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DESIGN AND MODELING OF A PROPORTIONAL DERIVATIVE CONTROLLER FOR A THREE-PHASE INDUCTION MOTOR SPEED

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Abstract

Many applications require variable speed operation. The motor speed needs to be controlled to save more power. It became highly imperative for further research to find out an efficient method that can yield an optimal speed control. This study presents the design and modeling of a proportional derivative controller for a three-phase induction motor speed control. The scalar control methodology was used to investigate the performance of motor speed control. For the controller approach, proportional-integral (PI) and proportional-derivative (PD) controllers were investigated. Simulation results using MATLAB (Simulink) software is presented. Furthermore, investigation of the PI, and PD performance shows that the PI controller performed poorly due to existence of high peaks, overshoots and rise time. However, the PD controller yielded satisfactory results. Hence, PD controller revealed a better performance with a 1.01s settling time and a steady state error of 1.0 as against that of the PI controller which was unstable, an overshoot of approximately 96% and a steady state error of 1.22.

1.0 INTRODUCTION

In modern industrialized countries, most of the electrical energy is converted to mechanical energy to drive industrial motors for the production process. An induction motor as the name implies is a unique type of AC motor whose power supply to the rotor is made possible by electromagnetic induction rather than commutator or slip rings as in other motor types such as DC or synchronous motors [1].

Revolutionary advances in modern control, electrical and electronic engineering led to the emergence of induction motors. These motors have unique designs and construction and have peculiar adaptability to modern electrical system applications [2]. Induction motors are the most widely used electrical motors [3]. The major problem in induction motors is that they are sensitive to deviation in estimated motor parameter values used in the control algorithm [4]. These motors are not good for appliances that need considerable speed control. The benefit of improving the motor drive industry has touched diverse applications including mechatronics [5]. Besides the limitations of the voltage and frequency (V/F) control method, it is complex [6]. Operation of induction motors at very low speeds is still problematic despite all the efforts

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and progress because a standard set of tests or benchmarks has not been agreed [7].

We have single-phased and multi-phased induction motors. However, most electrical appliances use variable speeds which may not be suitable for single-phase appliances [1][8]. An induction motor is an electrical drive used to drive a system. It is the means of giving motion to load(s) [9]. The three-phase induction motor has played a leading role in enhancing productivity in modern industries and it is therefore responsible for the reduction in labour cost of manufacturing concerns throughout the industrialized world [10]. Three-phase induction motors are used to drive pumps, fans, compressors, mixers, agitators, mills, conveyors, crushers, machine tools, and cranes. This system is popular due to its simplicity, reliability, higher efficiency, robustness, higher starting torque less maintenance, and low cost [11][12].

The speed control technique is essential in an adjustable speed drive system [13]. The control techniques are developed to take advantage of the advances in semiconductor technologies and control algorithms. Speed control methods can be classified into scalar and vector control [14]. The scalar control method is the widely used scheme for controlling the speed of an induction motor [15][16]. The scalar control technique is based on steady-state relationships where the magnitude (voltage or current) and frequency are controlled. The classical variable frequency V/F scheme is a scalar control based on this principle. Constant V/F speed control is the most widely used scalar control scheme [17]. Scalar control, especially open-loop gives an economical drive with good behavior. The behaviour can be improved, perhaps with better parameter variations, particularly of stator resistance [18]. The difference between the stator (synchronous speed) and rotor speeds is called the slip. The rotation of the magnetic field in an induction motor has the advantage that no electrical connections need to be made to the rotor [19]. A slip control loop is used in the closed loop method since the slip is proportional to the induction motor torque [15].

The maintenance cost of an induction motor can be neglected due to its construction [20]. Three-phase motor is utilized due to the ratio of the power to speed in the industrial application; V/F scalar controller is used to confirm the execution of both the speed and torque [21]. Controllers help to regulate processes and performances. They could be linear or non-linear. Linear control systems are homogenous whereas non-linear controllers are non-homogenous. Linear controllers include P controllers, PI controllers, PID controllers, etc. while adaptive control, Fuzzy, and Neuro-Fuzzy control are examples of non-linear control methodologies [22][23][24]. PD-control contains the proportional control's damping of the fluctuation and the derivative control's prediction of process error [25]. It corrects an error between a measured process variable and a desired set point by calculating the difference and then performing a corrective action to adjust the process accordingly.

