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Nonlinear Control of SPWM Inverter Fed BLDC Motor Using Robust H Controller

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ABSTRACT
Brushless DC motorsare enhancing an enticing alternative to DC due to their admirable controllability and high efficiency. These motors also have power saving advantages relative to the other types of motors. Various types of control strategies have been illustrated for variable speed AC drives. When those control strategies are applied to the proposed drive, there are certain drawbacks like uncertainty, sensitive to parametric variations etc. The linear control theory is applicable for linear models only. So in this paper nonlinear controller using feedback linearization technique is suggested to transform a nonlinear model into a linear one. Along with this in order to increase the degree of stability and robustness of the system,H_∞controller is suggested. The BLDC motor is extensively simulated using MATLAB software for incremental/decremental changes in i) speed corresponding to different frequencies at a constant torque and ii) torque at a constant speed.

Keywords-Brushless DC Motor; Feedback Linearization Technique; Robust control.

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I. INTRODUCTION

A Brushless DC (BLDC) motor resembles like a DC motor according to the modeling aspect. It consists of a rotor in the form of a permanent magnet and stator in the form of poly phase armature windings. These motors have better speed versus torque characteristics, high efficiency, better dynamic response, long operating life due to lack of electrical and friction losses, noiseless operation even at high speed ranges. It produces less heat and less bearing stress because no winding is on rotor.

The working principle of a BLDC motor is same as that of brushed DC motor in view of internal shaft position feedback. In case of brushed DC motors the feedback is implemented using a mechanical commutator and brushes whereas in BLDC motor it is accomplished through multiple feedback sensors.Due to the elimination of slip rings the complexity is reduced.

As the flux distribution in a Brushless DC Motor (BLDCM) is trapezoidal, the voltage equations apart from the usual voltage drops, there are trapezoidal induced emfse_a^s, e_b^s, and e_c^s, which are the functions of θ_r [1]. It is significant to observe that from the mathematical modeling equations which are described below, the phase voltage equation is identical to the armature voltage equation of a DC machine [2]. Hence, this motor is named as BLDC motor. The control strategy for BLDC motor is elementary and the nonlinearity of the motor is initially linearized by using feedback linearization technique. Once the model is linearized, then the control aspects are enforced to getthe better dynamic performance of the system. The rotor speed is compared with reference speed and the error is given to a speed controller (PI), which produces the reference torque T_{estar} that leads to generate the reference currents.

The control system is designed using the concept of two loop control [3]. A given torque may be achieved by arbitrary selection of δ (torque angle) and ψ(internal power factor) of the motor. These angles can be suitably chosen to attain various control strategies like field oriented control etc. using the design guidelines. The speed and position signals of the motor are measured using a digital shaft encoder [4] and the current signals are measured through Hall Effect sensors. The block diagram is as shown below in Fig.1.

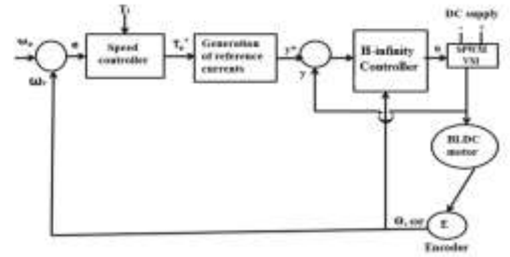

Fig.1. Block Diagram Representation of Proposed Control Scheme

II. MATHEMATICAL MODELING

The design of the control system requires mathematical model of the motor to attain admirableperformance of the drive. The model of BLDC has been developed on the rotor reference frame byneglecting the saturation, space harmonics and hysteresis and eddy current losses [5], [6].

The voltage equations of BLDC in rotor reference frame are,

$$v_q^{s*} = r_s i_q^s + l_q^s p i_q^s + l_q^a p i_q^r + \omega_r l_d^s i_d^s + \omega_r l_d^a i_d^r + \omega_r \psi + e_q^s$$
(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 $\Psi = l_d^a i_f^r$, air gap flux linkage.

