# COMPARATIVE ANALYSIS OF DYNAMIC PERFORMANCE OF 3-PHASE PERMANENT MAGNET BRUSHLESS DC MOTOR DRIVE +

**Rana Hilmi Abd Al-Jabar** *

**Abstract:**

**This paper presents a comparative analysis of 3-phase permanent magnet brushless dc motor drive having slightly different phase-emf waveform. Permanent magnet brushless dc motors of 12-slot/10-pole and 6-slot/4-pole are considered in this project. Both brushless dc motors have a permanent magnet surface-mounted rotor, and the stator windings employ single-tooth wound coils such that the phase-emf is trapezoidal. Therefore, both motors are conducive for rectangular-shaped stator phase current excitation in order to produce constant torque output. The mathematical model for BLDC operation and individual definition of the system blocks will be described. The model is later simulated in MATLAB/Simulink version 8. The generated 12-slot/10-pole and 6-slot/4-pole phase-emf data from finite element analysis are used in the Simulink blocks to examine the dynamic performance of both permanent magnet motors.**

**Keywords: permanent magnet, simulation, BLDC, phase-emf, brushless**

# تحليل مقارن للأداء الحركي لمسوقات محركات المغناطيس الثابت بدون فرش ثلاثية الطور

رنا حلمي عبد الجبار

المستخلص :

هذا البحث يقدم تحليل مقارن للأداء الحركي لمسوقات محركات المغناطيس الثابت بدون فرش ثلاثية الأطوار التي تملك اختلاف بسيط في شكل موجة القوة الدافعة الكهربائية . في هذا البحث تم اخذ نموذجين للدراسة , محرك مغناطيس ثابت بدون فرش يحتوي على 12 شق و10 أقطاب والمحرك الأخر يحتوي على 6 شقوق و4 أقطاب . في كلا المحركين يوجد المغناطيس الثابت على العضو الدوار مثبت بشكل سطحي وملفات العضو الساكن ملفوفة بحيث تعطي شكل موجي شبه منحرف للقوة الدافعة الكهربائية . لذلك كلا المحركين ملائم لمرور تيار شبه مربع في كل طور من اجل إنتاج عزم ثابت . النموذج الرياضي للمحرك تم تحليله وعرضه بشكل مفصل وكذلك استخدام برنامج الماتلاب (version 8) لمحاكاة النموذج الرياضي لكلا المحركين بالإضافة إلى استخدام تحليلات العناصر المنتهية (finite element analysis) في تحليل سلوك المحركين واستخدام البيانات الناتجة من تحليلات العناصر المنتهية في برنامج الماتلاب لمحاكاة وفحص الأداء الديناميكي لكلا المحركين.

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* Assistant Lecturer / Technical College / Kirkuk

## 1. Introduction :

There is a growing interest in permanent magnet brushless motor due to its increasing use and development in modern speed and position control applications such as in automotive and aerospace [1,2]. Besides, the improvements on the permanent magnet materials such as the magnetic properties, thermal properties and electrical properties used in the permanent magnet brushless motor have also increase the complexity in the design of the motor to meet the stringent requirements and specifications. One of the most widely used permanent magnet motor is brushless dc motor also known as BLDC. Different from brushed dc motor, this type of motor doesn't use a brush but instead it use permanent magnet material mounted on the rotor such as neodymium iron boron (NdFeB) in order to provide the required rotor magnetic fields. Besides, it is highly efficient due to the absence of rotor winding, resulting in almost negligible rotor loss. Furthermore, this type of motor can produce higher efficiency due to lower stator copper loss. This is because, similar slot and pole number can be employed in the design of the permanent magnet brushless motors which offer fractional winding arrangements such that single-layer or double-layer windings in single tooth wound coils which results in the shorter end winding portions [3]. This type of motor also offer low maintenance, greater longevity, high torque density, more compact construction and high power density. It is shown that, in permanent magnet brushless dc motor drive, the transformation of the machine equations from a,b,c frame to the d,q frame is not necessary the best approach if the phase-emf waveform employed by the motor is trapezoidal. This is different from permanent magnet brushless ac motor (BLAC) which has sinusoidal phase-emf. Since the phase-emf is trapezoidal, BLDC motor is more suitable to be operated using stator phase current having rectangular waveform. This is because to reduce the torque ripple produce by the motor. Hysteresis or pulse width-modulated (PWM) current controllers can be used to maintain the actual current flowing into the motor as close as possible to the reference values. Application of this method is being used because of its simplicity and acceptable accuracy [4]. Generally, the choice to operate the permanent magnet (PM) motor either in BLAC mode or BLDC mode is influenced by the characteristic of the phase-emf of the motor. Hence, it is important to analyze and predict the precise phase-emf waveform. So, finite element software can be used to predict the phase-emf. Besides, a computer simulation tools is needed to perform dynamic analysis of the motor. Recently, there have been many computer simulation tools introduced to perform the dynamic analysis of the motor i.e. IsSpice, Saber, PSIM, DYMOLA and MATLAB/Simulink [5,6,7]. In [8], the author proposed the use of precise phase-emf to be performed in IsSpice simulation tool. However, in this paper, the authors would like to present comparative study of 3-phase PM motor drive performance having slightly difference phase-emf waveform. Several design considerations have been taken into account by the finite element analysis such as number of stator slots, number of rotor poles, cogging torque ripples, operating speed range, maximum torque power, etc. All of the considerations will result in the phase-emf that will be used in the MATLAB/Simulink simulation package. Type of motors being used are 3-phase 12-slot/10-pole permanent magnet surface mounted rotor and 6-slot/4-pole permanent magnet surface mounted rotor. Each motor is having different shape of phase-emf waveform. Important parameters for the motors are given in Table 1

**Table (1) – Motor Parameters**

| Parameters | Value | |
|---|---|---|
| | 12-slot/10-pole | 6-slot/4-pole |
| Battery supply ($V_{dc}$) | 48 | 48 |
| Rated Speed (rpm) | 600 | 1200 |
| Slot Number $N_s$ | 12 | 6 |
| Pole Number 2p | 10 | 4 |
| EMF Constant $K_e$ (V/$rads^{-1}$ ) | 0.3947 | 0.1164 |
| Phase Resistance $R_s$(mΩ) | 520 | 750 |
| Self Inducatance $L_s$(mH) | 3.64 | 0.92 |
| Mutual Inductance $L_m$ (mH) | -0.35 | -0.2 |

## 2. Modeling of Brushless DC Motor :

### 2.1 Fundamentals of BLDC Drives :

The permanent magnet brushless dc motor (BLDC) has 3-phase windings in the stator iron and permanent magnets mounted on the rotor iron. Since both the magnet and the stainless steel retaining sleeves have high resistivity, rotor-induced currents can be neglected and no damper windings are required to be modeled. Fig. 1 shows the representation of the motor drive circuit.

