Model-based Speed Control of a DC Motor Using a Combined Control Scheme

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***Abstract*—The separately-excited DC motor is a high-performance variable speed drive vital for industrial applications such as robotics, actuation, control and guided manipulation because of its precision, simplicity, continuous control feature and wide speed range. Hence there is need to accurately regulate and drive the motor at desired speed. The individual armature voltage and field current methods are flawed in their inability to control the motor speed over a wider range. Hence this paper is proposing a combined armature voltage and field current control method using Internal Model Control (IMC) feedback control scheme that will ensure reference speed tracking, a fast and non-oscillatory response for the DC motor speed. The armature voltage and field current control techniques are both modelled, fully capturing the dynamic effects of the armature and field excitation of the DC motor. The derived model is then used to obtain optimal settings for a PID controller that will control the motor speed. This model-based controller enhances the performance of the motor. Computer simulations are presented to show the effectiveness of the proposed control scheme.**

Keywords—DC motor control, Internal Model Control, Speed control, Armature voltage control, Field current control

I. INTRODUCTION

The DC motor is an example DC machine that converts electrical energy into mechanical form. It achieves this using direct current in both stator and rotor. It has widespread industrial application, supportive of sustainable development, such as in machine tools, robotic manipulators, household appliances, servomotors, paper mills, and propulsion systems for electric vehicles. This is due to its precision, simplicity, continuous control features and because its speed can be controlled over a wide range with relative ease. As a distinguishing feature of DC machines, the field circuit and the armature circuit can be interconnected in several ways to deliver a wide range of performance characteristics. A variant of DC motors is the separately-excited motor where the field circuit and the armature circuit are fed with independent voltage sources. This type of high performance variable speed drives is vital for industrial applications such as robotics, actuation, control and guided manipulation where precision movements are essential [1,2,3,4,5].

A major performance feature of the DC motor is the torque-speed characteristic, which is a description of how the torque produced by the machine varies as a function of the speed of rotation of the motor for steady speeds. Hence, a servo drive system is rated 'high performance' when the shaft speed can be made to follow a desired reference at all time. A major control objective for the machine is to regulate and drive the motor at desired speed in the presence of parameter variations and changing operating conditions [1,5]. It is desired that a speed control system for the DC motor should satisfy the following performance criteria: stability of the closed loop system, robustness i.e. insensitivity to motor variations, and excellent reference speed tracking [6].

The PID (Proportional Integral and Derivative) controller, the conventional and popular feedback control scheme, used in the industry for control gives a performance that is unacceptable because of its oscillatory response and sensitivity to motor parameter variations. It is also limited in its ability to deal with inverse-response and to provide predictive control action to compensate for changing operating conditions. The PID controller is thus, not the optimal control strategy for variable speed drive applications [2,6,7]. This presents the need to design a robust and high-performance controller that will achieve the desired objectives for the DC motor speed.

Hence, the main contribution of this paper is to propose a combined control scheme – that is, the armature voltage control method and field current control method combined together – that will effectively regulate the speed of a separately-excited DC motor; which will be designed using internal model control techniques. Unlike the individual control methods, in the combined control scheme the armature voltage, V_a and the field voltage, V_f are varied simultaneously in order to vary the speed. A model of this dynamic relationship is developed for both parts of the motor, stating desirable control objectives for the speed of the DC motor, and from these optimal settings for the PID control algorithm is obtained. Various reference speeds – below the rated speed, at the rated speed, and above the rated speed – will be utilised to test the performance of the combined armature voltage and field current control method on the DC motor. The results obtained from the combined control method is compared with the individual control methods. This paper, therefore, has the following objectives:

- To model the dynamic relationship between the armature voltage and field current with the DC motor speed.
- To design and build an optimal IMC-tuned PID (feedback) controller for both parts of the motor for improved performance of the DC motor speed.
- An evaluation of the performance of the designed model-based control scheme and a comparison with the individual armature voltage control and field control methods.

