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Performance of a Direct Current Motor Speed Control using a Three-Phase Bridge Thyristor Rectifier

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Abstract: This paper x-rays the workability of a direct current(DC) electric motor speed control via a 3- Φbridge thyristor rectifier. The devices are applied to control the given power so as to check the speed of the DC motor. The gadgets are inserted on a heat sink to lower the heat ratio of the semi-conductor for effective running and good performance of the system. Armature Voltage Control method is applied in this study where the voltage supplied to the winding of the armature of the D.C motor is checked to alter the velocity of the direct current motor. The model of mathematics is utilized to design a D.C. motor that is separately excited whose rating is 5HP (3.78kW), with a voltage of 240V and speed of 1750 rpm. MATLAB Simulink software is used for the analysis and simulation. Speed of the Armature voltage is checked using different 1-ΦAC/DC converters such as half converter, semi converter, full converter and dual converter thyristor-based circuits for speed control of the DC motor. This is actualized through the use of power semi-conductor devices. Conclusively, the study carried out showed that a thyristor can be used in controlling the speed of a direct current motor.

Keywords: *Speed control, direct current motor, three-phase, thyristor rectifier,performance of a D.C. motor*

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I. INTRODUCTION

Motors are essential electrical devices which are common to homes, used in computers, cars etc and for driving of loads in the industry. D.C. motors can be used in steel mills, mines and electric trains. For industrial drives, D.C. motors are the most recommended among the three-phase induction motors[1].

When power is fed to a D.C. motor, it will start rotating until the power is withdrawn. Some D.C. motors rotates at high rpm as seen in computer cooling fans, radio controlled car wheels. A control mechanism is usually suited in a D.C. motor to regulate its motion. It helps to usher in the needed system response. In some cases, PWM-pulse width modulation is employed to control the speed. It works by pulsing the power on and off. The amount of time used in cycling the on and off ratio gives the speed of the motor. For instance, if the energy is cycled at 50% (i.e, half on, half off), the motor will rotate at half the speed of 100%. Each pulse appears rapid such

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that the motor is seen to continuously spin[2].

Many of the motors used in the industry are fed direct from the power line and as such, the response of the motor depends largely on the kind of load attached to its axis. When the load is light in weight, the motor rotates at low speed and sets up a low torque and when the load is heavy, the motor runs at low speed and brings forth more torque to meet up the load demand. When a motor is connected directly to a D.C. electrical network, its response is fixed and remained unaltered for a defined voltage in the power supply network. In a large industrial sector however, there are ways of controlling the operating characteristics of a motor such as varying the speed and frequency[3].

D.C. motors are the earliest form of electro-mechanical machines which are more preferable over other AC machines because of their speed control ability. The speed of a D.C. motor varies directly proportional to its armature voltage by changing the armature voltage. Getting an appropriate speed controller is very crucial[4]. D.C. motors offer better quality with increase in torque and small volume. In the past, rheostatic armature control technique was used greatly in controlling the speed of small power D.C. motors, but the controllability, low cost, increase in efficiency, and greater current carrying capacities of static power converter, gave rise to drift in the performance of Electrical drives[5]. D.C. motors have high starting, accelerating and retard torque, high response features, fast braking and easy control adaptations. They are vast and flexible in terms of speed control. D.C. machines are applied in robotic systems, vehicles that are controlled, rolling steel mills, cutting machines, overhead cranes, electrical traction etc. They are simple and cheaper when compared with AC drives[6].

D.C. motors have high ratio of power to weight, absence of current excitation, low noise operation and of course, less expensive which make them more utilised than others. Proportional(P), Integral(I) and Derivative(D) or PID controller are mostly used as speed control measures which have some hiccups such as undesired overshoot, staggered operation due to abrupt change in load torque and the sensitivity to controller gains Ki and Kp parameters. Controller operation depends on the precise nature of the model and control system variables[7]. The researchers therefore proposed artificial intelligence (AI) techniques in solving the problems.

