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Performance Analysis for Open Loop Brushless DC Motor Drive

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***Abstract:** This paper presents a broad explanation on the effect of performance of an open-loop representation of a Brushless Direct Current (BLDC) Motor drive supplied from a two-level voltage source inverter (VSI) working on 120-degree mode of conduction. This research work is programming based and it is done in the MATLAB software for both No-load and load condition. BLDC motors are currently growing popularity and replacing brush motor in so many applications, as it can be used in both low and high-speed vehicle system and also in servo drives. The high reliability, good efficiency, high power concentration, less maintenance, simplicity of control and mainly the brushless operation make the BLDC motors superior to others. The presence of electronic elements for the smooth operation of the motor makes it less costly compare to other motors. It has a permanent magnet as a rotor with a balanced 3-phase conductor assembly as armature in its stator. The armature winding is driven by a power electronics inverter which is operating the switches according to the rotor position, sensed by an optical encoder or a Hall Effect sensor. It is found that by tuning the value of rotor position, no-load condition, and trapezoidal armature phase current, the variation in torque can be minimized. Different performance parameters for no-load and load condition of the BLDC motor like phase voltages and currents, speed, electromagnetic torque, d, q axis current and rotor position etc. are determined in MATLAB environment. These parameter evaluations is necessary to achieve better performance in both load and no load condition of BLDC motor in terms of speed and torque as these are the vital point for the selection of the application field of BLDC motor drive.*

Index Terms: Brushless DC motor, load and no load, MATLAB, Open loop model, position sensor (encoder), voltage source inverter (120-degree mode).

I. INTRODUCTION

A Brushless DC motor has three-phase windings which are distributed in nature and are placed on a stator, which is formed of stacked steel laminations. Due to this construction of stator, a trapezoidal back electromagnetic force (EMF) is generated in the machine. Permanent magnets are utilized for the construction of rotor of the machine, these magnets may either be placed as surface mounted or buried magnet type.

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As depicted in the schematic diagram of VSI fed BLDC drive of fig.1, the machine is mainly supplied by a power converter, generally voltage source inverters (VSI)[5]. The inverter operation depends on the power electronics-based switches and the ON and OFF operation of those switches relies on the location of the rotor. There are myriad ways of sensing the rotor position of the machine such as using hall sensors, optical encoders, and resolvers or by using sensor-less methods. The commutation in BLDC motor is through an electronic method based on rotor position sensing as mentioned earlier, whereas in conventional DC motor is the DC supply is converted to AC EMF with the help of commutator and brushes which in turn have losses and affect the efficiency of the machine[16].

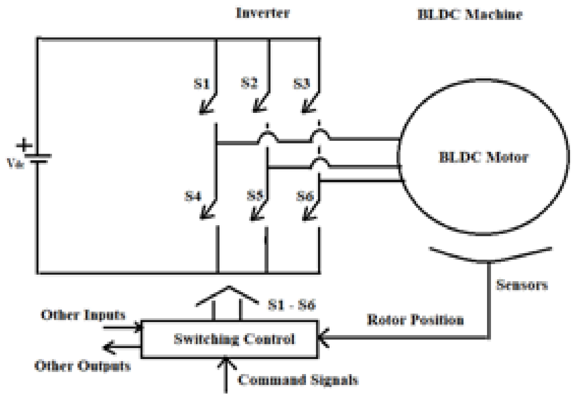

Fig.1 Schematic Diagram of VSI Fed BLDC Drive.

The conventional DC motor has the demerit of the spark that may be produced due to the uneven distribution of current. Due to the above-cited demerits of conventional DC motors and the less efficiency offered by single-phase induction motors owing to the ohmic losses in the rotor and the displacement between the stator current and the back EMF[18], the researchers shifted to BLDC motors which have the traits such as copiousness to operate at low voltages, high torque to weight ratio, less electromagnetic interference, ruggedness, negligible maintenance[10]-[11]. The aforementioned characteristics make the BLDC motor most sought-after motor for applications such as aerospace, defense, consumer, automation, medical, etc. [5]. These motors are giving tough competition to AC motor drives in applications such as pumping of water to heights and other applications in which conventional energy is utilized [7].

II. OPEN LOOP BLDC MOTOR DRIVE

The universal open-loop representation of Brush Less DC motor drive consists of three primary blocks, i.e.

the inverter block, d-q transformation block and the machine block as shown in Fig.2. This operation of this type of motor can be explained by assuming the 120° conduction mode of an voltage source inverter.

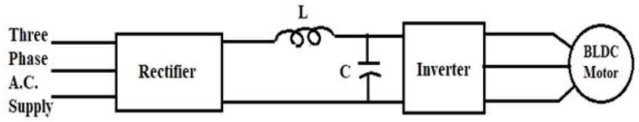

Fig.2 Open Loop Model of Brush Less DC Motor Drive.

A. Three Phase Inverters

An inverter is a static converter which converts DC waveform into an AC waveform by conversion of DC power into AC power which is mainly desired by adjustable speed drives (ASD), voltage compensators, flexible AC transmission systems (FACTS), Uninterrupted power supplies (UPS), aircraft power supplies etc. Inverters are mainly categorized into two types such that Voltage Source and Current Source Inverter. The Voltage Source Inverter (VSI) consists of stiff voltage source with negligible internal impedance whereas Current Source Inverter (CSI) typically consists of a stiff current source which is DC in nature. The transition of firing pulses from one power switch to another in a defined sequence is termed as a step. Each step is of 60-degree duration in a cycle of 360-degree. There are mainly two modes of conduction, viz. 180-degree and 120-degree mode but in both the modes the gating pulses are present for 60-degree of the output voltage wave. As the back EMF wave is trapezoidal in BLDC motor so 120-degree mode power converter is used to deliver power to the motor[11]. The location of the rotor is sensed by the sensor which acts as an encoder and the encoded signal is given to the controller which provides proper switching pulses to the switches. Fig.3 depicts the schematic diagram of the three-phase 120-degree voltage source inverter.