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II. BACKGROUND

Recently considerable effort has been devoted to DC motor speed control using different approaches, like PID, fractional-order dynamics, sliding mode control (SMC), but no attempt has been made to use a combined model of the armature and field parameters of the DC motor to obtain optimal tuning settings for a PID controller for speed control.

An approach based on linear parametric models, derived using state estimation and system identification techniques, is used to control the motor, but their displacement response had oscillations and due to plant-model mismatch the controller performance is reduced [8]. An approach incorporated fractional-order dynamics to improve the performance and change the dynamics of the entire DC motor by eliminating the original influence of the conventional PID, without making internal changes into the system. But indices like settling time, rise time, steady-state error and overshoot were not use to evaluate its performance [9]. An effective and profound approach based on SMC and Adaptive PID with SMC gives a good motor speed performance with acceptable robustness. The only flaw with this technique is that the performance characteristics however are not as optimized as a larger rise time is observed with the SMC method than with the conventional, and there is the chattering phenomenon where the control signal switches between two structures leading to high frequency oscillations [2,10].

An approach using Universal Learning Networks (ULNs), a class of Neural Networks, for the identification and control of a separately excited DC motor, loaded with a centrifugal pump, gave an overall satisfactory performance. Firstly, offline a Universal Learning Network Identifier (ULNI) is trained to emulate the dynamic behaviour of the DC motor system, using the forward propagation algorithm. This identifier is then used online to train a Universal Learning Network Controller (ULNC) that regulates the motor speed to track a desired reference signal. Performance indicators, like settling time, rise time, steady-state error and overshoot were not discussed here [11]. The above stated limitations with literature will be handled by this paper.

This paper is organised as follows. First a mathematical model of the separately-excited DC motor (SEDCM) is derived in Section III. The proposed IMC-based PID control technique; designed using a model of the motor is introduced in Section IV. Section V presents the simulation results as well as an evaluation of the performance of the approach. Finally, and in Section VI, major conclusions are drawn.

III. MODELING OF THE SEDCM

The separately excited DC motor is a machine wherein the field and armature circuit have independent voltage sources. The equivalent circuit showing the electromechanical arrangement of this type of DC motor is shown in Fig. 1.

The motor speed consistent with the rated armature voltage is its rated speed. Armature voltage control serves to smoothly vary the motor speed from zero to its rated speed (base speed) by varying the armature voltage in the constant torque region. The armature current increases with increase in the armature voltage, which consequently leads to an increase in the development torque and, hence the motor speed [1,4,12]. The dynamics of the motor and its load are represented by the following set of differential equations:

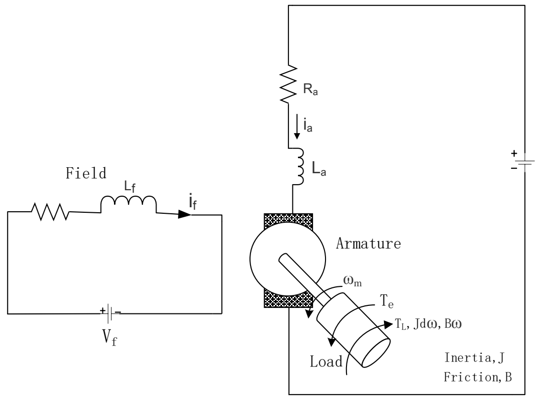

Fig. 1. Equivalent Circuit of the SEDCM.