2.0 THREE PHASE INDUCTION MOTOR MODEL

This paper looked at three methods of speed control; by varying the supply voltage, by varying line frequency and by varying frequency, and keeping the V/F ratio constant. The V/F method is compared with the listed methods of speed control in terms of performance and efficiency.

The methodology comprises the design and modeling of the induction motor controllers and the simulation of the designed controllers using SIMULINK. Related equations were adopted to appropriately model a three-phase induction motor. The synchronous speed N_s per minute is given by [26];

$$N_s = \frac{120}{P} \quad rpm \tag{1}$$

Where, P is the number of poles.

The rotor speed N_r is given in Equation (2):

$$N_r = N_s(1 - S) \tag{2}$$

The slip is given in Equation (3);

$$S = \frac{N_s - N_r}{N_s} \tag{3}$$

Representation of the rotor current is expressed as;

$$I_2 = \frac{V_0}{\left[\left(R_s + \frac{R_r}{s}\right)^2 (X_s + X_r)^2\right]^{0.5}} \tag{4}$$

The electromagnetic torque (T) is expressed as [23];

$$T = \left[\frac{3}{N_s}\right]\left[\frac{R_s}{S}\right]\left\{\frac{V_0}{\left[\left(R_s + \frac{R_s}{s}\right)^2 (X_s + X_r)^2\right]^{0.5}}\right\} \tag{5}$$

Where, V_0 is the stator voltage, R_r is the rotor resistance, R_s is the stator resistance, X_s is the stator reactance, and X_r is the rotor reactance.

3.0 THREE PHASE INDUCTION MOTOR CONTROLLERS DESIGN AND MODELING

A servo motor controller was deployed in this work as shown in Figure 1,

The applied voltage (V_s) is given by;

$$V_s(s) = (R + L_s)I_s + V_0(s) \tag{6}$$

Where, I_s is the armature current (amps), R is the armature resistance (ohms), L_s is the motor winding inductance (Henries).

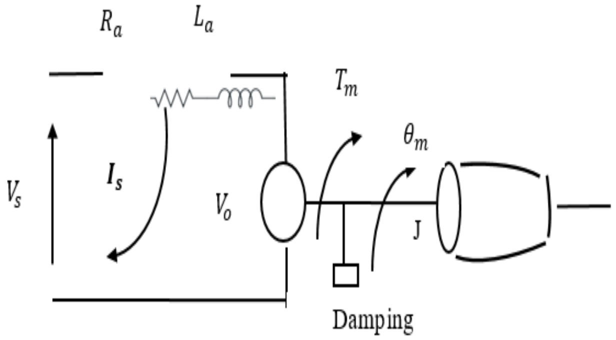

Figure 1: Servo motor controller

$$V_s(s) = Z_s I_s + V_0(s) \quad (7)$$

The constant V_0 is expressed as;

$$V_0(s) = \frac{d\theta}{dt} = K_t S\theta_m(s) \quad (8)$$

The load torque T_m is the load torque;

$$T_m = K_b I \quad (9)$$

Where K_b is the motor voltage constant and I_s is the armature current.

$$I_{(S)} = \frac{T_m(s)}{K_b} \quad (10)$$

Mechanical rotational system from Newton 2nd law is expressed as;

$$\sum T = J\ddot{\theta}m \quad (11)$$

The load torque, $\theta_m(s)$ is given by;

$$\theta_m(s) = \frac{T_m(s)}{JS^2 + DS} \quad (12)$$

Where, *J*, is the total inertia of motor armature plus load and *D* is the friction coefficient.

The transfer function of the induction motor, $G_{(S)}$;

$$G_{(S)} = \frac{K_b/_{LJ}}{S^3 + \left[\frac{RJ+LD}{JL}\right]S^2 + \left[\frac{RD+K_bK_t}{JL}\right]S} \quad (13)$$

Substituting, values, where; $K_b = 0.0190859317 rev^{-1}m$; $K_t = 0.5$; $\mathrm{J} = 0.0076\, kgm^2$; $\mathrm{D} = 0.0007\frac{kgm^2}{s}$; $\mathrm{R} = 2.3\Omega$; $L = 0.261\mathrm{H}$. Equation (13), becomes:

$$G_{(S)} \approx \frac{10}{S^3+9S^2+6S} \quad (14)$$

3.1 PI and PD Systems Design and Modeling

3.1.1 PI system design and modeling

The transfer function for PI industrial motor drive control is derived from Figure 2. The second operational amplifier (OP-AMP) in the circuit is provided so that positive polarity can be obtained at the output voltage if the input voltage is positive and vice versa.