Ref[8]used Pulse Width Modulation(PWM) method in managing the speed of the motor in conjunction with Atmel AT89s52 microcontroller which generates the pulse. This method is only efficient on low frequency though the method enables the motor to run at fixed speed irrespective of load. The PID techniques of Ziegler-Nichols, and Chien-Hrones Reswick are proposed for D.C. motors speed control[9]. GUL/MATLAB are used in implementing the model. The result obtained shows Ziegler-Nichols having faster system response with favorable overshoot while Chien-Hrones Reswick gives lower overshoot with suitable system transient response.

Ref[[10]used PID via Genetic Algorithm (GA) to control the speed of DC motors taking into cognizance the nonlinearities and instabilities of the model. The speed is analysed in MATLAB using Proportional (Kp),Integral(Ki) and Derivative(Kd). The result of the combination of GA and PID shows better performance in terms of least ascent time, settling time, overshoot and near steady state error. D.C. motor is essential in changing electrical energy-D.C. into mechanical energy(rotary motion). Ref[1]described an accurate dynamic model used in studying DC motor controller using FPGA. The experimental results proved right the dynamic model. The real time responses portray the relationships between the acceleration and output of the motor. Ref[2]proposed a model of controlling the speed of DC motors using PID controller in LabView which sends serial command to the D.C. motor using PWM pins on the ATmega 8A microcontroller board. The motor's speed is tracked via an Infrared sensor(IR) which is returned backed to the PID controller as feedback for computing and compensating the error produced if any. The method applied helps in sustaining the stability of the system.

Ref[4]looks at comparative study between PID tuning methods and the Modified Ziegler-Nichols methods of controlling the speed of permanent magnet direct current (PMDC)motor. The researchers adopted ATmega 328 microcontroller and IBT-2 driver to checkmate the motor's speed via PWM. The result showed Modified Zieglar-Nichols tuning method of better performance for it provides more dynamic response to load disturbance with a bearable overshoot. An individual PID controller and a Fuzzy Based PID controller has been studied to control the speed of a DC motor. The issue with PID controller is the tuning of the parameters and so, the researchers chosen Fuzzy instead. The performance of the PID parameters are 0.009s of rising time, 0.082s settling time while Fuzzy-PID controller has rise time of 0.006s and 0.066s settling time. In comparing the PID controller with past works, the damping ratio increased by 10%, rise time increased by 30%, settling time dropped by 20% and peak time improved by 25% while Fuzzy-PID controller damping ratio is enhanced by 14.29%, rise time improved by 58.57%, settling time reduced to 19% and peak time improved by 30%. Fuzzy-PID is found to perform better than PID controller[11].

Thyristor is a four-layered, three terminal semiconductor components, with each layer comprising P-type or N-type material. Whenever the gate accepts a set of current, it begins to act until the voltage across it is under forward bias, thus it goes about as a bistable switch under this condition. To control the huge measure of current of the two leads, we need to model a three-lead thyristor just by merging little current to that current. This activity is known as control lead. If the expected potential difference between the two leads is under breakdown voltage, a two-lead thyristor is utilized to turn on the thyristor. Thyristor is otherwise called a Semiconductor-controlled-Rectifier (SCR) or Silicon-Controlled-Rectifier (SCR).

The objectives of this study are to :

- Study the instantaneous and average values of the armature voltage for 3-ϕbridge thyristor rectifier
- Examine the rotor speed by varying thyristor firing angle for a 3- thyristor rectifier
- Evaluate the armature under varying angle for a 3-ϕbridge thyristor rectifier
- Examine the electromagnetic and load torque response by varying the firing angle.

II. EXPERIMENTAL AND METHODS

A. Materials

Separately excited DC motor, three-phase bridge thyristor rectifier and laptop are the materials used for this analysis as listed in table 1,2 and 3.

