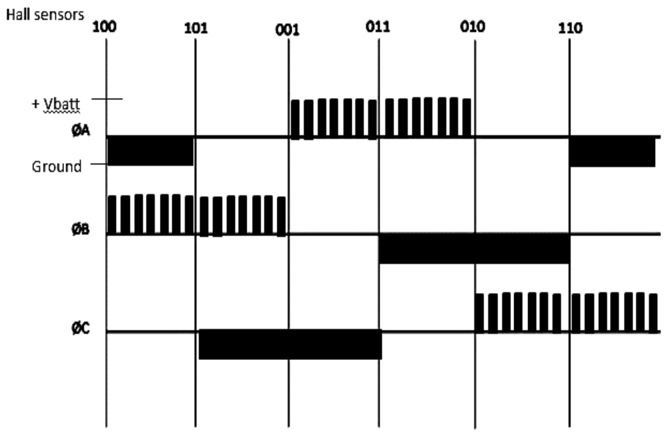

Figure 7. Soft chopping PWM for one electrical cycle trapezoidal commutation at 50 % duty cycle, Vbatt represents full bus bar voltage

C. Hysteresis Current Control (HCC)

HCC monitors the current through the motor and forces it to stay within a predefined band, this indirectly controls the voltage. Unlike the previous two strategies the on/off frequency is not a fixed values instead it varies depending on the load conditions. This variable switching frequency can result in switching harmonics that appear over a wide frequency making the filtering relatively difficult. HCC however does have advantages, the switching frequency is generally less resulting in lower switching losses for the controller and it is protected from overcurrent and damaging the motor or controller if the rotor was to become locked.

IV. NOVEL CURRENT CONTROLL

The proposed novel power control technique is aimed at increasing the part load efficiency of BLDC power systems of high inertia or systems running at high speed. By centering the driving current around the optimum flux interaction point and bringing the PWM frequency down to that of the commutation frequency to reduce switching losses within the system, without adding any extra components or physical parts to the system, that is it will be entirely software based.

Consider one commutation step for traditional trapezoidal commutation using PWM to limit current flow (Fig. 8). Each time one of the pulses rises/falls the switching device acts as a variable resistor resulting in hefty copper losses, independent of duty cycle. The proposed technique will replace the many voltage inputs by one prolonged input where the duty cycle is the ON time of the pulse relative to the time of the commutation step (Fig. 9). Reducing the switching losses and increasing the controller efficiency at the expense of torque ripple, many research projects have been aimed at reducing the torque ripple produced by commutation [11, 12], to reduce the vibrations in the motor and reduce the audible noise. However for many applications that is high speed or high inertia the weight of the system smooth's any minor ripples out before it has a major effects on the system as a whole. The torque ripple associated with the proposed control technique could well fall within this safe range of ripple torque.

There are several limitations to this technique, it cannot be used at low speeds or low duty cycles, and these situations will be dealt with by using the traditional PWM control, the transition between techniques will be handled by the controller without the addition of a small amount of code.

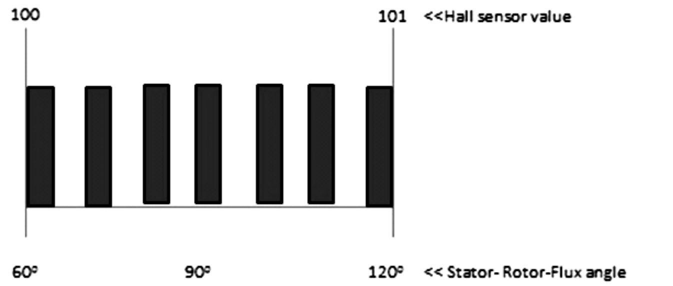

Figure 8. Input signal to high side switch of phase over one commutation step at a duty cycle D = 50 %

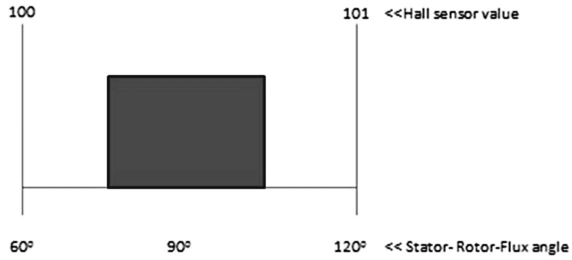

Figure 9. Proposed driving signal to high side switch, duty cycle D = 50 %.

