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Modeling and Adaptive Control of Novel Electromechanical Inverter

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Abstract- **A novel idea of electromechanical inverter (EMI) is proposed. This inverter minimizes the complexity and cost of conventional rotating magnetic field inverters. The electromechanical inverter works on phenomena of rotating magnetic field in which changing flux in the external coils induced an emf in the output coil. The rotation of external coils is controlled by dc motor. For controlling the speed of dc motor and rotation of coils, the adaptive control is used to avoid the saturation in magnetic field. The adaptive control system that is used for the electromechanical inverter (EMI) is model-reference adaptive control (MRAC) which has four parts i.e., plant, reference model, adaptation mechanism and control law. An adaptation mechanism is designed with MIT rule of MRAC. It is a novel inverter architecture with simple structure and reduce cost. A dynamic voltage and phase regulation is achieved using this electromechanical inverter. The authenticity of proposed control technique for electromechanical inverter is verified by simulation results. The simulation result shows efficacy of proposed adaptive control technique using MATLAB.**

Index Terms— Electromechanical Inverter, DC Motor, MRAC, speed control, MIT rule.

I. INTRODUCTION

The dc / ac converter technology [1] is critical for industrial use, as it requires a huge number of inverters also including vehicles and systems with renewable energy power [2]. Lately, inversion technology has grown more quickly along with new topologies, that increases power supply. DC (direct current) mode as well as dc power in the batteries are used in electric vehicles are utilizes after converting dc into ac (alternating current). Hence there arises a necessity for transferring direct power to alternating power by using an inverter that is specially designed for this purpose [3]. Power inverters [4] are the most suitable solution for providing various current or voltage power supply to run many applications including alternating current motor drives [5], ac uninterruptible power supply, active harmonic filter [6] and in applications for photovoltaic (PV) [7]. The key purpose associated with the commonly used inverter is sending power from a direct source of power to an alternating capacity by changing its given input dc voltage in order to obtain any desired ac voltage [8]. They are broadly categorized as a single-phase or a 3-phase inverter. Whereas, single-phase inverters are generally utilized in low power domestic applications while the three-phase inverters utilized in utility or business applications [9]. In order to change the dc input, transformers can be used with inverters. Inverters can be characterized dependent on numerous factors for example (I) output waveform type which may be a sine, PWM (Pulse Width Modulation), quasi square and square. (II) inverters utilized as electric devices such as a thyristor, semiconductor, MOSFETs (Metal Oxide Semiconductors Field Effect Transistor) and IGBTs (Integrated Gate Bipolar Transistors) [10]. (III) the design utilized including parallel, series, full or half-bridge also the kind of travel circuit utilized [11]. Depending on the availability of power or current source as a dc connector, two types of inverters can be seen, known as voltage source inverter generally termed as VSI and current source inverter termed as CSI, respectively [12]. The inverter associated with grid assure that the dc connection is kept up at its set reference point [13].

A voltage source inverter (VSI) has a dc power supply which is a direct current voltage with a limit or zero impedance on the inverter input terminals [14]. The current source inverter (CSI) is supplied with an adjustable current from a high-power dc source [15]. Henceforth, a current source inverter (CSI) is a kind of inverter where the current at the dc side keeps up the polarity and therefore, the limit of the dc side voltage decides the flow of normal power through the inverter. Commonly the CSI has not been generally utilized for power applications analyzed to the VSI [16]. This feature is because of the bipolar electronic switches which are required by these inverters [17]. In current source inverters, the dc side is in series connection with a quite huge inductor, that holds the current and is more regular of a current source. The semiconductor industry is that as it may yet to deliver commercially a far and wide inventory of fully controllable bipolar switches [19]. In a voltage source inverter (VSI) dc source voltage keeps up a similar polarity and the limit of the dc source current decides the development of the converter for the normal flow of power [18]. In this typical design, the regular capacitor is used. Typically, the terminals of the dc source of a VSI are in parallel arrangement with a huge capacitor that is illustrative of a voltage source. VSI is utilized for changing over energy from a dc source to an AC, both in an independent mode or when in system associated mode [20]. Rather than the CSI, a VSI needs to invert directing switches or switch cells. Blocking diode isn't required in voltage source inverter design. VSI is less expensive, lighter in weight, and empowers better control which is more adaptable than the CSI [21]. The Z-source inverter (ZSI) is the third kind of inverter structure that utilizes a normal capacitor and an inductor [22]. ZSI comprise X-molded LC impedance, which is responsible for modification in structure from the traditional voltage or current source inverters. The ZSI was generally utilized in three-phase systems before, and the presence of the LC impedance helps in increasing the voltage level [23]. The previously done research is on multi-level is more focused on switching pattern and total harmonics distortion. For eliminating lower order harmonics, the latest methods are being used. The benefit of a multi-level inverter is that this type of inverter provides high power at low switching losses with the best power quality and high voltage ability. But the multi-level inverter does have some disadvantages the primary disadvantage of these it requires numerous switches [24]. Each switch is connected to its driving circuit given that the general system turns out to be more complex and costly [25].