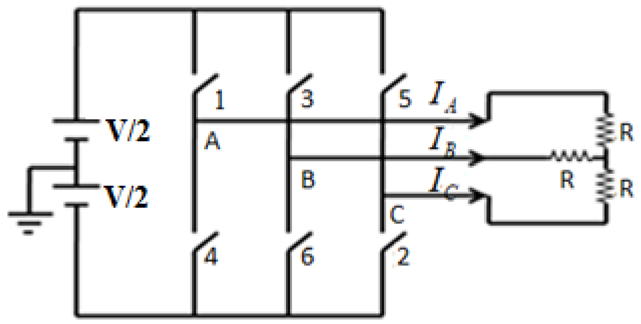

Fig.3 Schematic Diagram of Two-level Three-Phase VSI.

There are some important points to be considered in case of 120-degree conduction mode of inverter operation. Always either one switch of the above (positive) three inverter switches and one switches out of the below(negative) three inverter switches are ON synchronously. From Table 3.1 we can say that the total of phase voltage is always nil and thus if one voltage is positive, another one is negative and the other phase voltage is nil. This is applicable for all the switching sequence. As it is a 120 Degree Conduction mode so always two phases will carry voltage the other one will be of zero value [1].

Table 1 Phase Voltage of 120^0 mode of three phase VSI.

Phase Voltage	61	12	23	34	45	56
V_{xn}	$\frac{V}{2}$	$\frac{V}{2}$	0	$-\frac{V}{2}$	$-\frac{V}{2}$	0
V_{yn}	$-\frac{V}{2}$	0	$\frac{V}{2}$	$\frac{V}{2}$	0	$-\frac{V}{2}$
V_{zn}	0	$-\frac{V}{2}$	$-\frac{V}{2}$	0	$\frac{V}{2}$	$\frac{V}{2}$

Table 2 Line voltage of 120^0 mode of three Phase VSI.

Line Voltage	61	12	23	34	45	56
V_{xy}	V	$\frac{V}{2}$	$-\frac{V}{2}$	$-V$	$-\frac{V}{2}$	$\frac{V}{2}$
V_{yz}	$-\frac{V}{2}$	$\frac{V}{2}$	V	$\frac{V}{2}$	$-\frac{V}{2}$	$-V$
V_{zx}	$-\frac{V}{2}$	$-V$	$-\frac{V}{2}$	$\frac{V}{2}$	V	$\frac{V}{2}$

III. MATHEMATICAL MODELING OF BLDC MOTOR

If the mathematical modeling of BLDC motor is generally done with the help of "Park transformation theory". The ‘Motor' block of the model established acquire different components like d-axis (Vds) and q-axis (Vqs) of BLDC motor armature(stator) voltage, the spontaneous rotor angle and the details of load-torque (TL, fn) as inputs and calculates other parameters viz. stator currents, flux in stator in two phase (d-q) reference frame and electromagnetic-torque(T_{em})[6]. The necessary equations related to the machine are shortened ahead, where symbols signify their usual standard meaning. The stator winding equations of the motor as follows[3]:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \quad (1)$$

Assuming three symmetric phases we have,

$$L_{aa} = L_{bb} = L_{cc} = L\,, \quad (2)$$

$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M \quad (3)$$

Substituting equation (2) & (3) in equation (1),

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \quad (4)$$

The Simplification of equation (4) leads to,

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} (L-M) & 0 & 0 \\ 0 & (L-M) & 0 \\ 0 & 0 & (L-M) \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} \quad (5)$$

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The electromagnetic torque of the BLDC machine is put in terms of equation as,

$$T_e = [e_{as}i_{as} + e_{bs}i_{bs} + e_{cs}i_{cs}]\frac{1}{\omega_m} \qquad (6)$$

The equation of motion and load torque T_l for a simple system with required terms is given by,

$$J\frac{d\omega_m}{dt} + B\omega_m = (T_e - T_l) \qquad (7)$$

The dependence of rotor speed on position is also expressed as,

$$\frac{d\theta_r}{dt} = \frac{P}{2}\omega_m \qquad (8)$$

Merging all the above equations in form of the state equation we have,

$$\dot{x} = Ax + Bu \qquad (9)$$

Where, $x = [i_{as} \quad i_{bs} \quad i_{cs} \quad \omega_m \quad \theta_r]^t$ (10)

$$A = \begin{bmatrix} \frac{-R_s}{L_1} & 0 & 0 & -\frac{\lambda_p}{L_1} f_{as}(\theta_r) & 0 \\ 0 & \frac{-R_s}{L_1} & 0 & -\frac{\lambda_p}{L_1} f_{bs}(\theta_r) & 0 \\ 0 & 0 & \frac{-R_s}{L_1} & -\frac{\lambda_p}{L_1} f_{cs}(\theta_r) & 0 \\ \frac{\lambda_p}{J} f_{as}(\theta_r) & \frac{\lambda_p}{J} f_{bs}(\theta_r) & \frac{\lambda_p}{J} f_{cs}(\theta_r) & \frac{-B}{J} & 0 \\ 0 & 0 & 0 & \frac{P}{2} & 0 \end{bmatrix} \qquad (11)$$

$$B = \begin{bmatrix} \frac{1}{L_1} & 0 & 0 & 0 \\ 0 & \frac{1}{L_1} & 0 & 0 \\ 0 & 0 & \frac{1}{L_1} & 0 \\ 0 & 0 & 0 & -\frac{1}{J} \\ 0 & 0 & 0 & 0 \end{bmatrix} \qquad (12)$$