Other potential benefits of this technique include increased immunity to inefficient flux interaction angles brought about by flux skewing, driving waveform lag and added security from damage in locked rotor situation due to the pulse length being time dependent and not reliant on input from position sensors.

V. FUTURE WORK

To verify the concept behind the PWM-PPM hybrid current control technique and conclude the conditions under which it can efficiently operate, simulation will be carried out. They will be aimed at investigating the commutation techniques effect of efficiency and operating characteristics, the main characteristic of interest being speed fluctuation.

The simulations will be carried out using MATLAB Simulink due to its wide spread usage. Assuming that the driving currents/waveforms from the controller are of the same shape and in phase with the BEMF of the motor it is possible to relate the torque produced by the motor to the total current input of the motor (1).

$$\tau_e = [e_a i_a + e_b i_b + e_c i_c] * [1/\omega_r] \qquad (1)$$

Where τ_e is the electrical torque, e_a is the BEMF of phase, i_a is the current flowing through phase-a and ω_r is the angular velocity of the rotor.

The interaction of τ_e with the load torque τ_L will allow simulation of how the motor speeds up from a standstill, reacts to changes in load conditions and the speed change of the motor arising from torque ripple by manipulation of equation-2 [13].

$$\tau_e = \tau_L + J\left(\frac{d\omega r}{dt}\right) + Fr\ \omega_r \qquad (2)$$

J- Moment of inertia   Fr-Friction

With very few assumptions it is possible to accurately model a BLDC motors reaction to driving inputs ,Fig. 10 shows the equivalent circuit diagram for the stator of a star wound motor it takes into account the resistance (R), inductance (L) and BEMF (e) of each phase that will be used to build the equations needed to model the motor. In order o calculate the electrical torque produced by the motor it is necessary to derive the current flowing through the windings for use in (1).

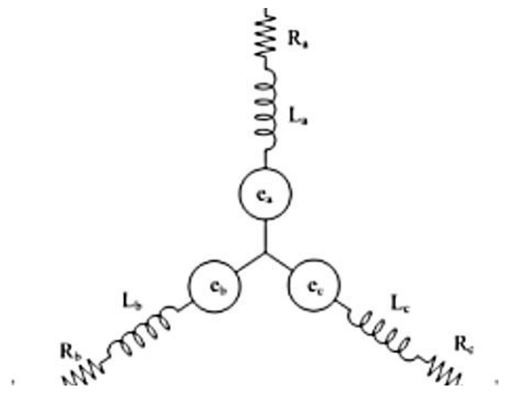

Figure 10. Equivalent stator circuit

Calculating the current flowing through the motor is accompanied by extra complexity as the current is a function of winding resistance, inductance and BEMF, this is best described by the general motor equation [13, 14]:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} Ra & 0 & 0 \\ 0 & Rb & 0 \\ 0 & 0 & Rc \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} Laa & Lab & Lac \\ Lba & Lbb & Lbc \\ Lca & Lcb & Lcc \end{bmatrix} \frac{d}{dt} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} ea \\ eb \\ ec \end{bmatrix} \tag{3}$$

Where R is resistance, L inductance, i current and e BEMF the subscripts show the relative phase. With the assumption that all three phases are balanced and if there is no change in the rotor reluctance with angle because of a non-salient rotor, this can be simplified to:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} Laa & 0 & 0 \\ 0 & Lbb & 0 \\ 0 & 0 & Lcc \end{bmatrix} \frac{d}{dt} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} ea \\ eb \\ ec \end{bmatrix} \tag{4}$$

This matrix can then be manipulated to evaluate the current across each phase dependent upon the input voltage from the controller, and the calculated currents can be substituted back into equation (1), to calculate the instantaneous torque at that moment.

