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Hybrid Self Tuned Fuzzy PID controller for speed control of Brushless DC Motor

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Original scientific paper

The objective of the proposed work is to investigate the performance of hybrid self tuned fuzzy proportional integral derivative (STFPID) controller for brushless DC (BLDC) motor drive. The proposed hybrid STFPID controller includes a proportional integral derivative (PID) controller at steady state, a PID type self tuned fuzzy logic (FL) controller (STFLC) at transient state thereby combining the merits of both the controllers. The switching function incorporated in the controller ensures desired control response at various operating conditions by appropriately switching between PID and STFPID based on speed error. A detailed simulation study and performance comparison with other control approaches is performed to highlight the merits of the proposed work. The simulation results indicate that the proposed controller is robust with fast tracking capability and less steady state error. The experimental results are provided to validate the simulation study.

Key words: BLDC motor drive, speed control, self tuned fuzzy logic controller, Hybrid controller, PID controller.

Hibridni samopodešavajući neizraziti PID regulator za upravljanje brzinom bezkolektorskog istosmjernog motora. Cilj ovog rada je istražiti performance hibridnog samopodešavajućeg regulatora za bezkolektorski istosmjerni motor. Predloženi hibridni samopodešavajući neizraziti regulator uključuje PID regulator u stacionarnom stanju i samopodešavajući neizraziti PID regulator (STFLC) za vrijeme trajanja prijelazne pojave kombinirajući prednosti oba regulatora. Funkcija prekapčanja regulatora omogućava upravljanje u različitim uvjetima odgovarajućim odabirom između PID i samopodešavajućeg neizrazitog PID regulatora na temelju brzine pogreške. Provedena je detaljna simulacijska analiza i usporedba performansi s ostalim metodama upravljanja kako bi se istaknule prednosti predloženog rada. Iz simulacijskih rezultata je vidljivo je robusno svojstvo predloženenog regulatora te smanjena pogreška u stacionarnom stanju. Sustav pravljanja testiran je i eksperimentalno kao potvrda simulacijskih rezultata.

Ključne riječi: BIM motori, upravljanje brzinom, samopodešavajući neizraziti regulator

1 INTRODUCTION

There has been an escalating interest towards the use of BLDC motors in several industry and consumer applications due to their high efficiency, torque density and lower motor maintenance [1], [2]. BLDC motors are primarily used in servo, actuation, positioning and variable speed applications where precise motion control and stable operation are critical due to changes in system structure and occurrence of uncertainties. This necessitates the design of an efficient controller to achieve continual control performance under varying operating conditions.

The performance of traditional motor controllers such as proportional integral (PI) and PID controllers are affected by parameter variations, load disturbances and speed variations [3] - [5]. Hence, researchers have explored numerous other controllers, which account for nonlinearity and be adaptable to load and speed variations. A comparison of robustness of different controllers has been analyzed by C. P. Coleman et al [6]. The performance of sliding mode controller (SMC) for electric drive application has been discussed by T. O. Kowalska et al [7]. The results reveal that SMC control method has quick response and is insensitive to parameter uncertainties. A major drawback in SMC is that it suffers from chattering problems which leads to the degradation of system performance. A novel hybrid control strategy based on adaptive fuzzy sliding mode control mechanism has been proposed in [8] to overcome the chattering effect in conventional sliding mode control. H∞ based control algorithm has been applied for a permanent magnet synchronous motor drive system discussed in [9].The authors indicate that the performance of the H∞ controller is satisfactory in presence of disturbances. In [10], the authors have proposed a robust H∞ controller design for linear synchronous motor drive. The proposed H∞ control system has improved tracking performance in comparison to the conventional control system with good dynamic response and robustness. Eventhough a considerable progress has been made in terms of designing H∞ optimal controllers, design complications are still the main problem in H∞ controller. Complex mathematical computations of SMC and H∞ controllers have opened up new avenue for researchers to experiment the design and analysis of controllers for electric drive applications based on artificial intelligence (AI) techniques.