The eq.(1) and (2) can be written as

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

$$v_d^s = v_d^{s*} - e_d^s = r_s i_d^s + l_d^s p i_d^s + l_d^a p i_d^r - \omega_r l_q^s i_q^s - \omega_r l_q^a i_q^r$$
(6)

The developed electric torque is

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(l_d^a - l_q^a\right) i_q^s i_d^s + l_d^a i_q^s i_d^r - l_q^a i_q^r i_d^s + \psi i_q^s\right]$$
(7)

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

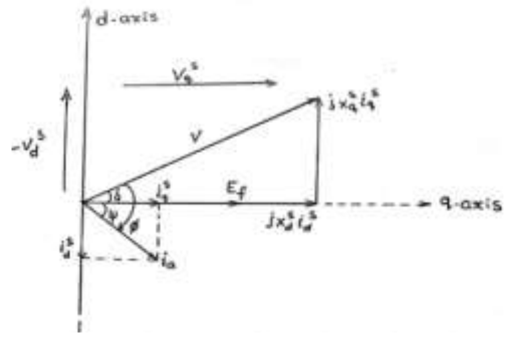

Fig.2. Phasor Diagram of a BLDC motor

$$\tan\delta = \frac{-v_d^s}{v_q^s}$$
(8)

Under steady state conditions,using v_d^s and v_q^s the above equation can be written as

$$\tan\delta = \frac{-\left(r_s i_d^s - \omega_r l_q^s i_q^s + e_d^s\right)}{r_s i_q^s + \omega_r l_d^s i_d^s + \omega_r \Psi + e_q^s}$$
(9)

$$\tan\psi = \frac{i_d^s}{i_q^s} \quad (10)$$

Also

$$T_e = 3\left[\left(l_a^d - l_a^q\right) i_d^s i_q^s + \Psi i_q^s\right]$$
(11)

By combining all the equations we get,

$$i_{qstar} = \frac{T_e}{3\left[\left(l_a^d - l_a^q\right) i_{dstar}^s + \Psi\right]} \quad (12)$$

$$i_{dstar} = \frac{-q_2 \pm \sqrt{q_2^2 - 4 q_1 q_3}}{2 q_1}$$
(13)

$$q_1 = 3\left(l_a^d - l_a^q\right)\left(-r_s - \omega_r l_d^s \tan\delta\right)$$

$$q_2 = -3\left(l_a^d - l_a^q\right)\left(e_d^s + \omega_r \Psi + e_q^s\right)\tan\delta + 3\psi\left(-r_s - \omega_r l_d^s \tan\delta\right)$$

$$q_3 = -3\Psi e_d^s - 3\Psi^2 \omega_r \tan\delta - 3 e_q^s \Psi \tan\delta - \left(r_s \tan\delta - \omega_r l_q^s\right) T_{estar}$$
(14)

With permanent magnet rotor, the motor has a constant flux linkage, Ψ.There are three sets of formulae to derive the reference currents, one is with stipulatedtorque angle δ [7], second is with stipulatedinternal power factor angle, ψ and the third is withBlaschkefield oriented (FO)case. By varying δ or ψ within a particular range the dynamic performance of the drive can be improved. Here the results are discussed only for variation of δ.

III. FEEDBACK LINEARIZATION TECHNIQUE

It is observed that from the mathematical modeling of BLDC motor, the system matrices are functions of ω_r which varies with the operating point thus makes the system model non-linear. To design a control system, the standard techniques of linear system theory can't be applied directly to a nonlinear system. In order to conquer this problem, feedback linearization technique has been suggested which is used to transform a nonlinear model into linear model[8].

The state equation of the model is expressed as

$$\dot{x} = Ax + Bu \quad (15)$$

Here the system matrix A has a term proportional to ω_r. The matrix A can be subdivided into two terms such as A^1 and A^{11}. Where A^1 is the linear matrix and A^{11} is the nonlinear matrix[9]. As the product of two state variables leads to nonlinearity, it is necessary to go for cancellation of the term A^{11}, which depends on $\omega_r x$. If the input vector is sectioned into two parts u_1 and u_2, such that these are the input control vectors of the nonlinear and linear parts of the system matrix respectively.