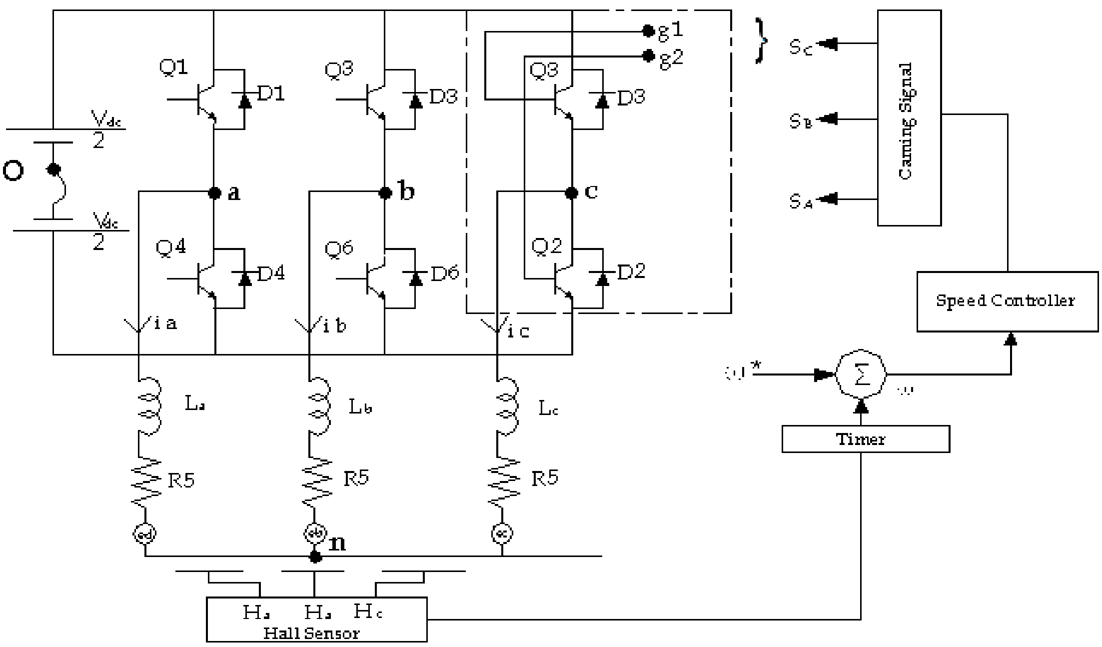



**Figure (1) - Representation of the motor drive circuit.**

The voltage equations of the stator windings in phase variables can be given by:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_b & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Assuming that there is no change in the rotor reluctance with angle, then,

$L_a = L_b = L_c = L$

$L_{ab} = L_{ca} = L_{cb} = M$

Thus,

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

In the star connected windings with balanced state currents

$$i_a + i_b + i_c = 0 \quad (3)$$

Therefore,

$$Mi_b + Mi_c = -Mi_a \quad (4)$$

Hence equation (2) can be simplified as follows

$$(L - M)\frac{di_a}{dt} = V_{an} - R_s i_a - e_a \quad (5)$$

$$(L - M)\frac{di_b}{dt} = V_{bn} - R_s i_b - e_b \quad (6)$$

$$(L - M)\frac{di_c}{dt} = V_{cn} - R_s i_c - e_c \quad (7)$$

Introducing the null point of dc link (0), the phase voltages are given by

$$V_{an} = V_{ao} - V_n \quad (8)$$

$$V_{bn} = V_{vo} - V_n \quad (9)$$

$$V_{cn} = V_{co} - V_n \quad (10)$$

Adding equations (5),(6) and (7) into a single mathematical form, then,

$$(L - M)\left(\frac{di_a}{dt} + \frac{di_b}{dt} + \frac{di_c}{dt}\right) = V_{an} + V_{bn} + V_{cn} - R_s(i_a + i_b + i_c) - (e_a + e_b + e_c) \quad (11)$$

Substituting equations (8),(9) and (10) into right hand-side of equation (11) and taking into account balanced state
currents,

$$V_{ao} - V_{no} + V_{bo} - V_{no} + V_{co} - V_{no} - (e_a + e_b + e_c) = 0 \qquad (12)$$

Hence, for star connection of phases with balance supply,

$$V_{n0} = \frac{[(V_{ao} + V_{bo} + V_{co}) - (e_a + e_b + e_c)]}{3} \qquad .(13)$$

Here, $n$ represents the star connection point of stator windings. $a0\ V$ , $b0\ V$ , $c0\ V$ could be easily be related to the dc link voltage and switching state.

The generated electromagnetic torque is

$$T_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} \qquad (14)$$

The equation of motion is

$$\frac{d\omega_r}{dt} = \frac{(T_e - T_L - B\omega_r)}{J} \qquad (15)$$

The rotor position can be determine using the following equation :

$$\frac{d\theta}{dt} = \frac{P}{2}\omega_r \qquad (16)$$

## 2.2 Reference phase-emf modeling :

Basically, the design of the motor is performed under finite element software packages i.e. Motor Solve and Opera2d(Opera two dimension software for design electric machine) . This design includes all the characteristics of the motor. Thus, the analysis performed under finite element software will result in the phase-emf, cogging torque, flux linkage etc. Hence, the data of the reference phase-emf under MATLAB/Simulink environment is taken from the finite element analysis. In this study, Opera2d has been employed to predict the electromagnetic performance of the 12-slot/10-pole and 6-slot/4-pole motors. Using time-stepping rotating motion solver in Opera2d, the phase-emf can be computed accurately and then be used in the MATLAB/Simulink environment. FFT analysis is performed on the computed phase-emf. As a result, the exact profile of phase-emf can be represented as a Fourier series which comprises all the harmonics contents such that:

$$EMF\ (\theta) = \sum_{n=1,3,5..}^{\infty} V_n \cos(n\theta + \lambda_n) \qquad (17)$$

The result later can be used in the Simulink environment as a series of mathematical equations that comprises all the harmonic contents or as a form of lookup table. Fig. 2 and Fig. 3 shows the comparison of the reference phase-emf waveform done under finite element software and using FFT under MATLAB environment.