In this paper a novel idea of electromechanical inverter is proposed. The inverter used adaptive control mechanism to compensate phase lag and lead in the power line [26]. The proposed model also deals with line voltage fluctuations. It is used to provide regulated and uninterrupted rated power to load side in case of any sudden load variations and faulty situations. The model is executed by arranging two external inductive coils magnetically connected with an internal output inductive coil. A unique approach is being implemented which used mechanical rotation of the magnetic field. These rotating magnetic field lines passes through the inner coil and as a resultant an emf is induced in the inner coil. This emf is sinusoidal emf and a pure sine wave is generated in the coil. The previously discussed inverters use a lot of electronics devices, switches, capacitors and line transformers which increase the circuit complexity. Various control strategies and switching pattern are used in the current source inverters, voltage source inverters and Z-source inverters which make their implementation difficult in practical applications. In addition to this, these inverters are not cost effective as they use a large number of electronics components. The model presented in this paper deals with phase and voltage regulations electromechanically. The model used the novel technique of electromechanical rotation of magnetic field which overcome the circuit complexity of conventional inverters. Moreover, the proposed adaptive controlled design of electromechanical inverter is able to compensate the voltage and phase regulation against varying load.

Following contributions are incorporated in this paper, (I) a novel inverter architecture with Simple structure and reduce cost, (II) a novel structure for rotation of magnetic field is proposed, (III) dynamic adaptive voltage and phase regulation is achieved using proposed control methodology deals with regulated frequency and voltage as the load is varying by using adaptive control technique.

This paper is organized as follows. Section II presents the description of proposed system. Section III presents control methodology of proposed system. Section IV presents the adaptation mechanism for proposed system. Section V presents the results of simulation and last section presents the conclusion based on the purpose of the paper.

II. PROPOSED SYSTEM DESCRIPTION

Fig 1 shows the electromechanical inverter (EMI) in which an inductive coil Lo connected to load is placed between two external coils Le1 and Le2. These two coils are wound on the motor shaft and connected to supply through brushes, slip rings and voltage regulator circuit. Both the motor and coils i.e Le1 and Le2 get power through solar panel. An adaptive controller is also connected to the motor as shown in Fig 1.