In equation (12), $L_1 = L - M$ (13)

$$u = [v_{as} \quad v_{bs} \quad v_{cs} \quad T_l]^t \qquad (14)$$

The four important equations after performing transient analysis on the machine are as follows:

$$\frac{di_d}{d\theta} = \frac{1}{\omega_r L_d}[\mathrm{v}_d(\theta) - \mathrm{r}\mathrm{i}_d + \omega_r \mathrm{L}_q \mathrm{i}_q] \qquad (15)$$

$$\frac{di_q}{d\theta} = \frac{1}{\omega_r L_q}[\mathrm{v}_q(\theta) - \mathrm{r}\mathrm{i}_q + \omega_r(\psi_0 + \mathrm{L}_d \mathrm{i}_d)] \qquad (16)$$

$$\frac{d\theta}{dt} = \omega_r \qquad (17)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J\omega_r}\left[\left(\frac{P}{2}\right)^2(\psi_d \mathrm{i}_q - \psi_q \mathrm{i}_d) - f_m\omega_r - \left(\frac{P}{2}\right)T_l\right] \qquad (18)$$

Based on equations (15), (16), (17) & (18) a program and an open-loop model is developed which utilizes the equations from mathematical modeling also and provides the inverter output voltages and currents along with the motor speed, torque, q- axis current, d- axis current, rotor position during no-loaded and load condition of the motor[19]. The flowchart of the MATLAB program is presented in fig.4 and the simulation model of the overall system is shown in fig.5.

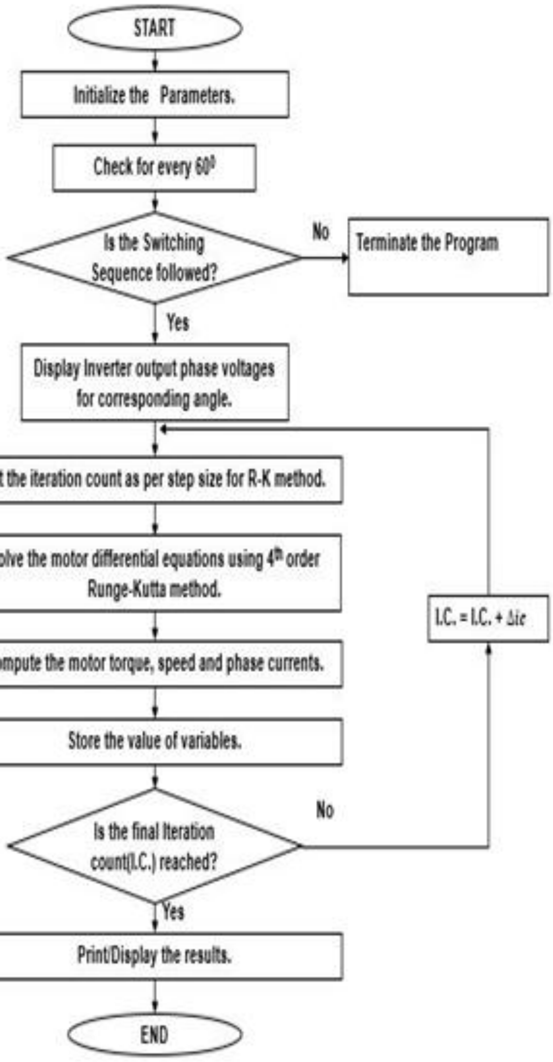

Fig.4 Program flowchart

IV. RESULT

The flowchart shows all the vital steps followed during the program simulation. It is a general program where different motor parameters can be considered as input and some parameters are need to be initialized.

The switching of VSI has been considered as decision parameter for program termination and continuation and accordingly the phase voltages plotted.

Next as the equations 15, 16, 18, 19 are need to be solved to get the other parameters, so, the Runga-Kutta iterative numerical analysis has been considered and number of iterations are set for this purpose. Now as the iteration continues, it generates the values of the required parameters viz. speed, torque and axis current and store in the memory. After completing the final iteration count, the program ends and parameters variation plotted with respect of time. These results are shown in below from fig.6 to fig.35.

The fig.5 depicts the MATLAB Simulation model of BLDC motor drive which is identical for 180-degree and 120-degree inverter except for the change in pulse width which is 50 percentage and 33.33 percentage for 180-degree and 120-degree mode inverter respectively. The following fig.6 & fig. 7 shows the different outputs which are the rotor speed, electromagnetic torque, stator current, back emf and rotor angle obtained after the application of input through the VSI for 180-degree mode inverter. The fig.8 & fig. 9 depicts the same parameters when the motor is subjected to 120-degree mode inverter operation.

It can be noticed from the obtained result that by this direct connection the results obtained consists of ripples. The desired result of constant speed, trapezoidal back emf is not obtained which motivated us to develop a program for a 180-degree and 120-degree mode. This approach helped us to get the speed, torque results for both the load and no-load operations of the motor along this other variations of machine performance parameter under consideration is observed.