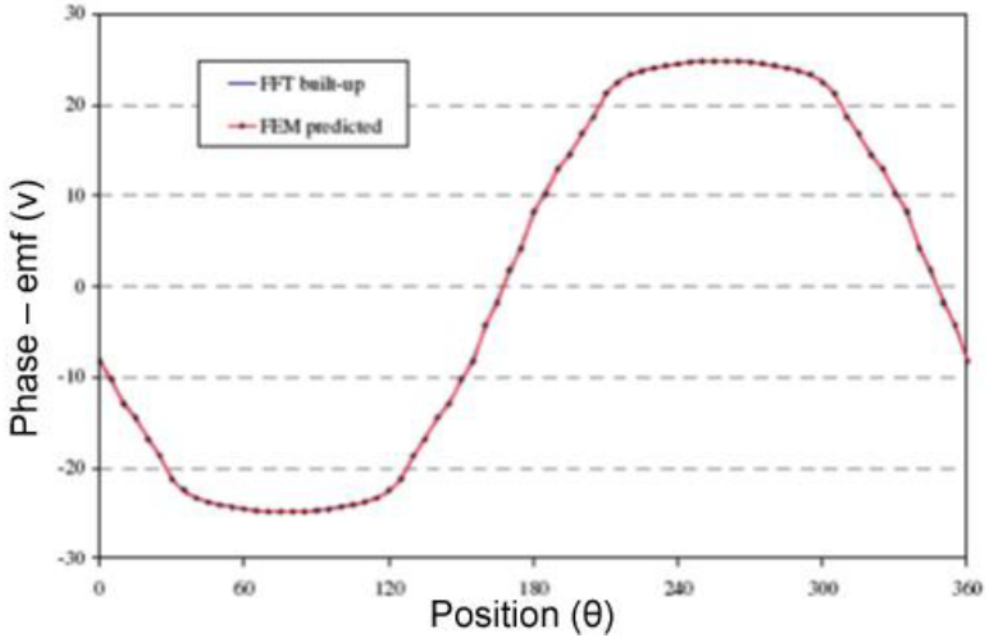



**Figure (2): Comparison of FEM predicted and FFT built-up phase-emf for 12-slot/10-pole motor**

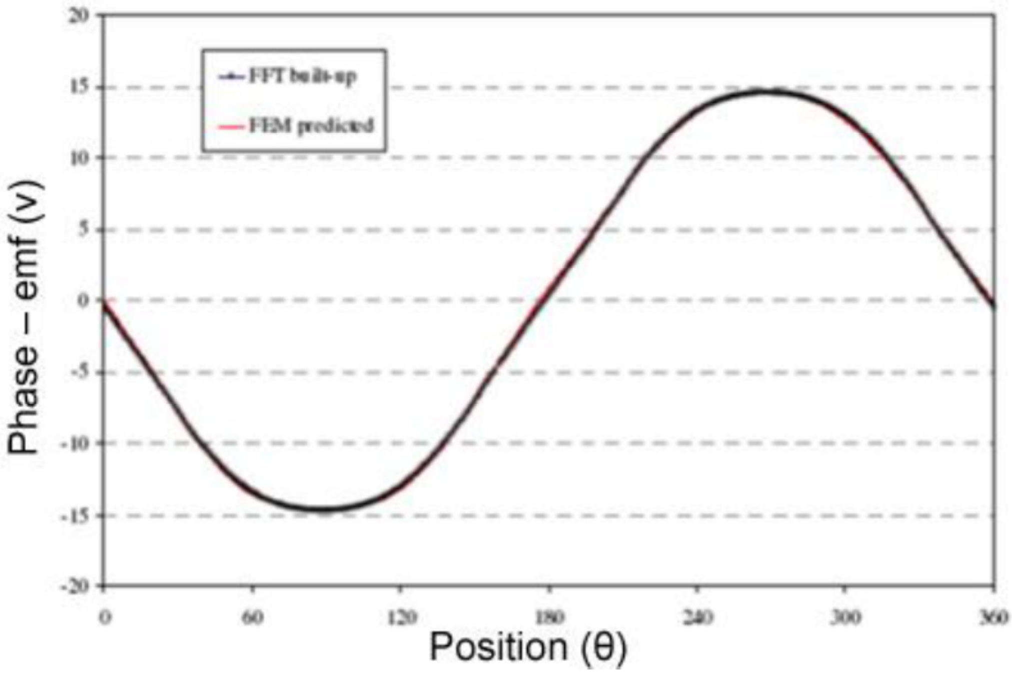



**Figure (3): Comparison of FEM predicted and FFT built-up phase-emf for 6-slot/4-pole motor**

From Fig. 2 and Fig. 3 above, it is shown that two different types of phase-emf waveforms are used in the analysis. The motor having 12-slot/10-pole has more trapezoidal shape of phase-emf whereas 6-slot/4-pole motor has more sinusoidal shape of phase-emf waveform. Besides, it has been clear from both figure that the use of FFT phase-emf in the simulation is valid as the shape of the waveforms are the same to those obtained the FEM.

## 2.3 Simulation of reference phase emf. :

Fig. 4 show the reference phase-emf block under MATLAB/Simulink environment.