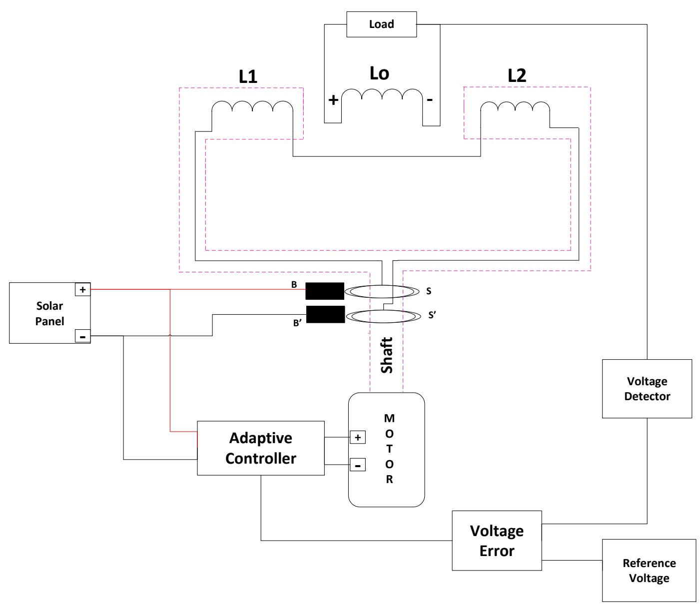

FIGURE 1. Proposed Electromechanical Inverter

When power is ON, current passes through the two coils. The magnetic field lines originates in the coils and coils behave like a bar magnet. As both coils are wound on the shaft, so when motor start running the coils also rotates around an inductive coil Lo. The magnetic field lines of external coil Le1 and Le2 also cut the internal output inductive coil Lo. Due to rotation of external coils, the flux which cuts the internal coil Lo also vary. The voltage is induced according to Faraday's law in which rate of flux increases when the voltage increases and rate of flux decreases when the voltage decreases. In this way the voltage produced across the output coil is sinusoidal wave. The frequency of the generated sine wave depends upon the rotation of external coils Le1 and Le2 that

is rotation of motor shaft. So that the desired frequency can be achieved by monitoring the load and consequently by changing the speed of shaft. An voltage regulator is comprises of FET and PWM generator. The PWM generator is used to generate the duty cycle which is pulsating signal connected to FET's gate terminal. The pulsating signal is generated on the basis of the error between the current sensor and reference current value. The current sensor detect the current in the circuit and compare it to rated current value to calculate the error. In this way, amplitude of the output can be adjusted on the basis of duty cycle generated from PWM.
The loads draws more current during load variations in the power lines. As a result, the output inductive coil Lo of electromechanical inverter also draws more current. Maximum current results in saturation of magnetic field lines in output coil Lo. The motion of output inductive coil slows down due to strong magnetic effects. To maintain the continous motion of external inductive coils, we use adaptive control mechanism.

III. CONTROL METHODOLOGY

The section of control methodology is organized as follows. Section A presents the description of dc motor which contain the modeling of dynamic system. Section B presents the proposed adaptive controller and section C illustrates the adaptation mechanism for proposed system.

A. MODELING OF DC MOTOR

A dc motor gives directly mechanical and rotary motion. It can also give translational motion. In electromechanical inverter, dc motor generates rotating magnetic field around output coil by rotating the motor shafts as shown in Fig 1. The schematic representation of dc motor is shown in Fig 2 [27].

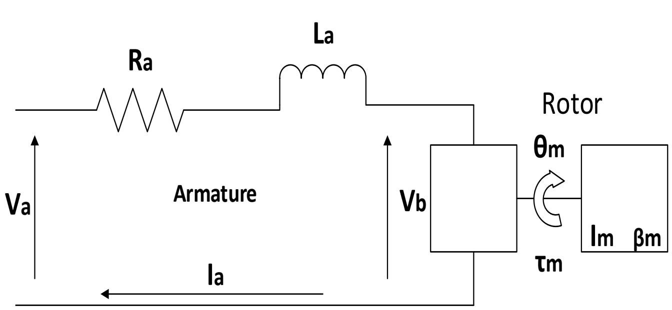

FIGURE 2. Proposed Electromechanical Inverter System.

By following the Fig 1, the equation (1) can be derived on the basis of Newton's second law and equation (2) can be derived on the basis of Kirchhoff's voltage law and it represents the state of dynamics of dc motor. The differential equations are as follows.

$$I_m \frac{d^2\theta}{dt^2} = \tau(t) - \beta_m \frac{d\theta}{dt} \quad (1)$$

$$L_a \frac{dI_a}{dt} = v_a(t) - R_a I_a(t) - v_b(t) \quad (2)$$

The parameters of dc motor are shown in Table 1.