AI techniques based on FL approach, proposed by Lotfi A. Zadeh [11], which is highly effective in controlling non-linear systems does not require mathematical model of the plant and it is based on only linguistic rules. In recent years, researchers have highly focused on different techniques to enhance the performance of FL controller. A novel nonlinear model predictive controller (MPC) based on Takagi-Sugeno fuzzy model, has been proposed for electric vehicle applications[12].The merits of the approach are highlighted by comparing the results of the proposed approach with those of the conventional MPC controller and the optimal fuzzy PI controller. A similar approach based on time varying PI controller based Type 2 FL for speed control of electric vehicle was proposed in [13], in order to get an optimal performance and reduced computation complexity. An intelligent robust PI adaptive control strategy for speed control of Electric vehicles is reported in the literature [14]. This method uses least squares support vectors regression [LS-SVR] for handling dynamic variations of the plant. A self tuning load frequency control strategy for microgrids using human brain emotional learning has been proposed in [15]. Here the emotional controller with the self tuning has a better performance with higher accuracy than conventional controllers. Based on self adaptive modified bat algorithm, a new intelligent online fuzzy tuning approach for multi-area load frequency control is presented in [16], which guarantees the robustness and stability against uncertainties caused by external disturbances. K. Premkumar et al proposed the fuzzy PID supervised online adaptive neural fuzzy inference systems (ANFIS) based speed controller for brushless dc motor [17]. In this paper, the speed control based on different online ANFIS methods is compared and the control system parameters are measured to verify the effectiveness of the controller. An adaptive fuzzy neural network controller for minimizing torque ripple is presented in [18]. A design technique for adaptive deadbeat PI current and speed controllers of BLDC motor drives using particle swam optimization and ANFIS paradigms is presented in [19].In addition to conventional fuzzy and neuro fuzzy systems, self tuned fuzzy approaches have been proposed to have feasible control in the presence of load and parameter variations. Self tuning control method provides a promising way of realizing an ideal controller for the problems of uncertainties caused by external disturbances in the plant [20].

It is in this perspective this paper highlights the application and merits of STFPID controller for the control of BLDC motor. With the objective of designing a robust and adaptable controller, this work combines the merits of conventional PID control and self tuned fuzzy approach. The merits of the proposed controller are analyzed in terms of steady state and transient conditions. The proposed paper is organized as follows: The BLDC motor drive system is presented in section 2. The design of self tuned FL controller is discussed in section 3.Section 4 discusses the proposed Hybrid STFPID controller for BLDC motor drive. Section 5 validates the simulation results and the results of comparison with various controllers are presented. The hardware implementation and results are discussed in section 6 and section 7 presents the conclusion.

2 BRUSHLESS DC MOTOR DRIVE SYSTEM

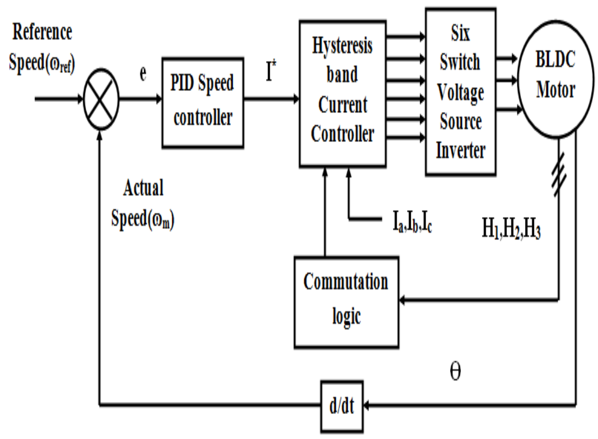

Fig. 1. Block diagram of BLDC motor drive system

The block diagram of BLDC motor drive system with conventional PID controller is shown in Fig. 1. The PID controller regulates the speed by generating a reference current in accordance with the speed error. The hysteresis current controller regulates the stator winding current within the specified hysteresis band by appropriately generating the switching commands to the inverter devices in accordance with rotor position information.

3 SELF TUNING FUZZY LOGIC CONTROLLER

The self tuning fuzzy approaches have been proposed to enhance the adaptability of fuzzy controllers in presence of external disturbances. The techniques used to enhance the adaptability of fuzzy controllers are rule base modification, scaling factor tuning, inference mechanism improvement, and membership function redefinition and shifting. Amongst this, the scaling factor tuning method has significant impact on parameter variations and hence is explored in this work [21]. The block diagram of STFPID controller is shown in Fig. 2.

