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Optimal Full State Feedback Controller for Two DC Motor Configurations with Buck Chopper

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Abstract: *This workutilizesa State Feedback (SF) control scheme to control two DC Motor (DCM) configurations the Separately Excited DC Motor (SpEDCM) and the Series Excited DC Motor (SrEDCM) with variable speed.The DCM is modeled in MATLAB by applyingthe acceleration of angular speed and the derivative of currentdynamics. Furthermore, modeling of the buck chopper ismade in MATLAB and the controlling outcome of DCM speed are produced at distinct set points. The transient indices of the speed of SpEDCMare considered using theOptimal Full SF (OFSF) controller.The optimal parameter set improves speed control of a DCM by reaching the performance that is required for the system.The suggestedOFSF controller has a straightforward tuning process and scheme while provides animproved reference tracking in contrast with theconventional proportional-integral (PI) controller.*

Keywords: *Buck chopper, DC Motor, MATLAB, Modeling, Optimal control*

INTRODUCTION

A DCM is a broad actuator in the industrialsystemsand itprovides the translational orrotational motions depending upon the application by joining itwith the suitable mechanical parts. DCM is used in different applications for its reliability, easiness, and flexibility. DCMsare capable of keepingclosely a fixed speed with the variableexogenous torque. In other words, DCMs are noncompliant to adjustable speed drives than AC motors. The ability of DC motor of adjusting its speed over wide ranges and by a variety of methods are the motives for the solid competitive position of DCM in recentindustrialized drives [1,2].

Precisetorque and speed control of a DCM drive circuit aregenerallynecessary. In industrial systems, dynamic and fast control of a DCM drive circuit is essential to be industrialized. This improvement can be accomplishedby tracking a high-quality dynamic speed and load torque responses [3]. In addition, the power chopper performance circuit and controller methodshave an effect on the drive circuit efficiency. Usually,the PI controller is utilizedfor adjustingthe DCM speed, which has a negligible steady-state error during a speed reference value with step input [4].

In [5], the pole placement was applied through SF. This proposal method required information of the plant and every state are known. In [6], a PI controller combined with a SF controller was considered established on the pole placement technique. In [7], a quadcopter control based on full SF technique was realized in MATLAB environment. The work [8] studied SF approach for controlling rotor speed fixed on one end of a lever of which central point is fixed as pivot point and the other end of the lever has some passive counterweight. The paper [9] employed a state-feedback (pole placement) control scheme to control the current charging of the Lithium-Ion battery. The suggested SF controller had a straightforward design and tuning procedures while offered a improved reference tracking in contrast with the conventional PI.

Numerouscontrollersareconsidered to fulfill the objective of achieving speed control of DCMsuch as the combination between proportional integral derivative (PID) and Fuzzy Logic Controller (FLC) to produce Fuzzy PID controller [10].

DC-DC choppers have been established to ensure high performance, high power efficiency, and reduces overall cost. In addition to the DC-DC choppers allow generate distinct levels of voltage for one power source, they are used to reduce ripples irrespective of the change in input voltage or load current [11]. They utilize pulse width modulation(PWM) to control switching devices. The switching of the power MOSFET controlled by the PWM usually causes supply bouncing. This kind of phenomenon will cause noise in remaining circuits. It can be reduced using a slew-rate modulation that allows increasing of slew times [12].

In this paper, two DC motor configurations are employed as a plant controlled through a full SF with its gain parameters are tuned to obtain optimal performance metric and construct what called in this work OFSF controller. This work does not utilizes a pole placement method in contrast to other methods that are presented in the literature survey, which reduces the analysis process and provides a flexible and efficient method for parameter evaluation.

The rest of this paper is structured as follows. In section II, the background of mathematical models of SpEDCM ,SrEDCM and buck chopper are described. In section III, the optimal controller of design is simulated, with a view to certify of the proposed OFSF controller algorithm. Result and discussion has been seen in Section IV. The conclusion is considered in the last section in Section.

THEORETICAL BACKGROUND

A. SpEDCM Mathematical Model

Since SpEDCMcan be regulated over a wide-ranging of speed, a diversity of approaches are considered. The method called Armature voltage control is used in this work. In this method, the armature current is controlled by armature voltage v_a, without changing the current of the field windingi_f.The state-spacemodel is given as [13]:

$$\frac{di_a}{dt} = \frac{1}{L_a}(v_a - R_a i_a - k_b\omega) \qquad (1)$$

$$\frac{d\omega}{dt} = \frac{1}{J}(k_t i_a - B\omega) \qquad (2)$$

where v_a (V) is the armature voltage,i_a (A) is the armature current, R_a (Ω) is the armature resistance,L_a (H) is the armature inductance, J (kg/m²) is moment of inertia,B(Nm/ (rad/sec)) is friction coefficient of the motor, and ω (rad/sec) is angular velocity. The parameters of the DCM utilized in this work are listed in Table 1.

