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Control Strategy of Buck Converter Driven Dc Motor: a Comparative Assessment

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Abstract: This paper presents the detailed account on the control design for input tracking of a buck converter driven dc motor. Proportional-Integral (PI), Proportional-Integral-type Fuzzy Logic controller (PI-type FLC) and Linear Quadratic Regulator (LQR) are the techniques proposed in this investigation to control the speed of a dc motor. The dynamic system composed from buck-converter/dc motor is considered in this investigation and derived in the state-space and transfer function forms. Complete analyses of simulation results for PI, PI-type FLC and LQR techniques are presented in frequency domain and time domain. Performances of the controllers are examined in terms of input tracking capability, duty cycle input energy and armature current. Finally, a comparative assessment of the impact of each controller on the system performance is presented and discussed.

Key words: Buck-converter driven dc motor, PI controller, PI-type FLC, LQR controller.

INTRODUCTION

Dc motor has good speed control respondence, wide speed control range. It is widely used in speed control systems which need high control requirements, such as rolling mill, double-hulled tanker, and high precision digital tools. When it needs control the speed stepless and smoothness, the mostly used way is to adjust the armature voltage of motor. One of the most common methods to drive a dc motor is by using PWM signals with respect to the motor input voltage (Wu, H., 2008). However, the underlying hard switching strategy causes unsatisfactory dynamic behavior. The resulting trajectories exhibit a very noisy shape. This causes large forces acting on the motor mechanics and also large currents which detrimentally stress the electronic components of the motor as well as of the power supply (Antritter, F., 2006). Since it is usually necessary to add a power supply component, anyway, this contribution shall present a control for the entire system of buck-converter/dc motor. The combination of dc to dc power converters with dc motors has been reported in (Boldea, I. and S.A. Nasar, 1999).

In particular, the composition of a buck converter with a dc motor has been proposed in (Linares-Flores, J. and H. Sira-Ramirez, 2004; Linares-Flores, J. and H. Sira-Ramirez, 2004). The buck type switched dc to dc converter is well known in power-electronics. Due to the fact that the converter contains two energy storing elements, a coil and a capacitor, smooth dc output voltages and currents with very small current ripple can be generated. The control issue of the converter/motor is to design the controller so that the dc motor can track a prescribed trajectory velocity precisely with minimum error. In order to achieve these objectives, various methods using different technique have been proposed.

DC machines are extensively used in many industrial applications such as servo control and traction tasks due to their effectiveness, robustness and the traditional relative ease in the devising of appropriate feedback control schemes, especially those of the PI and PID types. The increasing availability of feedback controller design techniques and the rapid development of circuit simulations programs, such as PSpice, offer much wider possibilities to analyze, and redesign, currently used dc motor drive systems (Linares-Flores, J. and H. Sira-Ramirez, 2004). The implementation of PID controller for power converter and motor control has been reported in (Liping, G., 2005; Kadwane, S.G., 2006; Liping, G., 2007; Zhou, H., 2008). Moreover, there have been several publications which apply fuzzy logic controllers to control power electronic converters (Ayob, S.M., 2006; Ayob, S.M., 2007; Viswanathan, K., 2005). The smooth trajectory input tracking using dynamic feedback controller for buck-converter driven dc motor has been reported in (Linares-Flores, J. and H. Sira-Ramirez, 2004; Linares-Flores, J. and H. Sira-Ramirez, 2004).

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This paper presents investigations of speed control of a dc motor based on smooth trajectory tracking. A simulation environment is developed within Simulink and Matlab for evaluation of the control strategies. In this work, the dynamic model of the buck converter driven dc motor is derived in the transfer function and state-space forms. Three feedback control strategies which are conventional PI, PI-type Fuzzy Logic and LQR are developed in this simulation work. Performances of each controller are examined in terms of angular velocity input tracking, duty cycle input energy and armature current. Finally, a comparative assessment of the impact of each controller on the system performance is presented and discussed.

2. Buck-converter Driven Dc Motor System:

The simplified model of the overall system buck-converter driven dc motor is shown in Figure 1. The switching devices have been replaced by an ideally switched voltage source. This is indicated by the multiplication of U_e with the switching variable $u \in \{0,1\}$. An additional resistance R_L has been added to the model in order to take into account the ohmic resistance of the coil windings. The motor has been modeled by an inductance L_M with ohmic resistance R_M and electromagnetic voltage source ωK_E. An input voltage U_e has been used which value is equal to the maximum voltage of the dc motor. In this study, the buck converter circuit with coil inductance, L, coil resistance, R_L and capacitance, C is considered.