Parameters	Symbols
Moment of inertia	I_m
Torque constant	K_a
Friction coefficient	β_m
Armature current	I_a
Back EMF constant	K_b
Back EMF voltage	v_b
Electrical resistance	R_a
Electrical inductance	L_a
Angle of motor shaft	θ
Input voltage	v_b
Developed torque	τ_m
Load torque	τ_L

TABLE 1. Block diagram of DC Motor.

By using Laplace transform, (1) and (2) changed into the frequency domain in order to obtain transfer function in (3). For controlling the EMI (Electromechanical Inverter) system, we can get the transfer function by incorporating the parameters of dc motor shown in Table 1.

$$\frac{\omega(s)}{V_a(s)} = \frac{K_a}{(L_a s+R_a)(I_m s+\beta_m)+K_a K_b} \quad (3)$$

The transfer function here in (3) presents the rotational speed ω with respect to armature voltage Va. The block diagram of dc motor is shown in Fig 3.

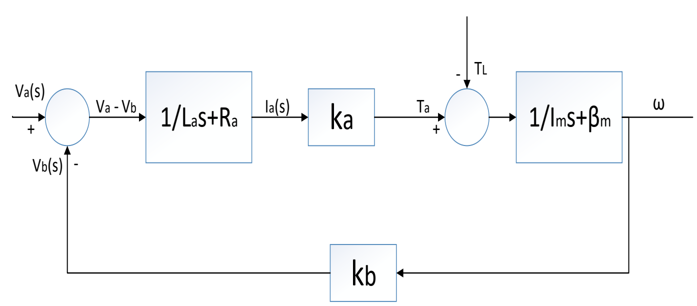

FIGURE 3. Block diagram of DC Motor.

B. PROPOSED ADAPTIVE CONTROL

The adaptive control for proposed electromechanical inverter (EMI) is model-reference adaptive control. This adaptive control has four parts: i) reference model that defines the desired output of control system, ii) an adjustment mechanism for upgrading the adjustable parameters, iii) a feedback control law that contains adjustable parameters and iv) a plant that contains undetermined parameters. The desired response of reference model is compared with output of the system. The controlled parameters that are upgraded based on its error. The purpose of this proposed adaptive control is to converge the parameters into ideal values, that originate the plant response to match the response of the reference model [28]. The block diagram of model reference adaptive control is shown in Fig 4.

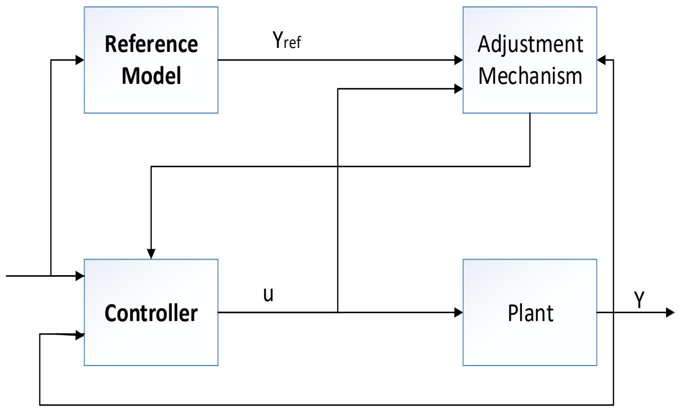

FIGURE 4. Block diagram of MRAC.

C. ADAPTATION MECHANISM FOR PROPOSED EMI SYSTEM

The parameters in the control law are calculated by using the adaptation mechanism. The main purpose of this adaptation is to make the tracking error zero. The adaptation law explores the parameters in model-reference adaptive control (MRAC) systems, such that the response of the system under adaptive control became identical as that of reference model.
There are so many methods which are used in adaptive mechanism such as Lyapunov theory, MIT rule etc [29]. Here MIT rule of adaptation mechanism [28] [30] is used to tune the controller parameter of electromechanical inverter (EMI). First of all, tracking error (e) is defining in model-reference adaptive control (MRAC). The tracking error is expressed in (4). Yp is the output of system and Ym is the output of reference model as shown in Fig 5.

$$e = Y_p - Y_m \quad (4)$$

In MIT rule of MRAC, closed-loop system is considered. The controller of closed-loop system has one adjustable parameter θ. The adjustable parameter in EMI system compensates the voltage and phase regulations. The equation of the error cost function is expressed in (5).

$$J(\theta) = \frac{1}{2}e^2 \quad (5)$$

The main objective is to reduce the tracking error and minimize it to zero. For the purpose of minimizing error, negative gradient of J changes in the direction of parameter θ. γ is an adaptation gain.

