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Design Guidelines for Nonlinear Vector Control of Permanent Magnet Brushless DC Motor

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Abstract: ***Brushless DC motor drives are fast becoming an attractive alternative to DC and Induction motor drives, especially in the low speed, high power range. Different types of control schemes have been suggested for variable speed AC drives nourished from static power sources. A difficulty of the Field oriented control scheme when applied to induction motor drives is that the motor always operates at a lagging power factor. In this work, a generalized design strategy is suggested for the speed control loop of BLDC motor drive, in which, its intrinsic flexibility to generate the same torque for different combinations of currents is exploited, that can attain more general types of control. A suitable nonlinear and a robust controller using H-∞ makes the drive with a better dynamic performance for a step change in speed corresponding to an incremental and decrementfrequency at a constant torque and a step change in torque at constant speeds corresponding to a particular frequency. This paper gives more information regarding the design aspects of BLDC motor and simulation for closed loop system. The BLDC motor is extensively simulated using MATLAB software.***

Keywords: Brushless DC Motor; Feedback Linearization Technique, Pole Placement Technique; Field Oriented Control; Internal power factor angle control; Torque angle control

1. Introduction

PM synchronous machines having trapezoidal induced emfs are known as Brushless DC machines. The major reason for the popularity of these machines over their counterparts is control simplicity. In contrast to the PMSM which requires continuous and instantaneous absolute rotor position [1], the PMBLDCM position feedback requirement is much simpler. It requires only 6 discrete absolute positions for a 3-phase machine, resulting in the major cost saving in the feedback sensor. Further the control involves significant vector operations in the PMSM drive where as such operations are not required for operation of BLDCM drive.

The flux distribution in a PMBLDCM is trapezoidal and the voltage equations apart from the usual voltage drops across resistances and inductances, there are induced emfs, which are the functions of θ_r and have the same shape as e_a^s, e_b^s, and e_c^s[2] with a maximum magnitude of ±1 which is shown in Fig.5. The emfs are the resultant of the flux linkage derivatives and the flux linkages are continuous functions. It is significant to observe that the phase voltage equation is identical to the armature voltage equation of a DC machine [3]. Hence, the name of this machine is BLDC machine. The control scheme for BLDC motor is simple and the nonlinear motor is initially linearized by a suitable feedback linearization technique [4], [8], [9] and then the control aspects are applied for the robust dynamic performance of the system. The rotor speed is compared to its reference, and the error is amplified through a speed controller(PI), which provides the reference torque T_{estar} that in fact generates the reference currents [5].

The developed electrical torque is a function of the states i.e., the stator and rotor currents of the PMSM. Since this function is nonlinear, there are many possible values of these currents for the generation of the same torque. Thus, there is a great deal of flexibility in the choice of the reference values for these currents.

With a permanent magnet on the rotor, the motor has a constant flux linkage, Ψ. Three sets of formulae for the reference currents are derived-one with specified δ, second with specified ψ and the third with field oriented (FO) case[7]. The dynamic performance of the drive could be improved by varying the torque angle δ within a particular range.

The control system is designed around the concept of two loop control. The outer speed control loop generates a torque reference using a suitable controller. A given torque may be realized by arbitrary selection of torque angle and internal power factor angle of the motor. These angles can be suitably chosen to achieve various control strategies such as field oriented control. With these specifications, unique values of current references are generated. The speed and position signals are measured using a digital shaft encoder and the current signals are measured via Hall Effect sensors.

