

A Simpler Approach to the Modelling of Permanent Magnet Brushless DC Machine in MATLAB Environment

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Abstract—This paper presents a new approach to the modelling of a Permanent Magnet Brushless DC (PMBLDC) machine in MATLAB. The mathematical model of the PMBLDC machine is introduced and the problems in the conventional modelling i.e., in Simulink domain are discussed. A new modelling approach is proposed as a solution. The reliability of the new model is verified by its simulation in MATLAB and comparing the results with the existing in-built machine in power system library of MATLAB, given the same set of input parameters. The speed is maintained by open loop voltage control technique.

Keywords—brushless DC; modelling; power system library; MATLAB/Simulink; reliability.

I. INTRODUCTION

Permanent Magnet Brushless DC [PMBLDC] machines have become very popular in a variety of industrial applications with the advancements in permanent magnet materials and solid state devices. PMBLDC machines have various advantages over the conventional machines, such as high efficiency, high power density, low cost, low weight, high reliability and low maintenance requirements. The mechanical commutation of the brushes in DC machine is replaced by the electrical switching in PMBLDC machine. The elimination of brushes result in noiseless operation of the machine, wide range of speed and a longer operating life. Hence, the study and effective modelling of the PMBLDC machine becomes important. The stator of the machine consists of three phase windings and the rotor is made of permanent magnet. A mathematical model of the machine is introduced in the next section. The conventional modelling approach of the mathematical model and problems associated to it are discussed in the subsequent section. A new approach as a solution to these problems is proposed. The proposed solution is modelled in MATLAB R2014a/Simulink and its reliability is verified by comparing it with the power system library machine block-set. The model is driven by open loop voltage control technique and the speed of the machine is maintained at a fixed value.

II. MATHEMATICAL MODEL

The stator armature winding can be realized by a resistor, an inductor and a back-emf term in series, where the back-emf represents the effect of rotor on the stator side [1].

The equations describing the relation between the speed, torque, voltage, current, and back-emf of the machine are summarized from (1) to (6) [2]. The described equations are valid under the assumption that the permanent magnet has high sensitivity, negligible rotor currents and balanced stator currents. The stator armature resistance and inductance of the three phases are assumed to be equal, which is reasonable and justified. The mutual inductances between the three phases are assumed to be equal. The unit trapezoid function (f) is shown in Fig. 1, which defines the back-emf waveforms. The symbols used in the equations are mentioned in Table 1 corresponding to the quantities they represent.

$$V_a = R_s I_a + (L - M) \frac{d(I_a)}{dt} + K_e \omega_m f(\theta) \quad (1)$$

$$V_b = R_s I_b + (L - M) \frac{d(I_b)}{dt} + K_e \omega_m f(\theta - 120^\circ) \quad (2)$$

$$V_c = R_s I_c + (L - M) \frac{d(I_c)}{dt} + K_e \omega_m f(\theta - 240^\circ) \quad (3)$$

$$T_e = K_t [I_a f(\theta) + I_b f(\theta - 120^\circ) + I_c f(\theta - 240^\circ)] \quad (4)$$

$$J \frac{d(\omega_m)}{dt} + B \cdot \omega_m = T_e - T_l \quad (5)$$

$$\frac{d(\theta)}{dt} = \frac{P}{2} \cdot \omega_m \quad (6)$$

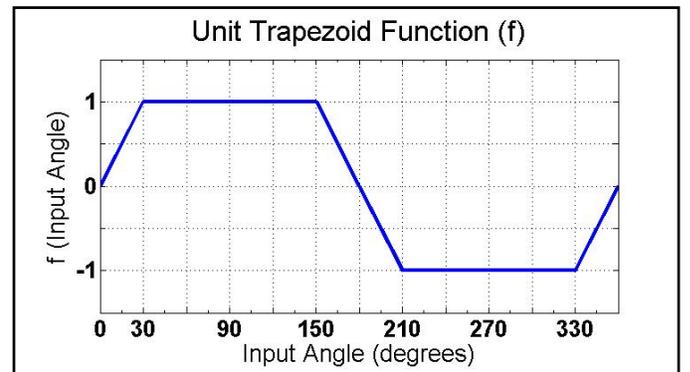


Fig. 1. The unit trapezoid function 'f', defining back-emf of BLDC machine.