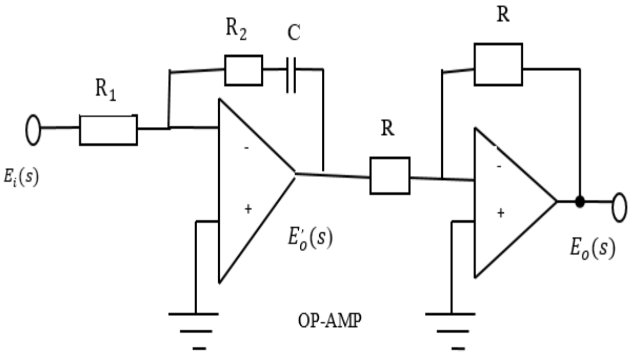

Figure 2: Circuit diagram of an OP-AMP PI controller

The transfer function for *PI* industrial motor drive control is depicted;

$$\frac{|E_o'(S)|}{|E_i(S)|} = \frac{R_2}{R_1} + \frac{1}{R_1SC} = K_P + \frac{K_1}{SC} \quad (15)$$

Where, K_P and K_1 are proportional constant and integral constant, respectively.

3.1.2 PD system design and modeling

The transfer function for PD industrial motor drive control is derived from Figure 3. The second OP-AMP in the design is provided to maintain input polarity at the output voltage.

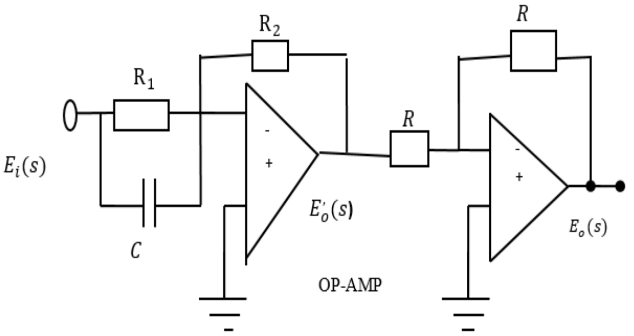

Figure 3: Circuit diagram of an OP-AMP PD controller

The transfer function for PD industrial motor drive control is given by;

$$\frac{|E_O(S)|}{|E_i(S)|} = \frac{R_2}{R_1} + R_2SC = K_P + K_DS \quad (16)$$

Where K_P is the proportional constant and K_D is the derivative constant of the controller.

4.0 RESULTS AND DISCUSSION

Stability tests, controllability tests, and observability tests, were performed to ascertain the suitability of the system.

4.1 Stability Test

Using Routh Hurwtz criterion, the characteristic equation is depicted;

$$S^3 + 9S^2 + 6S = 0 \quad (17)$$

$$\begin{array}{c|cc} S^3 & 1 & 6 \\ S^2 & 9 & 0 \\ S^1 & 6 & 0 \\ S^0 & 0 & 0 \end{array}$$

The system is stable since the first column is of the same sign, all positive.

4.2 Controllability Test

Converting the transfer function, Equation (14) into Matrix form;

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -6 & -9 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 10 \end{bmatrix} U, Y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \quad (18)$$

The controllability test is depicted in;

$$Q_{CB} = [B: \quad AB: \quad A^2B: \ldots A^{n-1}B \quad (19)$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -6 & -9 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 10 \end{bmatrix}, Y = C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \quad (20)$$

$$A^2B = \begin{bmatrix} 0 & 0 & 1 \\ 0 & -6 & -9 \\ 0 & 54 & 75 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 10 \end{bmatrix} = \begin{bmatrix} 10 \\ -90 \\ 750 \end{bmatrix} \quad (21)$$

$$\mathrm{Q_{CB}} = \begin{bmatrix} 0: & 0: & 10 \\ 0: & 10: & -90 \\ 10: & -90: & 750 \end{bmatrix} \quad (22)$$

The system is controllable since,

$$|Q_{CB}| = -1000 \quad (23)$$

4.3 Observability Test

The observability test is depicted;

$$Q_{OB} = [C^T: A^T C^T: (A^T)^2 C^T: \ldots (A^T)^{n-1} C^T \quad (24)$$

$$C^T = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, A^T \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & -6 \\ 0 & 1 & -9 \end{bmatrix} \quad (25)$$

$$(\mathrm{A^T})^2 \mathrm{C^T} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -6 & 54 \\ 1 & -9 & 75 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (26)$$

$$\mathrm{Q_{OB}} = \begin{bmatrix} 1: & 0: & 0 \\ 0: & 1: & 0 \\ 0: & 0: & 1 \end{bmatrix} \quad (27)$$

$$|Q_{OB}| = 1 \quad (28)$$

The system is observable since $|Q_{OB}| \neq 0$. Rank $\mathrm{Q_{CB}} = 3$ and $n = 3$.