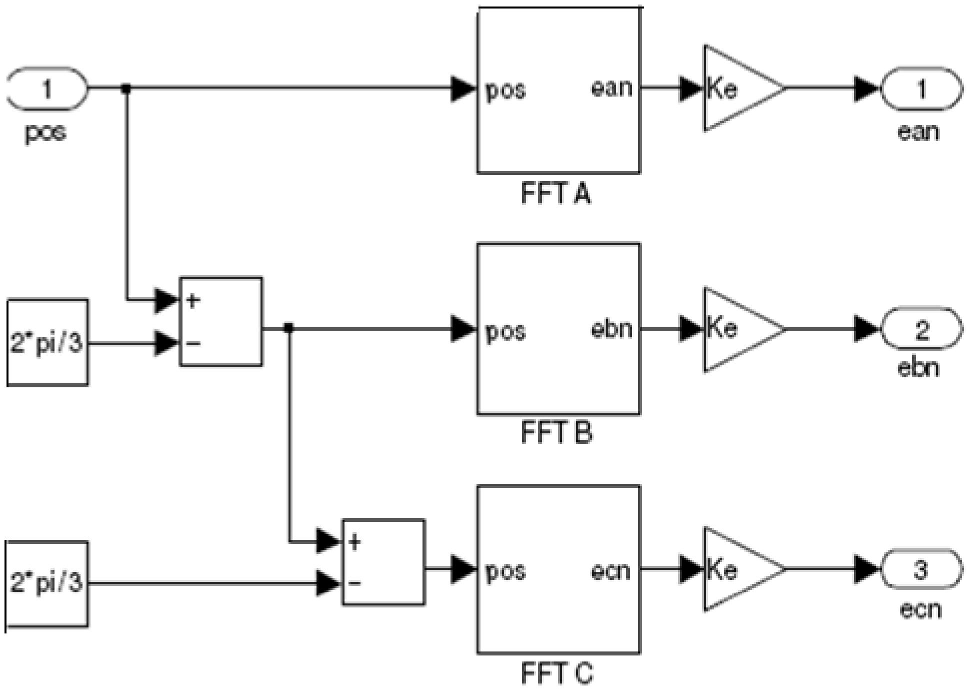



**Figure (4): Simulink block diagram of a reference phase-emf**

## 2.4 Simulation of a brushless d.c motor drive :

Based equations 8,9,10 and 13 used for generate phase and neutral point voltage .equation 14,15 and 16 for electrical torque , electrical speed and rotor angle respective. The simulation block details in appendix 2

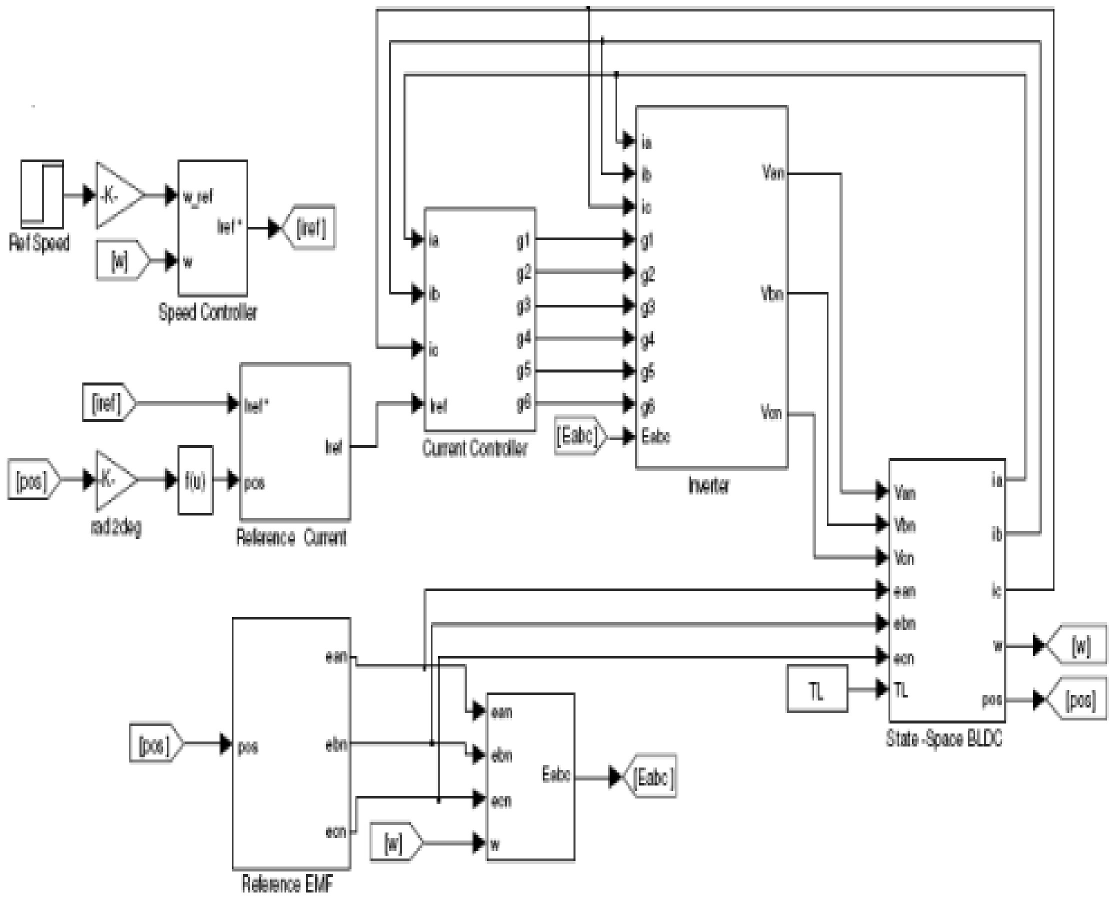
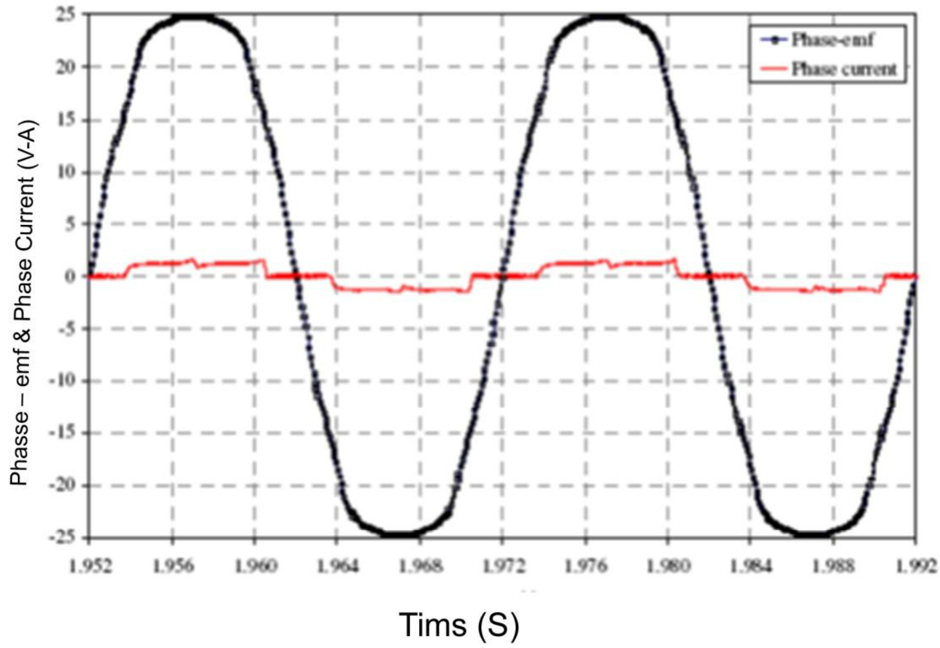


