Fractional Order Modified AWPI Based DC-DC Converter Controlled SEDC Motor

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Abstract In this paper, a fractional order modified Anti Windup (AW) proportional–integral (PI) scheme is designed to generate the switching gate pulse of buck converter to control the speed of separately excited DC (SEDC) motor for low speed applications. Input saturation is a constraint on all real-time motors. Furthermore, for DC-DC power converters, the duty cycle is the natural control input. Therefore, to keep off the wind up phenomena, the output of a new modified fractional order back calculation-based AW scheme with PI controller is compared to the repetitive sawtooth waveform for switching pulse generation in closed loop speed tracking system. Here, fractional tuning gain of integrator contributes additional flexibility. To ameliorate the steady state error as well as tracking speed performance compared to the AWPI and fractional order AWPI controller, this new controller is formulated by taking the difference between AW tracking time constant and proportional gain connected to the output capacitor voltage signal. It can be observed that the new controller, with its two configurable parameters, outperforms in terms of speed tracking. Also, it can minimize the integral time absolute error (ITAE) and integral squared error (ISE). In presence of noise, both fractional order controllers perform well compared to the integer order controller by showing their potency for speed tracking as well as disturbance rejection.

Keywords Fractional order modified AWPI controller · DC-DC Buck converter · SEDC motor

1 Introduction

A DC-DC converter, an electromechanical device, turns the unregulated DC input into a controlled DC output at a preferred voltage level by adjusting the duty ratio for different DC motor drive applications such as fuel cell vehicles [1], in PV system [4], battery operated system [6], etc. DC-DC buck converter [2–4] is addressed by employing an anti windup PI approach in [3]. Here, a perturbed buck converter is

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designed using a Lyapunov based constructive approach for output feedback stabilization. Valenzuela [4] introduced a Lyapunov based PI with back calculation AW controller for input saturation. To optimize the performance during saturation and to restrict inductor current within a specific range, an anti windup strategy is used in [5–8]. Because of the superior performance, dependability, and changeable speed control, direct current (DC) motors play a large part in modern industrial drives such as battery operated [17] vehicles, electric trains, and so on [9]. Researchers have used a variety of control measures [9, 10] for controlling the motor's speed to avert machine damage, slow rise time and high overshoot. Khubalkar et al. used an embedded platform to construct the digital fractional order proportional integral derivative (FOPID) controller for speed control of buck converter fed DC motor [11]. In simulation environment of the buck converter driven DC motor in [12], two feedback control techniques (LQR and PI controller) are constructed and tested. A solar panel [13] is linked to the DC-DC converter's input for controlling speed of separately excited DC motor [15, 16] for getting below rated speed [13, 14]. To drive the gate pulse of DC-DC converter fed DC motor's speed control in closed loop approach, PI controller is compared with repetitive sawtooth waveform to generate pulse width modulation [18]. However, traditional controllers have constraints in optimizing between contradicting objectives such as fast reaction, small overshoots, and zero steady state errors as well as being insensitive to load-torque disturbances [10]. To obtain more precise and robust control performances, the fractional order (FO) [19] PID controller [20] is also studied in speed control of DC motor [10, 11, 15]. In practice, it is often observed that the performance of a PID controller [4] or FOPID controller [8, 9, 15] can be severely restricted due to the saturation of the actuators [7, 8], converter driven DC motor drives [11, 15, 18]. Therefore, consideration of actuator saturation is necessary to avoid poor performance of the controller and the instability [11]. Here, an effective methodology for speed control of buck converter driven SEDC motor model is taken and a fractional order modified anti windup PI controller is designed and compared to the repetitive wave to generate PWM signal for the converter. The performance of this new controller is compared with FO-AWPI and IO-AWPI controller. This paper has been articulated as follows: in the next Sect. 2, the description of converter with SEDC motor is demonstrated. The tuning parameter of derivative gain is kept zero. A fractional order modified AWPI controller is manifested in Sect. 3. Section 4 delineates the performance study and the comparison of the three controllers.