Let $u_1 = \omega_r k_1 x$, where k_1 is the feedback gain matrix.

$$\dot{x} = (A^1 + \omega_r A^{11})x + B(u_1 + u_2) \quad (16)$$

$$\dot{x} = A^1 x + Bu_2 + \omega_r (A^{11} + Bk_1)x \quad (17)$$

From the above expression it is observed that in order to get exact cancellation of nonlinear term,

$$A^{11} = -Bk_1 \quad (18)$$

The feedback gain matrix k_1 is suitably selected such that above equation is satisfied.

IV. STATE FEEDBACK CONTROL

In order to have a comprehensive control over the dynamics of the system, pole placement technique is used[10]. If the system is completely state controllable, measurable and are accessible for feedback then pole placement technique can be applied. Pole placement technique is a methodwhich can be employed in feedback control system theory to locate the closed loop poles of a system at desired locations in the negative half of the s-plane. Thus by designing a feedback control system via pole placement method we can choose a controller gain that places the poles on their desired location.

For the regulator model of the multivariable systemthe output variables are coordinated to the set points through state feedback control. The linear feedback control law[11] is applied with a gain matrix of k_2.

Using state feedback control law $u_2 = k_2 x$ (19)

Then the state equation of the closed loop becomes

$$\dot{x} = (A^1 + Bk_2)x \quad (20)$$

Now by separatingk_2 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

$$\dot{u} = k_2 z = \begin{bmatrix} K_{bs} & K_{is} \end{bmatrix} \begin{bmatrix} \dot{x} \\ y - y_r \end{bmatrix} \quad (21)$$

Integrating and simplifying, the control law comes out as

$$u = K_{bs} x + K_{is} \int_0^t (y - y_r) dt \quad (22)$$

The state feedback control law including the integral of output error (IOE) is used in order to achieve zero steady state error with respect to the reference current specification, while at the same time for improving dynamic response.

V. ROBUST CONTROL

In control theory robust control is an approach to controller design that explicitly deals with uncertainty. Robustness is of crucial importance in control system design because real engineering systems are susceptible to external disturbance and noise signals[12]. Robust control methods are designed to function properly provided that uncertain parameters of disturbances. A successfully designed control system should alwaysbe able to maintain stability and performance levels in spite of uncertainties in system dynamics. The difference between the model of the plant and the actual plant is called uncertainty.

System design based on the robust control theory will possess a) Robust stability and b) Robust performance. H infinity (H_∞) control technique[13] is a robust control technique. This technique is used in control theory to synthesize controllers to achieve stabilization with guaranteed performance. H_∞controller design expresses the control problem as a mathematical optimization problem and then finds the controller that solves the optimization. H_∞norm is the maximum singular value of the function over that space. This can be interpreted as a maximum gain in any direction and at any frequency. For SISO systems, this is effectively the maximum magnitude of the frequency response. This technique can be used to minimize the closed loop impact of a perturbation depending on the problem formulation. This impact will either be measured in terms of stabilization or performance.

As the dynamic model of the BLDC motor is nonlinear before going for a controlling technique the system model has to be linearized. So with the use of FLT we can go for H_∞ along with SFC in current loop and PI controller in speed loop to make the system robust. By using a robust controller, a plant can be stabilized and satisfy certain performance levels in the presence of disturbance signals, noise interference and plant parameter variations. The generalized plant diagram for H_∞ controller is shown in Fig. 3.

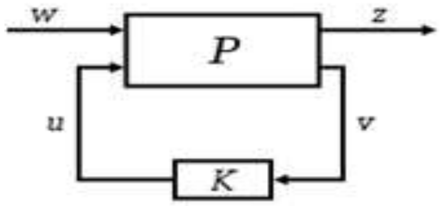

Fig. 3. Generalized Plant diagram for H_∞ controller

The bode diagram of H_∞ norm is shown in Fig. 4.