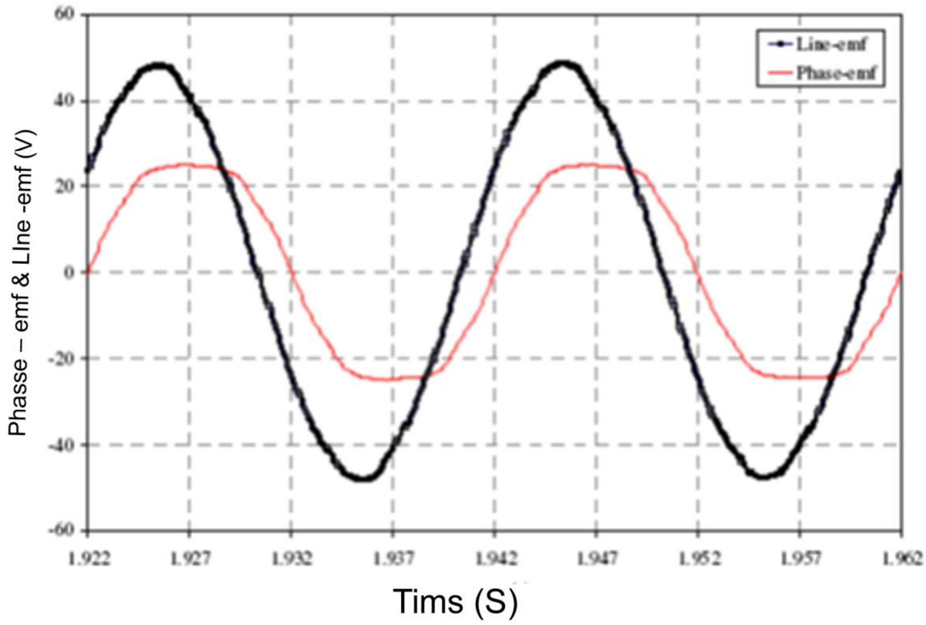

**Figure (5): Simulink block diagram of a brushless dc motor drive**

## 3. Simulation Results :

Further analysis is performed for the proposed type of motor under MATLAB/Simulink environment in order to study the dynamics characteristics of the motor during BLDC operation. In the operation of BLDC motor, six step switching techniques have been used. In this mode of operation, only two phase windings are switched on, while the remaining phase is switched off. Fig. 5 shows the whole block diagram of the brushless dc motor drive under MATLAB/Simulink environment. Fig. 6, Fig. 7 and Fig. 8 shows the simulation result of the proposed BLDC motor running under MATLAB/Simulink.

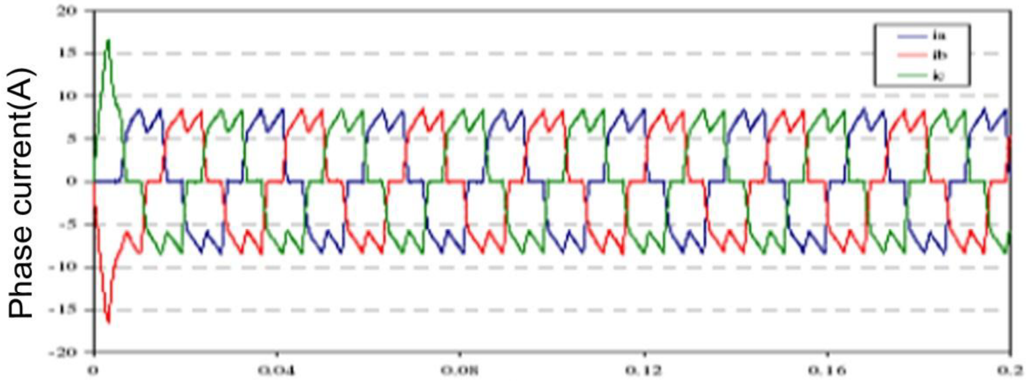



**(a) emf and current waveform of phase a**

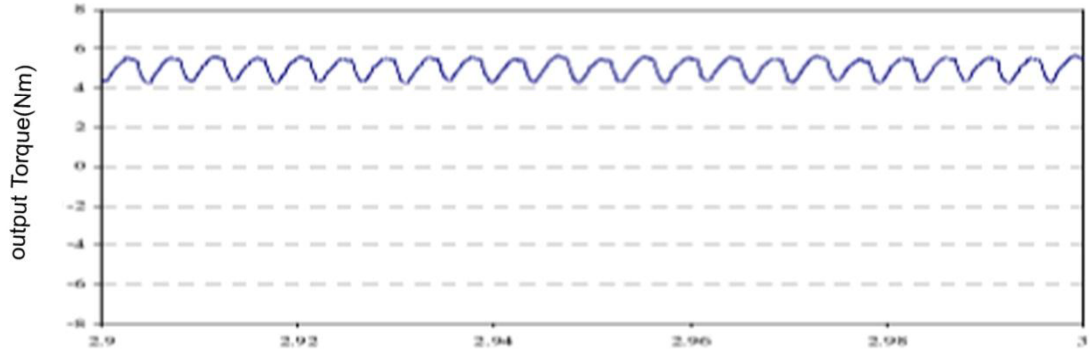



**(b) phase emf and line emf**

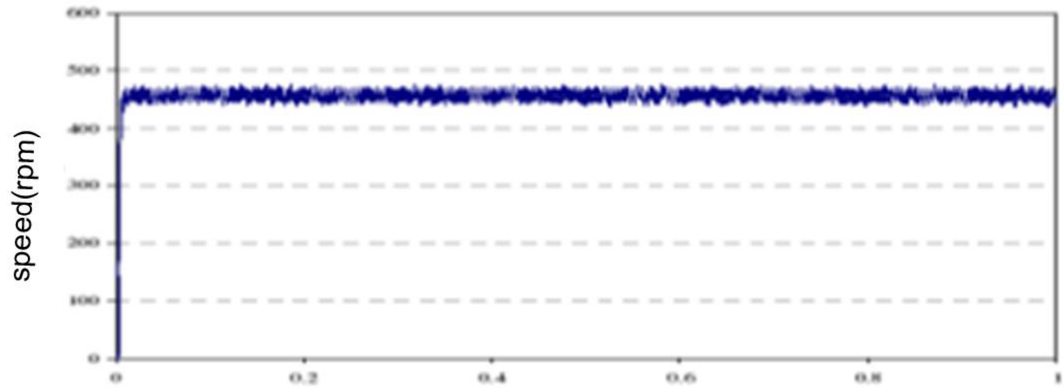
**Figure (6): Simulation results of 12-slot/10-pole BLDC motor at rated speed = 600 rpm**