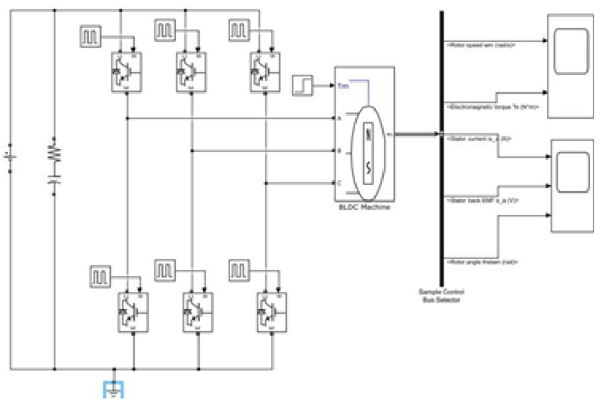

Fig.5 The Open Loop Model of BLDC Motor with 180-degree & 120-degree mode Inverter.

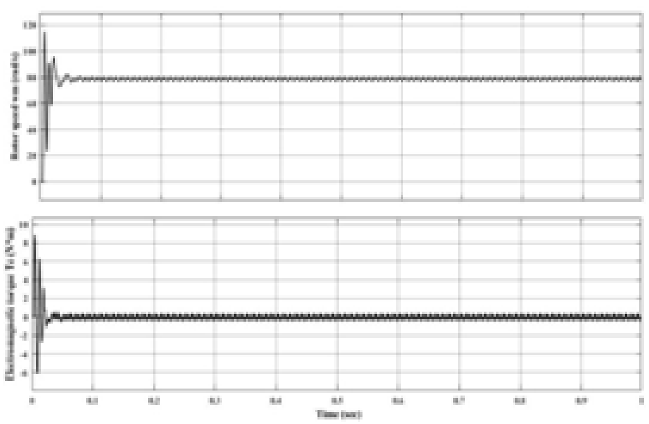

Fig 6: Speed Vs Time & Electromagnetic torque Vs Time output of Motor with 180-degree mode Inverter.

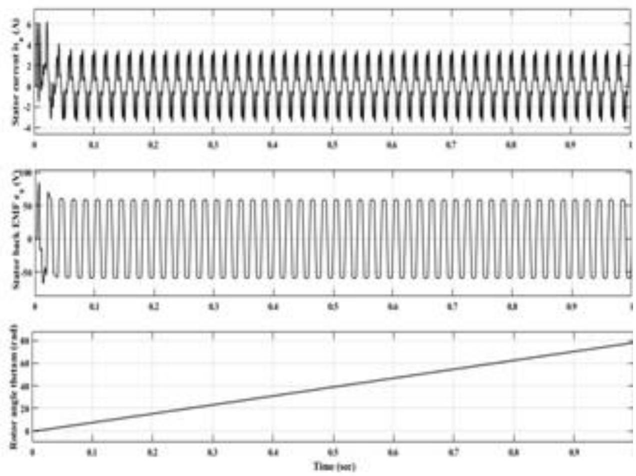

Fig 7: Stator current, Back EMF, Rotor angle Vs Time output of Motor with 180-degree mode Inverter

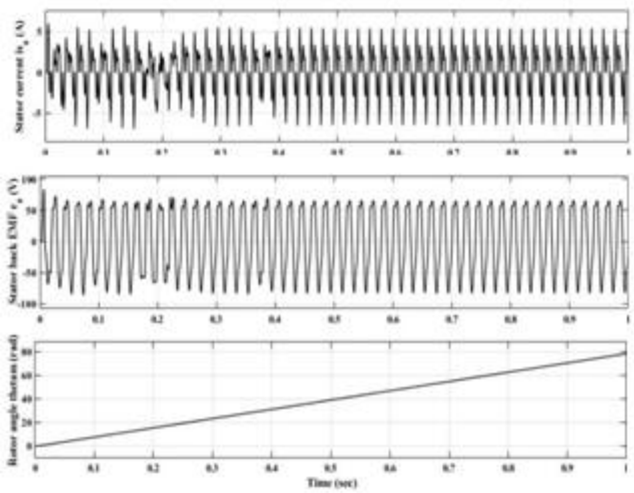

Fig 8: Speed Vs Time & Electromagnetic torque Vs Time output of Motor with 120-degree mode Inverter.

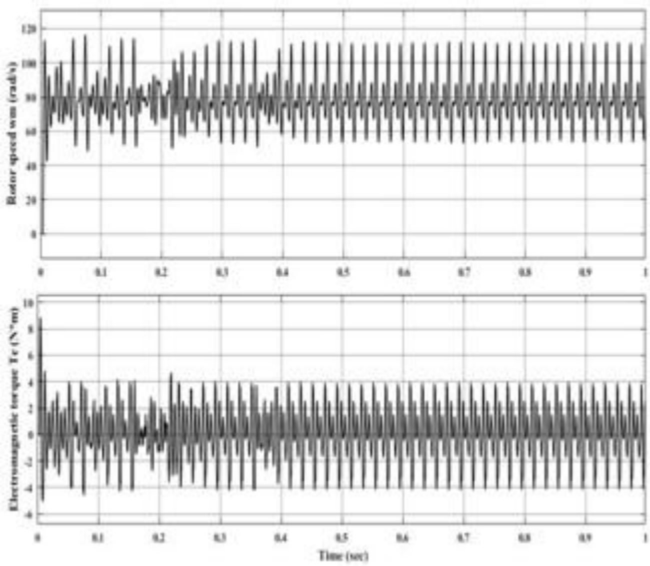

Fig 9: Stator current, Back EMF, Rotor angle Vs Time output of Motor with 120-degree mode Inverter.