3. Modelling of Buck-converter Dc Motor System:

This section provides a brief description on the modelling of the buck-converter driven dc motor, as a basis of a simulation environment for development and assessment of the proposed control techniques. The dynamic system composed from converter/motor is considered in this investigation and derived in the transfer function and state-space forms.

Considering the dynamic system of the converter/motor, the system can be modelled as

$$uU_e = R_L i_L + L\frac{di_L}{dt} + u_C \tag{1}$$

$$i_L = C\frac{du_C}{dt} + i_a \tag{2}$$

$$u_C = R_M i_a + L_M\frac{di_a}{dt} + K_E\omega \tag{3}$$

$$J\frac{d\omega}{dt} = K_M i_a \tag{4}$$

where J is the moment of inertia and K_M is the tacho generator gain of the motor. In (1) and (3), the very low measurement amplifier resistances R_4 and R_6 have been neglected.

From the equations (1) to (4), the state space modeling complete with mechanical equation that describes the dynamics of the motor shaft, a linear fourth order system is obtained as

$$\begin{aligned}\dot{x} &= \mathbf{A}x + \mathbf{B}u \\ y &= \mathbf{C}x\end{aligned} \tag{5}$$

with the vector $x = \begin{bmatrix} i_L & u_C & i_a & \omega \end{bmatrix}^T$ and the matrices A, B and C are given by

$$\mathbf{A}=\begin{bmatrix} -\frac{R_L}{L} & -\frac{1}{L} & 0 & 0 \\ \frac{1}{C} & 0 & -\frac{1}{C} & 0 \\ 0 & \frac{1}{L_M} & -\frac{R_M}{L_M} & -\frac{K_E}{L_M} \\ 0 & 0 & \frac{K_M}{J} & 0 \end{bmatrix}, \tag{6}$$

$$\mathbf{B}=\begin{bmatrix} \frac{U_e}{L} & 0 & 0 & 0 \end{bmatrix}^T, \quad \mathbf{C}=\begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$$

According to (Ortega, R., 1998), the discrete input $u \in \{0,1\}$ can be replaced with the duty ratio $\delta \in \{0,1\}$ when using a PWM-strategy to generate δ from an analog input signal. Hence, for the given setup we may refer to a so-called averaged dynamic model, given by

$$\dot{x} = \mathbf{A}x + \mathbf{B}\delta \tag{7}$$

where the new input is the duty cycle δ. Note that this linear system description is valid only as long as it can be ensured that no saturation effects occur in the coil. Otherwise the inductance *L* would depend nonlinearly on the current i_L.

In this study, the values of the parameters are defined as L_M = 8.9 mH, R_M = 6 Ω, K_E = 0.0517 V-s/rad, K_M = 0.0517 N-m/A, $J = 7.95\times10^{-6}$ kg-m^2, U_e = 24 V, L = 1.33 mH, R_L = 0.2 Ω, and C = 470 μF. For the converter, a switching frequency of f = 45 kHz has been used.

4. Control Algorithm:
Proportional-Integral (PI) Control Scheme:

To demonstrate the performance of the PI controller in controlling the motor angular velocity, the angular velocity ω(s) of the dc motor is fed back and compared to the desired angular velocity $\omega_d(s)$ as shown in Figure 2. The angular velocity error is regulated through the proportional and integral gains and applied to the buck converter driven dc motor in terms of control duty cycle, δ(s), where it can be obtained as

$$\delta(s) = G_c(s)[\omega_d(s) - \omega(s)]$$

Hence, the closed loop transfer function is obtained as

$$\frac{\omega(s)}{\omega_d(s)} = \frac{G_c(s)G(s)}{1+G_c(s)G(s)}$$

where $G_c(s) = K_p + K_i / s$ and $G(s) = \omega(s)/\delta(s)$.