TABLE I. SYMBOLS USED AND THEIR CORRESPONDING QUANTITY

Symbol	Quantity	Parameter value
V_k	phase - k input voltage	-
I_k	phase - k current	-
R_s	stator resistance	0.6 Ω
L	stator inductance	0.8 mH
M	mutual inductance	0.057 mH
ω_m	rotor speed	-
θ	rotor position	-
T_e	electromagnetic torque	-
T_l	load torque	-
K_e	back-emf constant	0.035 Vs/rad
K_t	torque constant	0.035 Nm/A
J	rotor inertia	24 * 10 ⁻⁶ kgm ²
B	friction coefficient	100 * 10 ⁻⁶ kgm ²
P	Number of rotor poles	8

k implies a, b, c

III. CONVENTIONAL APPROACH AND ITS PROBLEM

The basic architecture of the working of BLDC machine is shown in Fig. 2. It is often required to model the motor under study to have a better and precise understanding of the motor operation and thus develop the control based on the model. The usual practice followed is to implement the model in MATLAB Simulink domain as the control algorithm is also implemented in Simulink. Thus the motor under study, the required control and the power converter are all modelled in Simulink domain.

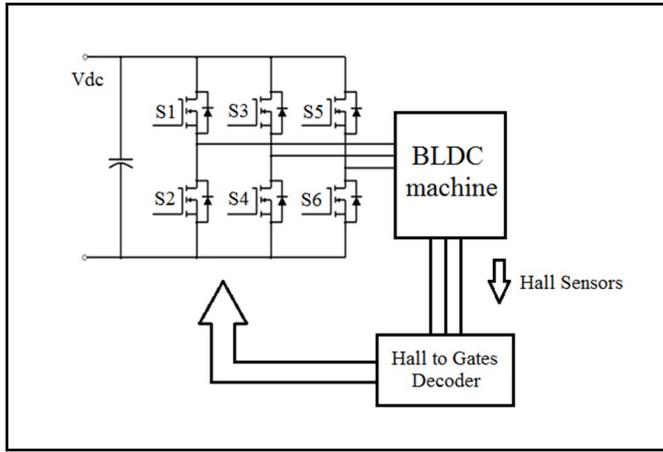


Fig. 2. The working architecture of the BLDC machine.

The 3-leg 2-level inverter, shown in Fig. 2, can be modelled using (7), (8) and (9). [3]

$$V_a = (2S_a - S_b - S_c) * V_{dc}/3 \quad (7)$$

$$V_b = (2S_b - S_c - S_a) * V_{dc}/3 \quad (8)$$

$$V_c = (2S_c - S_a - S_b) * V_{dc}/3 \quad (9)$$

The inverter model as defined by the above set of equations works well for sinusoidal Pulse Width Modulation (PWM) based inverter system. It is to be noted that this model of inverter does not include the diode conduction period which plays an important role in the case of BLDC operation. Therefore, the conventional inverter model cannot be utilized for exciting a BLDC in Simulink domain. There arises a need to model the inverter in detail, such that the period of diode conduction is included. This can be done by taking feedback of the motor currents to estimate the diode conduction and feed-out proper excitation voltages. The modelling of inverter thus becomes complex and also varies with the type of control used for BLDC i.e., PWM chopping mode of control might require even more detailed diode conduction model of inverter. The above issue complicates the modelling of BLDC drive in Simulink.

One solution to which students stumble upon is using a combination of Simulink and power system blocks. Here, BLDC is modelled in Simulink and the inverter available in the power system block-set is used for excitation. This approach uses transfer function blocks to implement (1) to (6) and represents the machine behaviour with three phase voltages as input. Note that these input ports accept Simulink wire connections, not the power system wire connections. Hence, the line to line voltages from the inverter are measured and fed to the BLDC Simulink model. This system involves a serious issue of coupling between the Simulink BLDC model and power system inverter. The period 0° to 30°, 150° to 210° and 330° to 360° in Fig. 1 corresponds to the diode conduction period. This system was simulated and it was observed, as shown in Fig. 3, that the diode conduction required in BLDC operation is not communicated to the inverter as there is no current feedback. The diode effect makes the current zero in the interval when both the switches, S1 and S2, are turned off. The current as seen is not quasi-square as one would expect.