TABLE 1
RATED MOTOR PARAMETERS (SOURCE: [12])

S/N	Parameter	Rating
1	Power	5HP (3.78KW)
2	Armature voltage	240V
3	Field Voltage	300V
4	Speed	1750rpm

TABLE 2
MACHINE PARAMETERS

S/N	‘ Parameter	Rating
1	‘ Resistance in the armature	2.581 Ω
2	‘ Inductance in the armature	0.028H
3	‘ Field Resistance	281.2 Ω
4	‘ Inductance in the field	1.56H
5	‘ EMF and Torque Constant	0.9483Wb
6	‘ Moment of Inertia	0.0222Kgm^2
7	‘ Coefficient of Viscous Friction	0.003Nms

TABLE 3
THYRISTOR RECTIFIER PARAMETERS

S/N	Parameter	Rating
1	Voltage (three-phase RMS)	400V
2	Frequency	50Hz

B. Method

The research method adopted is Armature Voltage Control Method. The voltage from the grid to the winding of the armature of the DC machine is checked so as to alter the velocity of the direct current machine. Simulink is used to model the thyristor so as to regulate the velocity of the direct current machine at its output. The principle of mathematics is utilized to model a DC motor that is excited separately for better control and implementation as in Figure 4. The dynamic model of the DC motor is obtained from the equivalent circuit diagram of a DC motor as in Figure 2. The control system technique is mathematically modelled. Based on the various mathematical models of the system, a Simulink model is built using appropriate Simulink library-boxes as in Figure 3. Finally, a simulation of the selected DC motor with the incorporation of the control system is carried out under various dynamic conditions.

1) Dynamic modelling of DC motor :

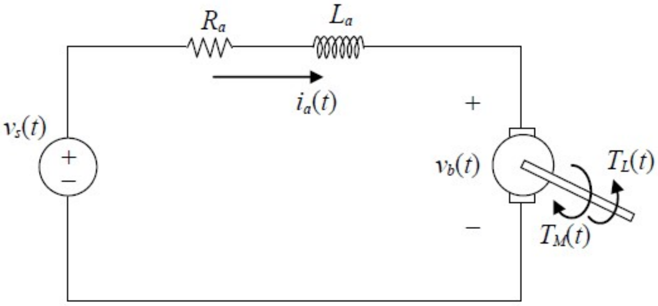

Fig. 1. Equivalent circuit of DC motor (Source: [**?**])

The dynamic model equations of the DC motor is gotten from the equivalent circuit of the DC motor as in Figure 1, where R$_a$ represents the armature resistance and L$_a$ represents the winding leakage inductance [13]. With respect to Kirchhoffs voltage law, the DC motor electrical equation is described in (1), Ref [12]

$$R_a i_a(t) + L_a \frac{di_a(t)}{dt} + v_b(t) = v_s(t)......(1)$$

Where i$_a$ (t) is the current in the armature, v$_b$ (t) is back e.m.f. voltage and v$_s$ (t) is voltage source. The back emf voltage v$_b$ (t) is proportional to ω(t) (angular velocity) of the rotor in the motor, written as

$$v_b(t) = k_b \omega(t)....(2)$$

Where k$_b$ is the back e.m.f Constant. Also, the machine creates a T$_M$ (torque) which is proportional to the current in the armature i$_a$ (t) written as

$$T_M(t) = k_T i_a(t)....(3)$$

Where k$_T$ is the torque Constant If the voltage entering the machine v$_s$ (t) = V$_s$ remains unchanged, the emerging current in the armature i$_a$ (t)=I$_a$, angular velocity ω(t)= $\Omega$and torque T$_M$ (t) = T are also unchanged during the steady state. (1) to (3) gives

$$R_a I_a + k_b \Omega = V_s.....(4)$$

$$T = k_T I_a.....(5)$$

Having in mind that power can be conserved, the input power I$_a$ V$_s$ is same as the outside power T$\Omega$and the power R$_a$ I$_a{}^2$ dissipated in the resistance, that is,

$$V_s I_a = T\Omega + R_a I_a^a.....(6)$$

Putting V$_s$ into (6), it gives

$$T = k_a I_a....(7)$$

Arising from (5), both k$_T$ and k$_b$ are the unchanged. From (2), we can rewrite (1) and (3) as