Before designing the PI controller, the transfer function of the buck converter driven dc motor should be obtained. From (5) and (6), the output-to-control small signal transfer function of Figure 1 can be obtained as

$$G(s) = \frac{U_e}{\frac{JLL_M C}{K_M} s^4 + \frac{JC}{K_M}(R_M L + R_L L_M) s^3 + \left[K_E LC + \frac{J}{K_M}(R_L R_M C + L + L_M) \right] s^2 + \left[K_E R_L C + \frac{J}{K_M}(R_L + R_M) \right] s + K_E} \quad (8)$$

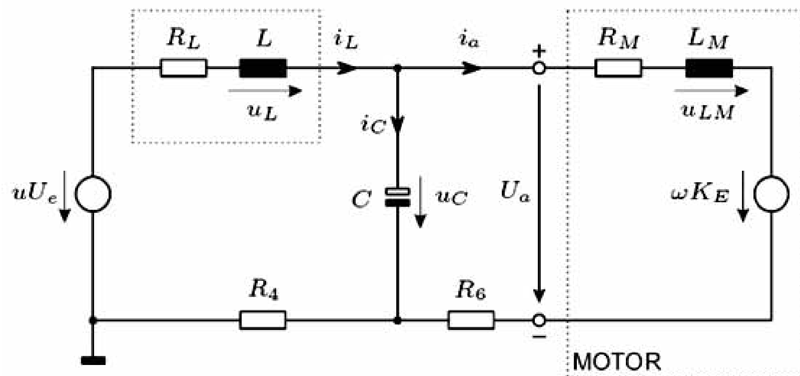

Fig. 1: Description of the buck-converter driven DC motor system.

From (8), the output-to-control transfer function of the buck converter driven dc motor at the nominal operating point is obtain as

$$G(s) = \frac{2.805 \times 10^{13}}{s^4 + 824.5s^3 + 1.978 \times 10^6 s^2 + 1.120 \times 10^9 s + 6.043 \times 10^{10}} \quad (9)$$

The transfer function in (9) has complex conjugate poles at $-105.6 \pm j1343.1$ which causes a 180° phase delay at the approximate frequency of 2490 rad/s. The bode plot for the system is shown in Figure 3. The bode plot shows that the gain margin is –31.1 dB and the phase margin is –159° which indicate the instability of the system. A PI controller was designed for the control of the buck converter driven dc motor at steady state to reduce steady state oscillation. One pole was placed at the origin and one zero was placed at 57.5 rad/s. The dc gain of the controller was adjusted to obtain sufficient phase margin and high crossover frequency. The transfer function of the PI controller is given by

$$G_c(s) = 0.0069 + \frac{0.3968}{s}$$

The bode plot for the PI compensated system is shown in Figure 4. The bode plot shows that the gain margin is 12.4 dB, the phase margin is 71° and the bandwidth is 2680 rad/s.

Proportional-Integral-type Fuzzy Logic Control (PI-type FLC):

Fuzzy logic can be defined as a theory of vagueness and uncertainties. This theory provides an approximate yet effective, means of describing the behaviour of the systems, which are too complex and ill defined to permit precise

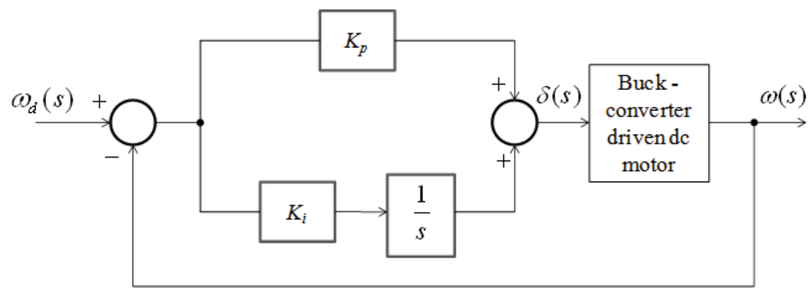

Fig. 2: PI control structure.

