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Modelling and Analysis of Five-Phase Permanent Magnet Synchronous Motor in Machine Variables

***Abstract**. The direct-phase variables (DPV) model of a five-phase permanent magnet synchronous motor is developed, presenting a more detailed set of equations for the motor in machine variables. The developed DPV model is simulated in MATLAB/Simulink to observe the characteristics response of speed and torque. The results were directly compared with a similar model developed in Ansys Maxwell Finite Element Analysis (FEA) software. Comparable results were obtained thereby validating the accuracy of the DPV Model.*

Streszczenie.** Przedstawiono model pięciofazowego silnika synchronicznego z magnesami trwałymi. Model analizowano z wykorzystaniem programów Matlab/Simulink. Wyniki są zbliżone do modeloewania ptrzy wykorzystaniu programu Ansys Maxwell Finite Element Analysis (FEA).* ***Modelowanie i analiza pięciofazowego silnika synchronicznego z magnesami trwałymi

Keywords: PMSM, finite element analysis (FEA), direct phase variable (DPV), direct-on-line
Słowa kluczowe: silnik pięciofazowy, PMSM, metoda elementów skończonych,.

Introduction

The advantages of permanent magnet (PM) machines and it decreasing cost have seen increase in its designed and utilisation for optimum performance. Among these advantages includes high efficiency, high power factor, high power density and ease of control [1,2,3,4,5]. The utilization of power electronics and drives systems has helped in improving machine performance as multi-phase and advanced switching configurations can be employed. Despite these advantages of PM machines, the high cost of permanent magnet has greatly limited its use to where the advantages outweigh the cost [6], as can be seen in its usage in aviation industries [7, 8], maritime industries [9, 10] and road transportation system [1,11].

The utilization of the multi-phase system has shown some important benefits, including higher torque performance, better faults tolerance [12] as evidence in the use of five-phase models [3,13,14] and the use of dual stator windings [15].

Considering the fact that the use of a five-phase system shows a better performance and greater efficiency as compared to the three-phase system [16], much is expected of the five-phase permanent magnet synchronous motor (PMSM).

The use of the phase variable model is considered essential in predicting the machine performance during faults and unbalanced conditions [16]. The phase variable model accounts for the machine parameters while avoiding the transformation of these parameters to avoid the dependency of inductances on rotor position [9, 10].

The work in [17], presented more detailed equations for the voltage and the torque in machine variables for the three-phase permanent magnet machine, and also can serve as a basis for the modelling of other multi-phase machines.

The present study models and analyses a five-phase Permanent Magnet Synchronous Motor (PMSM) using machine variables equations for voltages and torque, while considering its torque and speed characteristic performance during start, unloaded and when loaded. The finite element analysis (FEA) model of the 5-phase PMSM is used to validate speed and torque characteristics from start to synchronous speed and when loaded.

Phase variable model of five-phase permanent magnet synchronous motor

The voltage equation for a five-phase permanent magnet synchronous motor (PMSM) can be represented as in equation (1).

$$V_5 = R_5 I_5 + p\lambda_5 \tag{1}$$

where,

$$p = \frac{d}{dt} \tag{2}$$

λ_5 is the flux linkage, V_5 is the voltage matrix, R_5 is the resistance matrix and I_5 is the current matrix. Equation (3) presents the voltage equation of the stator circuit, but can be adapted to accommodate the rotor circuit.

$$V_5 = R_5 I_5 + p(L(\theta_r) I_5) \tag{3}$$

$$L(\theta_r)\, pI_5 = V_5 - \left(I_5 \left\{ R_5 + \left(\frac{d\{L(\theta_r)\}}{d\theta_r} \right)\omega_r \right\} + \left(\frac{d\{\lambda_{m5}(\theta_r)\}}{d\theta_r} \right)\omega_r \right) \tag{4}$$

$$pI_5 = L(\theta_r)^{-1} \left(V_5 - \left(\left\{ R_5 + \omega_r \left(\frac{d\{L(\theta_r)\}}{d\theta_r} \right) \right\} I_5 + \left(\frac{d\{\lambda_{m5}(\theta_r)\}}{d\theta_r} \right)\omega_r \right) \right) \tag{5}$$

$$\omega_r = \frac{d\theta_r}{dt} \tag{6}$$

The stator voltage equation for a five-phase PMSM can be written as in equation (7). The five-phase variables under consideration are phases a, b, c, d and e.