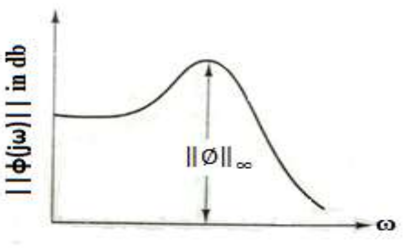

Fig. 4. Bode Diagram of H_∞ norm

The H_∞ norm of a stable system is the largest possible amplification factor of the steady state response to sinusoidal excitation. The term uncertainty refers to the differences or errors between the model of the plant and the actual plant. Uncertain elements in practical systems may be classified as **structured** uncertainty and **unstructured** uncertainty.A structured uncertainty is any parametric variation in the plant dynamics, such as variations in poles and zeros of the plant transfer function.An unstructured uncertainty is the difference acting if the actual plant is nonlinear and its model is linear. The proposed system is unstructured uncertainty as it is made linear.Stability of such a system can be examined by the H_∞ norm.There are three established approaches to solve robust control problems, which are (i) the Riccatti equations, (ii) linear matrix inequality and (iii) structural uncertainties by using μ analysis and μ synthesis approach.The H_∞ norm of $\varphi(s)$ is defined as $\|\phi\|_\infty = \bar{\sigma}[\phi(j\omega)]$. $\bar{\sigma}[\phi(j\omega)]$ means the maximum singular value of $|\phi(j\omega)|$. The singular value of transfer function ϕ is defined as $\sigma_i(\phi) = \sqrt{\lambda_i(\phi * \phi)}$. The value under the square root must be non-negative and real value. The maximum singular value $\|\phi\|_\infty$ is smaller, which indicates the effect of input on the output is smaller.

The transfer function of the system φ(s) is found as

$$\phi(s) = \frac{\omega(s)}{u(s)} = \frac{K_\phi / L_q^s J}{S^2 + S.\dfrac{R_s J + L_q^s \beta}{L_q^s J} + \dfrac{R_s \beta + K_\phi^2}{L_q^s J}}$$

Converting transfer function in s-domain into z-domain

$$\phi(Z) = \frac{\omega(Z)}{u(Z)} = \frac{K_\phi / L_q^s J}{Z^2 + Z.\dfrac{R_s J + L_q^s \beta}{L_q^s J} + \dfrac{R_s \beta + K_\phi^2}{L_q^s J}}$$

For linear matrix inequality, if H_∞ norm is $< \gamma$, then the controller gain k is found that it will make the system stable. At z=1, the value of the transfer function in z-domain is the H_∞ controller gain k.

The simulation results of closed loop speed control of H_∞controller fed BLDC motor for speed corresponding to a frequency of 50 Hz at a constant torque with δ variation for lagging through unity to leading power factors is shown in Fig. 6.

VI. RESULTS AND DISCUSSIONS

Fig. 5 indicates the comparison of the simulation results of closed loop control of BLDC motor at a set value of $\delta=40^0$ resulting to a leading power factor with SFC and H_∞ controller. On observation of all the plots of Fig. 5, it is seen that H_∞ controller is giving better performance in the transient state and the settling time is reduced.

Fig. 6indicates the simulation results of closed loop speed control of H_∞ controller fed BLDC motor for speed corresponding to a frequency of 50 Hz at a constant load torque with δ variation for lagging through unity to leading power factors.From Fig. 6.a and b, it is observed that i_q^s and i_d^s are counteracting to each other. With the variation of δ for lagging power factors, i_{dstar} is having higher value compared to that of leading and unity power factors. At the same time on contrary i_q^s is having more value for unity power factor reducing sequentially to leading and lagging power factors respectively. Fig.6.c and d shows that of damper winding currents i_{qr} and i_{dr}respectively, settling down to zero in a short period of time. Fig. 6.e and f shows that of δ vs time and pfvstime,with reference to the design guidelines (which is elsewhere explained and not taken up here) the values of δ for lagging, leading and unity power factors are verified. Fig. 6.g indicates that the developed torque for all power factors seemed to be same. Similarly, Fig. 6.h indicates the steady state value of speed is same for all power factors at desired speed $\omega_e=2\pi f_r=314.1593$ rad/sec.

Fig. 7 indicates the simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=40^0$ resulting to a leading pf, at a step increase in speed corresponding to a frequency of 30 Hz to 50 Hz at a constant torque. It is seen that the motor do not lose its stability at this operation.

Fig. 8 indicates the simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=40^0$ resulting to a leading pf, at a step decrease in speed corresponding to a frequency of 50 Hz to 30 Hz at a constant torque.