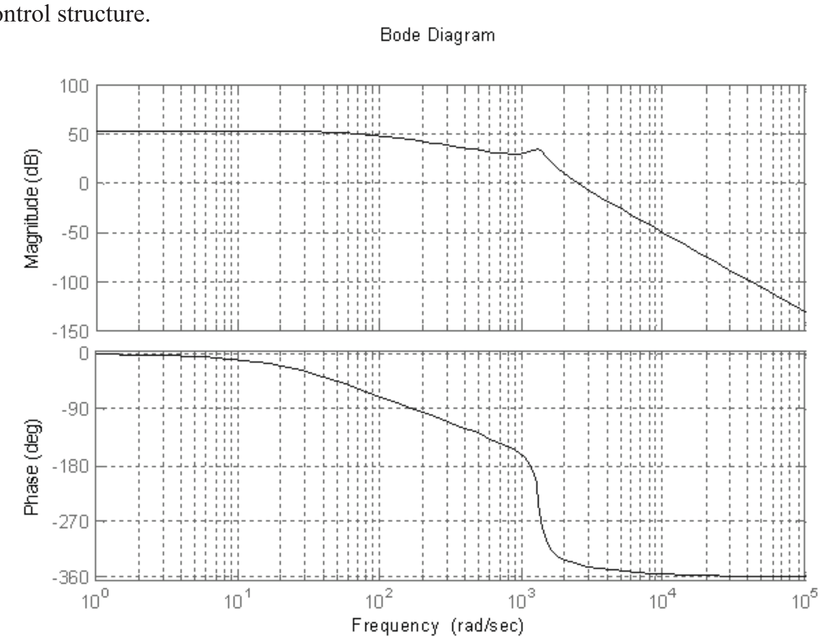

Fig. 3: Bode plot of buck-converter driven DC motor.

mathematical analysis. Typically, Fuzzy Logic Controller (FLC) consists of three stages, namely fuzzification, rule decision making and defuzzification. Fuzzification is a process to transform the non-fuzzy values from the physical measurement into a fuzzy linguistic range, i.e., positive big, positive small, negative small and so on. The assignment of the crisps input into fuzzy form is realized by membership function. The crisp input are first been normalized so that the input covers all the membership functions range. This can be realized by using input scaling factor that acts as forward gain. Presently, there is no generalized standard procedure on how to select the appropriate shape of membership function for specific applications. Membership function shape can be either trapezoid, triangular, singletone or bell-shape. However, triangular with 50% overlap between the adjacent membership function is more preferred shape since it contributes to a less computational process time. rule decision making consists of two components. They are rule table and rule evaluator. The rules stored in rule table actually relate the input-output relationship. For instance, for two inputs with equal five fuzzy sets, there will be 25 rules that relate the input-output relationship. The rule evaluator will decide which rules should be fired with a help of linguistic rule "IF... THEN...". For n inputs, there will be a maximum of $2n$ rules fired. The last stage is the defuzzifiction stage. Defuzzification is a stage where the fuzzy form is transform to physical values. Two methods usually carried out to perform the task are centroid method and mean maximum method (Ayob, S.M., 2006; Ayob, S.M., 2007).

In general, FLC can be classified into three types of controllers, namely PI-type FLC, PD-type FLC and PID-type FLC. Each name reflects their identical performance to their conventional PI, PD and PID control performance but with tuning adjustment features. PID-type FLC needs three inputs, namely error, change of error and sum of errors. This factor significantly expands the rule table and makes the design more complicated. Compared to PID-

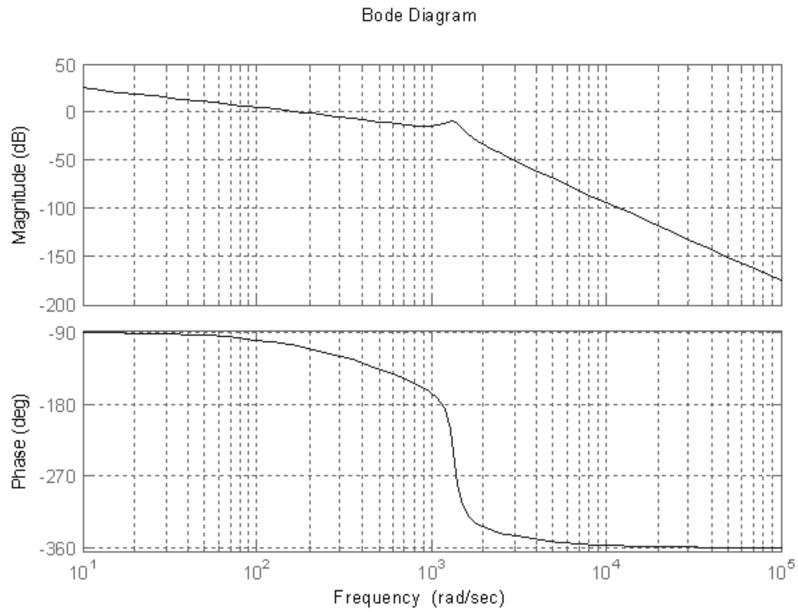

Fig. 4: Bode plot of PI compensator buck-converter driven DC motor.