(7) $$V_{s5} = R_{s5}I_{s5} + p(L_{ss5}I_{s5}) + p(\lambda_{m5s})$$

where,

(8) $$R_{s5} = \begin{bmatrix} r_{as} & 0 & 0 & 0 & 0 \\ 0 & r_{bs} & 0 & 0 & 0 \\ 0 & 0 & r_{cs} & 0 & 0 \\ 0 & 0 & 0 & r_{ds} & 0 \\ 0 & 0 & 0 & 0 & r_{es} \end{bmatrix}$$

(9) $$I_{s5} = [i_{as}\ i_{bs}\ i_{cs}\ i_{ds}\ i_{es}]^T$$

(10) $$V_{s5} = [v_{as}\ v_{bs}\ v_{cs}\ v_{ds}\ v_{es}]^T$$

(11) $$L_{s5} = L_{ls}I + L_{A5}M_{a5} + L_B M_{b5}$$

where, I is an identity matrix, λ_{m5s} is the stator mutual flux linkage and the expression for M_{a5} and M_{bs} are defined in equation (12) and equation (13) respectively.

The permanent magnet is introduced to enhance the existing reluctance; thus the magnetizing inductance of the stator has a greater value in the q-axis than the d-axis. The magnetic flux equation, as referred to the stator, is given in equation (14).

(12) $$M_{a5} = \begin{bmatrix} 1 & \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) \\ \cos\left(\frac{2\pi}{5}\right) & 1 & \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) \\ \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) & 1 & \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) \\ \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) & 1 & \cos\left(\frac{2\pi}{5}\right) \\ \cos\left(\frac{2\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{4\pi}{5}\right) & \cos\left(\frac{2\pi}{5}\right) & 1 \end{bmatrix}$$

(13) $$M_{b5} = \begin{bmatrix} \cos(2\theta_r) & \cos\left(2\theta_r - \frac{2\pi}{5}\right) & \cos\left(2\theta_r - \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{2\pi}{5}\right) \\ \cos\left(2\theta_r - \frac{2\pi}{5}\right) & \cos\left(2\theta_r - \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{2\pi}{5}\right) & \cos(2\theta_r) \\ \cos\left(2\theta_r - \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{2\pi}{5}\right) & \cos(2\theta_r) & \cos\left(2\theta_r - \frac{2\pi}{5}\right) \\ \cos\left(2\theta_r + \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{2\pi}{5}\right) & \cos(2\theta_r) & \cos\left(2\theta_r - \frac{2\pi}{5}\right) & \cos\left(2\theta_r - \frac{4\pi}{5}\right) \\ \cos\left(2\theta_r + \frac{2\pi}{5}\right) & \cos(2\theta_r) & \cos\left(2\theta_r - \frac{2\pi}{5}\right) & \cos\left(2\theta_r - \frac{4\pi}{5}\right) & \cos\left(2\theta_r + \frac{4\pi}{5}\right) \end{bmatrix}$$

(14) $$\lambda'_{m5s} = \lambda_m \begin{bmatrix} \cos\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{5}\right) \\ \cos\left(\theta_r - \frac{4\pi}{5}\right) \\ \cos\left(\theta_r + \frac{4\pi}{5}\right) \\ \cos\left(\theta_r + \frac{2\pi}{5}\right) \end{bmatrix}$$

Referring the rotor parameter to the stator, the voltage equation is given in equation (15).

(15) $$\begin{bmatrix} v_{s5} \\ v'_{qdr} \end{bmatrix} = \begin{bmatrix} R_{s3} + pL_{ss5}(\theta_r) & pL'_{5sr}(\theta_r) \\ \frac{2}{5}(pL'_{5sr}(\theta_r))^T & R_{qdr} + pL'_r(\theta_r) \end{bmatrix} \begin{bmatrix} i_{s5} \\ i'_{qdr} \end{bmatrix} + p\begin{bmatrix} \lambda_{m5s} \\ \lambda'_{m5qdr} \end{bmatrix}$$