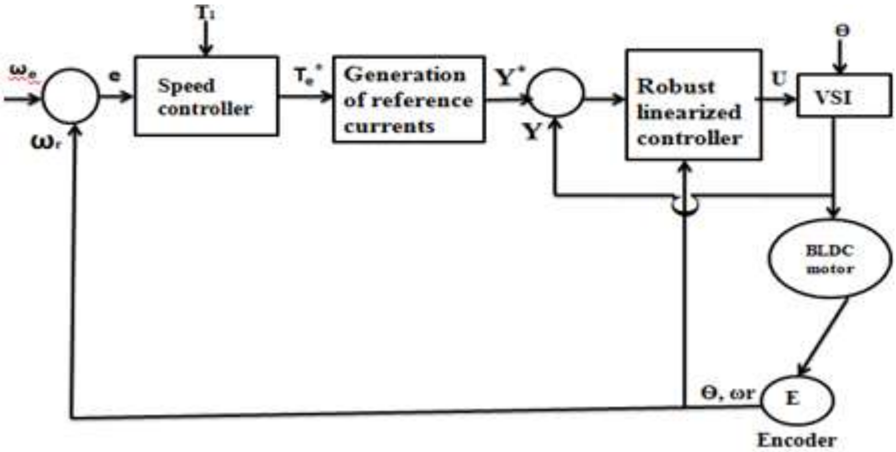

Figure 1: Block diagram representation of proposed control scheme

2. Modeling of PMBLDCM

The design of the control system for a highperformance drive requires a mathematical model of the motor [10], [11]. This is usually derived from the physical principles. Then, the parameters of the motor are determined through off-line testing or estimated on-line from the input/output operating records. The model of BLDC has been developed on the rotor reference frame using the following assumptions:

- Saturation is neglected.
- Space harmonics in the air gap are neglected.
- The induced e.m.f. is trapezoidal.
- Eddy current and hysteresis losses are negligible.

The voltage equations of BLDC in rotor reference frame are

$$v_q^s = r_s i_q^s + l_q^s p i_q^s + l_q^a p i_q^r + \omega_r l_d^s i_d^s + \omega_r l_d^a i_d^r + \omega_r \psi + e_q^s \quad (1)$$

$$v_d^s = r_s i_d^s + l_d^s p i_d^s + l_d^a p i_d^r - \omega_r l_q^s i_q^s - \omega_r l_q^a i_q^r + e_d^s \quad (2)$$

$$v_q^r = r_q^r i_q^r + l_q^r p i_q^r + l_q^a p i_q^s \quad (3)$$

$$v_d^r = r_d^r i_d^r + l_d^r p i_d^r + l_d^a p i_d^s \quad (4)$$

Where $\Psi = l_d^a i_f^r$, which is air gap flux linkage. The eq.(1) can be written as

$$v_q^{\ s} = (v_q^s - \omega_r \psi - e_q^s) = r_s i_q^s + l_q^s p i_q^s + l_a^{\ q} p i_q^r + \omega_r l_d^s i_d^s + \omega_r l_d^a i_d^r \quad (5)$$

The electric torque developed is

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(l_d^a - l_q^a\right) i_q^s i_d^s + l_d^a i_q^s i_d^r - l_q^a i_q^r i_d^s + \psi i_q^s\right] \quad (6)$$

3. Design of Speed Controller

In the conventional two loop structure as shown in Fig.1, a proportional plus integral controller is used as a speed controller in the outer loop. The output of the PI controller is reference torque T_e, from which the reference currents, i_q^{s*} and i_d^{s*} can be generated. The design of gain constants of this controller is

$$k_i = \frac{J}{2}\omega_n^2 \quad (7)$$

$$k_p = J\zeta\omega_n - \frac{\beta}{2} \quad (8)$$

Assuming the proper values of ζ and ω_n and using the values of J and β, the numerical value of k_p and k_i can be computed.

4. Determination of Reference Currents

The developed electrical torque in eq.(6) is a function of the states i.e., the stator and rotor (field and damper) currents of the BLDC. Since this function is a non-linear, there are many possible values of these currents for the generation of same torque. Thus, there is a great deal of flexibility in the choice of the reference values for these currents. The following three conditions are imposed to obtain unique solutions for these reference currents

a) The arbitrary setting of internal angle, ψ
b) The arbitrary setting of torque angle, δ
c) All the reference currents should be real valued.

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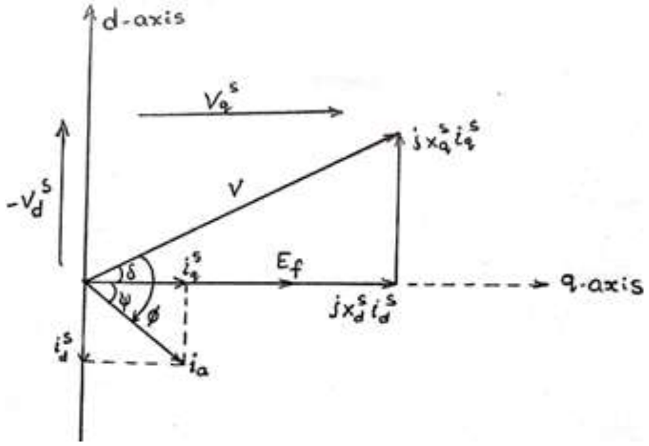