type FLC, PI-type FLC and PD-type FLC are much simpler and more applicable. It is known, the PI-type FLC is more practical than PD-type FLC because PD-type FLC usually produces system steady state error because of lack integral function in its control nature (Petrov, M., 2002).

The hybrid fuzzy control system proposed in this work is shown in Figure 5, where $\omega_d(s)$ and $\omega(s)$ are the desired angular velocity and angular velocity of the dc motor, whereas k_1, k_2 and k_3 are scaling factors for two inputs and one output of the fuzzy logic controller used with the normalised universe of discourse for the fuzzy membership functions. In this study, triangular membership functions are chosen for angular velocity error, integral of angular velocity error, and duty cycle with 50% overlap. Normalized universes of discourse are used for both angular velocity error and its integral and duty cycle. Scaling factors k_1 and k_2 are chosen in such a way as to convert the two inputs within the universe of discourse and activate the rule base effectively, whereas k_3 is selected such that it activates the system to generate the desired output. Initially all these scaling factors are chosen based on trial and error. To construct a rule base, the angular velocity error, angular velocity error integral, and duty cycle are partitioned into five primary fuzzy sets as

Angular velocity error E = {NM NS ZE PS PM},
Angular velocity error integral V = {NM NS ZE PS PM},
Duty Cycle U = {NM NS ZE PS PM},

where E, V, and U are the universes of discourse for angular velocity, angular velocity integral and duty cycle, respectively.

A PI-type fuzzy logic controller was designed with 11 rules as a closed loop component of the control strategy for maintaining the speed of dc motor. The rule base was extracted based on underdamped system response and is shown in Table 1. The three scaling factors, k_1, k_2 and k_3 were chosen heuristically to achieve a satisfactory set of time domain parameters. These values were recorded as $k_1 = 0.0866$, $k_2 = 23.0756$ and $k_3 = -0.6$.

Linear Quadratic Regulator (LQR) Control Scheme:

A more common approach in the control of buck converter with DC motor systems involves the utilization linear quadratic regulator (LQR) design (Ogata, K., 1999). Such an approach is adopted at this stage of the investigation here. Figure 6 illustrates the LQR control structure. In order to design the LQR controller a linear state-space model of the buck converter with motor was obtained by linearising the equations of motion of the system. For a linear time invariant (LTI) system

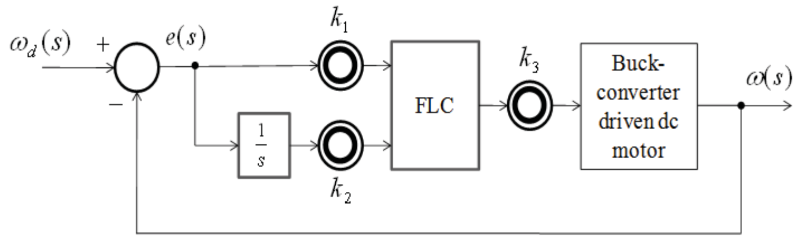

Fig. 5: PI-type FLC structure.

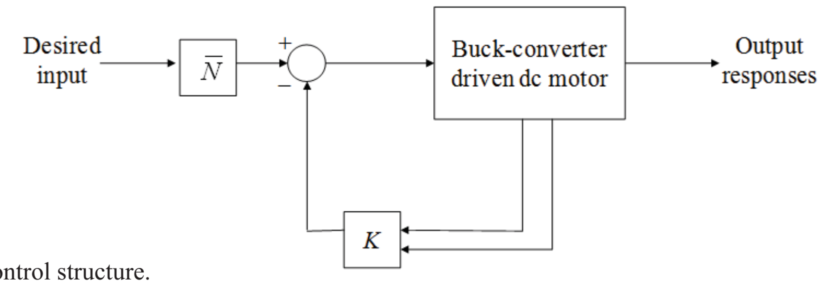

Fig. 6: LQR control structure.