where,

(16) $$\lambda'_{m5qdr} = \lambda_m \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$\lambda_{5sr}^{'} = \begin{bmatrix} L_{mq}\cos\theta_r & L_{md}\sin\theta_r \\ L_{mq}\cos\left(\theta_r - \frac{2\pi}{5}\right) & L_{md}\sin\left(\theta_r - \frac{2\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r - \frac{4\pi}{5}\right) & L_{md}\sin\left(\theta_r - \frac{4\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r + \frac{4\pi}{5}\right) & L_{md}\left(\theta_r + \frac{4\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r + \frac{2\pi}{5}\right) & L_{md}\sin\left(\theta_r + \frac{2\pi}{5}\right) \end{bmatrix} \begin{bmatrix} i_{qr}^{'} \\ i_{dr}^{'} \end{bmatrix} + \lambda_m \begin{bmatrix} \cos\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{5}\right) \\ \cos\left(\theta_r - \frac{4\pi}{5}\right) \\ \cos\left(\theta_r + \frac{4\pi}{5}\right) \\ \cos\left(\theta_r + \frac{2\pi}{5}\right) \end{bmatrix} \tag{17}$$

Alternatively, a fictitious voltage from the permanent magnet, v_m, having a magnetizing current $i_{mr}^{'}$ supporting the rotor q-axis flux, equivalent to a damper winding in the rotor q-axis and a damper winding in the d-axis and a permanent magnet, supporting the q-axis flux. The permanent magnet equivalent magnetizing inductance is represented as L_m, and equation (17) is re-casted as in equation (18).

$$\lambda_{5sr}^{'} = \begin{bmatrix} L_{mq}\cos\theta_r & L_{md}\sin\theta_r & L_m\cos\theta_r \\ L_{mq}\cos\left(\theta_r - \frac{2\pi}{5}\right) & L_{md}\sin\left(\theta_r - \frac{2\pi}{5}\right) & L_m\cos\left(\theta_r - \frac{2\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r - \frac{4\pi}{5}\right) & L_{md}\sin\left(\theta_r - \frac{4\pi}{5}\right) & L_m\cos\left(\theta_r - \frac{4\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r + \frac{4\pi}{5}\right) & L_{md}\sin\left(\theta_r + \frac{4\pi}{5}\right) & L_m\cos\left(\theta_r + \frac{4\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r + \frac{2\pi}{5}\right) & L_{md}\sin\left(\theta_r + \frac{2\pi}{5}\right) & L_m\cos\left(\theta_r + \frac{2\pi}{5}\right) \end{bmatrix} \begin{bmatrix} i_{qr}^{'} \\ i_{dr}^{'} \\ i_{mr}^{'} \end{bmatrix} \tag{18}$$

where,

$$\lambda_m = L_m i_{mr}^{'} \tag{19}$$

Thus for the 5-ph PMSM,

$$L(\theta_r) = \begin{bmatrix} L_{ss} & L_{sr}^{'} \\ \frac{2}{5}(L_{sr}^{'})^T & L_r^{'} \end{bmatrix} \tag{20}$$

$$\begin{bmatrix} L_{asas} & L_{asbs} & L_{ascs} & L_{asds} & L_{ases} \\ L_{bsas} & L_{bsbs} & L_{bscs} & L_{bsds} & L_{bses} \\ L_{csas} & L_{csbs} & L_{cscs} & L_{csds} & L_{cses} \\ L_{dsas} & L_{dsbs} & L_{dscs} & L_{dsds} & L_{dses} \\ L_{esas} & L_{esbs} & L_{escs} & L_{esds} & L_{eses} \end{bmatrix} \tag{21}$$

$$L_r^{'} = \begin{bmatrix} L_{lkq}^{'} & 0 \\ 0 & L_{lkd}^{'} + L_{md} \end{bmatrix} \tag{22}$$

$$L_{5sr}^{'} = \begin{bmatrix} L_{mq}\cos\theta_r & L_{md}\sin\theta_r \\ L_{mq}\cos\left(\theta_r - \frac{2\pi}{5}\right) & L_{md}\sin\left(\theta_r - \frac{2\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r - \frac{4\pi}{5}\right) & L_{md}\sin\left(\theta_r - \frac{4\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r + \frac{4\pi}{5}\right) & L_{md}\sin\left(\theta_r + \frac{4\pi}{5}\right) \\ L_{mq}\cos\left(\theta_r + \frac{2\pi}{5}\right) & L_{md}\sin\left(\theta_r + \frac{2\pi}{5}\right) \end{bmatrix} \tag{23}$$

where L_{ss} is the stator inductance matrix, $L_r^{'}$ is the rotor inductance matrix referred to the stator and $L_{5sr}^{'}$ is the mutual inductances between the stator and the rotor referred to the stator.