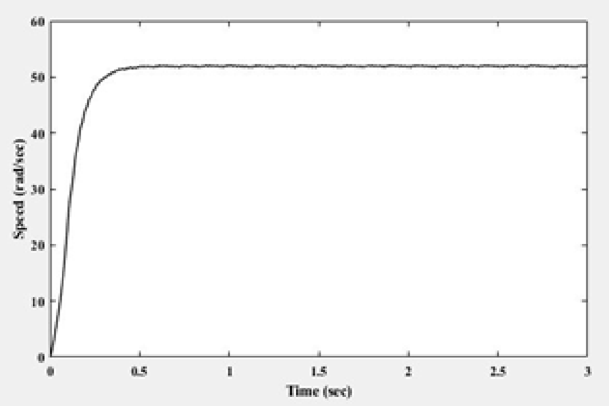

FIG 10: Speed Vs Time, When V_{dc}=100 V, T_l= 0, 120-degree mode

The speed and Electromagnetic torque are plotted in fig.10 and fig.11 and is obtained when the DC voltage is 100 Volt and the motor load is zero. The speed vs time plot of fig.10 shows rise of the motion in steps and settles to a constant value in a no-load condition of the machine. The torque in fig.11 increases sharply initially for higher current passing through an open-loop model and then slowly settles down to a steady-state behavior with some ripples in it which can be noticed in fig.11.

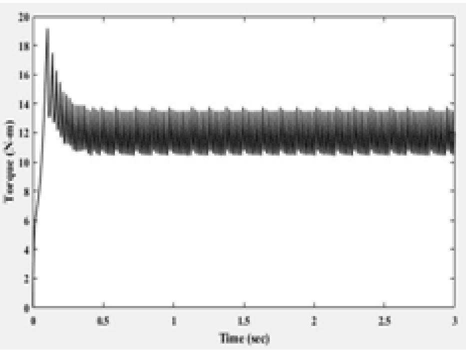

Fig 11: Electromagnetic Torque Vs Time. When V_{dc}=100 V, T_l= 0, 120-degree mode

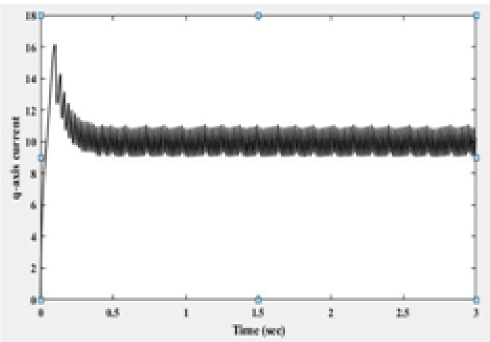

Fig 12: q-axis current vs time response of a BLDC motor drive for V_{dc}= 100 V, T_l=0, 120-degree mode.

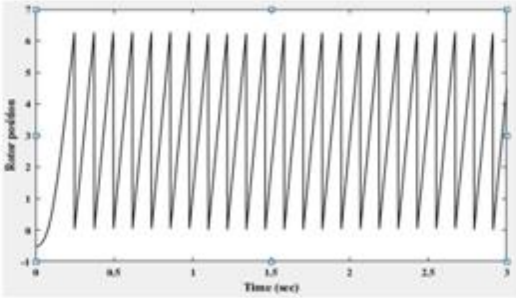

Fig 13: Rotor Position vs Time response for BLDC Drive for V_{dc}=100 V and T_l=0, 120-degree mode

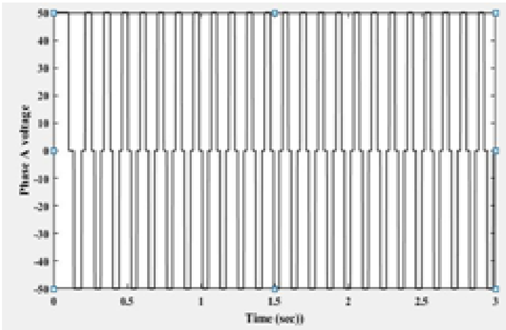

Fig 14: Phase A Voltage, V=100V Tl= 0

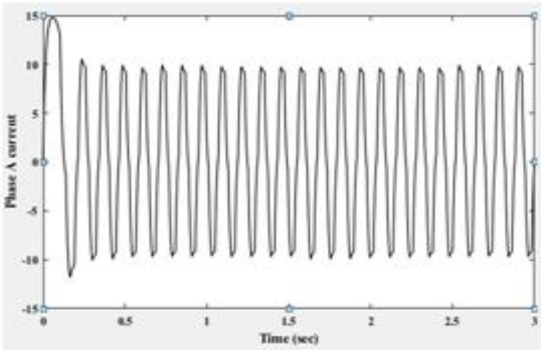

Fig 15: Phase A Current, Tl= 0

Fig.12 shows the q-axis current for the no-load condition. The electromagnetic torque curve is identical to current response as it is the torque producing component of this machine which can be verified from fig.11 in which electromagnetic torque is illustrated.