Table 1: Linguistic rules of FLC

No.	Rules
1.	If (*e* is NM) and (*e*/*s* is ZE) then (*u* is PM)
2.	If (*e* is NS) and (*e*/*s* is ZE) then (*u* is PS)
3.	If (*e* is NS) and (*e*/*s* is PS) then (*u* is ZE)
4.	If (*e* is ZE) and (*e*/*s* is NM) then (*u* is PM)
5.	If (*e* is ZE) and (*e*/*s* is NS) then (*u* is PS)
6.	If (*e* is ZE) and (*e*/*s* is ZE) then (*u* is ZE)
7.	If (*e* is ZE) and (*e*/*s* is PS) then (*u* is NS)
8.	If (*e* is ZE) and (*e*/*s* is PM) then (*u* is NM)
9.	If (*e* is PS) and (*e*/*s* is NS) then (*u* is ZE)
10.	If (*e* is PS) and (*e*/*s* is ZE) then (*u* is NS)
11.	If (*e* is PM) and (*e*/*s* is ZE) then (*u* is NM)

$$\dot{x} = \mathbf{A}x + \mathbf{B}u$$

the technique involves choosing a control law $u = \psi(x)$ which stabilizes the origin (i.e., regulates x to zero) while minimizing the quadratic cost function

$$J_c = \int_0^\infty [x(t)^T Qx(t) + u(t)^T Ru(t)]\,dt \tag{10}$$

where $Q = Q^T \geq 0$ and $R = R^T > 0$. The term "linear-quadratic" refers to the linear system dynamics and the quadratic cost function.

The matrices Q and R in (10) are called the state and control penalty matrices, respectively. If the components of Q are chosen large relative to those of R, then deviations of x from zero will be penalized heavily relative to deviations of u from zero. On the other hand, if the components of R are large relative to those of Q, then control effort will be more costly and the state will not converge to zero as quickly.

A famous and somewhat surprising result due to Kalman is that the control law which minimizes J_c always takes the form $u = \psi(x) = -Kx$. The optimal regulator for a LTI system with respect to the quadratic cost function above is always a linear control law. With this observation in mind, the closed-loop system takes the form

$$\dot{x} = (\mathbf{A} - \mathbf{B}K)x$$

and the cost function J takes the form

$$J_c = \int_0^\infty [x(t)^T Qx(t) + (-Kx(t))^T R(-Kx(t))]\,dt$$
$$= \int_0^\infty x(t)^T (Q + K^T RK)x(t)\,dt$$

In this investigation, the tracking performance of the LQR applied to the buck converter with motor was investigated by setting the value of vector K and $\bar{N}$ which determines the feedback control law and for elimination of steady state error capability respectively. For the buck converter with motor described by the state-space model given by Equation (5), the LQR gain matrix for

$$Q = 10\left[\begin{array}{c|c} I_{2\times2} & 0_{2\times2} \\ \hline 0_{2\times2} & I_{2\times2} \end{array}\right] \quad \text{and } R = 1$$

was calculated using Matlab and was found to be

$$K = \begin{bmatrix} 3.3007 & 4.0256 & 18.6835 & 2.9562 \end{bmatrix} \text{ and } \bar{N} = \begin{bmatrix} 3.1665 \end{bmatrix}.$$

5. Implementation and Results:

In this section, the proposed control schemes are implemented and tested within the simulation environment of the buck converter driven dc motor and the corresponding results are presented. The control strategies were designed by undertaking a computer simulation using the fourth-order Runge-Kutta integration method at a sampling frequency of 1 kHz. The angular velocity of the dc motor is required to follow a smooth trajectory within the range from 0 to 150 rad/s as shown in Figure 7. The system responses namely angular velocity, duty cycle input energy and armature current are observed. The performances of the control schemes are assessed in terms of input tracking capability, time response specifications, duty cycle response and armature current response. Finally, a comparative assessment of the performance of the control schemes is presented and discussed.