$$R = \begin{bmatrix} R_{as} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_{bs} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{cs} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{ds} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{es} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{kq} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{kd} \end{bmatrix} \tag{24}$$

R is the resistance matrix. The electromagnetic torque is given in equation (25)

$$T_e = \left(\frac{p}{2}\right)\left(\frac{1}{2} I_s^T \frac{\partial\{L_{ss}(\theta_r)\}}{\partial\theta_r} I_s + + I_s^T \left\{ \frac{\partial\{L_{sr}(\theta_r)\}}{\partial\theta_r} I_r + \frac{\partial\{\lambda_{msx}(\theta_r)\}}{\partial\theta_r} \right\}\right) \tag{25}$$

$$(26)\ T_e=\left(\frac{p}{2}\right)\left(\begin{array}{l}-L_B\left\{\left(i_{as}^2+2(i_{bs}i_{es}+i_{cs}i_{ds}\right)+A_1\cos\frac{4\pi}{5}+B_1\cos\frac{2\pi}{5}\sin 2(\theta_r)+\left(A_2\sin\frac{4\pi}{5}+B_2\sin\frac{2\pi}{5}\right)\cos 2(\theta_r)\right\}-\\ \left\{(L_{mq}i'_{qr}+\lambda_m)((i_{as}+C_1)\sin\theta_r+D_1\cos\theta_r)+(L_{md}i'_{dr})((i_{as}+C_1)\cos\theta_r-D_1\sin\theta_r)\right\}\end{array}\right)$$

where;

$$(27)\ L_B=\left(\frac{2}{25}\right)(L_{mq}-L_{md})$$

$$(28)\ A_1=(i_{bs}^2+i_{es}^2+2\{i_{as}i_{cs}+i_{as}i_{ds}+i_{bs}i_{cs}+i_{ds}i_{es}\})$$

$$(29)\ A_2=(-i_{bs}^2+i_{es}^2+2\{-i_{as}i_{cs}+i_{as}i_{ds}+i_{bs}i_{cs}-i_{ds}i_{es}\})$$

$$(30)\ B_1=(i_{cs}^2+i_{ds}^2+2\{i_{as}i_{bs}+i_{as}i_{es}+i_{bs}i_{ds}+i_{cs}i_{es}\})$$

$$(31)\ B_2=(i_{cs}^2-i_{ds}^2+2\{-i_{as}i_{bs}+i_{as}i_{es}+i_{bs}i_{ds}-i_{cs}i_{es}\})$$

$$(32)\ C_1=\left((i_{bs}+i_{es})\cos\frac{2\pi}{5}+(i_{cs}+i_{ds})\cos\frac{4\pi}{5}\right)$$

$$(33)\ D_1=\left((-i_{bs}+i_{es})\sin\frac{2\pi}{5}+(-i_{cs}+i_{ds})\sin\frac{4\pi}{5}\right)$$

$$(34)\ I_r=\left[I_{qr}\quad I_{dr}\right]^T$$

Neglecting the damping coefficient associated with the rotational system of the machine and the mechanical load [14], equation (35) gives the torque equation for motor action.

$$(35)\ T_e=J\left(\frac{P}{2}\right)\frac{d\omega_r}{dt}+T_l$$

where,

I_s is the stator current matrix and I_r is the rotor current matrix, J is the inertia expressed in kilogram metre^2 (kg-m^2) or joule-seconds^2 (J.s^2), T_l is the load torque in N-m, while P is the no of poles of the machine.

Simulation of the Dynamic Process

A PMSM modelled and simulated using the machine parameters of Table 1. Also, Fig. 1 shows the ANSYS Maxwell model, highlighting the winding arrangement for the five phase PMSM.