4.4 MATLAB Simulations Results

Simulation was carried out on the torque against speed for the three-phase induction motor. Graphs are presented in this section to represent the steady-state behaviour of the three-phase induction motor. Various sensitivities were performed to investigate the effect of the changing parameters on the torque-speed value for the three-phase induction motors. For the controller approach, PI, and PD controllers were investigated. Figure 4 presents the graph of electromagnetic torque and speed at varied supply voltage.

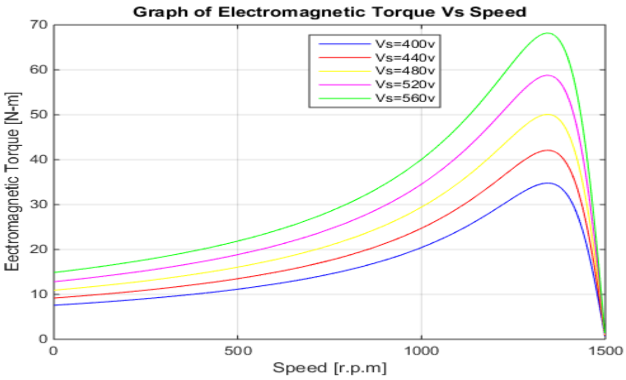

Figure 4: Torque -speed at varied supply voltage

From Figure 4, it can be observed that as the supply voltage increases, the torque increases and the speed remains constant. To understand this, for a voltage of 400v, the torque peaked at 35 NM corresponding to 1350 rpm. While for 560v, (green line) the torque peaked at 68.2 NM corresponding to 1350 rpm. Thus, as the voltage increases, the torque increases while the rotor speed remains constant (i.e. at the same slip).

The effect of varying line frequency on the torque-speed characteristics of the three-phase induction motor is represented in Figure 5. It can be observed that as the line frequency increases, the torque decreases, and the speed increases. For a line frequency of 40Hz, the torque observed is 43.6 NM while the rotor speed is 1076 rpm. But for a line frequency of 80Hz, the peak torque was observed at 22 NM while the corresponding rotor speed was 2152 rpm.

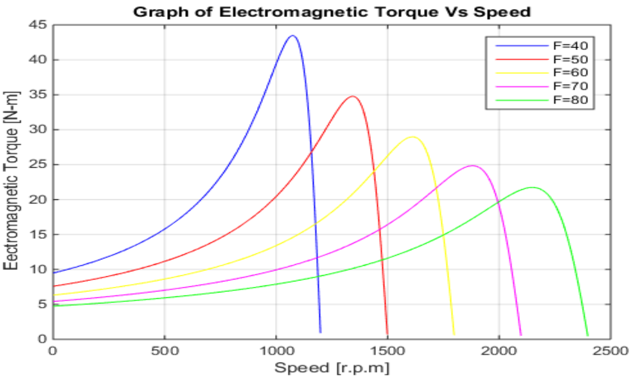

Figure 5: Torque-Speed at varied line frequency

Figure 6, presents graph of electromagnetic torque-speed at varied frequency and constant v/f ratio. It can be observed that as the line frequency increases at a constant v/f ratio, the torque increases, and the speed also increases. For a line frequency of 50Hz, the torque observed from Figure 6, is 34.2NM while the rotor speed is 1320 rpm. But for a line frequency of 60Hz, the peak torque was observed at 42 NM while the corresponding rotor speed was 1614 rpm.