The STFPID controller includes control rule base for the gain updating factor 'α' called fuzzy tuner [22] in addition to a conventional fuzzy controller. The role of fuzzy tuner is to adjust the scaling gains such that the domain of the input and output variables may be varied so as to have faster settling time and fewer oscillations around the preset speed.

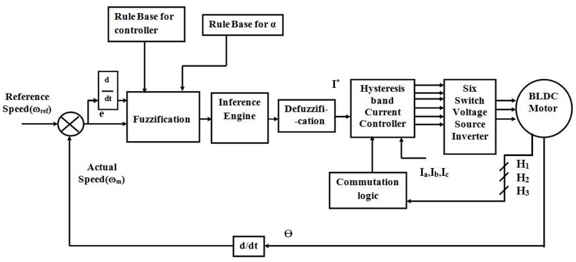

Fig. 2. Block diagram of self tuning FLC for BLDC motor drive system

In the Self tuning FL controller, the input speed error (e) and change of error (Δe) to the FL controller are divided into seven linguistic variables: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). The output gain from FL controller is divided into three linguistic variables: Positive (P), Negative (N), and Zero (Z). For the gain updating factor, the linguistic variables are ZE, PS, PMS, PM, PLM and PL which represent Zero, Positive Small, Positive Medium Small, Positive Medium, Positive Large Medium and Positive Large respectively. Here the rule base for controller gains and gain updating factor are presented in Table 1 and Table 2.

4 HYBRID SELF TUNING FUZZY PID CONTROLLER FOR BLDC DRIVE

This work envisages the application of hybrid STFPID controller for BLDC motor drive combining the advantages of PID controller at steady state and STFPID during transient state [23 – 25]. The flowchart representation of the proposed hybrid STFPID Controller is shown in Fig. 3.

Here, the hybrid controller consists of a simple logical comparator where a logical switching mechanism is employed which changes the control action from one controller to another controller based on the speed error value. The conventional PID controller is active when the speed error is less than 10 rpm whereas the hybrid STFPID controller is active when the error is greater than 10 rpm.

Table 1. Rule base for controller gains

	Gain	**Change of error(Δe)**						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
Error(e)	**NB**	P	Z	N	N	N	Z	P
		P	Z	N	N	N	Z	P
		N	P	P	N	P	P	N
	NM	P	P	Z	N	Z	P	P
		P	P	Z	N	Z	P	P
		N	Z	P	P	P	Z	N
	NS	P	P	Z	N	Z	P	P
		P	P	Z	N	Z	P	P
		N	N	Z	P	Z	N	N
	ZE	P	P	P	Z	P	P	P
		P	P	P	Z	P	P	P
		N	N	N	Z	N	N	N
	PS	P	P	Z	N	Z	P	P
		P	P	Z	N	Z	P	P
		N	N	Z	P	Z	N	N
	PM	P	P	Z	N	Z	P	P
		P	P	Z	N	Z	P	P
		N	Z	P	P	P	Z	N
	PB	P	Z	N	N	P	Z	P
		P	Z	N	N	P	Z	P
		N	P	P	P	N	P	N

Table 2. Rule base for gain updating factor 'α'

e/ Δe	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	ZE	ZE	ZE	ZE	ZE	ZE	ZE
NM	ZE	ZE	ZE	ZE	ZE	ZE	PS
NS	ZE	ZE	ZE	ZE	ZE	PS	PMS
ZE	ZE	ZE	ZE	ZE	PS	PMS	PM
PS	ZE	ZE	ZE	PS	PMS	PM	PLM
PM	ZE	ZE	PS	PMS	PM	PLM	PL
PB	ZE	PS	PMS	PM	PLM	PL	PL

5 RESULTS AND DISCUSSION

To validate the performance of the controller, the BLDC motor drive is simulated in MATLAB/simulink environment. The following equations are used to model the BLDC motor [26].