2 Converter Design for Separately Excited DC (SEDC) Motor

One of the main performance features for industrial applications in electric drives systems is an efficient dynamic speed command tracking response [18]. A separately

Table 1 Parameters of plant with converter

Plant with converter	Specifications
SEDC motor	5 hp, 240 v, 1750 rpm; Armature resistance (r_a) = 0.78Ω, inductance (L_a) = 0.0161 H, Field armature mutual inductance (L_{af}) = 1.234 H, Inertia (J) = 0.05 Kg-m^2, Viscous friction coefficient (B_m) = 0.01 N-m-S, coulomb friction torque = 0
DC-DC Buck converter	Input voltage (V_{Hv}) = 500 V, Output voltage (V_{Lv}) = 120 V-160 V, switching frequency = 16 kHz, 0.5%voltage-ripple ratio on the capacitors

excited DC motor (SEDC) is utilized as a plant in simulation instead of permanent-magnet DC motors due to constrained ratings such as few horsepower and a maximum speed constraint. This paper addresses armature voltage control approach to obtain the speed below rated speed of the SEDC motor using DC-DC Buck converter. The parameters of the plant (SEDC motor) with the converter are shown in Table 1.

The speed (ω_m) in rpm can be controlled [18] using (1)

$$\omega_m = \frac{1}{k_a \varphi_f}\left(V_t - \frac{R_a}{T} T_{em}\right) \tag{1}$$

Here, k_a = Armature constant; φ_f = Constant field flux in Weber; V_t = Buck converter output in volt; T_{em} = Electromagnetic Torque in N-m.

3 Fractional Order Modified AWPI Controller

The FO-PI controller with anti windup technique [8] is introduced here to ameliorate the controller performance by addressing the problem of actuator saturation [4, 8], i.e. a long time is required to reach the output in steady state [5]. However, inclusion of the fractional parameter in this method, the integral action for zero actuating signals is not fixed. In addition, by choosing the right fractional parameter value, it is possible to get a faster time response and better denoising. The AWPI controller [8] output signal is

$$u(t) = K_p e(t) + (K_I + T_I(u_{sat} - u)) \int e(t) d(t) \tag{2}$$

In this AW scheme, controlling the tracking constant (T_I), the integral value can be reduced during integral saturation. Here, modified back calculation-based anti windup scheme [8] is used and $\frac{1}{T_I}$ is chosen as half of $\sqrt{\frac{K_p}{K_i}}$. In the proposed fractional order AW strategy, integer order integrator in Eq. (2) is substituted by a fractional order integrator to obtain switching frequency of the gate terminal of buck converter.

Here, the Riemann–Liouville definition of fractional integration is employed [19]. To generate FO-AWPI control output ($u_{\text{fc}}(t)$), Eq. (2) is modified:

$$u_{\text{fc}}(t) = K_{\text{P}}e(t) + (K_{\text{i}} + T_{\text{i}}(u_{\text{sat}} - u))D^{\mu} \int e(t)d(t) \tag{3}$$

where K_{P} and K_{I} are proportional and integral gain value. Here, $\mu \in \Re; \Re < 0$. D^{μ} can be written as $D^{-\mu}$. The term fractional integration $D^{-\mu}\ e(t)$ [19] is defined as

$$D^{-\mu}e(t) = \frac{1}{\Gamma(\mu)} \int_0^t (t - \tau)^{\mu-1} e(\tau)\text{d}\tau \tag{4}$$

Here, control laws are taken as (i) overshoot should be less than 20%; (ii) 2% settling time. Based on this control law, the FO-AWPI scheme for SEDC motor control furnishes large steady state error (e_{ss}) though it can reduce the settling time and percentage (%) overshoot for tracking speed performance compared to the IO-AWPI controller. But in both cases, e_{ss} is much higher. In this paper [20], a new integer order PID control scheme is proposed to control the gate pulse of the boost converter. Motivated from the given idea in [20], this new PID control structure was incorporated initially with a FO-AWPI controller for buck converter-based SEDC motor control. But implementing this scheme for FO controller does not help to reduce the steady state error. Therefore, a modified scheme is introduced with a FO-AWPI controller. The output voltage of capacitor is fed back and the modified control (u_{mfAW}(t)) signal is shown below:

$$u_{\text{mfAW}}(t) = K_{\text{P}}e(t) + (K_{\text{i}} + T_{\text{I}}(u_{\text{sat}} - u) - K_{P1} * V_c)D^{\mu} \int e(t)\text{d}(t) \tag{5}$$

Here, the feedback capacitor voltage is multiplied with proportional gain K_{P1} only. Initially, the term ($K_{\text{P1}} * V_{\text{c}}$) was added to the tracking time constant (T_{I}). If K_{P1} increases, the integration of three added gain values increase the overshoot and settling time with reduction of steady state error. But low value of K_{P1} provides longer time to settle. Therefore, the control signal in Eq. (5) is designed to improve the tracking performance. Here, Z-N tuning method is utilized for K_{P} and K_{i} value. These values are kept constant for all control structures. For modified fractional order AWPI controller, K_{P1} value is used by taking $\frac{K_{\text{P}}}{T_{\text{I}}}$ and regulated to study its performance. Fractional order modified AWPI controller is implemented using MATLAB SIMULINK which is shown in Fig. 1.