Figure 2: Phasor diagram

The phasor diagram of a BLDC is as shown in Fig.2

$$\tan\delta = \frac{-v_d^s}{v_q^s} \tag{9}$$

Substituting v_q^s and v_d^s values in eq.(10)

$$\tan\delta = \frac{-\left(r_s i_d^s + l_d^s p i_d^s + l_d^a p i_d^r - \omega_r l_q^s i_q^s - \omega_r l_q^a i_q^r + e_d^s\right)}{r_s i_q^s + l_q^s p i_q^s + l_q^a p i_q^r + \omega_r l_d^s i_d^s + \omega_r l_d^a i_d^r + \omega_r \psi + e_q^s} \tag{10}$$

Under steady state conditions the above equation can be written as

$$\tan\delta = \frac{-\left(r_s i_d^s - \omega_r l_q^s i_q^s + e_d^s\right)}{r_s i_q^s + \omega_r l_d^s i_d^s + \omega_r \Psi + e_q^s} \tag{11}$$

$$\tan\psi = \frac{i_d^s}{i_q^s} \tag{12}$$

From eq.(11)

$$\left(r_s \tan\delta - \omega_r l_q^s\right) i_q^s = i_d^s(-\omega_r l_d^s \tan\delta - r_s) - (\omega_r \Psi + e_q^s)\tan\delta - e_d^s \tag{13}$$

$$T_e = 3\left[\left(l_a{}^d - l_a{}^q\right) i_d^s i_q^s + \Psi i_q^s\right] \tag{14}$$

$$i_q^s = \frac{T_e}{3\left[\left(l_a{}^d - l_a{}^q\right) i_d^s + \Psi\right]} \tag{15}$$

$$i_{dstar} = \frac{-q_2 \pm \sqrt{q_2^2 - 4q_1 q_3}}{2q_1} \tag{16}$$

$$q_1 = 3\left(l_a{}^d - l_a{}^q\right)\left(-r_s - \omega_r l_d^s \tan\delta\right)$$
$$q_2 = -3\left(l_a{}^d - l_a{}^q\right)\left(e_d{}^s + \omega_r \Psi + e_q{}^s\right)\tan\delta + 3\psi(-r_s - \omega_r l_d^s \tan\delta)$$
$$q_3 = -3\Psi e_d{}^s - 3\Psi^2 \omega_r \tan\delta - 3e_q^s \Psi \tan\delta - (r_s \tan\delta - \omega_r l_q^s) T_e^* \tag{17}$$

With a permanent magnet on the rotor, the motor has a constant flux linkage, Ψ. Three sets of formulae for the reference currents are derived- one with specified δ,second with specified ψ and the third for field oriented (FO) case [8].

5. Robust Linearized Feedback Controller

For the regulator model of given multivariable system, the linear feedback control law [6] is applied with a gain matrix of K. In addition, to have complete control over the system dynamics a pole placement technique is used. In this, the poles or eigen values of closed loop system are placed at the desired locations in negative half of the s-plane. Now partitioning K into K_{bs} and K_{is}, multiplied with the regulator model, the control signal 'u' in terms of state vector and integral of the differences of output and reference vectors is given as

$$\dot{u} = Kz = \left[K_{bs} \quad K_{is}\right] \begin{bmatrix} \dot{x} \\ y - y_r \end{bmatrix} \tag{18}$$

Integrating and simplifying, the control law comes out as

$$u = K_{bs} x + K_{is} \int_0^t (y - y_r) dt \tag{19}$$

From the above equation, it is concluded that the integral of output error (IOE) feedback makes the controller as robust from the modeling imperfections and step like disturbances.

6. Guideline Strategies

The design methodology for the PMBLDCM as outlined through the various voltage, current and torque equations allows one to choose ψ or δ or both of them independently in order to meet a certain control objective such as unity power factor, field orientation and flux weakening operations [9].