Time (s)
( a ) Phase current*s*

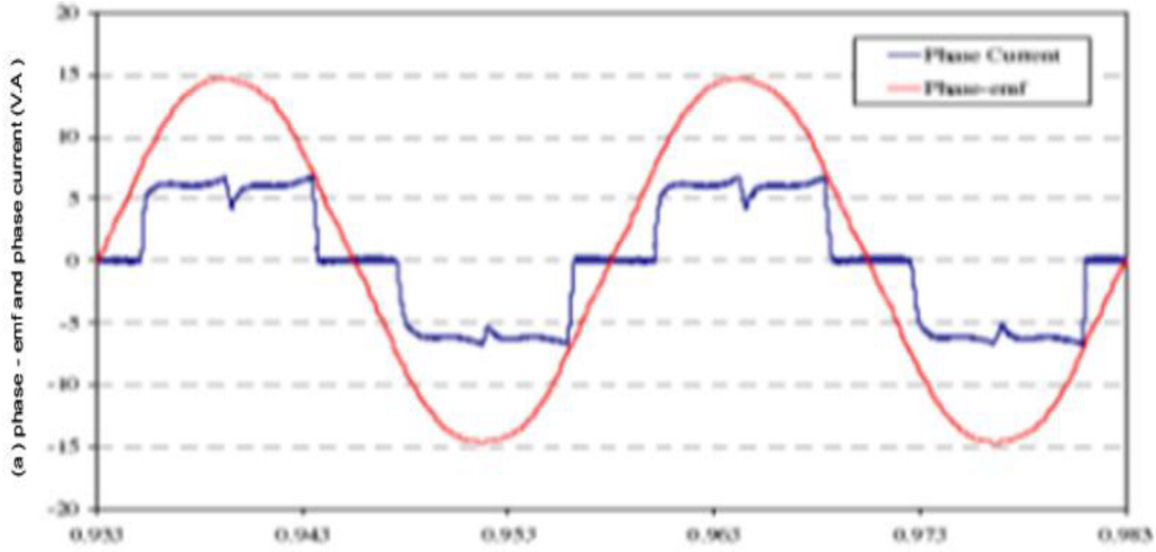



Time (s)
( b ) Output torque

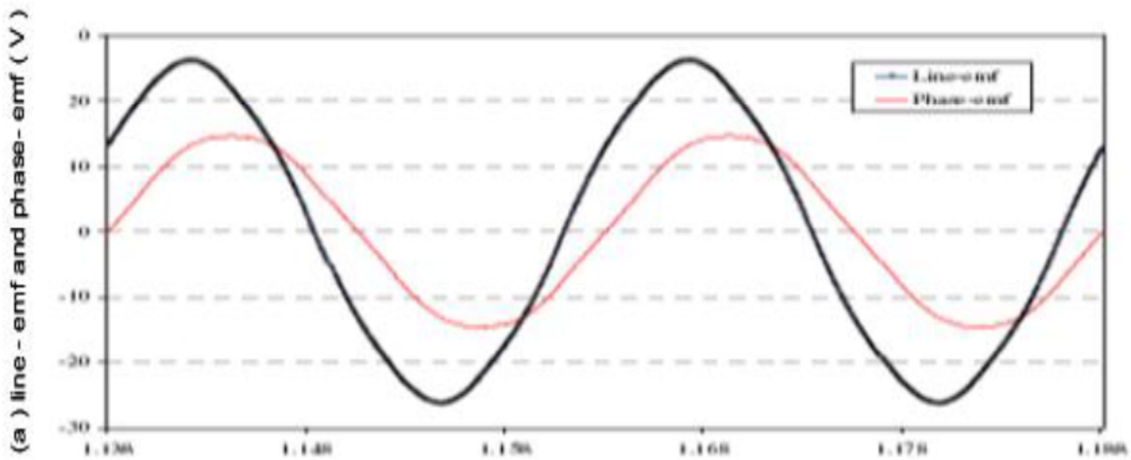



Time (s)
( c ) Motor speed

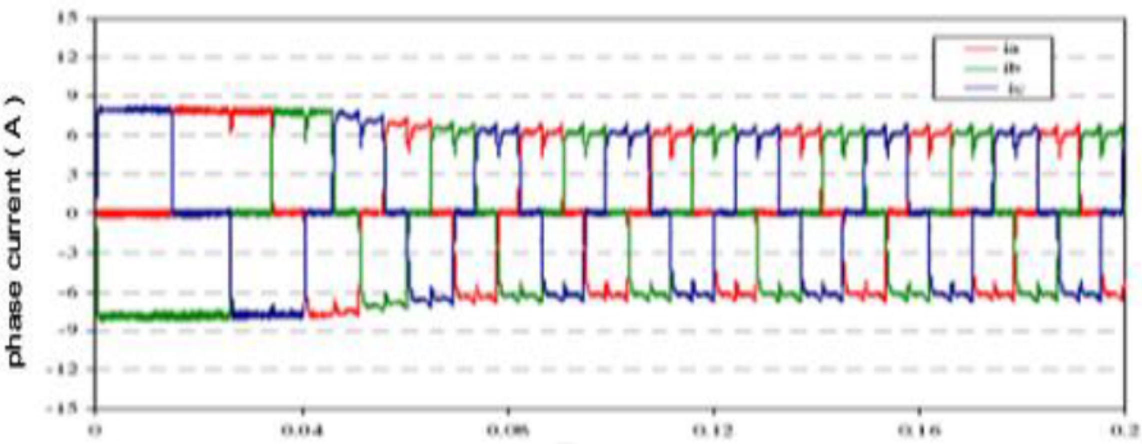
**Fig (7): Simulation result of 12 slot / 10 pole BLCD motor at rated torque 5 N.m and speed 460 pmr**