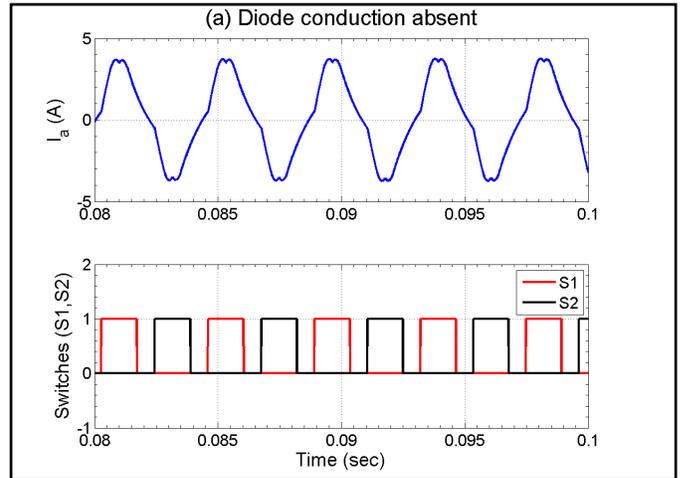


Fig. 3. Absence of diode conduction effect in BLDC Simulink model.

To avoid the complex inverter modelling involved when the whole of PMBLDC is modelled in Simulink and at the same time, have a self-modelled system which is simple to implement, a simpler solution of PMBLDC drive implementation is needed. Care would be needed to properly link the developed sub-system blocks to accommodate the diode-conduction and the custom-made PMBLDC model.

IV. A NEW SIMPLER SOLUTION

A simpler approach is proposed in this section for modelling BLDC drive. This approach utilizes the partial use of both power system blocks and Simulink blocks with proper coupling at an appropriate interface. The diode conduction effect discarded in the approach discussed in previous section was because of inefficient point of interface between the power system and Simulink block-sets.

In this new approach, the interfacing is done through back-emf and speed. These two are naturally isolated quantities as one is an electrical quantity and other is a mechanical quantity. The BLDC machine model is divided into two parts, electrical model and mechanical model, for simple and better understanding. The electrical model is implemented by power system blocks, whereas the mechanical model is implemented by Simulink blocks. The electrical model takes the inverter output and produces currents for mechanical model, whereas the latter takes load torque as input and produces speed for the former. Both the models are coupled through current and speed. The architectural block diagram of the model is shown in Fig. 4. The electrical model consists of a three phase series RLE circuit, where R represents the stator resistance, L represents the stator inductance and E represents the back-emf. The RLE topology has been used for explanation purposes, but has never been directly used for modelling before. The back-emf is realised through a voltage dependent voltage source, which depends on the value of speed and the unit trapezoid waveform derived by the position of the rotor. The dependency of this voltage source is the chosen interfacing point between the power system and Simulink blocks. This approach is simple to understand due to the fact that all of the electrical behaviour is modelled using power system block-set and all of the control behaviour is modelled using Simulink block-set.

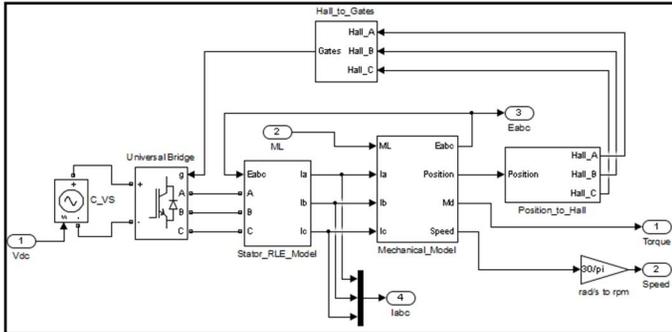


Fig. 4. The architecture of the new simpler modelling approach.