4 Experimental Result

Here, a SEDC motor is controlled by a DC-DC step down converter or buck converter whose input DC voltage is 120 V. The motor is considered for low speed application

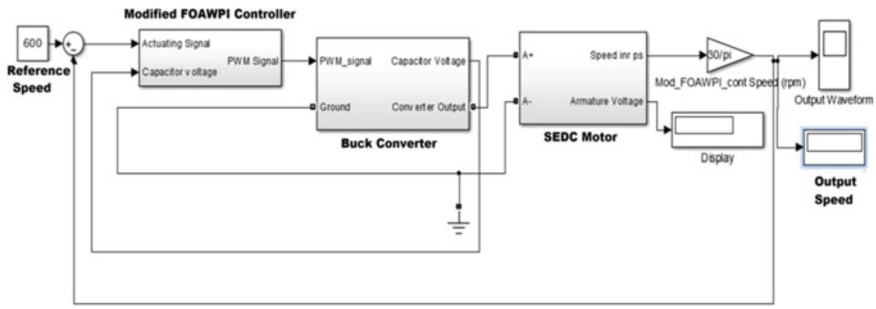

Fig. 1 Fractional order modified AWPI controller for buck converter controlled SEDC motor

with 2% pulsating torque at 600 rpm. Here, 300 V NiMH battery is considered and a battery source is used as input of the converter in the MATLAB SIMULINK block. The design specifications are shown in Table 1. From Table 1 data, for 5 hp motor with converter, the calculations are shown below:

2% basis permissible pulsating torque = 0.4069 N-m;

Rated torque = 20.3427 N-m.

The fundamental current to produce 2% pulsating torque = 0.3272 A;

To meet the fundamental current, the required switching frequency is 15.826 kHz. Therefore, in constant torque region, pulse width modulation (PWM) technique with switching frequency $\left(f_s = \frac{1}{T_s}\right)$ of 16 kHz is applied to the buck converter. Here, closed loop feedback speed control of SEDC motor is designed to keep constant the speed during any load disturbances.

Here, duty cycle is $D = \frac{T_{On}}{T_s}$; T_{On} = On time of the pulse in ms; T_s = Switching time. During T_{ON}, inductor current is calculated.

$$\Delta I_L = \frac{1}{f_s L}(V_s - V_o)D = 49.7067\,\text{Amp}$$

The average inductor current (I_{Lavg}) or output current = 31.0667 Amp. For continuous inductor current operation, minimum inductance 72.425 μH is considered. Here, in an open loop mode, the motor provides sluggish output speed response.

To generate the switching pulse to trigger the power switch, PI controller with anti windup strategy is used and compared to the sawtooth signal in [4, 5, 8]. Here, to enhance the performance of AWPI controller, integer order integral controller is replaced by fractional parameter. The additional tuning knob provides extra flexibility without disturbing the proportional and integral gain value in presence of noise [19]. This fractional order AWPI controller is then modified by connecting the gain K_{P1} to add an extra tuning knob to achieve more flexibility as well as to improve tracking performance and denoising performance without disturbing the other three tuning knobs with or without noisy system. The MATLAB SIMULINK block with new

Table 2 Performances of controllers

Specifications	AWPI controller	FO-AWPI controller	FO modified AWPI controller
% Maximum overshoot	2.2347	1.2876	0.8887
Rise time in s	0.0607	0.0632	0.0641
Settling time in s	0.0819	0.0725	0.0668
Peak time in s	0.0778	0.0789	0.0789
Steady state error	2.2480	2.2798	0.1049
% Initial undershoot (%IU)	2.5780	2.5760	2.5761

control scheme-based converter controlled motor shown in Fig. 1 is used to control the speed in 600 r.p.m. The performances of three controllers, i.e. IO-AWPI, FO-AWPI, and fractional order modified AWPI controller are shown in Table 2. The output speed responses are shown in Fig. 2. From Table 2, it is seen that by keeping the gain values K_P, K_i, T_I, and μ constant and by varying only K_{P1} value, the tracking performances of new controller such as percentage maximum overshoot (%MO), settling time (T_s), and steady state error (e_{ss}) are reduced. In comparison with IO and FO controller, it is found from Table 2 that fractional parameter helps to improve tracking performance by reducing %MO, T_s, and %IU. But it leaves a higher e_{ss} value for the FO-AWPI controller-based motor speed tracking case. New modified controller improves tracking performance but it increases rise time which indicates slightly sluggish response compared to other two controllers.

