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Experimental Investigation of PID Control Strategy for Three-Phase Induction Motor Speed Control System Implemented on a Scaled Railway Vehicle Roller Test Rig Driver

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Abstract

This paper presents development of electric motor speed control system for railway vehicle roller test rig. For maneuver flexibility reason, each must be independently controlled, and consequently, must be precisely controlled to prevent excessive yaw motion of the vehicle. To fulfill this requirement, a control system is built on a 3:10 scaled single roller rig which is driven by a low-cost motor, i.e., AC induction motor. The scale implies acceleration requirement as 1.1 m/s^2 and targeted speed as 2000 RPM. The system adopts PID control strategy with Ziegler-Nichols as its tuning method. As a result, the system yields settling time as 12.42 second with steady-state error of 0.75% when the system is being subjected to a step function input. Additionally, the system manages to reject disturbance which is proven by its ability to recover its speed once an amount of disturbance torque is applied. The findings indicate that AC induction motors with PID control strategy offers considerable speed performance over AC servo motors, which are typically much more costly. These findings indicate that AC induction motors with a PID control strategy offer considerable speed performance, making them a viable, cost-effective alternative to the typically more expensive AC servo motors. Moreover, the results have been validated against the roller-rig's operational conditions, confirming that the system meets the required performance criteria.

Keywords

Roller-rig; Three-phase induction motor; Speed control; PID; Ziegler-Nichols

1 Introduction

The application of roller-rig to vehicle dynamics research and railway development has become more widespread in recent decades. The use of roller-rig has proven to be an efficient experimental method to study dynamics contact between wheels and rails, as well as other issues in railway vehicle running dynamics [1,2]. Based on this application, roller-rig requires a drive motor with an accurate speed control system that achieves the specified target speed [1,3]. Drive motors such as three-phase induction motors (IMs) are a popular choice for railway development applications replacing DC motors since 1990 because of their simple structure, reliability, low cost, high efficiency, and safe operation with minimum maintenance [4–9]. In these applications, the motors are operated with variable speed, thus speed accuracy becomes an essential performance. The performance of an IMs drive essentially depends on the control strategy used. The selection of a particular control scheme aims primarily to maximize the use of the best performance for the drive [6,10]. In addition, the simplicity of the controller was also a major concern.

The scalar Voltage/frequency (V/f) control strategy, characterized by its ease of implementation, easy design, and minimal steady-state error, is a simple control technique used to control the speed of complex and non-linear IMs behavior based only on the magnitude and frequency of the applied voltage [5], [8], [11].

For this reason, this control strategy is widely adopted by manufacturers and industries [11]. However, this control strategy only has the advantage of stability in accurately controlling the speed in the medium to high-speed range [5], [6], [12], and it is sensitive in the transient phase to parametric variations [7], [8]. During the transient phase, the flux will have strong oscillations with significant amplitude, and its modulus will vary during transient conditions [8]. These oscillations can have a negative impact on torque and speed quality, reducing the performance while in transient conditions.

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Development of V/f control performance have been researched in many studies. Conventional controls such as PID, PI, PD are three types of controllers that are commonly used to control the speed response of IMs. The use of these controls has existed in the field of control engineering for a long time and is still considered effective for most real-life situations [13]. Although there have been many advanced control techniques developed over time, this control remains in demand due to its simple practicality. The importance in designing PID, PI, PD controllers is to determine the PID coefficient values, namely the proportional value K_p, integral value K_i, and derivative value K_d [14]. Determining the coefficients of this control can be done using two commonly used tuning methods, the classical tuning method and the modern tuning method. The classical method uses experimental response, while the modern method relies on process model [15].