Conventional synchronous motor in general, is a doubly excited machine. Its armature winding is energized from an inverter and its field winding from a DC source. When the synchronous motor is working at constant applied voltage, then the resultant air gap flux which is demanded by constant terminal voltage remains substantially constant. This resultant airgap flux is established by the cooperation of both AC in the armature winding and DC in the field winding. If the field current is sufficient enough to set up the airgap flux, as demanded by constant applied voltage the magnetizing current or lagging reactive volt amp required from the AC source is zero and therefore the motor operates at unity power factor. This field current, which cause unity power factor operation of the synchronous motor is called normal excitation or normal field current.

If the field excitation, E_f is made less than the normal excitation i.e., the motor is under excited, then the deficiency in the flux (constant air gap flux-flux set up by DC in the field winding) must be made by the armature winding. In order to do the needful, the armature winding draws a magnetizing current or lagging reactive volt amp from the AC source and as a result of it, the motor operates at a lagging power factor. In case the field is made more than its normal excitation, i.e, the motor is over excited then the excess flux (flux set up by the DC in the field winding-resultant airgap flux) must be neutralized by the armature winding. The armature can do so only if it draws demagnetizing component from the AC source. Since in a motor the magnetizing current lags the applied voltage by

90^o, the demagnetizing component of current must lead the applied voltage by 90^o. In view of this, the excess flux can be counter balanced only if the armature takes a demagnetizing current or leading reactive volt amp from the AC source, then consequently the PMBLDCM operates at a leading power factor.

In the present work PMBLDCM is taken up as a case study. The ratings of the machine as well as the values of the parameters are given in the appendix.

The design guidelines for different values of δ[8] and T_{estar}, and for different values of T_{estar} and ψ are considered by computing the reference values of currents i_{qstar}, i_{dstar}. Then the phase $i_a = \sqrt{(i_{qstar})^2 + (i_{dstar})^2}$ .These characteristics predict and give us the good guidelines for different power factors starting from lagging to leading values and also give us a clear picture of $\delta > 90^0$for flux weakening operation as a rotor is a permanent magnet, also the field oriented case which has definite lagging power factor is also been justified by design guidelines.

7. Results and Discussions

Noting that the mutual flux linkage (λ_m) of PMBLDCM is the resultant of rotor flux linkages and stator flux linkages

$$\lambda_m = \sqrt{(\lambda_{af} + L_d i_{ds}^r)^2 + (L_q i_{qs}^r)^2} \quad (20)$$

Also

$$T_e = \frac{3}{2}\frac{P}{2}\left[(l_d^s - l_q^s)\left(\frac{1}{2}\right) i_a^2 \sin 2\delta + \lambda_{af} i_a \sin\delta\right] \quad (21)$$

For $\delta = 0^0$, i_{dstar} goes negative which makes λ_m to decrease in eq.(16) and keeping phase current i_a positive which is totally governed by i_{qstar}. For $\delta = 90^0$, for a PMBLDCM as flux is constant, the torque is controlled by the stator current component i_{qstar}, giving an operation very much similar to that of armature controlled separately excited DC motor. For $\delta > 90^0$, i_{dstar} becomes negative as shown in Fig.3.b, hence the resultant mutual flux linkage decreases. This is the key to flux weakening in the PMBLDC motor drive.

For the values of negative δ (ie., from -13^o to $0^o$from Fig. 3.d) with respect to the rotor or mutual flux linkages the machine works like a generator. It is seen from Fig. 3.d. for δ varying from 0^0 to 10.5^0 the machine is motoring with lagging power factor and UPF occurs at $\delta = 10.5^0$.

For $10.5^0 < \delta < 70^0$ the machine will work at leading power factor. From Fig 3.d, the second unity power factor at occurs at $\delta = 70^0$ and hence $\psi = 70^0$. For $\delta > 70^0$ the cycle repeats as depicted in Fig 3.d. Also, interestingly from Fig.3.d it is observed that CD of ψ versusϕ plot is the counter part of AB of δ versus ϕ plot. Similarly, CF of ψ versus ϕ plot is the counter part of AE of δ versus ϕ plot.

From Fig 3.b and 3.c, it is observed that i_a is totally governed by i_{qstar}, the torque component of stator currentfrom $\delta = -13^0$ to 0^0also from Fig 3.a at $\psi = 0^0$ it is found that $\phi = 9^0$the corresponding value of i_{dstar} from Fig 3.b is 0^0 which is nothing but FOC and power factor is found to be lagging. Therefore from Fig 3.c i_a is totally governed by i_{qstar} from minimum value of δ to 0^0, for which the motor is found to be working from leading to lagging through unity power factors, beyond which i_a is governed by i_{dstar} till 90^0 for which the motor is found to be working with only lagging power factors.