In Figure 8, the angular velocity response is shown whereby it reaches the required velocity from 0 to 150 rad/s. It demonstrates that the proposed control schemes are capable in tracking the desired input. Performance of the controllers in terms of time response specifications and integral square error (ISE) are summarized in Table 2. It is observed that, while the ISE of LQR is five times lower as compared to PI, the ISE of PI-type FLC is extremely lower as compared to both PI and LQR controllers. With lower ISE, the actuator response required less time to achieve to desired velocity. The comparison of the specification of the angular velocity response for all control schemes are summarized in Figure 9. It is shown that, the rise time for all controllers are almost equal. However, in terms of settling time, PI-type FLC results in fastest input tracking response, followed by LQR and PI.

Figure 10 shows the duty cycle input energy responses of the buck converter driven DC motor using PI, PI-type FLC and LQR. It is noted that, the duty cycle for PI controller and PI-type FLC settled down at 150 ms, while the duty cycle for LQR controller settled down at 200 ms, with the final average duty cycle value of 0.323 for all controllers. However, the PI controller and PI-type FLC result in smooth input energy as compared to the LQR which results in a full duty cycle from 50 ms to 160 ms. It is also noted that, the duty cycle response of PI-type FLC reaches the steady state value faster than the case of PI and LQR controllers. It shows that, by combining PI with FLC, the speed of the duty cycle can be improved. It also shows that, the LQR controller utilizes high energy consumption due to a lot of switching in the control signal during the transaction between 0 to 150 rad/s when the system is tracking the desired response. This is the main disadvantage of time optimal control and it is the reason why the time optimal controller is not used in practice.

The armature current response is illustrated in Figure 11. It shows that, all controllers produce high amplitude of armature current before settled down at 200 ms. It is noted that PI-type FLC produce the highest maximum magnitude of armature current with the value of 0.3491 A, followed by LQR controller and PI controller with the values of 0.3457 A and 0.3418 A, respectively. On top of that, for all controllers, the buck-converter supplies the highest amount of power to the motor during the transition period. Similar to the angular velocity and duty cycle response, the armature current response using PI-type FLC settled down to zero value faster than the LQR and PI controllers.

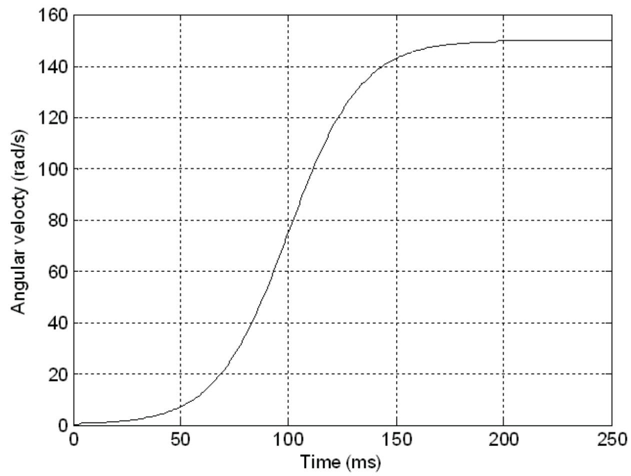

Fig. 7: The trajectory reference input.

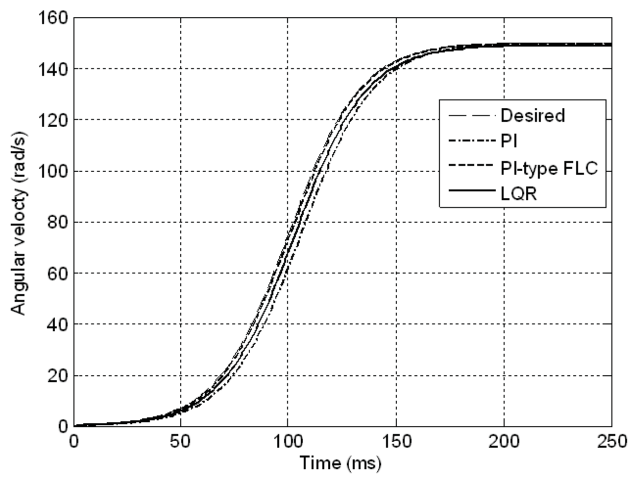

Fig. 8: Angular velocity response.