The voltage equation is given as,

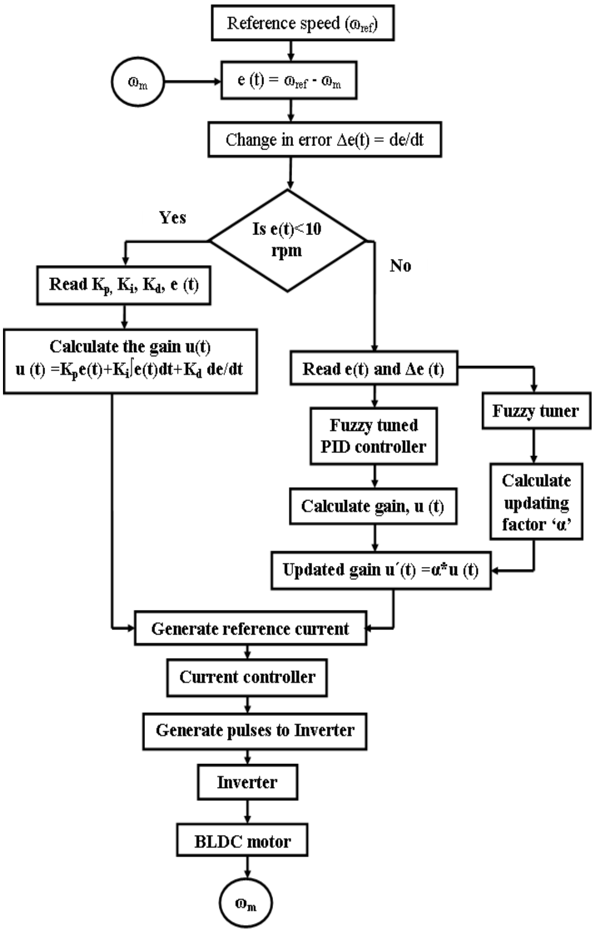

Fig. 3. Flowchart for Hybrid STFPID Control Algorithm

$$V_{dc} = 2\left[R_s i_a + (L-M)\frac{di_a}{dt}\right] + e_1 - e_2 = R_a i_a + L_a\frac{di_a}{dt} + e_1 - e_2 \quad (1)$$

where $L$and M are self-inductance and mutual inductance per phase respectively, R_s is the stator winding, e_1 and e_2 are the back electromotive force (EMF) of current carrying phases windings, i_a is the armature current.

$$R_a = 2R_s,\ \Omega\ \ and\ L_a = 2(L-M),\ H \quad (2)$$

The electromagnetic torque developed by the motor can be expressed as T_e,

$$T_e = T_L + J_M\frac{d\omega}{dt} + B_M\omega \quad (3)$$

where T_L is the load torque, J_M is the inertia, and B_M is the friction constant of the BLDC servomotor.The load

Table 3. Motor parameters

Voltage	310V
Rated Current	4.52A
Rated Speed	4600rpm
Rated power	1 hp
Stator phase resistance	3.07Ω
Stator phase inductance	6.57mH
Inertia	$1.8e^{-4}$ Kg m^2

torque can be expressed in terms of load inertia J_L and friction B_L components as

$$T_L = J_L\frac{d\omega}{dt} + B_L\omega \quad (4)$$

The output power developed by the motor is

$$P = T_e\omega \quad (5)$$

$$E = e_a = e_b = e_c = K_b\omega \quad (6)$$

where K_b is back EMF constant, E is back EMF per phase, and ω is the angular velocity in radians per second.

The parameters of the BLDC motor used in this work are tabulated in Table 3.

The performance of the proposed Hybrid STFPID controller is compared with conventional controller under varying speed and load conditions. Steady state error, rise time, peak time, settling time and speed ripple are considered as performance measures for evaluating the performance of the controllers. To verify the robustness of the proposed controller different simulation studies under different conditions are performed and the results are articulated.

The speed response of the BLDC motor drive under no load, constant load of 0.5 Nm and constant speed of 1500 rpm with varying load along with convergence curve for different controllers is illustrated in Fig. 4, Fig. 5 and Fig. 6 respectively. Performance analysis of the controllers due to change in speed reference is summarized in Table 4, Table 5 and Table 6. The convergence plot depicted in the below figures indicate the fast tracking capability of the proposed controller. From the convergence curve and performance parameters, it is evident that the proposed controller performs better than fuzzy PID controller.

From the analysis, it is evident that the proposed controller is robust and has fast tracking capability with respect to parameter variations and has better steady state and dynamic characteristics which are highly desirable in industrial drive and automotive applications. The proposed controller augurs well for the above mentioned variable speed applications.