$$R_a i_a(t) + L_a \frac{di_a(t)}{dt} + k\omega(t) = v_s(t).....(8)$$

$$T_M(t) = k i_a(t)....(9)$$

Where K= k$_T$= k$_b$., if the DC motor is used to drive an external torque T$_L$ (t) of payload, then its mechanical behaviour is described as

$$J_M \frac{d\omega(t)}{dt}(t) + B_M \omega(t) = T_M(t) - T_L(t).....(10)$$

Where J$_M$ is the rotor moment of inertia and B$_M$ is the friction coefficient Based on (8), (9) and (10), the dynamic equation of the DC motor can be expressed as

$$L_a \frac{di_a(t)}{dt} + R_a i_a(t) + k\omega(t) = v_s(t).....(11)$$

$$_M \frac{d\omega(t)}{dt}(t) + B_M \omega(t) - k i_a(t) = -T_L(t)....(12)$$

The electrical time constant L$_a$/R$_a$ can be done away with and (di$_a$ (t))/d$_t$ neglected and thus (11) becomes

$$i_a(t) = \frac{1}{R_a} v_s(t) - \frac{k}{R_a} \omega(t)....(13)$$

Substituting it into (12), we have

$$\frac{d\omega(t)}{dt}(t) + \left(\frac{B_M}{J_M} + \frac{k^2}{J_M R_a} \right) \omega(t) =$$
$$-\frac{1}{J_M} T_L(t) + \frac{k}{J_M R_a} v_s(t)......(14)$$

The motor is found to have two external sources, input voltage v$_s$ (t) to drive the motor and the torque T$_L$ (t) reacted from the payload.

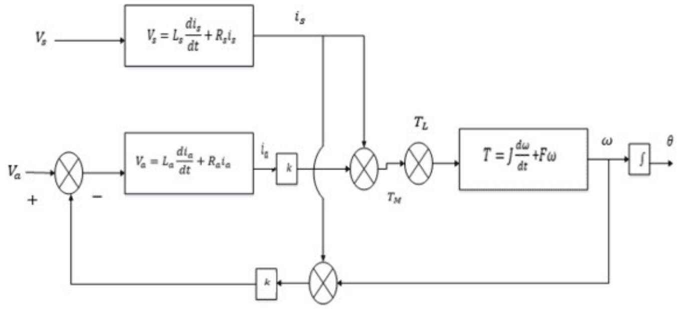

Fig. 2. Dynamic model of DC Motor

2) Design simulink model for simulation :