The stator RLE model representing the electrical behaviour of the BLDC machine is shown in Fig. 5. The results of this block are the three phase currents which serve as the coupling input for the mechanical model and produce machine torque. The mechanical model, as shown in Fig. 6, consists of two subsystems, namely the main machine and the trapezoid generation block that implements Fig. 1. The main machine block, as shown in Fig. 7, implements (4), (5) and (6) using Simulink blocks such as transfer function, integrator, adder, gain and product. The trapezoid generation block, as shown in Fig. 8, consists of three identical unit trapezoid function blocks. The input to the phase-A block is position, phase-B block is 120°

shifted position and phase-C block is 240° shifted position. The implementation of the unit trapezoid function is shown in Fig. 9.

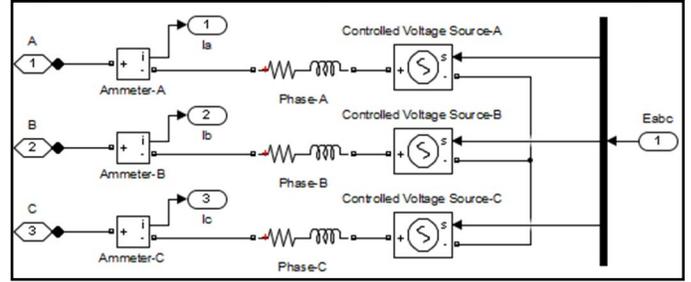


Fig. 5. The stator model representing the electrical nature of BLDC machine.

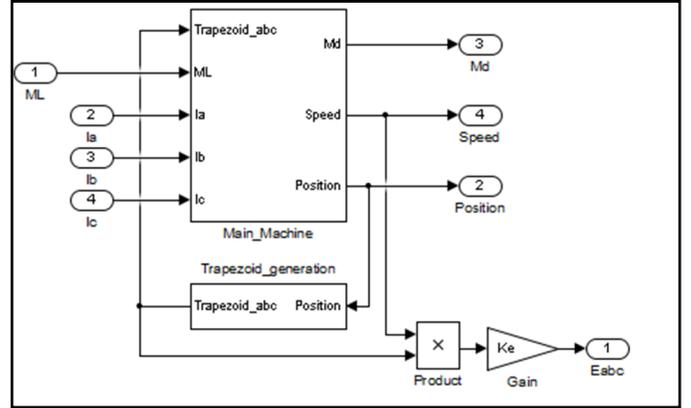


Fig. 6. The mechanical model representing the mechanical nature of BLDC.

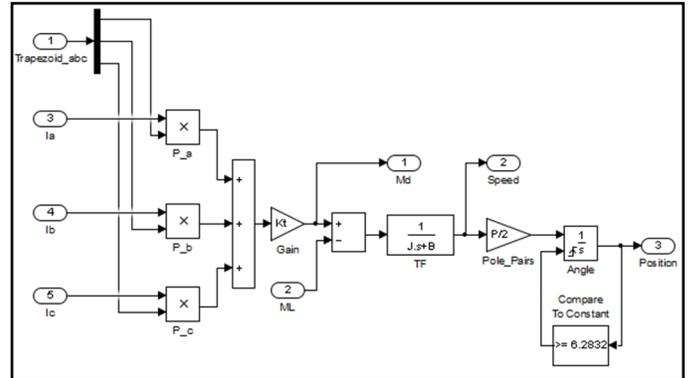


Fig. 7. The main machine block made of Simulink blocks.