Table 1. PMSM dimensions and circuit parameters

Quantities	Value	Quantities	Value
Stator outer / inner radius	105.02 / 68.09mm	Number of poles	4
Rotor radius	67.69mm	Frequency	50Hz
Effective stack length	120.00mm	Stator resistance, R_s	1.38Ω
Number of Stator slots	40	moment of inertia, J	0.00894kg/m2
Number of turns	48	Rotor q-axis leakage inductance, L_{lqr}	8.2mH,
Number of Rotor slots	32	Rotor d-axis leakage inductance, L_{ldr}	5.5mH
Phase voltage, $V5\ ph$	370v	Rotor q-axis resistance, R_{qr}	0.25 Ω
Stator slot depth	12mm	Rotor d-axis resistance, R_{dr}	0.12 Ω
Mutual flux linkage, λ_{5m}	0.03707 V.s	Stator leakage inductance, L_{ls}	19.00mH

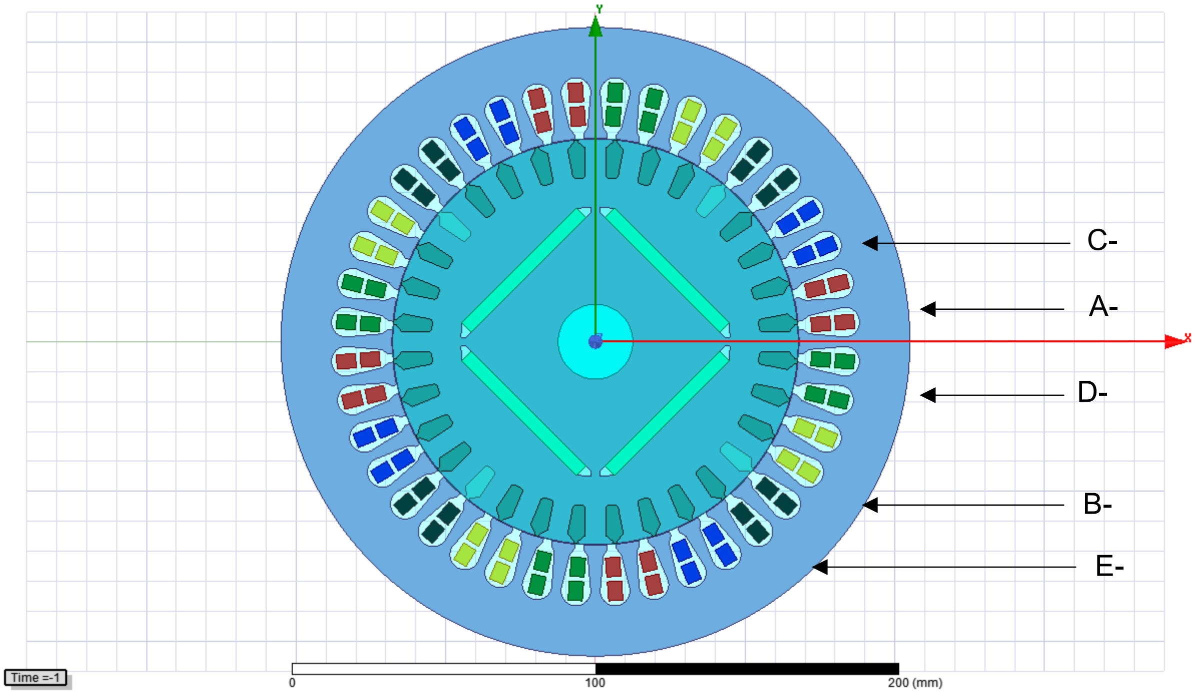

Fig .1. Figure showing winding layout for the PMSM

The FEA and the DPV models were simulated to study, the speed and the torque characteristics at start and subsequent 5 Nm loading.

The machine speed for the two models are presented in Fig.2, showing a higher transient speed value of 1924 rpm at start for the DPV model as compared to a speed value of 1738 rpm for the FEA Model.

After the initial starting transients, the DPV modelled machine reached synchronism at 0.37 seconds as compared to synchronism time of 0.35 seconds for the FEA model. The speed transient at loading for the two models shows a greater drop in speed value for the DPV model to a value of 1440 rpm as compared to that of the FEA having a value of 1471 rpm. A value of 1515 rpm above the synchronous speed is also observed for the DPV model as compared to the speed value of 1504 rpm for the FEA model. The speed characteristic showing transient at loading is presented in Fig. 3. Upon application of the 5 Nm load at 0.45 seconds, the FEA model settled at 0.58 seconds while the DPV settled at 0.62 seconds.

The simulated machine torque characteristics for the developed DPV and the FEA models are presented in Fig.4. The torque characteristics of the machine shows a higher torque value of 165.2Nm for the FEA model at 0.009 seconds as compared to a torque value of 145.7 at 0.0095 seconds for the DPV model.