Table 1: The DCM parameters

Parameter	***Value***
R_a (Ω)	***1***
L_a(mH)	***46***
B (Nm/ (rad/sec))	***0.008***
J (kg/m²)	***0.093***
k_t(N.m/A)	***0.55***
k_b(V/(rad/sec))	***0.55***

B. SrEDCM Mathematical Model

A SrEDCM related to the SpEDCM is a self-excited DC motor. It develops its name for the reason that the field winding is connected in series to the winding of the armature. They are also considered self-excited motors due to only requiring one voltage source t

supply both the armature and the field winding. The differential equations including the electrical and mechanical parts of a SrEDCM are given by [14]:

$$\frac{di_a}{dt} = \frac{1}{L_T}(v_a - R_T i_a - k_\emptyset k_b \omega i_a) \qquad (3)$$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(k_{\emptyset}k_t {i_a}^2 - B\omega\right) \quad (4)$$

where $k_{\emptyset}$ is the mutual inductance between the armature and field coils, $R_T = R_a + R_f$ is the total equivalent series resistance and $L_T = L_a + L_f$ is the total equivalent series inductance.

C. Buck Chopper

A buck chopper is a step down dc-dc choppercomprisingmainly of inductor and two switches (commonly diode and a transistor switch) for controlling inductor. It alters between connection of induction to input voltage to mount up energy in inductor and then discharging the inductor's energy to the load [11].For the buck choppershown in Figure 1,when the switch is closed, the voltage across the inductor(v_L) is $v_i - v_a$. The current flowing through inductor(i_L) linearly rises. The diode doesn't allow current to flow through it, since it is reverse-biased by voltage. When switch is opened, diode is forward biased and voltage is $v_L = -v_a$ (neglecting drop across diode) across inductor. Thei_L, which was rising in ON case, now decreases.In a buck chopper, the average output v_a is less than the input voltage,v_i.

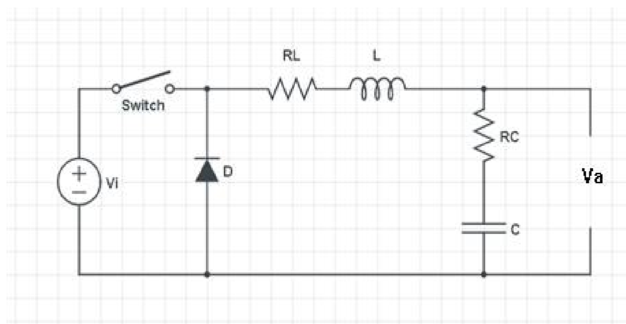


Fig1: Circuit diagram of a buck chopper.

The mathematical model of the buck chopper given in Figure 1 is given as:

$$\frac{di_L}{dt} = \frac{1}{L}(Dv_i - v_a - R_L i_L)(5)$$

$$\frac{dv_c}{dt} = \frac{1}{C}(i_L - i_a) \quad (6)$$

$$v_a = v_c + R_C(i_L - i_a) \quad (7)$$

where v_i (V) is the input voltage,i_a (A) is the armature current, R_L (Ω) is the inductor resistance,L (H) is the inductance of the buck inductor, C(F) is the capacitance of the buck chopper capacitor, $R_C(\Omega)$ is the equivalent series resistance, $D$is the duty cycle. The parameters of the buck chopper utilized in this work are listed in Table 2. Finally, the complete plant model is shown in Figure 2.

Table 2: The buck chopper parameters.

Parameter	Value
$R_L(\Omega)$	0.017
L(mH)	1.5
$R_C(\Omega)$	0.25
C (μF)	9400

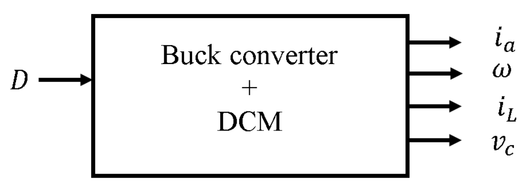


Fig2: Block diagram of the buck chopper and DCM.

CONTROLLER DESIGN

In this work, two types of controllers are simulated. The conventional PI controller is the first simulated controller (see Figure 3) with the following equations:

$$e = \omega - r \quad (8)$$

$$D = Sat\left(k_p e + k_i \int e\,dt\right) \quad (9)$$

$$Sat(e) = \begin{cases} 1 & e > 1 \\ e & 0 \le e \le 1 \\ 0 & e < 0 \end{cases} \quad (10)$$

where r is the reference input angular velocity, k_p and k_i are the PI controller parameters.