Fig. 9 indicates simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=10^0$ resulting to a lagging pf, at a step increase in torque from 0.5 Nm to 3 Nm corresponding to a constant frequency of 50 Hz.

Fig. 10 indicates simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=10^0$ resulting to a lagging pf, at a step decrease in torque from 3 Nm to 0.5 Nm corresponding to a constant frequency of 50 Hz.

VII. CONCLUSION

A PI controller for speed loop has been designed for BLDC drive by choosing suitable values of ζ and ω_n to improve the dynamics of the system. A nonlinear controller has been designed using feedback linearization technique. The pole placement technique has been adopted such that the system dynamics can be controlled by specifying the closed loop pole locations. H_∞ controller has been designed in addition to the state feed controller which is included in current loop to get the robustness of the system from the parameter imperfections and system dynamics. The control system has been extensively simulated using MATLAB. From the observation of results we can conclude that using H_∞ control techniques the dynamic performance is greatly increased.

Appendix

Machine Ratings and Parameters of Brushless DC Motor (BLDCM):

Ratings of Permanent Magnet Brushless DC Motor: Rated Voltage = 400V, Rated Current = 2.17A, Rated Speed = 1500 rpm, 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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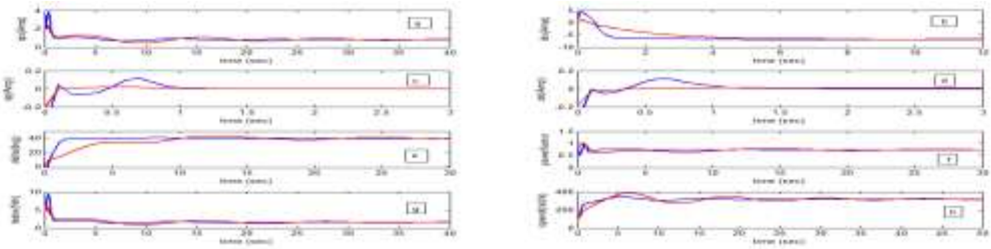

Fig. 5. Comparison of the simulation results of closed loop control of BLDC motor at a set value of $\delta=40^0$ for a leading pf with (i) SFC (red) (ii) H_∞ controller (blue)

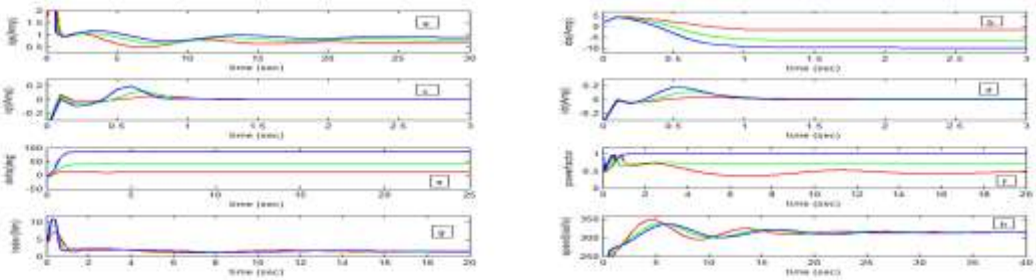

Fig. 6. Simulation results of closed loop Control of H_∞ controller fed BLDC motor for speed corresponding to afrequency of 50 Hzat a constant T_l with δ variationforlagging (red) through unity (blue) to leading power factors (green)

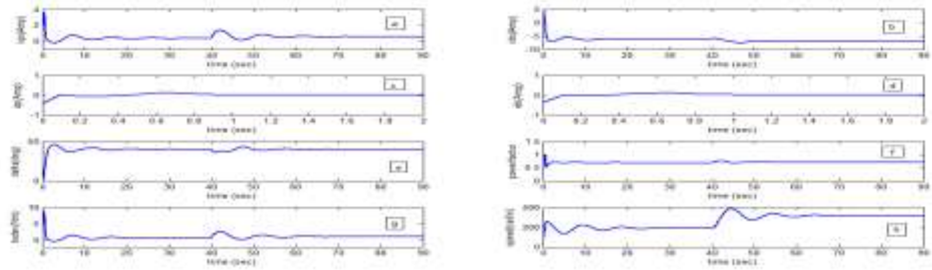

Fig. 7. Simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=40^0$ resulting to a leading pf,=at a step increase in speed corresponding to a frequency of 30 Hz to 50 Hz at a constant torque