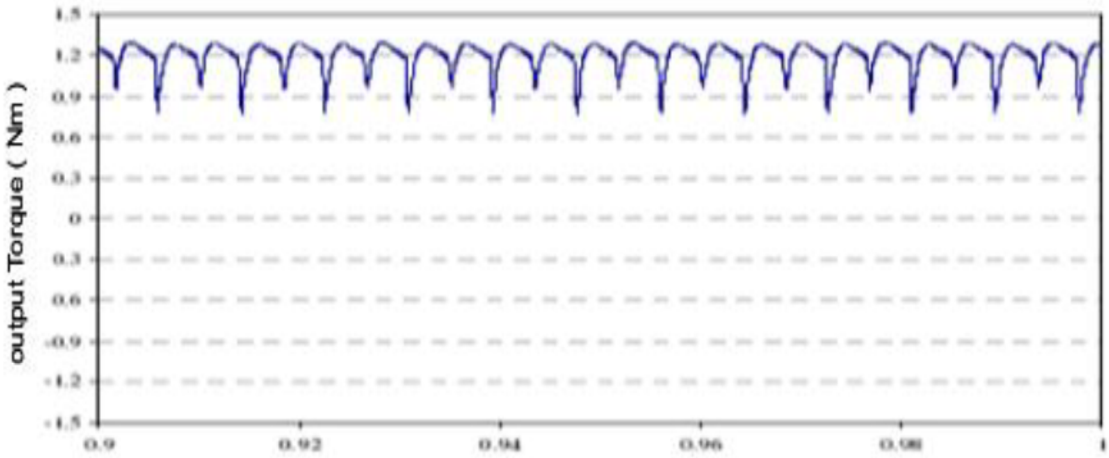

Time (s)
( a ) emf and current waveform of phase (a)



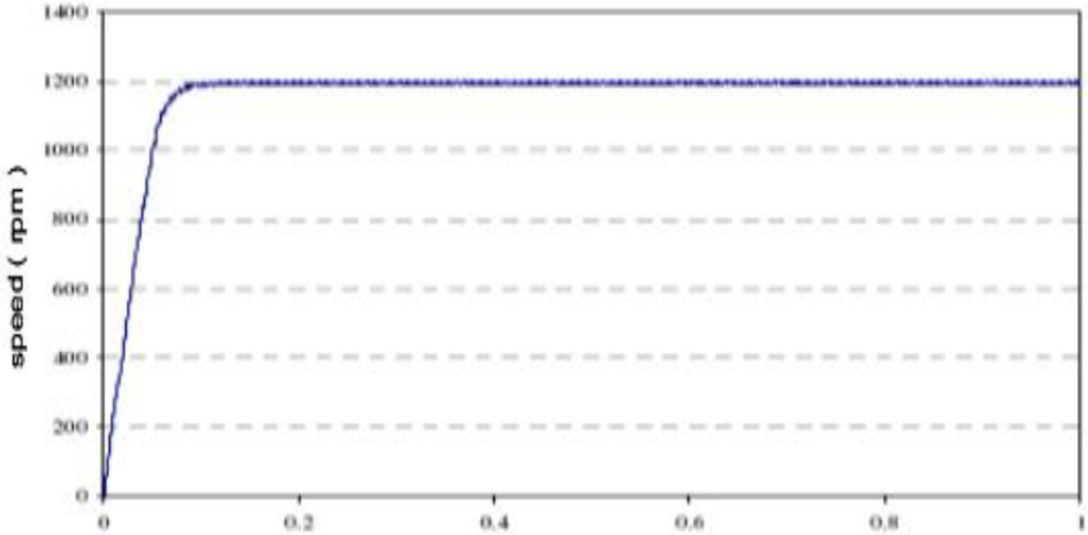

Time (s)
( b ) phase – emf and line and - emf




Time (s)
( c ) phase current




Time (s)
( d ) Output torque




Time (s)
( e ) Motor speed

**Figure (8): Simulation results of 6 slot / 4-pole BLDC motor at rated torque 1.2 N.m and speed 1200 rpm**

## 4. Analysis and Discussions :

Based on the Figs. 7 and 8, it is shown that different type of phase-emf waveform will give a different result for each motor. Fig. 7(a) and 8(c) show the result of the phase currents for both 12-slot/10-pole and 6-slot/4-pole motor. It is shown that the gradient for the 12-slot/10-pole motor is fix whereas 6-slot/4-pole motor is not fixed. The different result in the waveform of the phase currents for both motor is due to the effect of the inductance of both motor. Higher inductance value will give a result as in Fig. 7(a). Fig. 7(b) and Fig. 8(d) show the output torque developed by both motor. From these two figure, the waveform of the output torque developed by the 12-slot/10-pole motor is much closer to perfect waveform for typical PM motor rather than output torque produced by 6-slot/4-pole motor. This is because the waveform of the output torque is directly affect by the phase current waveform produced by the motor.

## 5. Conclusions :

In this paper, an analysis of brushless dc motor drive having 12-slot/10-pole and 6-slot/4-pole has been presented. The performance characteristic of motor drive has been studied using MATLAB simulation. The fundamental theory of brushless dc motor has been carried out as an useful reference in modeling the brushless dc in MATLAB/simulink environment software package. The introduction of FEM predicted phase-emf as a main source in analysis of brushless dc motor has been proved by the result from the simulation analysis.

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## Appendix –A :

### A-1. List of symbol :

| Symbol | Description |
|---|---|
| Van | phase voltage of phases a |
| Vbn | phase voltage of phases b |
| Vcn | phase voltage of phases c |
| ea | phase-emf of phases a |
| eb | phase-emf of phases b |
| ec | phase-emf of phases c |
| ia | phase current of phases a |
| ib | phase current of phases b |
| ic | phase current of phases c |
| Rs | stator winding resistance |
| L | self inductance |
| M | mutual inductance |
| *Te* | output torque |
| *TL* | load torque |
| *B* | friction |
| *J* | inertia |
| *r* | rotor speed |
| *P* | pole number |
| *Vn* | phase-emf magnitude |
| *n* | phase angle at *nth* harmonics |
| *ns* | motor speed in rpm |
| *f* | operating frequency |
| *p* | number of pole of the motor |