$$v_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + K\omega(t) \quad (1)$$

$$T_e = Ki_a = B\omega(t) + J\frac{d\omega(t)}{dt} + T_l(t) \quad (2)$$

Where $T_e = Ki_a$, $\mathrm{T_e} = \mathrm{Ki_a}$ is the development electrical torque, $E_b = K\omega \mathrm{E_b} = \mathrm{K}\omega$, is the back *EMF,* the constant K K denotes the torque/back *EMF* constant, B B denotes the viscous friction coefficient/motor damping, J J is the motor shaft inertia, ω ω is the motor speed and T_L $\mathrm{T_L}$ is the load torque: typically, T_L $\mathrm{T_L}$ is either constant or some function of the speed ω ω in a motor [1]. To derive the input-output relationship between the armature voltage V_a $\mathrm{v_a}$ and the motor speed ωω, the Laplace transformation of (1) and (2) yields:

$$V_a(s) = R_a I_a(s) + sL_a I_a(s) + K\omega(s) \quad (3)$$

$$KI_a(s) = B\omega(s) + sJ\omega(s) + T_L(s) \quad (4)$$

If current in the armature I_a is made the subject from (4) and resubstituted in (3) we have the system transfer function that depicts the input-output relationship between the motor speed ω and armature voltage V_a and load torque T_L:

$$\omega(s) = \frac{\frac{K}{L_a J}}{s^2 + \left(\frac{R_a J + L_a B}{L_a J}\right)s + \left(\frac{R_a B + K^2}{L_a J}\right)} V_a - \frac{sL_a + R_a}{s^2 + \left(\frac{R_a J + L_a B}{L_a J}\right)s + \left(\frac{R_a B + K^2}{L_a J}\right)} T_L \quad (5)$$

$$\omega(s) = G_m V_a + G_d T_L \quad (6)$$

Where G_m $\mathrm{G_m}$ is the transfer function that depicts the relationship between the motor speed ω and the armature voltage V_a, while G_d depicts the relationship between the motor speed ω and load torque, the disturbance$\mathrm{V_a}$. Hence (5) is rewritten to be (assuming that the $\mathrm{V_a}$load torque applied to the DC motor is negligible, $T_L = 0$):

$$\omega(s) = \frac{K}{JL_a s^2 + (R_a J + L_a B)s + (R_a B + K^2)} V_a \quad (7)$$

The expression in (7) can be represented with the block diagram shown in Fig. 2.

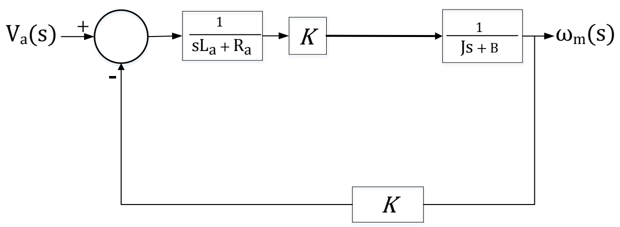

Fig. 2. Block Diagram Configuration of armature voltage control

With the field control method, the field voltage is varied in the constant power region while the armature voltage, and hence armature current, is constant [12]. The dynamics in the field of the motor is represented by the following set of differential equations:

$$\frac{dI_a}{dt} = -\left(\frac{R_a}{L_a}\right) I_a - \left(\frac{KI_f}{L_a}\right) \omega_m + \left(\frac{V_a}{L_a}\right) \quad (8)$$

$$\frac{dI_f}{dt} = \left(\frac{V_f}{L_f}\right) - \left(\frac{R_f}{L_f}\right) I_f \quad (9)$$

$$\frac{d\omega_m}{dt} = \frac{1}{J} K_b I_a I_f - \frac{B}{J}\omega_m - \frac{1}{J} T_L \quad (10)$$

Where $K = K_b I_f$. Taking the Laplace transformation of (1) - (3) the following expression is obtained:

$$\omega_m(s) = \frac{K^*}{L_f s + R_f} \cdot \frac{1}{B} V_f(s) - \frac{J}{B} s\omega_m(s) - \frac{1}{B} T_L(s) \quad (11)$$

Where $K^* = \left(\frac{K}{I_f}\right) I_a$. From (11), the block diagram configuration of the relationship between the field voltage and the motor speed is shown in Fig. 3 (assuming the V_a load torque, $T_L = 0$):