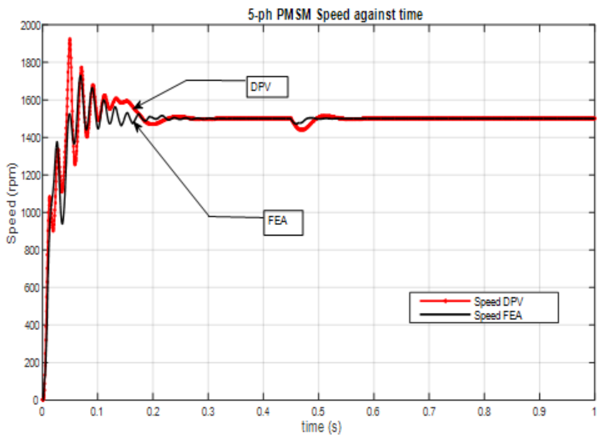

Fig 2. 5-ph PMSM Speed Characteristics (with 5Nm load Torque at 0.45 seconds).

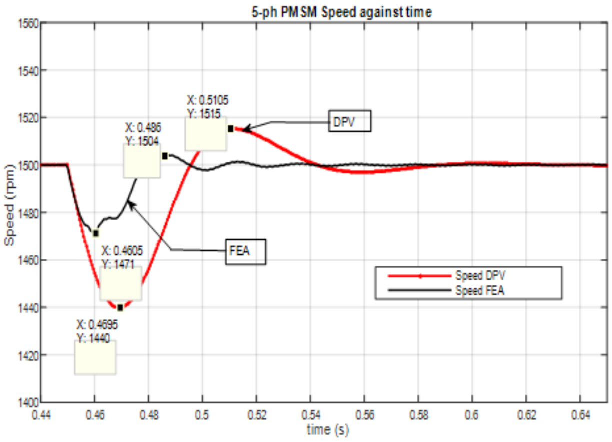

Fig. 3. 5-ph PMSM Speed Characteristics (Showing transient at loading)

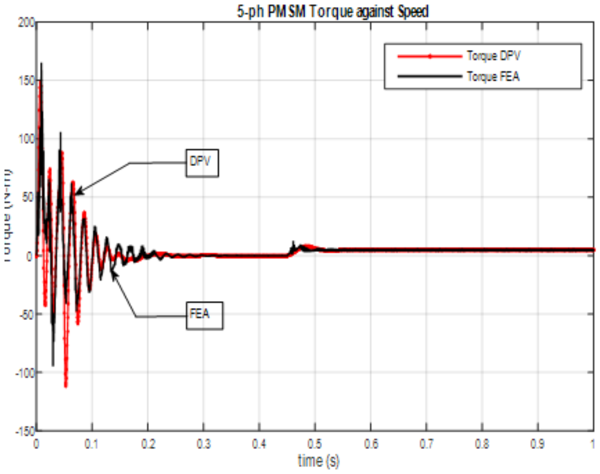

Fig.4. 5-ph PMSM Torque Characteristics (with 5Nm load Torque at 0.45 seconds)

Conclusion

In this paper, the five-phase permanent magnet synchronous motor has been modelled and analysed by presenting it voltage and torque equations in machine variables. The machine has been analysed using MATLAB/SIMULINK with consideration to the speed and torque performance characteristics at start and loading. The DPV has been used to clearly avoid the complexity of transformation of the stator inductances aimed at removing its dependence on the rotor position.

A 9.64% difference for the two models is observed for the maximum speed transient value, while an 11.8% difference is observed for the maximum transient torque. On loading, the maximum transient oscillating value of 0.83% is recorded for the FEA model, while a maximum oscillating value of 1.5% is recorded for the DPV model about the average load value. The developed model can also be modified to accommodate the third harmonics of the air-gap MMF, anticipating more accurate results.

Results show that the developed DPV model, which is simple due to the avoidance of transformations, is suitable to represent the characteristics of the machine. This is because the results obtained from the DPV model favourably compare with the results of the FEA model which is a more accurate representation of actual machine. Finally, it is worth mentioning that the developed DPV model can serve as a basis for the further development of other multi-phase machines and also contribute better understanding of the direct-phase variable modelling.

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