From Fig 3.dfor the values of negative δ (ie., from -13^o to 0^o from Fig. 3.d) with respect to the rotor or mutual flux linkages the machine works like a generator. It is seen from Fig. 3.d. for δ varying from 0^0 to 10.5^0 the machine is motoring with lagging power factor and UPF occurs at $\delta = 0^0$. For $10.5^0 < \delta < 70^0$, the machine will work at leading power factor.

From Fig 4.b for lower values of ψ (from -68^0 to 47^0) armature phase current is governed by torque component i_q^s of the stator current. For $\psi = 0^0$, $i_{dstar} = 0$ which is the special case of the machine (field oriented control FOC) and works always at lagging power factor which is clearly depicted from the Fig 4.d. For the values of ψ from 47^0 to tending to 90^0 the armature phase current is governed by flux component i_{dstar} of the stator current which is clear from the Fig 4.c.

From Fig 4.d it is observed that for the values of ψ from -68^0 to -64.5^0 the machine works at lagging power factor. At $\psi = -64.5^0$ the machine operates at unity power factor. For the values of ψ from -64.5^0 to -10.5^0 the machine works at leading power factor. At $\psi = -10.5^0$again the machine operates at unity power factor. For the values of ψ from -10.5^0 to tending to 90^0 again the machine operates at lagging power factor and hence the cycle repeats. Also, interestingly from Fig. 4.d, it is observed that IJ of ψ versusϕ plot is the counter part of GH of δ versus ϕ plot. Similarly, IL of ψ versus ϕ plot is the counter part of GK of δ versus ϕ plot.

The simulation results of the nonlinear controller to SPWM fed PMBLDC motor are shown in Fig.6.i_q^s, i_d^s of stator currents and i_q^r, i_d^r of damper winding and speed versus time is shown in Fig 6.a, 6.b, 6.c, 6.d respectively, corresponding to a frequency of 40 Hz and T_L = 5 N-m.All these characteristics by design guidelines are been verified through the extensive simulation by MATLAB.