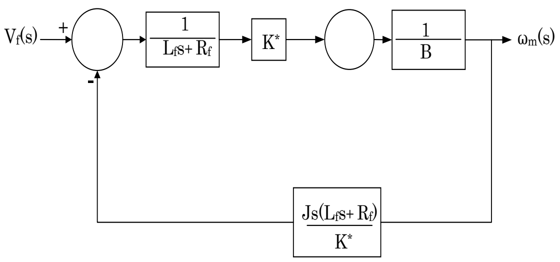

Fig. 3. Block Diagram Configuration of field current control model

The transfer function that defines the input-output relationship between the field coltage, V_f and motor speed, ω is given thus:

$$G_2(s) = \frac{K^*}{JL_f s^2 + (BL_f + JR_f)s + BR_f} \quad (12)$$

Where G_2 relates the motor speed to the field voltage, V_f.

IV. PROPOSED APPROACH

In the following subsections an IMC-based feedback controller, designed using both the armature and field models of the motor, is developed. The speed of the motor is controlled by simultaneously varying the voltage applied to the field winding and the armature. With this combined technique, speed control below and above the rated speed is achieved, and hence the limitations and flaws associated with the individual speed control methods is addressed.

A. IMC-tuned Feedback Control

The IMC control scheme is a model-based control strategy [13], that is based on an assumed system model which gives rise to analytical expressions for the controller settings. The benefit of this approach is that it permits model uncertainty and trade-offs between performance and robustness to be considered in a more systematic manner. Instead of setting a control structure and then trying to 'extract' optimality from this controller, as is the case with conventional PID control, the approach of this work is to postulate a model for both the field and armature parts of the DC motor with desirable control objectives for the speed of the DC motor specified. Then, from these a suitable control structure and parameters will be obtained in a straightforward manner [6,13].

The simplified control system configuration of the combined armature voltage and field current method using IMC approach is shown in Fig. 4. G_{IMC_1} is the IMC controller for the armature part, while $G_{IMC_2}$is the IMC controller for the field part.

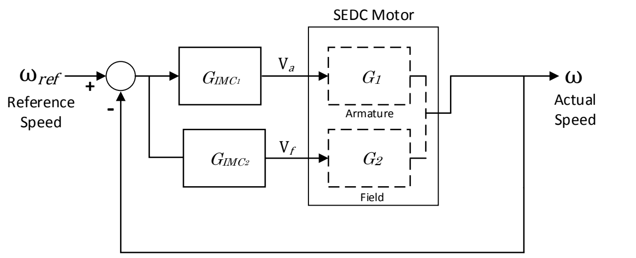

Fig. 4. Combined Control Structure using IMC approach

The equivalent feedback control structure derived using the Internal Model Control algorithm is shown in Fig. 5. Here, the assumed models of the DC motor, controller output and actual speed output are used to obtain optimal settings for the PID controller, G_C.

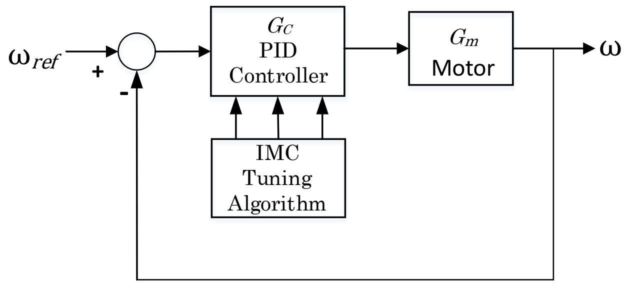

Fig. 5. Equivalent Feedback Control Structure

The combined armature and field control technique is executed in the MATLAB/Simulink environment as shown in Fig. 6. Here two distinct internal model controllers are designed and connected to the armature and field circuitry correspondingly. The output speed of the motor is measured and fed back to the input. The comparison between the reference speed and the actual speed of the DC motor generates an error signal which is utilized by the IMC-tuned PID controllers for control.