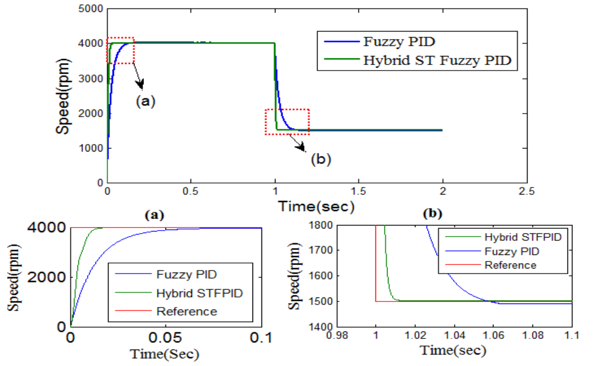

Fig. 4. Speed response and convergence curves of fuzzy PID and Hybrid STFPID under varying speed at no load condition.

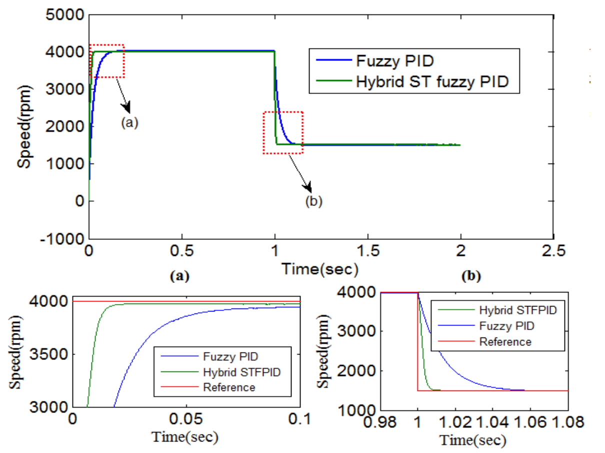

Fig. 5. Speed response and convergence curves of fuzzy PID and Hybrid STFPID under constant load at varying speed condition.

6 EXPERIMENTAL ANALYSIS

The experimental setup of the drive system is shown in Fig.7. The speed control algorithm is implemented using FPGA Spartan 3E board.

The experimental hall sensor output from the BLDC motor is shown in Fig. 8. The experimental voltage and current waveform for a speed of 1000 rpm is shown in Fig. 9 and Fig. 10 respectively. Fig. 11 shows the reference and actual speed response for the proposed controller at 1000 rpm. The hardware results indicate the suitability of the proposed controller for variable speed applications.

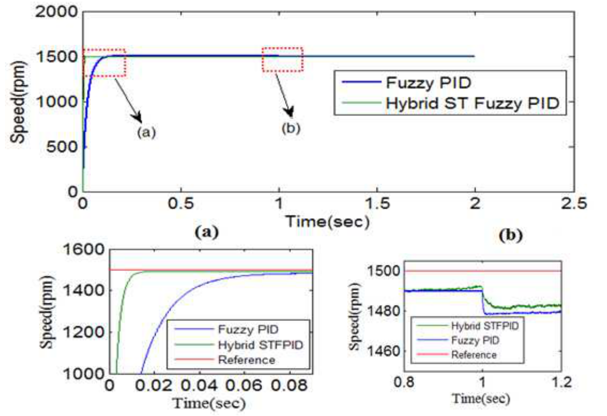

Fig. 6. Speed response and convergence curves of fuzzy PID and Hybrid STFPID under constant speed at varying load condition.

Table 4. Performance analysis of speed controllers in BLDC motor for change in speed at no load condition

Controller	Rise Time (sec)	Peak Time (sec)	Settling Time (sec)	Speed ripple	Steady State Error (rpm)
Fuzzy PID	0.01	0.06	0.1	0.1335	2.2628
Hybrid STFPID	0.005	0.015	0.012	0.0003	1.3374