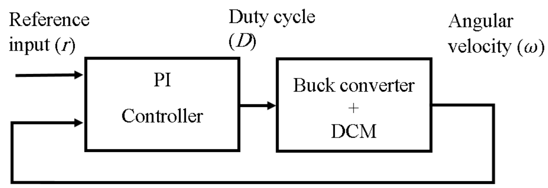


Fig3: Block diagram of the conventional PI controller.

The structure of the proposed OFSF controller is shown in Figure 4 with the control signal is generated in the following equation set:

$$D = Sat(r - (k_1x_1 + k_2x_2 + k_3x_3 + k_4x_4) + k_5 \int e\,dt) \quad (11)$$

where r is the reference input angular velocity, $(k_1, k_2, k_3, k_4, k_5)^T$is the gain vector of the OFSF, $(x_1, x_2, x_3, x_4)^T = (i_a, \omega, i_L, v_c)^T$ is the state vector of the plant.

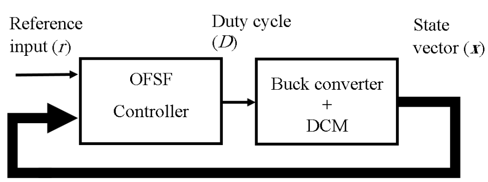


Fig 4: Block diagram of the OFSF controller.

SIMULATION RESULTS

For the purpose of verifying and comparing the performance of the PI and OFSE controllers for two DC configurations, a simulation was performed by MATLAB Package (see Figure 5). The parameters of both conventional and proposed controllers are obtained by using the MATLAB GA optimization tool with the parameters listed in Table 3.

Table 3: Parameters of the MATLAB GA optimization tool.

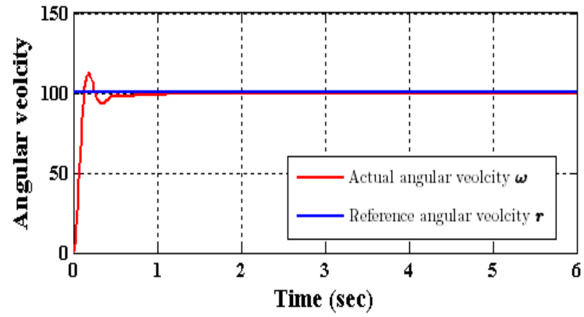
Parameter	Value
Fitness function	ITSE
Population size	20
Population Type	Vector of double numbers
Maximum generations	100
Mutation types	Gaussian
Cross-over types	Scattered crossover
Elite Count	2

The time response for a step reference input with the magnitude of 100 rad/sec of both controllers are shown in Figure 5. Two performance indices are selected to show the improvements they are Integral Time Square Error (ITSE) and Mean square Error (MSE), which are expressed as:

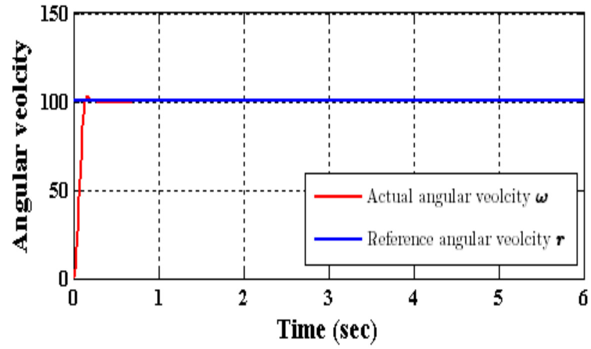
ITSE= $\int_0^6 te^2 dt$ (12)

MSE= $\frac{1}{6}\int_0^6 e^2 dt$ (13)

The results of both selected performance indices are tabulated in Table 4.



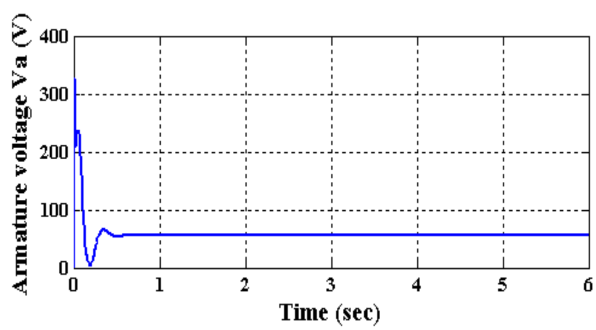
(a)



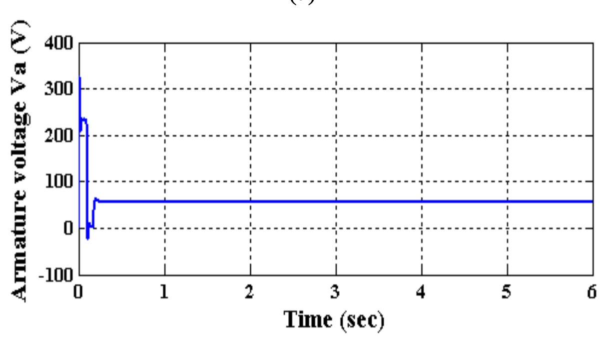
(b)

Fig5: Armature angular velocity of SpEDCM,

(a) PI controller (b) OFSF controller.