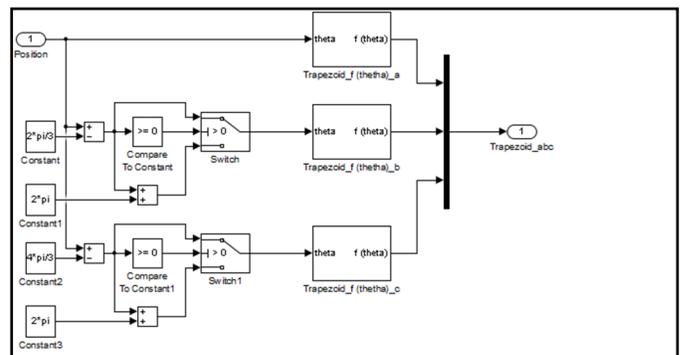


Fig. 8. The trapezoid generation block giving the outputs $f(\theta)$, $f(\theta - 120^\circ)$ and $f(\theta - 240^\circ)$.

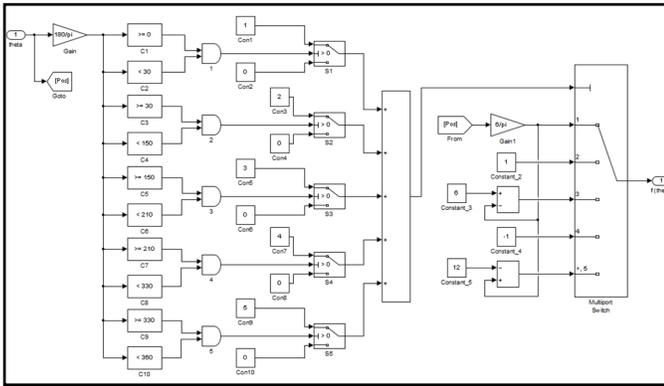


Fig. 9. The implementation of the unit trapezoid function.

The mechanical model gives the speed and the position as output, and not the hall logic. Hence, the hall sensors are also modelled using the information of position as shown in Fig. 10. The electrical commutation is performed using the hall information. The implementation of the hall to gates decoder is shown in Fig. 11.

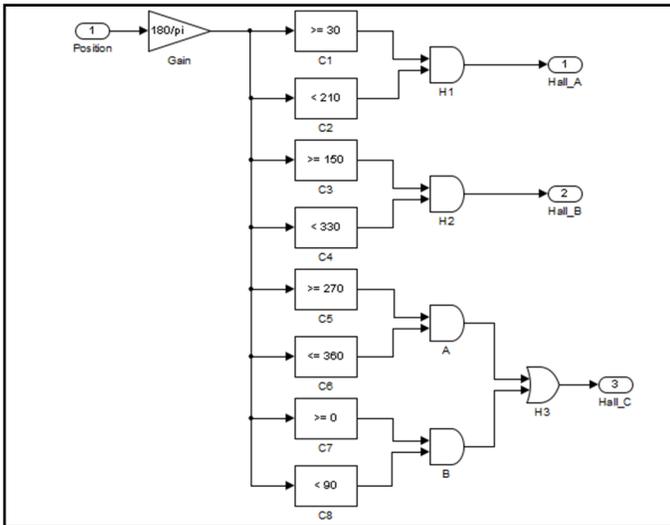


Fig. 10. The hall sensor model based on position information.

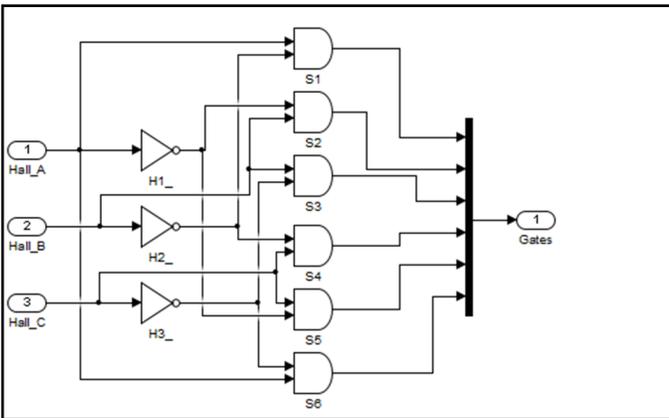


Fig. 11. The hall to gates decoder implementation.