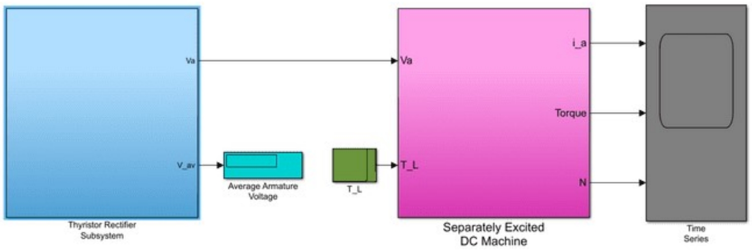

Fig. 3. The thyristor-fed DC drive simulink model

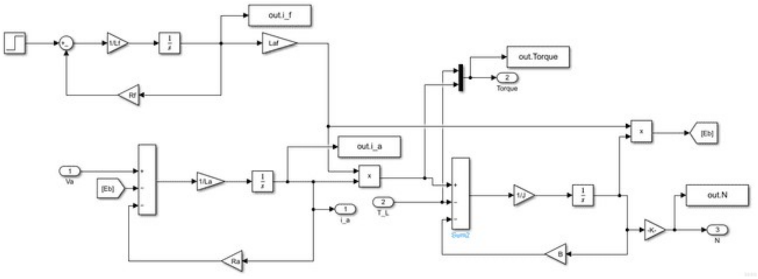

Fig. 4. Separately excited DC machine model internal view

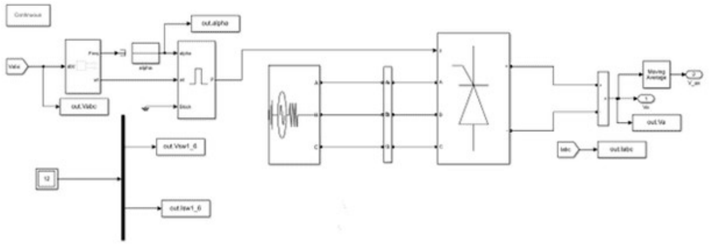

Fig. 5. Thyristor rectifier subsystem

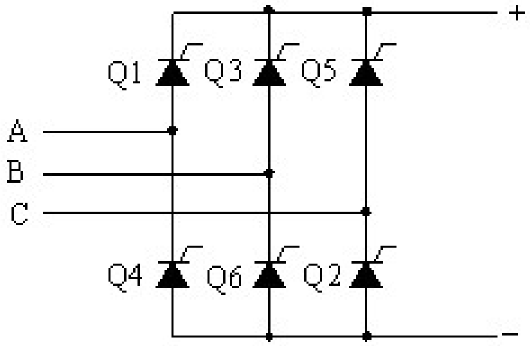

Fig. 6. Three-phase thyristor bridge configuration

III. RESULTS AND DISCUSSION

A. Instantaneous and average values of armature voltage for a three-phase bridge thyristor

The 3-ϕbridge thyristor gives the flexibility of higher output voltage as in Figure 8. Figure 7 shows the variation of the firing angle. The instantaneous value of the armature voltage has a peak value of 565.7V which is the amplitude of the line-to-line voltage as opposed to a value of 326V, the phase-to-earth value for a single-phase source. The average armature voltage at α= 300 firing angle, is 460V as in Figure 8. The higher average value of the three-phase topology allows a wider range of speed control particularly in the higher speed range.

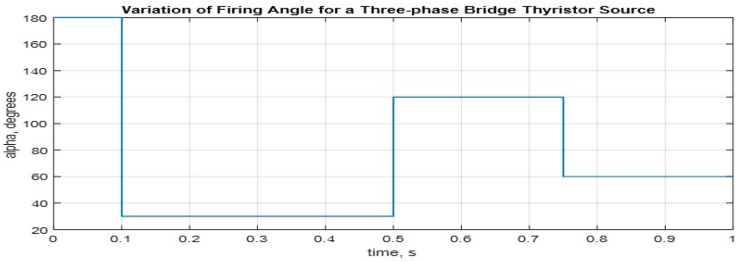

Fig. 7. Variation of the firing angle for a three-phase bridge rectifier

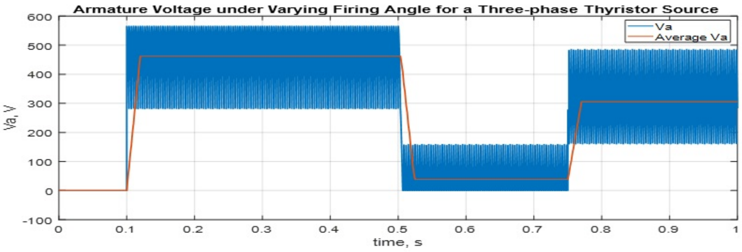

Fig. 8. Plot of the armature voltage instantaneous and average values for a three-phase bridge thyristor rectifier.

B. Rotor Speed by Varying Thyristor Firing Angle for a 3-ϕThyristor Rectifier

The rotor speed of the motor is 4350rpm when the firing angle is 300, A firing angle of α= 120^o gives an average armature voltage of 40V and a rotor speed of approximately zero. A firing angle of α= 60^o gives an average voltage of 300V and a speed of 2400rpm as in Figure 9. The 3-ϕrectifier shows a maximum output voltage ripple of 78.75V.