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} \quad (6)$$

$$\frac{d\theta}{dt} = -\gamma e \frac{\partial e}{\partial \theta} \quad (7)$$

MIT rule is used to get a method for adjusting the parameter of electromechanical inverter (EMI). This MIT rule adjusting the feed-forward gain. Control law u of MIT rule is composed of theta θ and control signal uc.

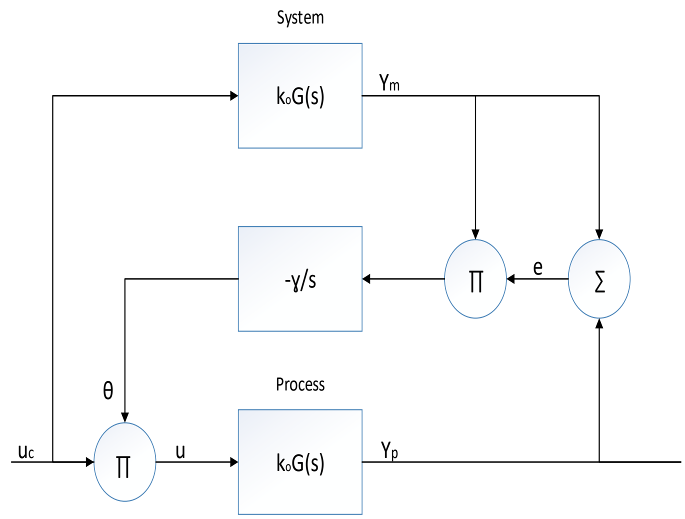

FIGURE 5. Block diagram of MRAC based on MIT rule.

PID control is used to produce control signal. The control law u is expressed in (8) as:

$$u = \theta u_c \quad (8)$$

$$\theta = \frac{k_o}{k} \quad (9)$$

The tracking error in (10) generate by following the Fig 5 in which p is the differential operator and equals to d/dt and becomes the sensitivity derivatives in (11).

$$e = Y_p - Y_m = kG(p)\theta u_c - k_o G(p) u_c \quad (10)$$

$$\frac{\partial e}{\partial \theta} = kG(p)\theta u_c \quad (11)$$

$$\frac{\partial e}{\partial \theta} = \frac{k_o}{k} Y_m \quad (12)$$

Based on the equations (6), (7), (11}) and (12), adaptation law for electromechanical inverter (EMI) can obtain by following MIT rule in (13) and (14).

$$\frac{d\theta}{dt} = -\gamma' \frac{k}{k_o} Y_{m^e} \quad (13)$$

$$\frac{d\theta}{dt} = -\gamma' Y_{m^e} \quad (14)$$

During load variations in electromechanical inverter (EMI) such as when load increase, suddenly it draws more current. As a result, more current passes through the output coil Lo as shown in Fig 1. Maximum draw of current results in more magnetic field, so internal coil Lo becomes a strong magnet which opposes the motion of the outer coils Le1 and Le2. In this way, the rotation of internal coil Lo decrease and output frequency also decreases. To maintain the output voltage up to rated line voltage with fixed frequency up to 50Hz, we use an adaptive controller with dc motor. The line voltage is continuously monitored and compared with reference value. The difference is calculated through comparator circuit and fed into adaptive controller. Based on the value of difference and tracking error, the controller generates the signal and act as a lead and lag compensator, and then delivered it to the motor. If the error is positive, then controller act as lead compensator for controlling the speed of dc motor. If the error is negative, then controller act as lag compensator for controlling the speed of dc motor. As we know that the frequency of output voltage depends upon the speed of regulation of magnetic field. The motor rotates the shaft with more power to catch the required speed. Thus, the desired frequency is achieved through adaptive control mechanism.