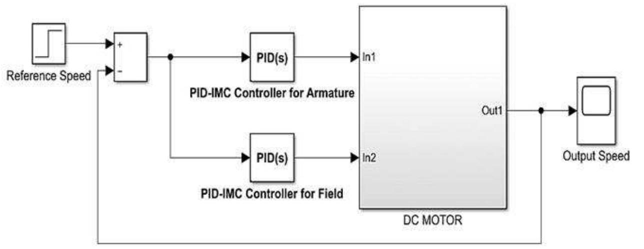

Fig. 6. Simulink Model for combined control of the SEDCM

The proposed model-based control scheme is designed in two steps:

Step 1. The DC motor model is factored as

$$G_m = G_{m+}G_{m-} \tag{8}$$

Where G_{m-} $\widetilde{\mathrm{G}}_{\mathrm{m-}}$ is the invertible part and G_{m+} $\widetilde{\mathrm{G}}_{\mathrm{m+}}$ is the non-invertible part containing any time delays and right-half plane zeros. Since there are no time delays or right-half plane zeros, the approximated plant model is the invertible part.

Step 2. The IMC controller is designed thus

$$G_{IMC} = \frac{1}{G_{m-}} f \tag{9}$$

Where f fis a low-pass filter with a steady-state gain of one and is typically of the form

$$f = \frac{1}{(\tau_c s + 1)^r} \tag{10}$$

τ_c $\mathrm{\tau_c}$is the desired closed-loop time constant – the choice of which is a major decision in the IMC design procedure, r ris a positive integer parameter that will be chosen as 1 for this design. The low-pass filter f f helps to ensure that the resultant IMC-tuned PID controller is reasonably robust, physically realizable and stable [6,14].

Since the desired closed-loop response (transfer function) for the DC motor is a second order system with the general form

$$G(s) = \frac{b_0}{s^2 + a_1 s + a_0} \tag{11}$$

The tuning parameter τ_c is obtained from the roots of the characteristic equation, that is, the poles of the system; which can either be real, or a complex conjugate pair. The systems *damping ratio* $\zeta < 1$, which means there is some overshoot to the step response. Typically for an underdamped response the poles of the system are a complex conjugate pair ($-\sigma \pm j\omega$), hence τ_c is obtained from the reciprocal of the real part of the poles [15].

$$\tau_c = \frac{1}{|Re(s)|} \tag{12}$$

The tuning parameter τ_c ensures a reasonable trade-off between performance and robustness, where a small value is ideal for performance while a large value favours robustness. This work utilizes a value of τ_c that will favour good performance subject to satisfactory robustness [16]. A value of 0.02 is chosen for τ_{c_1}, while a value of 0.05 is chosen for $\boldsymbol{\tau_{c_2}}$, for G_{IMC_1} and G_{IMC_2} respectively. Performance for the controller, here, is defined as excellent setpoint tracking, improved robustness, a fast and non-oscillatory response for the DC motor speed. Comparing the two block diagrams in Figs. 3 and 4, it can be seen from block diagram transformation that the feedback and IMC controllers are equivalent if G_c $\mathrm{G_c}$and G_{IMC} satisfy the relation:

$$G_c = \frac{G_{IMC}}{1 - G_{IMC}G_a} \tag{13}$$

Hence the equivalent feedback controller in Fig. 4 is a function of the DC motor model and IMC tuning algorithm. The derived IMC-tuned PID controller is in the parallel form and is expressed thus:

$$K_{PID}^{parallel}(s) = k_p + \frac{k_i}{s} + k_d s \tag{15}$$

where k_p $\mathrm{k_p}$is the proportional gain,$\mathrm{k_i}$ k_i is the integral gain while k_d is the derivative gain.