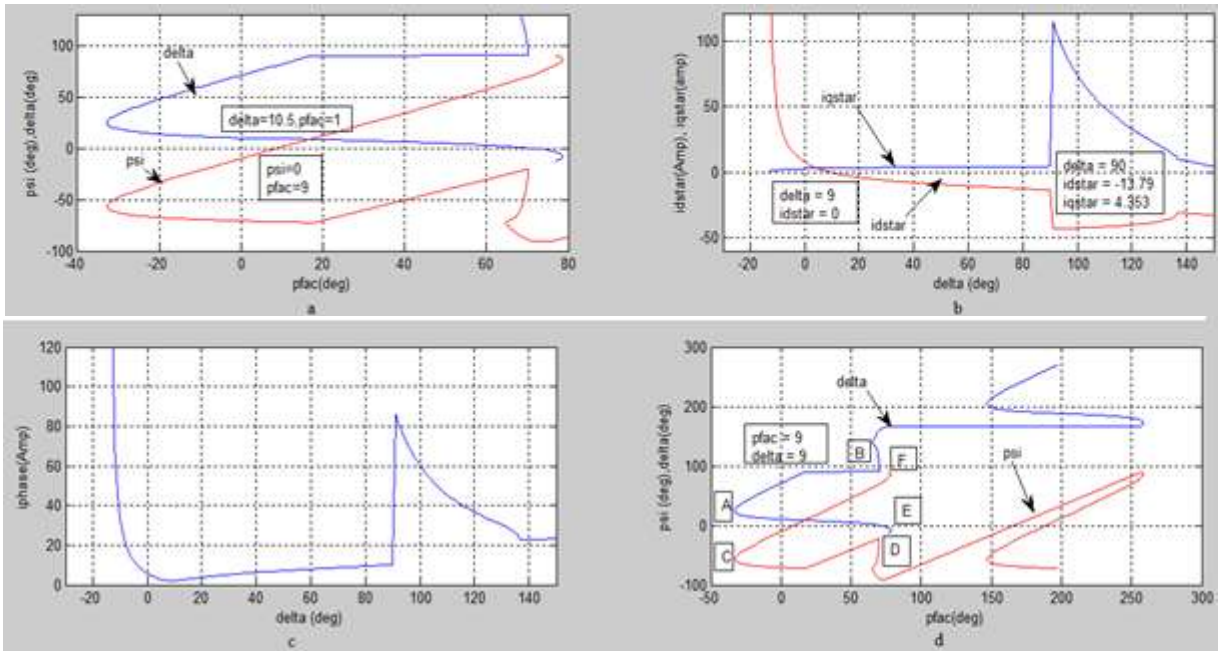

Figure 3: Guideline Strategies of PMBLDCM with torque angle δ variation

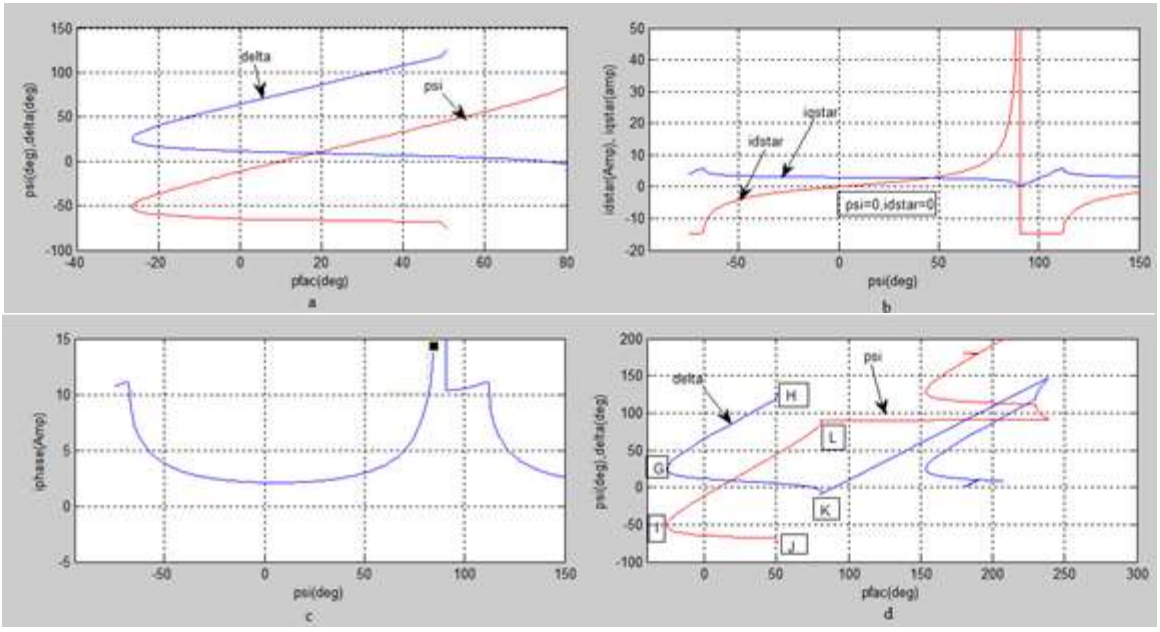

Figure 4: Guideline Strategies of PMBLDCM with internal power factor angle ψ variation