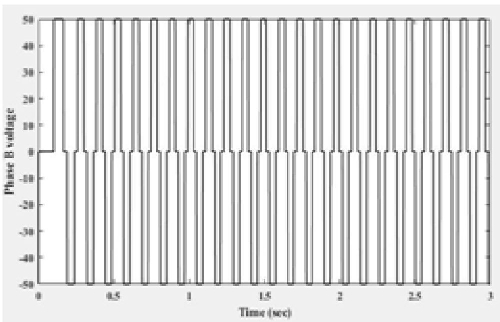

Fig 16: Phase B Voltage, V=100V Tl= 0

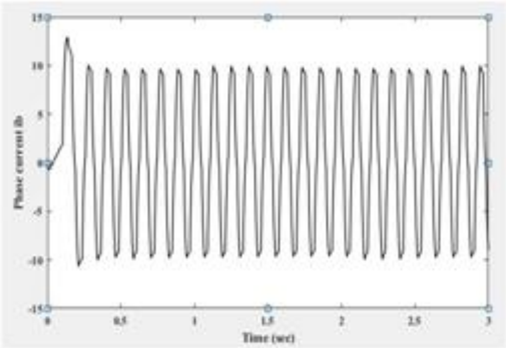

Fig 17: Phase B Current, Tl= 0

The response of rotor position vs time is shown in fig. 13. It can be noticed that it starts from a negative point as the angle assumed initially is negative but it goes up to positive maximum point due to change of position of switching sequence of voltage source inverter (VSI).

The phase voltage vs time plot of three different phase voltages of this open-loop model is observed from the fig.14, fig.16 and fig.18 correspondingly. The phase voltage response has stepped waveform for a two-level 120-degree mode VSI. Similarly, fig. 15, fig.17, fig.19 shows the three different phase currents for the motor. It is observed that the current waveforms are not pure sinusoid due to the motor load.

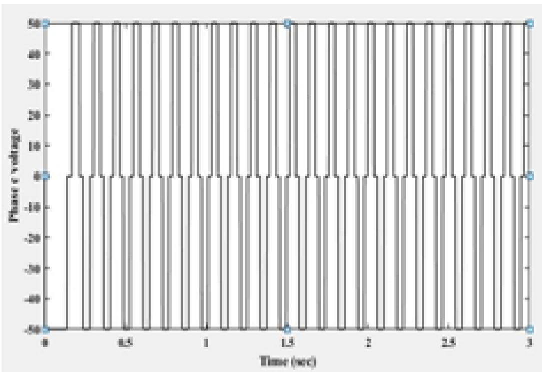

Fig 18: Phase C Voltage, V=100V Tl= 0

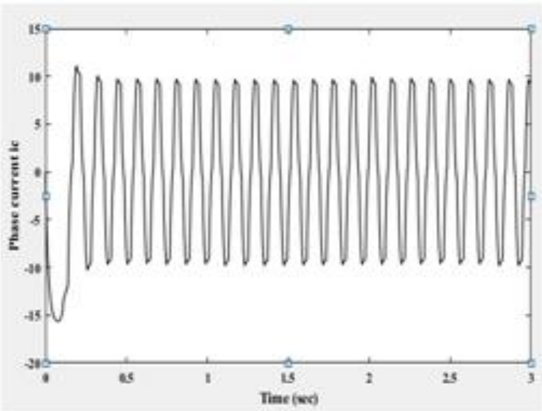

Fig 19: Phase C Current, Tl= 0xxz

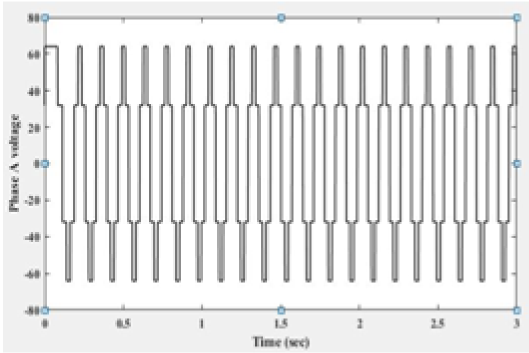

Fig 20: Phase A Voltage, V=96 V Tl= 0

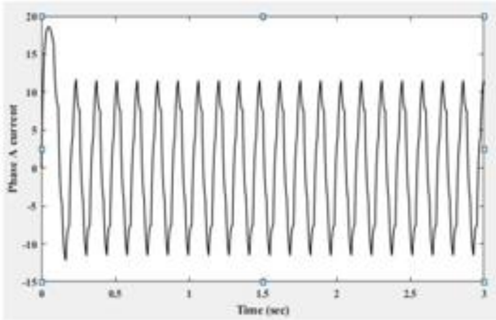

Fig 21: Phase A Current, Tl= 0

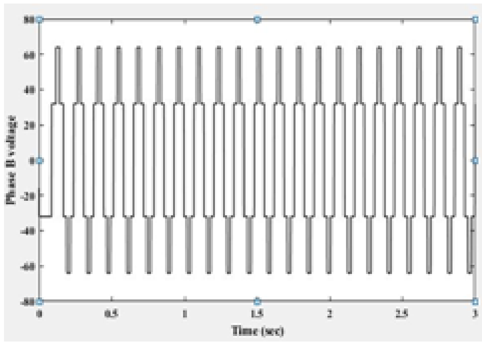

Fig 22: Phase B Voltage, V=96 V Tl= 0

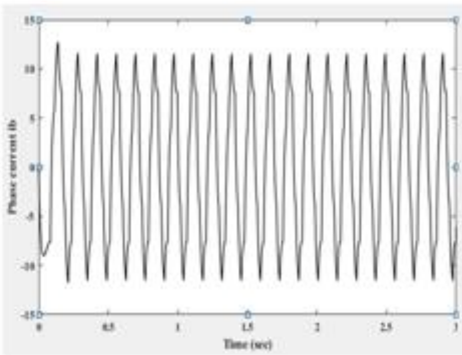

Fig 23: Phase B Current, Tl= 0

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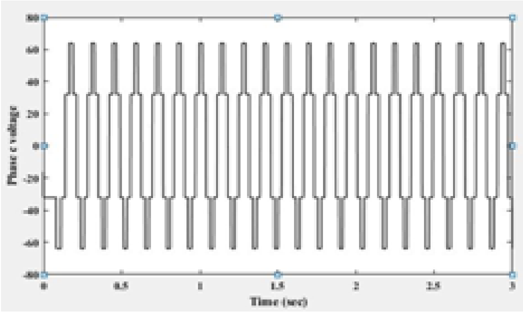