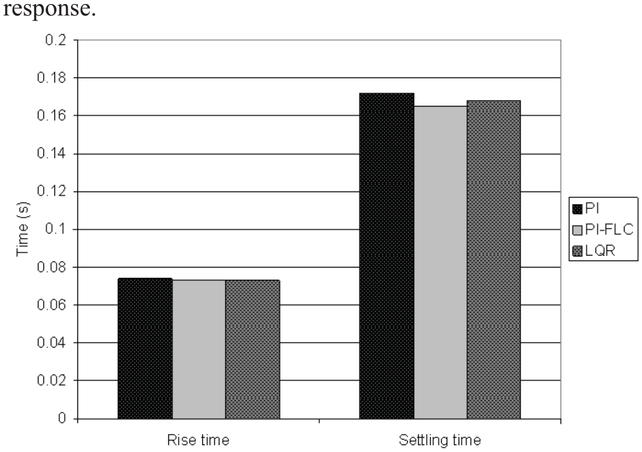

Fig. 9: Comparative assessment of time response specification of angular velocity.

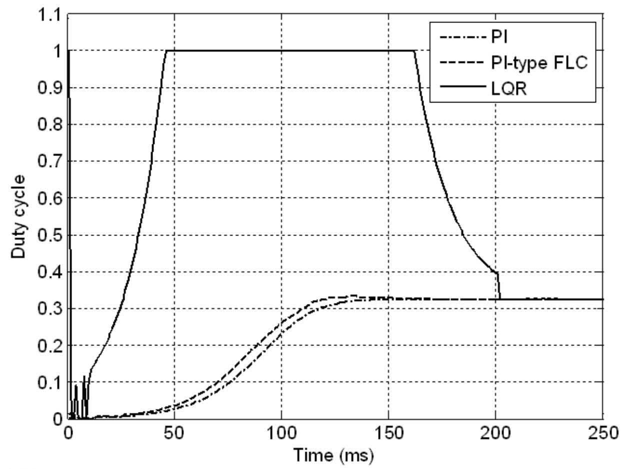

Fig. 10: Duty cycle response.

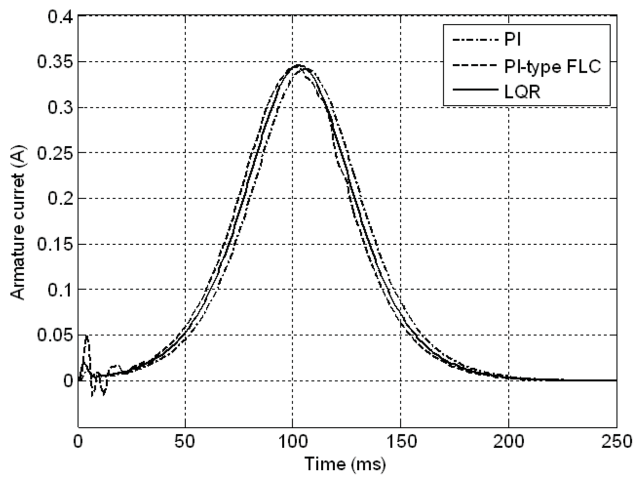

Fig. 11: Armature current response.

Table 2: Specifications of the angular velocity response of the DC motor

Controller	Specifications of angular velocity response		
	Rise time (s)	Settling time (s)	ISE
PI	0.074	0.172	6.519
PI-FLC	0.073	0.165	0.034
LQR	0.073	0.168	1.222

6. Conclusion:

Investigations into angular velocity control of buck-converter driven dc motor with PI controller, PI-type FLC and LQR controller have been presented. Performances of the controllers are examined in terms of angular velocity, duty cycle input energy and armature current responses. Acceptable input tracking capability has been achieved with all control strategies. A comparison of the results has demonstrated that the PI-type FLC is capable in tracking the smooth trajectory angular velocity with very minimum delay, as compared to the PI and LQR controllers. The results demonstrated that the trajectory tracking of angular velocity of buck-converter driven dc motor can successfully be handled by all PI controller, PI-type FLC and LQR controller. In terms of speed of the angular velocity response, the PI-type FLC provides fastest input tracking response as compared to others, which is proven by the smallest value of settling time. However, PI-type FLC results in a slightly higher input energy of duty cycle as compared to the PI controller. On the other hand, LQR controller consumes a high input energy which indicates the disadvantage of time optimal control.

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