(a)



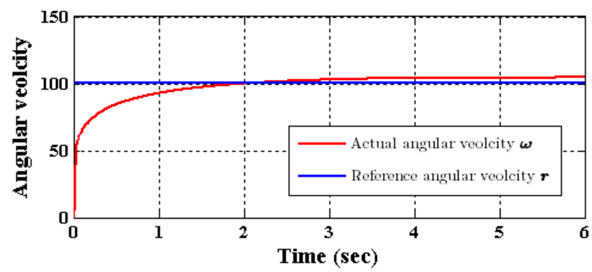
(b)

Fig 6: Armature voltage generated by buck chopper,

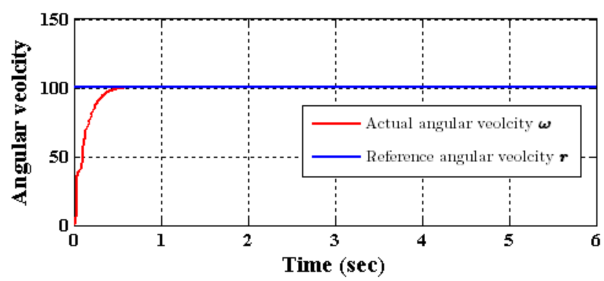
(a) PI controller (b) OFSF controller.

Table 4: The numerical results for the simulation of PI and OFSF controller with SpEDCM.

Controller type	ITSE	MSE
PI	23.6	102.8
OFSF	18.6	99.8
Reduction ratio	21.2%	2.9%



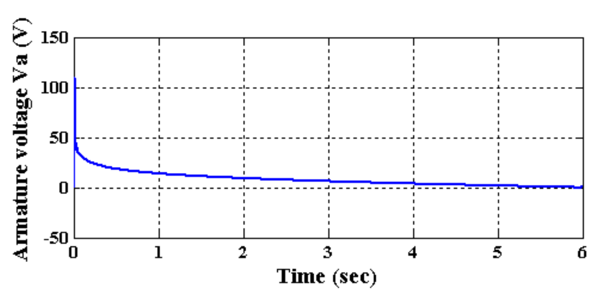
(a)



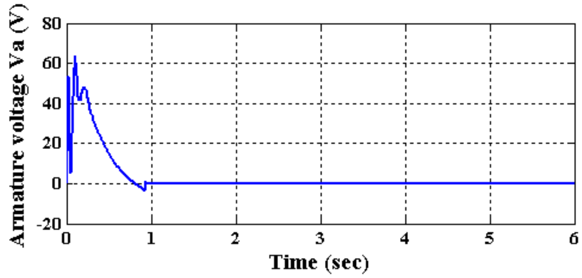
(b)

Fig7: Armature angular velocity of SrEDCM,

(a) PI controller (b) OFSF controller.



(a)



(b)

Fig 8: Armature voltage generated by buck chopper,

(a) PI controller (b) OFSF controller.

Table 5: The numerical results for the simulation of PI and OFSF controller with SrEDCM.

Controller type	ITSE	MSE
PI	371.5	117.2
OFSF	41.8	115.5
Reduction ratio	88.8%	1.5%

The time-response for the SpEDCM with respect to a step reference input showed in Figure 5 with an accurate reference tracking for the OFSF (see Figure 5(b)) in contrast to that of the PI controller (see Figure 5(a)). The transient period of the time response showed a minimum overshot and minimum settling time in the case of using OFSF controller, this improvement is due to two reasons. First, employing four states in the control law will ensure adding more information about the system than using one state in the case of a PI controller. Moreover, using optimization technique based on Genetic algorithm to obtain the suitable gain parameters of the OFSF controller to minimize the performance index ITSE. The result of the optimization algorithm was listed in Table 4. The armature voltage driven by the buck chopper controlled by the OFSF controller showed less activity than that of the PI controller. In the case of SrEDCM, a large seedy state error was associated with using the PI controller (see Figure 7(a)). This reflected in the large value of ITSE tabulated in Table 5. To deal with steady state error an integral term was incorporated in the control law given in (11).

CONCLUSION

The two DCM configurations and buck choppermodels arecreated in MATLAB/SIMULINKwith the aid of angular acceleration and derivative ofthe current dynamics. In addition, thecomplete circuit operation of DCMcontrolledbuck chopper is also simulated inMATLAB and result of the speed control is established. Numerical results show the validity of this speed control system in terms of overshot and steady state error reduction for the case of OFSF controller in contrast to the PI controller.

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