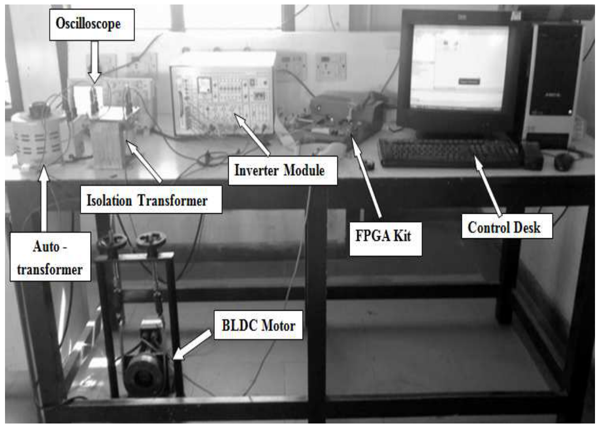

Fig. 7. Experimental setup of the BLDC motor drive

Table 5. Performance analysis of speed controllers in BLDC motor for change in speed at constant load condition

Controller	Rise Time (sec)	Peak Time (sec)	Settling Time (sec)	Speed ripple	Steady State Error (rpm)
Fuzzy PID	0.01	0.05	0.1	0.1351	3.5075
Hybrid STFPID	0.005	0.015	0.012	0.0006	3.1906

Table 6. Performance Analysis of speed controllers in BLDC Motor for change in load with constant speed

Controller	Rise Time (sec)	Peak Time (sec)	Settling Time (sec)	Speed ripple	Steady State Error (rpm)
Fuzzy PID	0.01	0.08	0.1	0.13	0.8230
Hybrid STFPID	0.0025	0.01	0.02	0.0003	0.5328

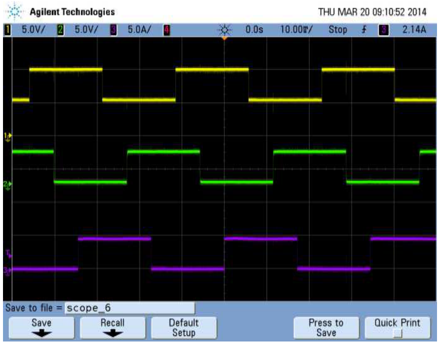

Fig. 8. Experimental hall sensor output of the BLDC motor

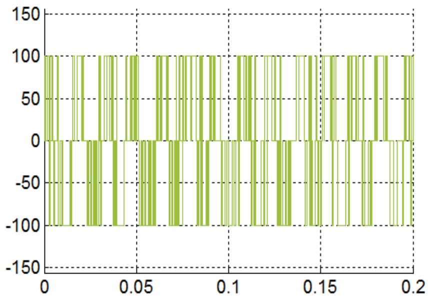

Fig. 9. Experimental voltage waveform at a speed of 1000 rpm

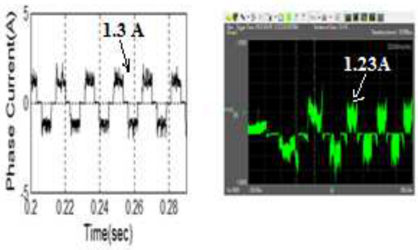

Fig. 10. Simulated and experimental current response at 1000 rpm at 0.5 Nm load

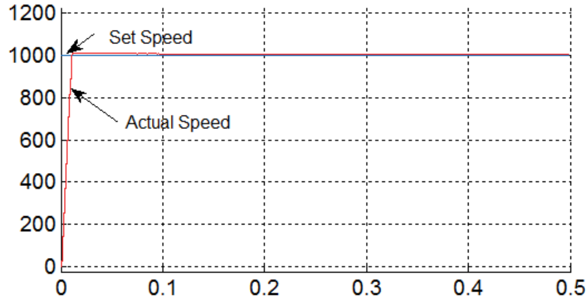

Fig. 11. Experimental speed response at 1000 rpm

7 CONCLUSION

The controller design for BLDC motor widely used in variable speed industrial and automotive applications need to account for non-linearity and parameter variations to ensure adaptability and robustness. It is in this outlook, hybrid STFPID controller has been proposed in this paper for speed control of BLDC Motor. The proposed hybrid STFPID controller combines the merits of PID controller and self tuning capability of fuzzy controller. To demonstrate its effectiveness, the performance of the proposed controller is compared with various controllers under varying speed and load conditions. The results indicate that the controller has less speed ripple, less steady state error and it is robust to load perturbation. The experimental results indicate the suitability of the proposed approach.

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