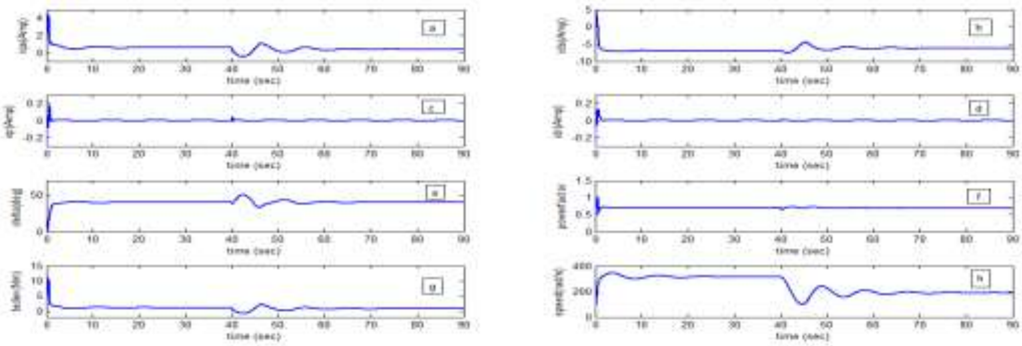

Fig. 8. Simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=40^0$ resulting to a leading pf, at a step decrease in speedcorresponding to a frequency of 50 Hz to 30 Hz at a constant torque

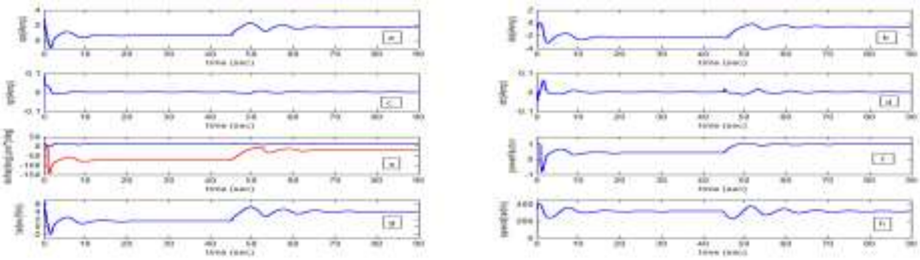

Fig. 9. Simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=10^0$, psi*=calculated value resulting to a lagging pf, at a step increase in torque from 0.5 Nm to 3 Nm corresponding to a constant frequency of 50 Hz

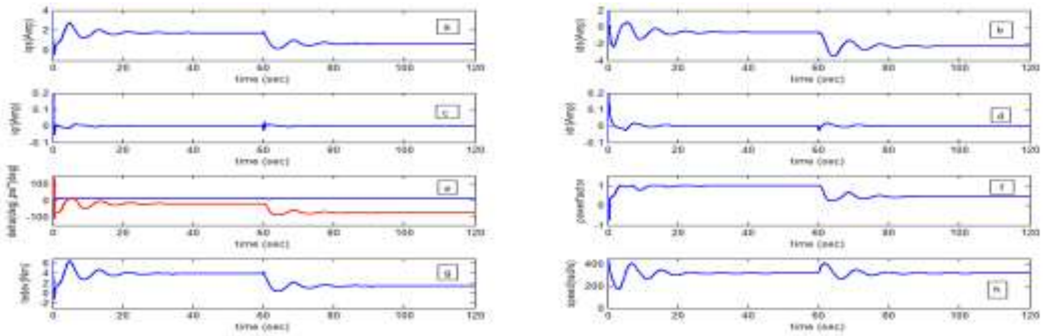

Fig. 10. Simulation results of closed loop H_∞ control of BLDC motor at a set value of $\delta=10^0$, psi*=calculated value resulting to a lagging pf,at a step decrease in torque from 3 Nm to 0.5 Nm corresponding to a constant frequency of 50 Hz

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