The simplicity of the proposed model can be appreciated by comparing it with the existing models. The modelling of BLDC motor in MATLAB Graphical User Interface (GUI) as presented in [8] also involves the modelling of the inverter block. The average-value modelling of BLDC motor as presented in [9] uses multiple reference theory for modelling the machine, whereas in [10], the dynamic average-value modelling of BLDC machine is presented. Another modelling approach is presented in [11] for Aerospace application. The modelling of BLDC drive based on switching functions is presented in [12]. It highlights the role of diode effect in the complex modelling of the inverter, which is avoided in our proposed model for the BLDC drive.

V. SIMULATION AND RESULTS

The proposed simpler model is simulated alongside with the power system BLDC block, with the same set of inputs and parameters as indicated in Table 1. The power system BLDC drive is shown in Fig. 12. Both the models are driven at no load till 0.07 sec and then a load torque of 0.19 Nm is introduced. Input voltage is 23 V till 0.12 sec and then it is increased to 29 V to maintain the machine speed. The results for speed, torque, phase-A back-emf and current are shown in Fig. 13 to Fig. 17.

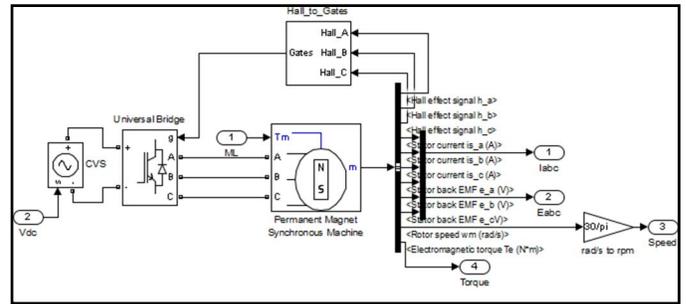


Fig. 12. The test setup for the power system BLDC block.

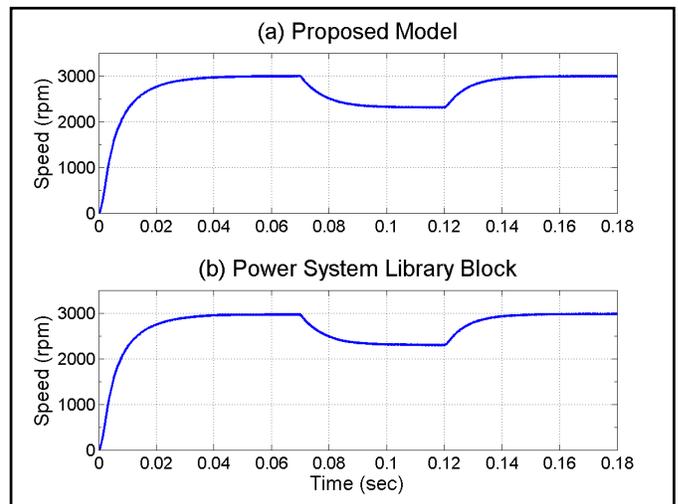


Fig. 13. Speed response of both the models.

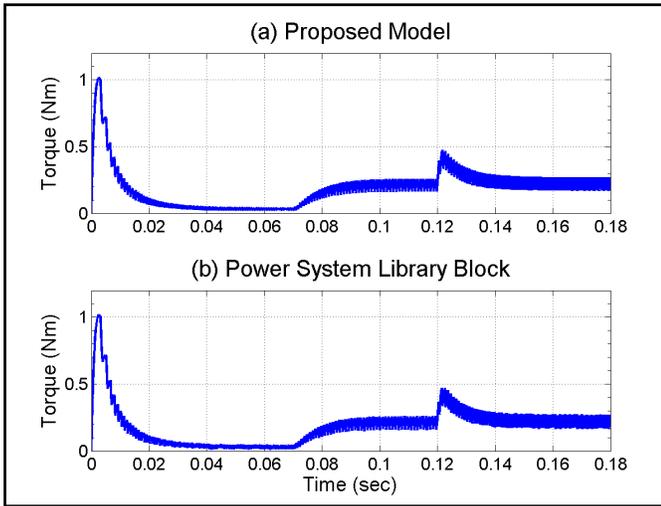


Fig. 14. Torque response of both the models.