IV. SIMULATION AND RESULTS

This proposed adaptive controlled electromechanical inverter (EMI) is tested through MATLAB simulations to observe the behavior of system. The MA5TLAB simulation is implemented via Simulink model. The Simulink model of system is shown in Fig 6.

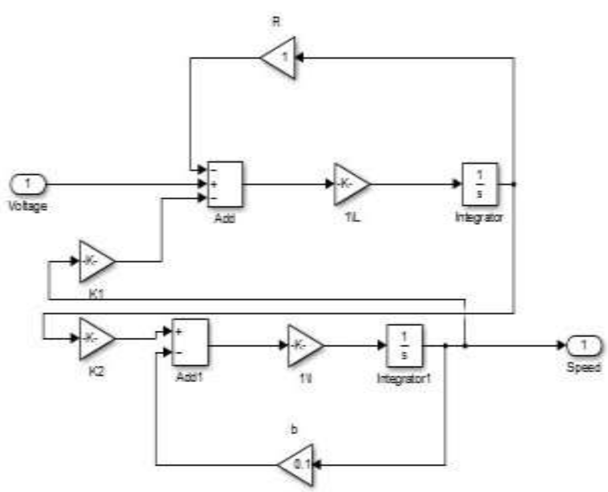

FIGURE 6. Simulink Model of System.

The parameter values of dc motor used during the implementation of model in MATLAB are given in Table 2.

Parameters	Values
Moment of inertia	I_m=0.01
Torque constant	K_a=0.01
Friction coefficient	$\beta_m = 0.1$
Back EMF constant	$K_b = 0.01$
Electrical resistance	$R_a = 1$
Electrical inductance	L_a=0.5

TABLE 2. Parameter values of DC Motor.

A. Case A (System performance without adaptive control)

First of all, linear model of system is implemented without adaptive control through Simulink model. The simulation result of electromechanical inverter without adaptive control is shown in Fig 7. The result of the system is not optimized and it shows slow response.

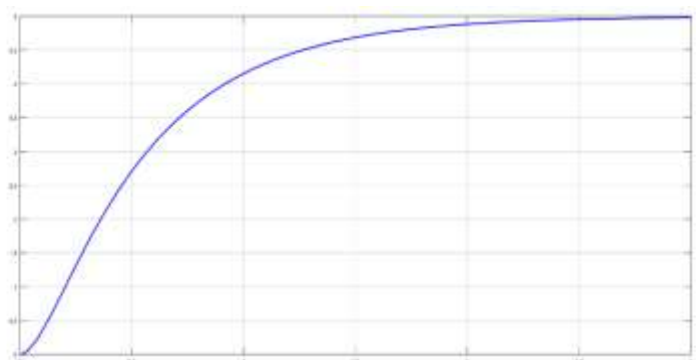

FIGURE 7. Behavior of system without adaptive control

B. Case B (System performance with adaptive control)

This section discusses the system performance in case of voltage and phase regulation.

1. (Case-1) Voltage Regulation:

In line voltage dips and swells, the voltage of the distribution line is compared with rated value and error is generated.

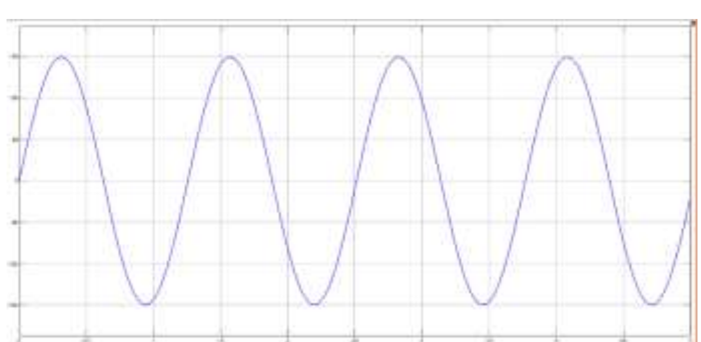

FIGURE 8. Simulation results after voltage regulation.