## A-2 . Block diagram details :

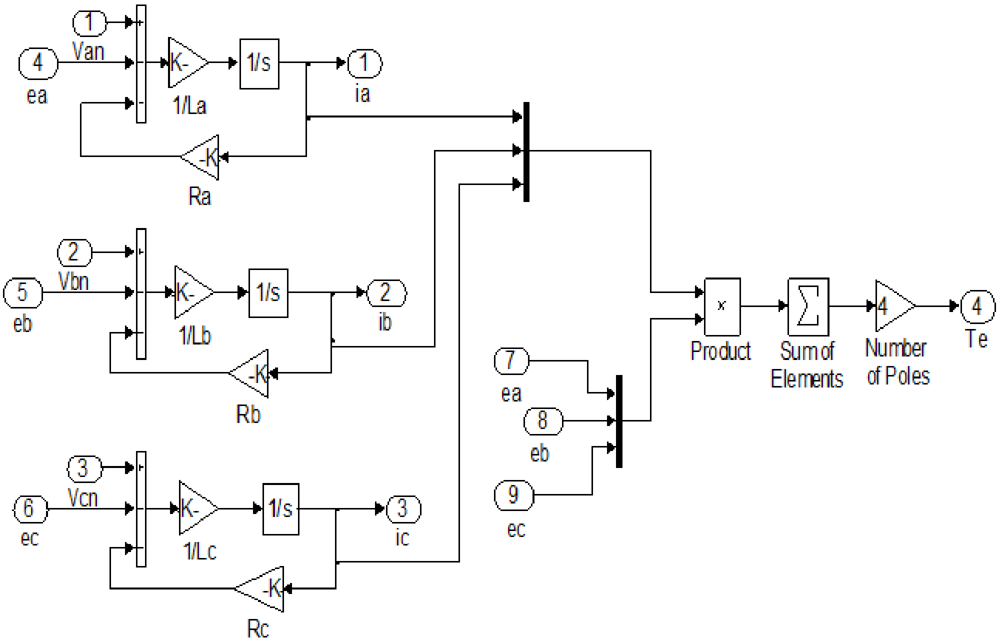


**Figure A-1 inside the BLDC sybsystem.**

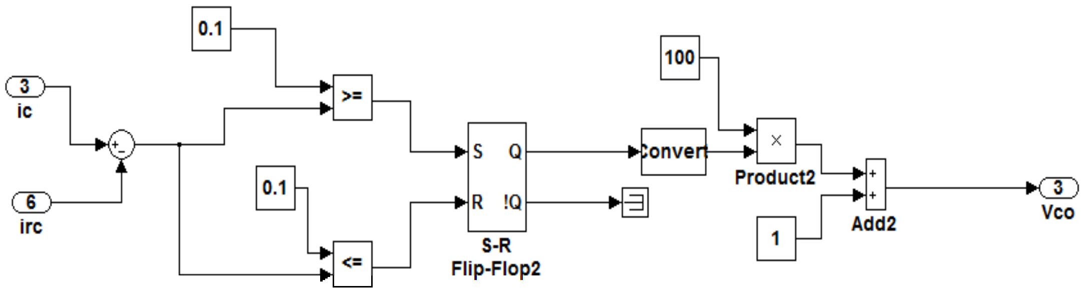


**Fig. A-2 inside the reference current and controller**

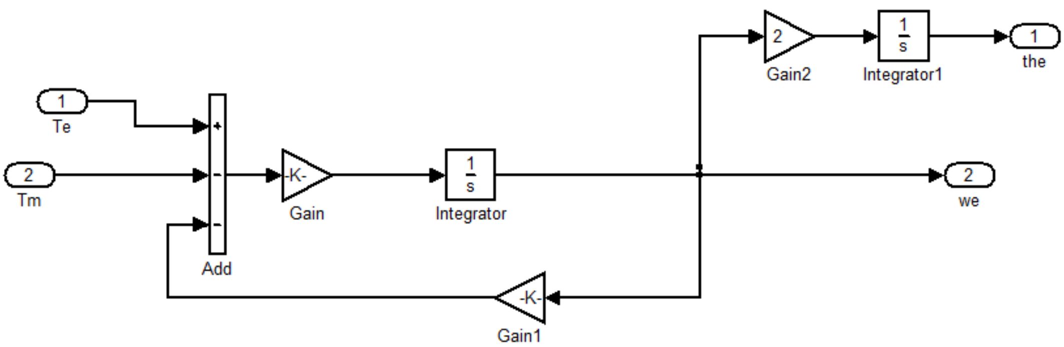


**Figure: A-3. inside the (Rotor motion eq.) subsystem.**

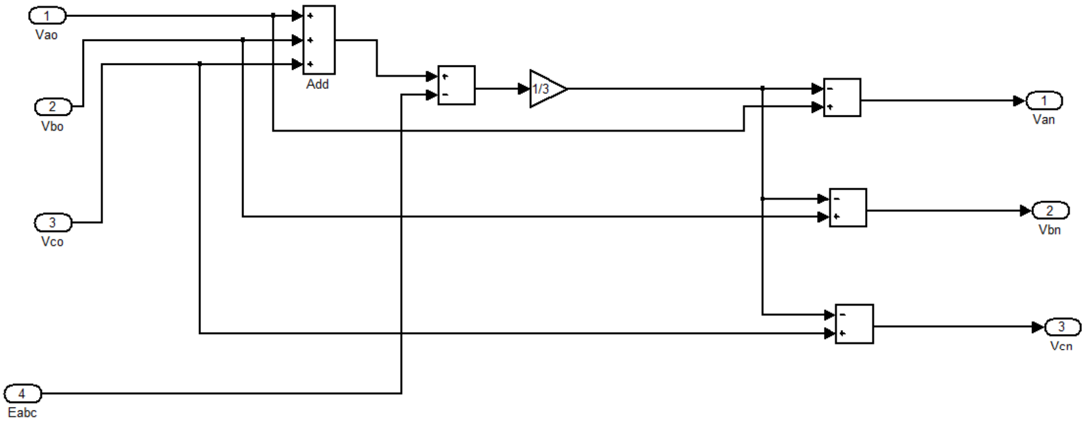


Figure: A-4. inside the (phase voltages Eqs.) subsystem.

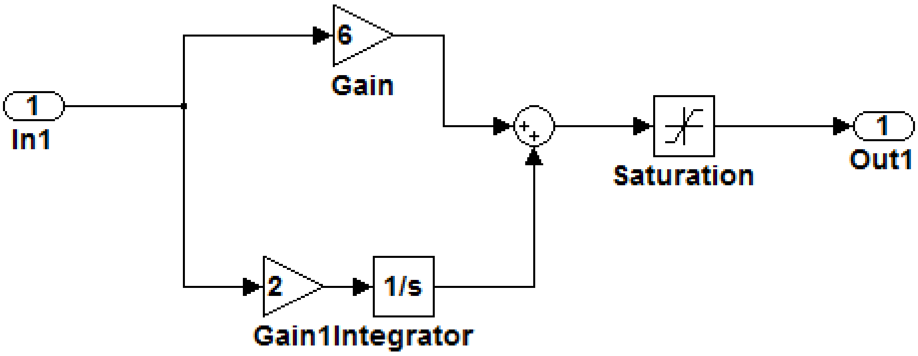


Figure: A-5. Inside the (speed controller) subsystem.

## FFTA block equation :

```
ean=sin(pos)+0.2*sin(3*pos)+0.051*sin(5*pos)+0.01*sin(7*pos)
```