Fig 24: Phase C Voltage, V=96 V Tl= 0

The phase voltage vs time plot of three different phase voltages of the open-loop representation of BLDC motor drive for 180-degree mode is shown in fig.20, fig.22 and fig.24 respectively. The phase voltage is a six stepped waveform for a two-level 180-degree mode VSI. Similarly, fig. 21, fig.23, fig.25 represents all the three phase currents for the motor drive respectively. It is being observed that here also due to the presence on load the current waveforms are not pure sinusoid.

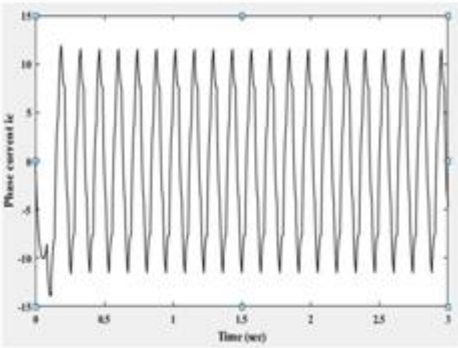

Fig 25: Phase C Current, Tl= 0

The change in speed with time because the load torque (ll) can be seen from fig.26. As can be seen that between 1.5 to 2.0 seconds the load torque is 8 N-m so that the speed drops significantly from 50 rad/sec to 30 rad/sec and then again at 2 seconds the motion is restored to 50 rad/sec as the Tl is reduced to zero from 2 seconds onward

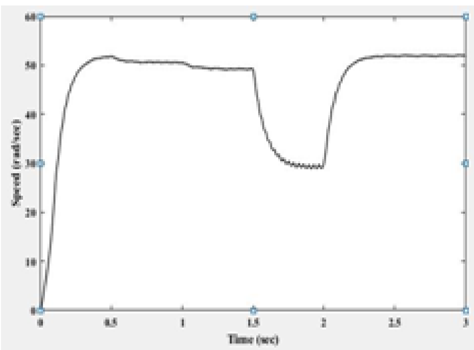

Fig 26: Speed Vs Time, When V_{dc}=100 V, with T_l Changing, 120-degree mode

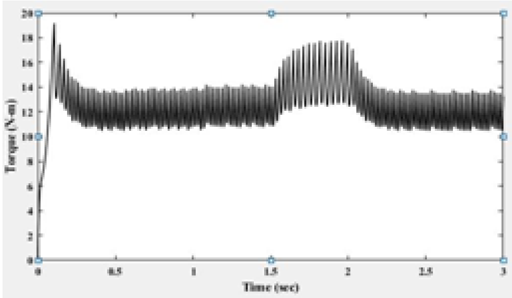

Fig 27: ElectromagneticTorque Vs Time. When V_{dc}=100 V, with T_l changing, 120-degree mode.

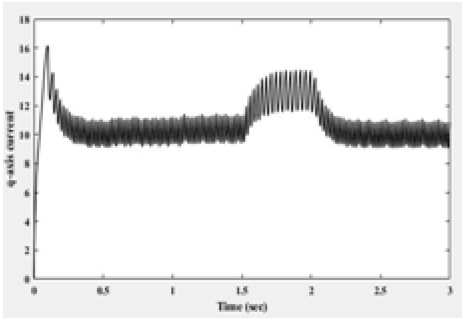

Fig 28: q-axis current vs time response of a BLDC motor drive for V_{dc}= 100 V, with changing T_l, 120-degree mode

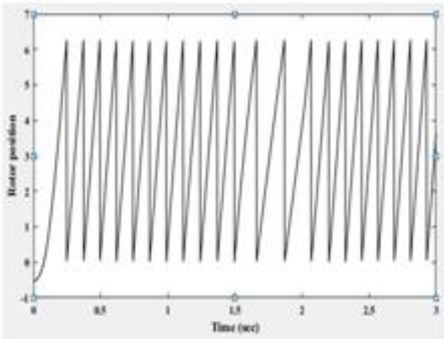

Fig 29:Rotor Position vs Time response for BLDC Drive for V_{dc}=100 V, with changing T_l, 120-degree mode