The next step will involve increasing the complexity of the simulation to take into account the losses from the controller, there are two main losses arising from the three phase inverter conduction losses (copper losses) and switching losses.

Assuming that both the high and low side of the three phase inverter use the same semiconductors it is possible to add their resistance to the corresponding phase resistance in (4), leading to (5):

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} Rt & 0 & 0 \\ 0 & Rt & 0 \\ 0 & 0 & Rt \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} Laa & 0 & 0 \\ 0 & Lbb & 0 \\ 0 & 0 & Lcc \end{bmatrix} \frac{d}{dt} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} ea \\ eb \\ ec \end{bmatrix} \tag{5}$$

Where R_t is the addition of the motor phase resistance and the controller resistance.

The average magnitude E of the BEMF of a motor is relatively easy to calculate due to it being linearly related to speed as such (6):

$$E = K_b\, \omega_r \tag{6}$$

Where K_b is a constant, the value is determined by the strength of the permanent magnets in the rotor and density of windings in the stator. Any respectable BLDC motor manufacturer will include this value within the motors data sheet.

An ideal BLDC motor has a trapezoidal BEMF per phase; the BEMF can be expressed as below [13]:

$$\begin{aligned}
e_a &= E && \text{when} \quad 0^o < \theta_r < 120^o \\
e_a &= \left(\frac{6E}{\pi}\right)(\pi - \theta r) - E && \text{when} \quad 120^o < \theta_r < 180^o \\
e_a &= -E && \text{when} \quad 180^o < \theta_r < 300^o \\
e_a &= \left(\frac{6E}{\pi}\right)(\theta r - \pi) - E && \text{when} \quad 300^o < \theta_r < 360^o
\end{aligned} \tag{7}$$

Where θ_r represent the rotor position in electrical degrees.

The combination of the above equations (1,2,5) provide enough information to efficiently model a BLDC motor, the actual modeling of the motor in the Simulink environment can be undertaken in one of three ways.

Block diagram, this is a visual method of describing a system, Fig.11 shows the block diagram representation of the relationship described in equation(2), it has the benefit of being able to set initial conditions like operating speed and torque. Any input, variable or internal variable can also be measured using this method.

Transfer function, the system can be condensed into a transfer function to reduce the size of the model, this however does not allow the setting of initial conditions or the measuring of internal variables.

State space model, the equations (1,2,5) are arranged into matrices of the standard state space form, this has the added benefit of reducing the size of the model whilst retaining the ability to set initial conditions.

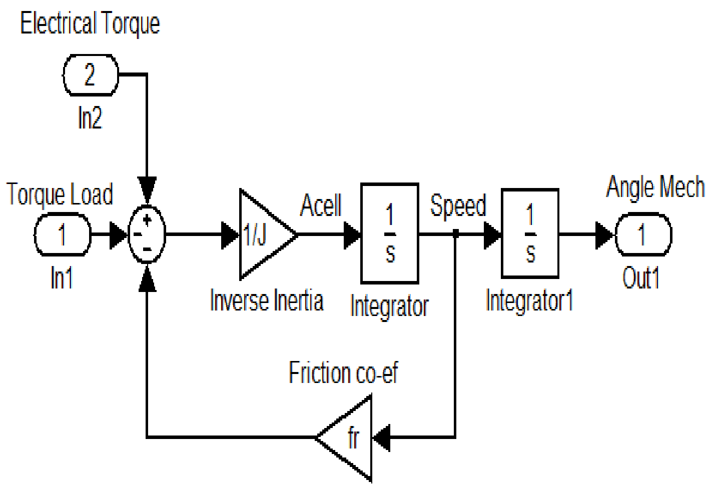

Figure 11. Block diagram representation of (2)

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