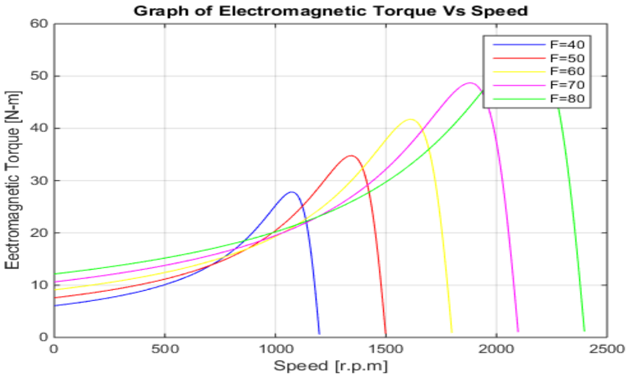

Figure 6: Torque-Speed at varied frequency and constant v/f ratio

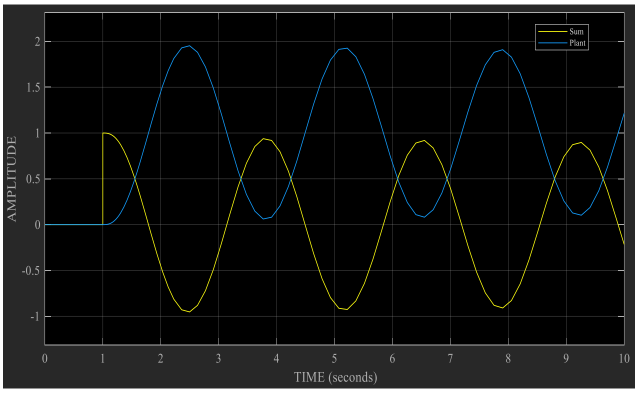

Figure 7: Closed loop of the Plant response with PI controller

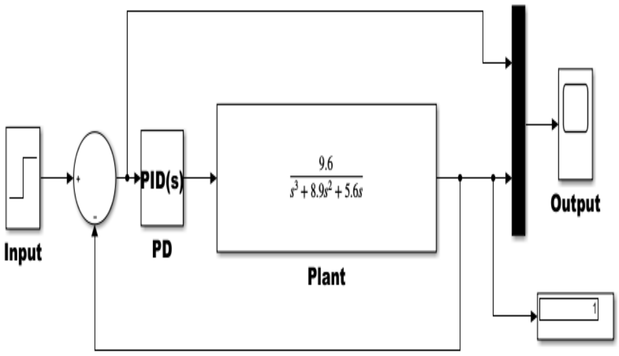

Figure 8: Closed loop system with PD controller

For the controller approach as seen in Figure 7, the PI controller did not yield satisfactory results as there were overshoots and deviations. The effect of PD controller was investigated by adding proportional and derivative gains (Kp and Kd) as shown in Figure 8, the system response was determined by adding a display and workspace. The PD controller response as depicted in Figure 9 shows the desirable performance for the plant. The system signal was brought to a steady state early enough than that of PI controller. The PD controller effect increases the stability of the system by reducing the rise time, overshoot, and improving the steady state response. PD controller has a fast settling time, and a steady-state error value of 1.0.

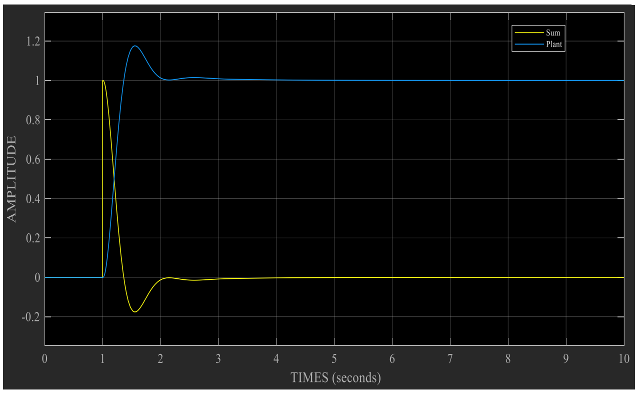

Figure 9: Structure of Closed Loop System response with PD Controller

Table 1: Summary of the characteristics of the three-phase motor speed control simulation

Method	PI	PD
Peak	1.96	1.15
Rise Time	0.46	0.25
Settling Time	-	1.01
Overshoot	95.60	15.10
Steady State Error	1.22	1.00

Table 1, gives the result of the characteristics as obtained by simulation of the three-phase induction motor speed control for both PI and PD controllers.

5.0 CONCLUSION

Speed control is a vital part of induction motor system control. The model and simulation approach of the scalar control methodology for the speed of three phase induction motor was investigated by varying several parameters such as voltage, and line frequency. The final control was accomplished by using linear controllers to investigate the performance of PD controller. Based on the results from the study; varying the supply voltage has no effect on the motor speed. Increasing the line frequency increases the motor speed while decreasing the torque. The variable frequency and constant v/f method were recognized as the best speed control techniques. However, linear controllers offer the best control option. The PD controller showed a better performance with a 1.01s settling time and an overshoot of 15.1% as against that of the PI controller which was unstable, did not settle and had an overshoot of approximately 96%.

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