V. SIMULATION RESULTS AND DISCUSSION

To illustrate the performance of the proposed feedforward – feedback controller, a separately excited DC motor is chosen with the following parameters:

L_a = 16.2mH, R_a = 2 Ω, V_a = 220 V, L_f= 71.47 H, R_f = 180 Ω, V_f = 220 V, K_m = 1.4, K_b = 0.699, I_f = 1.22 A, I_a = 45.95 A, T_L = 40N.m, B = 0.01 N.ms, J = 0.117 kg.m² ω_{rated} = 1750 rpm.

The IMC-PID controller parameters where designed to be k_{p_1}= 8.363; k_{i_1}= 70.717; k_{d_1}= 0.0677 for armature control and k_{p_2}= 8.240; k_{i_2}= 0.698; k_{d_2}= 3.17 for field control.

MATLAB/Simulink software was used to carry out the simulation, while the reference speed levels for the SEDCM were chosen as follows:

- 1500 rpm was chosen as the reference below the rated speed – DC motors are typically run at speeds their rated.
- 1750 rpm which is the rated speed of the motor.
- 2000 rpm – this reference was chosen, just slightly above the rated so as not to overrun and damage the motor.

Figs 6 to 8 shows the speed response of the motor with the combined approach compared with the individual methods at various setpoint values. Fig 6 illustrates the transient response of the DC motor at 1500 rpm reference speed. It is observed that the combined control method has a minimum overshoot (0.0026%), smaller settling time (0.058seconds) and, hence, faster response compared to the armature and field control methods. This means that the combined control method tracks the reference speed faster and more accurately.

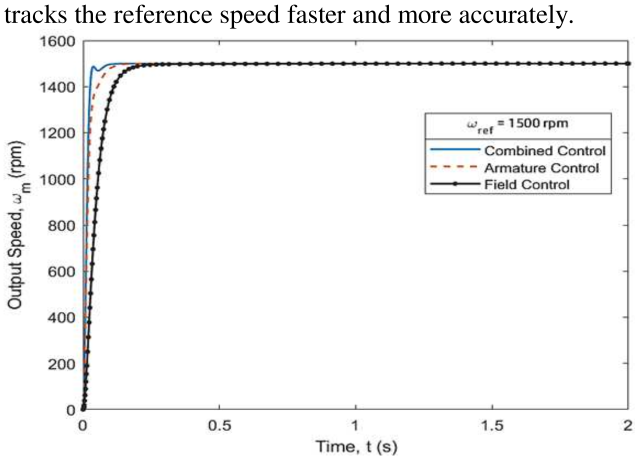

Fig. 7. Response of the SEDCM at 1500 rpm

A summary of the performance characteristics of the combined control method compared to the individual control methods, at reference speed 1500 rpm, is given in Table 1; where $\boldsymbol{t_s}$ is the settling time, $\boldsymbol{t_r}$ is the rise time, $\boldsymbol{e_{ss}}$ is the steady-state error, $\boldsymbol{M_p}$ the percent overshoot.

TABLE I. PERFORMANCE SUMMARY AT BELOW RATED SPEED

	Below rated speed (ω_{ref} = 1500 rpm)		
Parameter	Armature Control	Field Control	Combined Control
t_s (s)	0.0905	0.1654	0.0580
t_r (s)	0.0331	0.0882	0.0198
M_p (%)	0.0532	0.0168	0.0026
e_{ss}	0.00	0.00	0.00

At the rated speed, 1750 rpm, which is the that corresponds with the rated armature voltage, rated armature current, and rated field current. The field control and combined control methods are used to achieve and maintain the speed of the DC motor at the rated speed and above the rated speed. Armature voltage control is not considered here because it is only used to achieve speed below the rated [12]. Fig 7 shows the response of the motor at the rated speed of 1750 rpm. As can be seen from the response the combined control method has a faster response and minimal overshoot compared to the field control method.

The speed of the motor was then increased to just slightly above the rated speed, 2000 rpm, in order not to damage the motor. The combined control and field control methods are used to achieve this by maintaining the armature voltage at its rated value while varying the field current in the constant power region [12]. Fig. 8 shows the response of the motor at reference speed value, above the rated speed. It can be seen that the combined control method gives a better performance.