The error is fed into PWM generator to create the pulsating signal. The voltage dips and swell in distribution line can be adjusted on the basis of duty cycle generated from PWM. The MATLAB simulation results are shown in Fig 8. The result shows that the amplitude of output remain smooth and regulated on load variations.

2. (Case-2) Phase Regulation:

The linear model of system shown in Fig 6 is implemented through subsystem for the purpose of lead and lag compensator. For the lag compensator, a control function is designed for minimizing the error. The behavior of system with lag compensator is shown in Fig 9.

Similarly for the lead compensator, a control function is designed for minimizing the error. The behavior of system with lead compensator is shown in Fig 10.

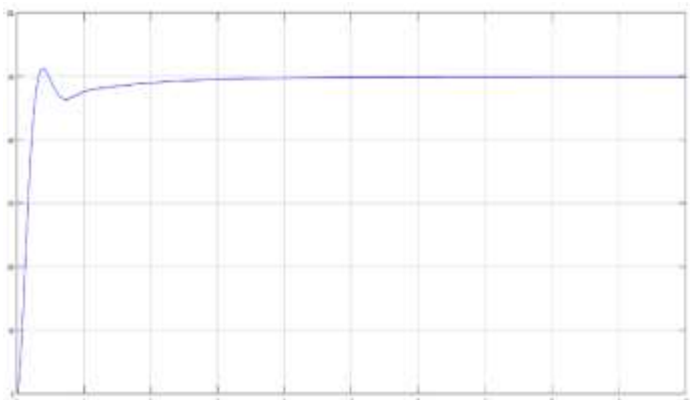

FIGURE 9. Behavior of system with lag compensator

FIGURE 10. Behavior of system with lead compensator

The Simulink model of lead and lag compensator for speed is shown in Fig 11. The behavior of the system with lead and lag compensator is shown in Fig 12. This scope represents the output of lead and lag compensator for controlling the speed of motor.

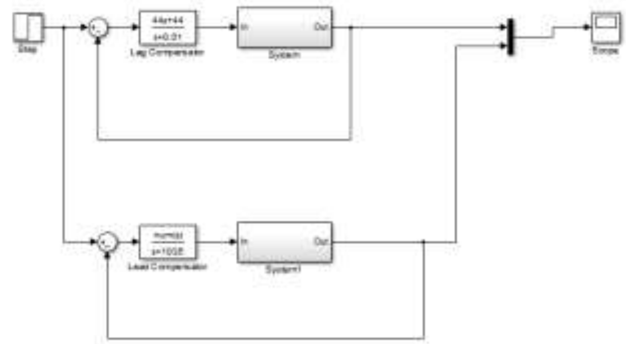

FIGURE 11. Simulink Model of System with lead and lag compensator.

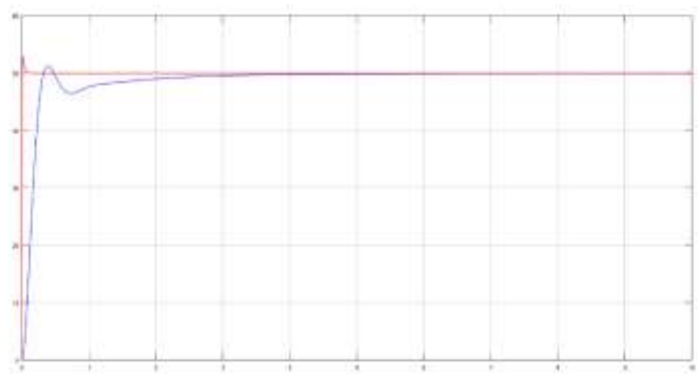

FIGURE 12. Behavior of system with lead and lag compensator.

V. CONCLUSION

This paper has proposed a novel idea for adaptively controlled electromechanical inverter (EMI) to deal with voltage fluctuations. Electromechanical inverter minimizes the complexity and cost of conventional rotating magnetic field inverters. Moreover, the MIT rule of MRAC has been able to compensate the voltage dips and swells against varying load. It also used for dealing the phase regulations. The simulation results are presented for compensating the voltage and phase regulation. In short, this novel electromechanical inverter is more efficient, more economical and easier to handle which can produce pure sine wave.

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