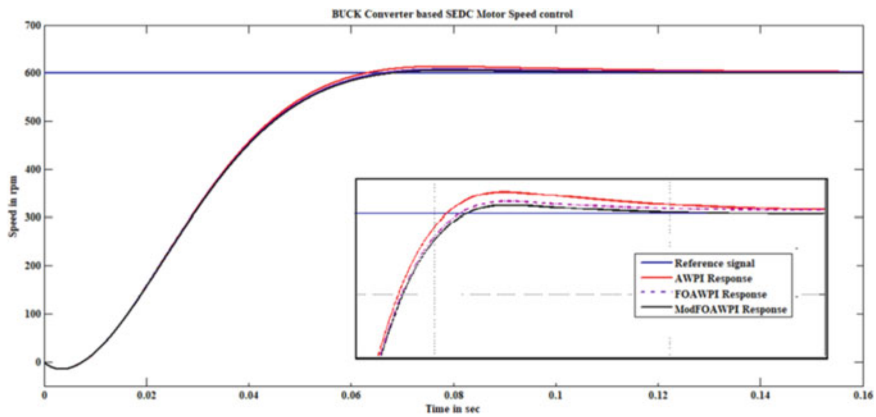

Fig. 2 The output speed tracking response of three controllers based buck converter controlled SEDC motor

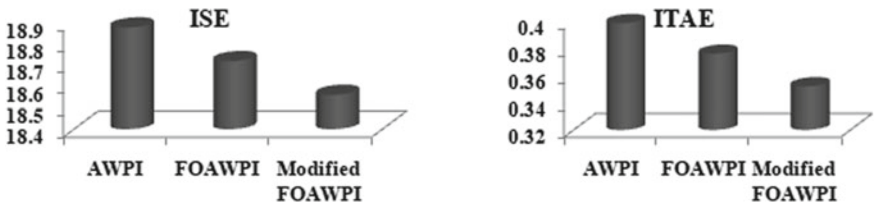

Fig. 3 Performance indices of three controllers

Here, the performance of the error signal, i.e. ISE or e_2 and ITAE or time multiplied e_1 is also measured and compared for three controllers shown in Fig. 3. It is observed that the new controller minimizes both ISE and ITAE. Also, both FO controllers perform well by minimizing integral time squared error (ITSE) compared to the integer one in this case.

To showcase the efficacy of the new controller in presence of noise, the band limited white noise with noise power 0.0005 W/Hz is taken. Compared to the performances of IO version shown in Table 3, FO-AWPI controller reduces rise time and steady state error. It also improves disturbance rejection performance, i.e. increases signal to noise ratio (SNR) by lowering mean squared error (MSE) [19]. In this case, IO controller slightly reduces %MO and settling time (T_s). Due to one extra knob, new controller yields better reduction of %MO and T_s compared to others. Therefore, by adjusting two flexible parameters of fractional order modified AWPI controller, both tracking and denoising performances can be ameliorated compared to the IO-AWPI controller-based converter controlled motor speed tracking system. It is also observed that both FO and new controller reduce the ISE and ITAE compared to integer order controller. The similar tracking and denoising performances are also observed for the magnitude of 0.001 W/Hz process noise with higher sampling rate case.

Table 3 Performances of controllers in presence of noise

Specifications	AWPI controller	FO-AWPI controller	FO modified AWPI controller
% Maximum overshoot	8.6333	8.8845	8.0734
Rise time in s	0.1156	0.1153	0.1163
Settling time in s	0.2657	0.2689	0.2586
Steady state error	13.2391	12.2657	14.0928
SNR in dB	13.6192	13.79	13.74

5 Conclusion

This paper introduces a new fractional order modified AWPI controller for switching pulse generation of buck converter controlled SEDC motor for low speed applications. The new controller's performance is measured and compared in closed loop mode to that of the FO-AWPI and IO-AWPI controllers. Because of its extra tuning value, this new controller furnishes lower maximum overshoot, settling time, and steady state error than the FO and IO versions. In addition, for noisy case, when compared to an IO controller, both FO and modified FO controllers perform well in terms of tracking the reference speed and improving denoising performance, i.e. increasing SNR and lowering MSE.

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