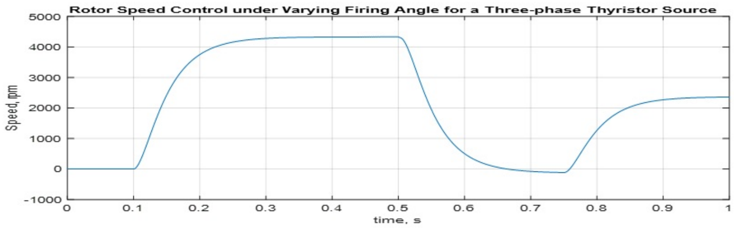

Fig. 9. Rotor speed control by variation of the thyristor firing angle for a three-phase bridge thyristor rectifier.

C. *Armature Current and Electromagnetic Torque Response by Varying Thyristor Firing Angle for a 3-ϕThyristor Rectifier*

The armature current and electromagnetic torque as in Figure 10 and 11, show similar waveforms. The peak starting current, and torque have higher values due to the higher applied voltage. They also show a similar ripple content. The maximum blocking voltage of the thyristors is 565.7V.

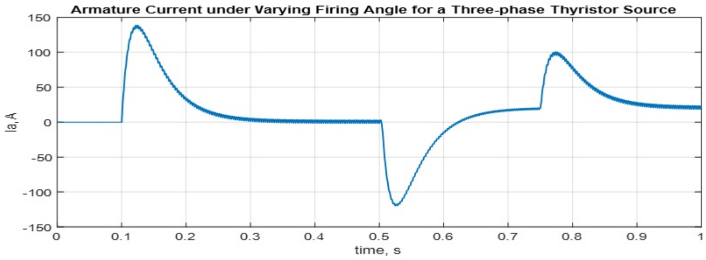

Fig. 10. Plot of the armature current under varying firing angle for a three-phase bridge thyristor rectifier

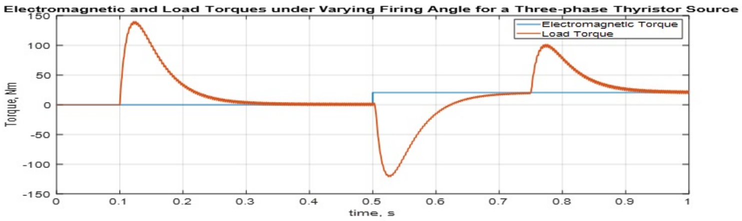

Fig. 11. Plot of the electromagnetic and load torques under varying firing angle for a three-phase bridge thyristor rectifier.

IV. CONCLUSION

Three-phase bridge thyristor rectifier has been proven as an effective means of controlling the speed of a D.C. motor. The response of the speed when the motor was fed by an ideal DC voltage source of 240V at time t = 0.1sec is that the excitation field reached steady state. When the excitation voltage of 300V is applied to the field winding at time t = 0.05sec, the excitation current reaches its steady-state value of 1.1A with a rise time of 0.03sec, settling at 0.08sec simulation time. The armature current has a similar exponential buildup of the field current as since it is modelled as a first-order ordinary differential equation. The buildup of the armature current is slower, though the inductance of the armature winding, La = 0.028H, is much less than the inductance of the field (excitation) winding, Lf = 1.56H. This can be explained by the fact that the applied (rated) voltage of the armature circuit Va is 240V less than the field voltage while the influence of the speed in the back emf also plays a role. From 0.1 to 0.5 sec of the simulation time, the motor operated in no-load condition. The rotor accelerates to a no-load speed of No = 2248rpm at time t = 0.4sec. In that interval, the armature current rises to a peak value of 72A which is approximately 350% of the rated value - and then falls to a value of approximately 2A instead of the theoretical no-load value of zero. This is due to the current drawn by the armature circuit to compensate for the viscous frictional torque which is proportional to the rotor speed.

V. DECLARATION OF COMPETING INTEREST

All authors declare that there is no conflict of interest.

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