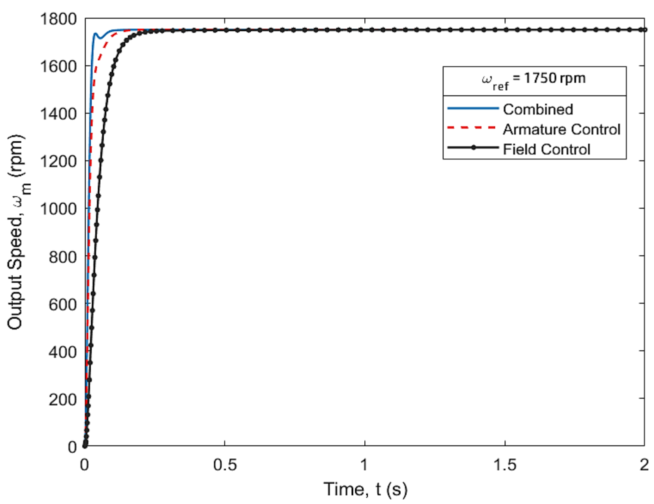

Fig. 8. Response of the SEDCM at 1750 rpm

TABLE II. PERFORMANCE SUMMARY AT RATED SPEED

	At rated speed (ω_{ref} = 1750 rpm)	
Parameter	Field Control	Combined Control
t_s (s)	0.1645	0.0580
t_r (s)	0.0880	0.0198
M_p (%)	0.0182	0.0028
e_{ss}	0.00	0.00

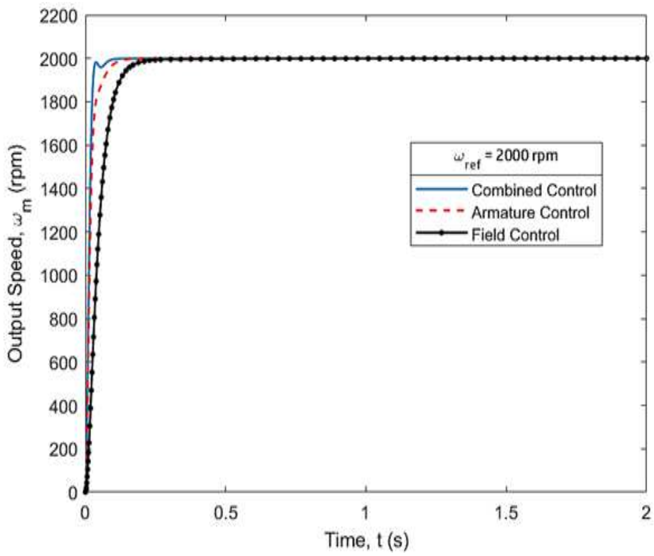

Fig. 9. Response of the SEDCM at 2000 rpm

TABLE III. PERFORMANCE SUMMARY AT ABOVE RATED SPEED

	Above rated speed (ω_{ref} = 2000 rpm)	
Parameter	Field Control	Combined Control
t_s (s)	0.1637	0.0580
t_r (s)	0.0878	0.0198
M_p (%)	0.0191	0.0024
e_{ss}	0.00	0.00

VI. CONCLUSION

In this paper, the speed of a SEDCM was successfully controlled using model-based control techniques. From the simulation results it is clear that modelling both the armature voltage and field current control methods is the most effective in accurately capturing the dynamic effects of the armature and field excitation of the motor. An accurate and robust model is essential for a better control performance.

A wider range of speed control – from below the rated speed to above the motor's rated speed – is achieved with the combined armature voltage and field current control methods, which is an added advantage compared to the individual control methods. From the performance comparisons it can be seen that the combined control method produces better result with respect to the rise time t_s, settling time t_r, and overshoot.

These results are indicative of the ability of the model-based control to suitably select an output voltage in order to achieve a steady motor reference speed.

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