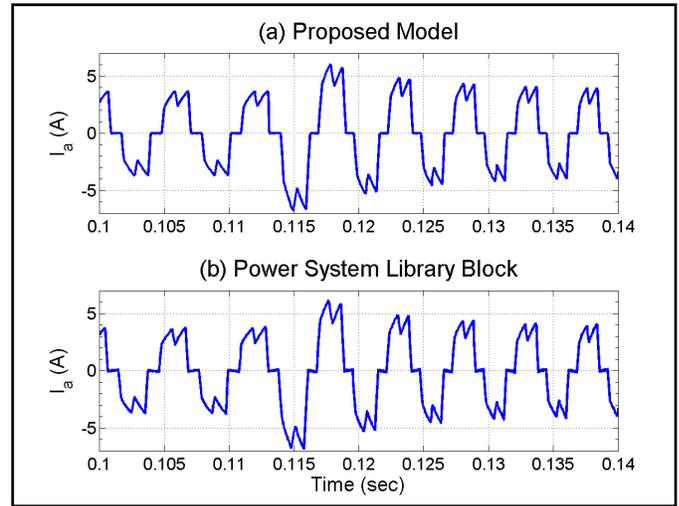


Fig. 17. Magnified view of the phase-A current response.

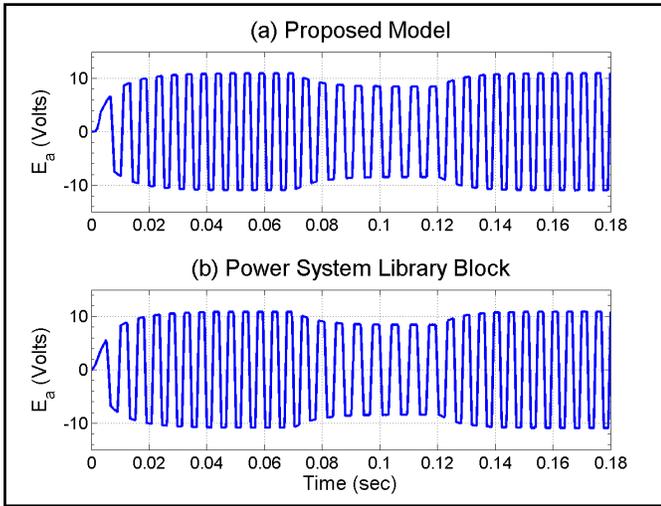


Fig. 15. Phase-A back-emf response of both the models.

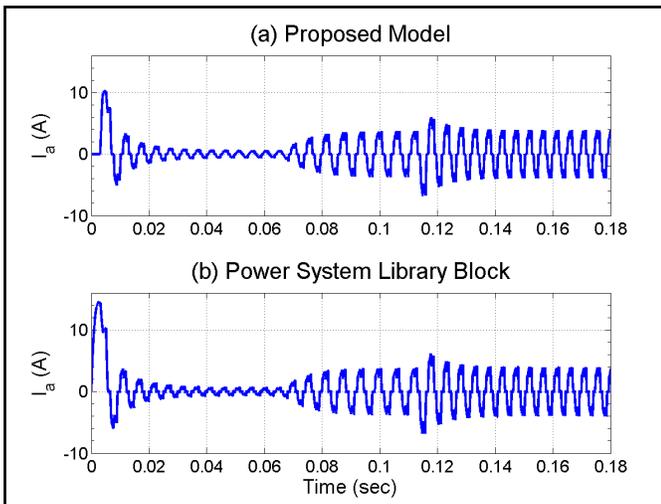


Fig. 16. Phase-A current response of both the models.

VI. CONCLUSION

In this paper, the conventional modelling of the BLDC machine and problems related to it were discussed. Some possible solutions were introduced and flaws in them were described. A new simpler approach for better understanding of the PMSBLDC machine & easier simulation in MATLAB was introduced, described briefly and tested for its reliability. The results show that the response of the developed model matches with the response of the power system library BLDC machine. Hence, the developed model can serve as a simple and a reliable representation of the PMSBLDC machine, for its study and testing of various algorithms and control techniques.

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