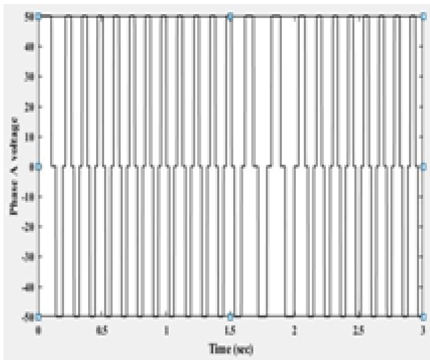

Fig 30: Phase A Voltage, V=100V with changing T_l, 120-degree mode

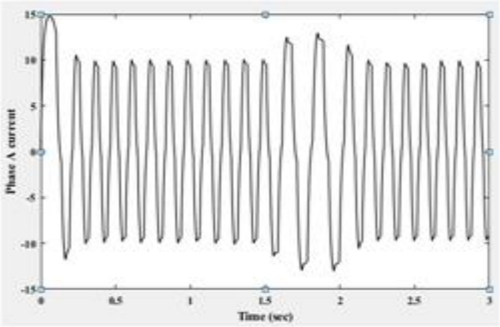

Fig 31: Phase A Current with with changing T_l, 120-degree mode

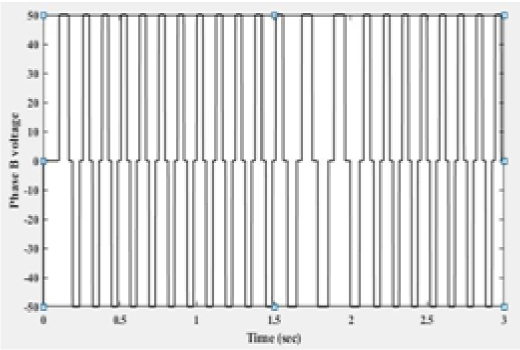

Fig 32: Phase B Voltage, V=100V with with changing T_l, 120-degree mode

It can be observed from fig. 27 that when the machine starts the electromagnetic torque (Te) is at its peak but soon it starts to decrease and settles 12 N-m to 14 N-m with some ripples but as soon as the load is applied, we can see the changes in the Te. Mainly the Te increases from 1.5 second and settles again with some ripples from 2 second onwards, this is because of the Tl= 8 N-m from 1.5 seconds to 2 seconds. As the torque is directly relative to the quadrature-axis current, both the plots i.e. fig.28 and fig.28 are showing similar type of waveform.

The response of rotor position vs time is shown in fig. 29. It can be noticed that it starts from a negative point as the angle assumed initially is negative (-300) but it goes up to positive maximum point due to change of position of switching sequence of voltage source inverter (VSI). It can also be noticed in the above fig. that the effect of high load torque can be observed in the behavior of rotor position which is observed from 1.5 seconds to 2 seconds.

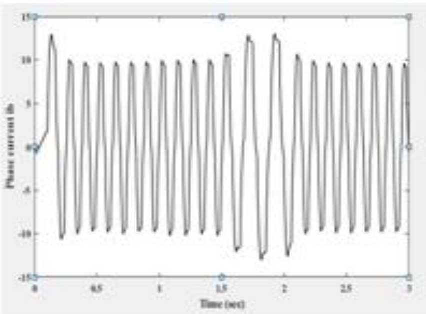

Fig 33: Phase B Current with changing T_l, 120-degree mode

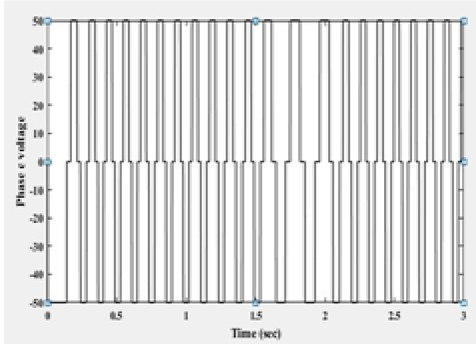

Fig 34: Phase C Voltage, V=100V with changing T_l, 120-degree mode

The phase voltage vs time plot of three different phase voltages of the open-loop model of BLDC motor drive is shown in fig.30, fig.32 and fig.34 respectively. The phase voltage response has stepped waveform for a two-level 120-degree mode VSI. It should be noted that with the application of high magnitude load torque during 1.5 to 2 second there is a significant change in the phase voltages. Similarly, fig. 31, fig.33, fig.35 shows all the three phase currents plot for the open-loop model of the motor. It is observed that the current waveforms are not pure sinusoid due to the motor load and also it is pertinent to observe that the phase currents increase drastically during the period of 0.5 seconds which is between 1.5 to 2.0 second which is also a period of high load torque application.

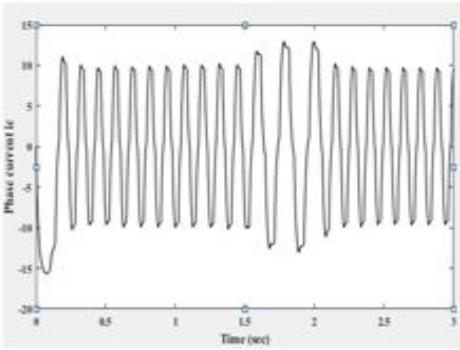

Fig 35: Phase C Current with changing T_l, 120-degree mode

V. CONCLUSION

This manuscript focuses on a comparative performance analysis between no-load and load condition of an open-loop representation of a Brushless DC Motor drive-by programming in MATLAB based software. The different block of the open-loop model of BLDC motor has been also discussed. The model is developed for a trapezoidal back EMF-based BLDC motor and so the motor is provided by a three-phase 120 degree mode VSI. This paper shows all the possible different parameter responses of an open-loop representation of the BLDC motor drive for both load and no-load operating conditions and these responses are speed response, position of the rotor, produced torque, phase voltages and currents,

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d-q axis currents. The DC input voltage to the inverter can be varied to enhance the speed control of BLDC motor in open-loop condition which is exactly same as separately excited conventional DC motor speed control by the armature voltage control. Further some other parameter optimastion may be done to acquire remarkable speed and torque response for both the conditions. This paper enriches the concept of the behaviour of different components of a BLDC motor in an open-loop load and no-load condition.

APPENDIX

The parameters considered for the study and analysis performed in this paper on the Brushless DC motor (BLDC) are mentioned below:

Poles (P) = 4, Stator resistance (Rs) = 3.199 Ω, Direct–axis inductance (Ld) = 0.0531 H, Quadrature – axis inductance (Lq) = 0.041 H, Rotor permanent flux linkage referred to stator = 0.418 Wb – turns, motor inertia (J) = 0.0609 kg-m^2.

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