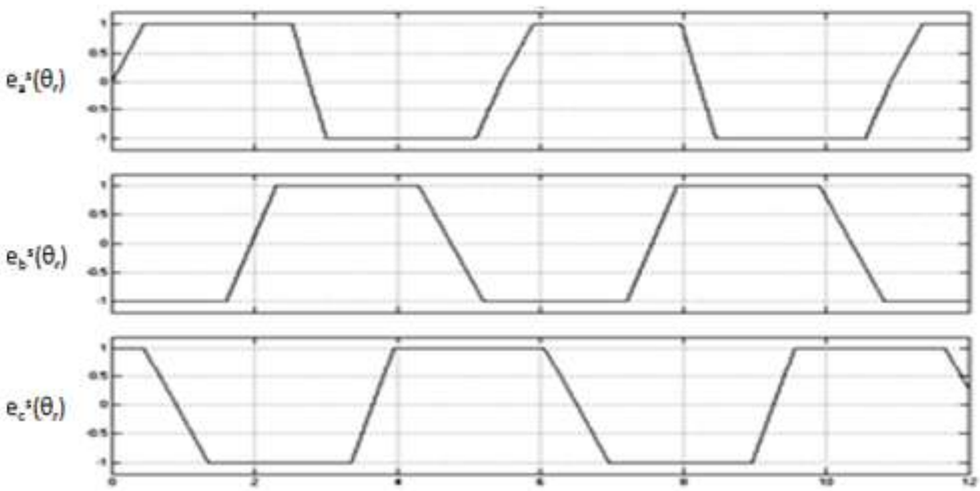

Figure 5: Trapezoidal Induced Emfs of Brushless DC Motor

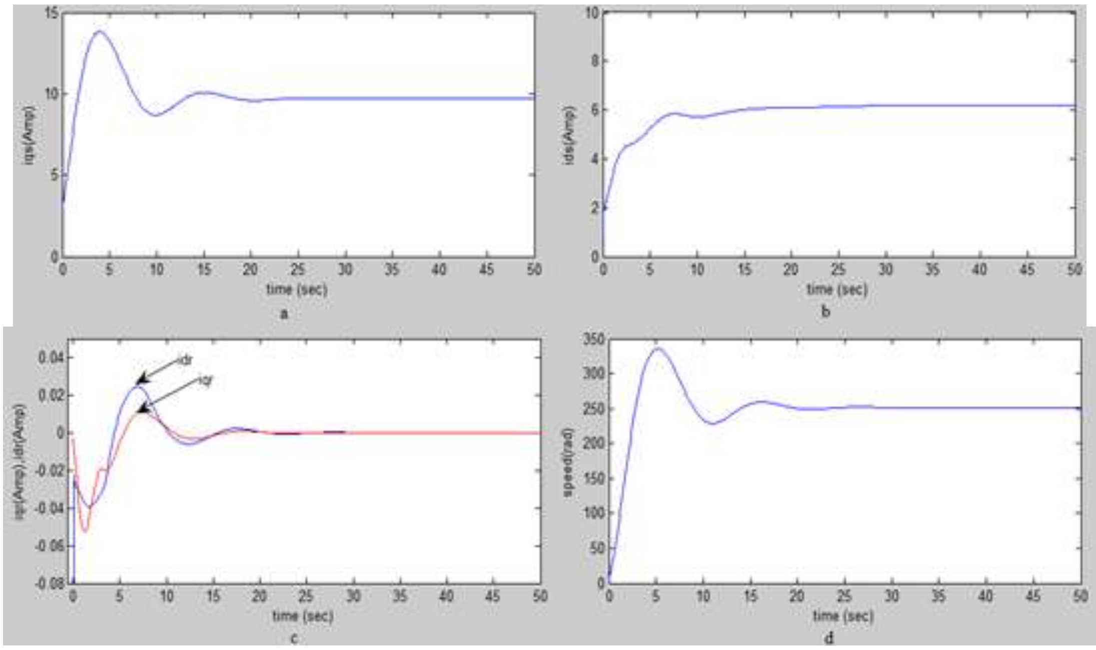

Figure 6: Closed loop system Simulation Results of Step change in speed corresponding to a frequency of 40 Hz at constant Torque of the proposed Nonlinear Controller

8. Conclusion

In this paper a generalized approach to the design for the torque angle control of a non-linear vector controller of BLDC has been presented. It is found that, by the variation of torque angle (δ) there is a wide range of dynamic performance. This also gives rise to the flexibility of choosing the power factor from lagging to leading (or vice versa) through unity. The special case of Field orientation control which is obtained from a different perspective, by choosing torque angle (δ) such that the internal power factor angle (ψ) made to be zero. This result incomplete decoupling between the armature and field flux, allowing them to be controlled independently, like a DC motor, improving the dynamic performance of the system.

Appendix

Machine Ratings and Parameters of Permanent Magnet Brushless DC Motor (PMBLDCM):

Ratings of Permanent Magnet Brushless DC Motor: Rated Voltage = 400V, Rated Current = 2.17A, Rated Speed = 1500rpm, No. of poles = 4, Rated power: 1.2/1.5 KW, 0.8/1.0 p.f, J = 0.048 Kg.m^2, β = 0.0048N.m/rad/sec.

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