The classical method, Ziegler-Nichols, was used by [12], [13] in experiments to optimize the PI coefficients. In modern methods, there are three groups of methods that have been developed by several researchers, such as Particle Swarm optimization (PSO), Neural-sensorless, Fuzzy-logic. PSO algorithm is present for simulation tuning PI parameter found on best coefficient value [16]. Neural-sensorless has been used to estimate the speed of the shaft without directly measuring the variables used to control induction motors [17]. Another method, called Fuzzy logic, has already been developed in several previous works with various algorithms. Fuzzy-genetic control [12] and Genetic-Adaptive Neuro-Fuzzy Inference System (ANFIS) model [13] are applied to optimize the PI coefficient and the experimental results were compared with the Ziegler-Nichols method. Modified PID-type fuzzy controller is proposed to control the speed of IMs with a combination of the two controllers: PID-fuzzy and the conventional PID [15]. The compara-tive performance of Fuzzy PI, PD, PID has been simulated by [14,18]. As the results, Fuzzy PID controllers attempt to main-tain system stability and reduce the possibility of significant overshoot as is often the case with Fuzzy PI controllers and the Fuzzy PID controller also overcomes the steady-state error that occurs in the Fuzzy PD controller.

From all the references mentioned above, they only conduct experiments with a speed reference input using a step function so that they cannot know the speed response during acceleration. In addition, there are only a few references that conduct experiments in the low to high-speed range such as in [16], [17] and thus cannot solve the issue of inaccurate V/f control at low speeds. In the context of a motor drive in a roller-rig, speed accuracy is required in all speed ranges, especially during acceleration. Therefore, to overcome the problems in V/f control such as inaccuracy at low speeds and inaccuracy when walking at different speeds, this study conducted experiments with speed reference inputs using step functions and ramp functions at low to high-speed ranges. Then the control method uses PID control with the classical Ziegler-Nichols method to optimize the PID coefficients. The classical method was chosen because the tuning process is simple and easy to implement in experiments. The main contribution of this research is to find the optimal configuration for controlling the speed of an induction motor during its acceleration from rest to 2000 RPM. This configuration is intended to meet the criteria for a scaled roller-rig drive.

The paper is organized as follows: Section 2 describes the method and experimental setup used for IMs control with V/f control, the performance results of the proposed method are discussed in Section 3, while Section 4 provides the conclusion of this paper.

2 Methodology and Experimental Setup

2.1 Methodology

The experiment is conducted on a roller that is driven by a three-phase induction motor which has been coupled with an optical incremental encoder. The encoder delivers digital signal to a frequency to voltage (F2V) converter, thus the F2V provides an analog signal representing roller speed ω_r. Furthermore, the analog signal, which behaves as feedback, is sent to the analog input pinout of the inverter. Within the inverter, there is a comparator subtracting this analog signal from another signal representing the desired roller speed. As a result, the inverter obtains a signal representing speed error. The error signal is delivered to the PLC for control action generation purpose. Once the control action generated by the PLC, the inverter actuates the motor employing V/f control with Space Vector Pulse Width Modulation (SVPWM) switching technique. In this case, the control action represents synchronous speed ω_s.

Other than the speed measurement system, there is a braking system consisting of a disk and its caliper. The braking systems installation aims to accommodate disturbance rejection testing for the control system. For monitoring purposes, braking force measurement is performed during the test, utilizing a load cell and its signal conditioner. Both braking force and rotor speed signals are acquired using a data acquisition system NI6008.

To meet control system performance and the requirements, the experiment is carried out in two steps, which are system identification and controller parameters optimization. System identification is done by applying a step function input to the open loop control system. During identification, the feedback is disabled, and the controller gain is set at $K_p = 1$. As the input is subjected to the open loop system, the response of the system, i.e., roller speed, is recorded for dynamic characteristic extraction purposes. In addition, the obtained dynamics characteristic is utilized to find controller parameters, which will be further implemented on closed loop system. There are two types of controllers to be implemented: PI and PID. The parameters for each are optimized using the Ziegler-Nichols method.

All tests are conducted with a target speed of 2000 RPM. To achieve the target, the closed loop system is subjected to a step function input first. This test aims to obtain step response, by which the open loop step response is compared. Thus, the performance improvement can be evaluated. In addition, the closed loop system is also subjected to a ramp function with saturation at 2000 RPM in accordance with the requirements and objective of the operating condition. This type of input simulates train operation during acceleration.

There are two primary performance criteria, which are speed tracking ability and disturbance rejection [18]. Speed tracking ability is evaluated using several transient parameters such as rise time, settling time, time delay and overshoot. In contrast, disturbance rejection is evaluated using steady state parameter, i.e., steady state error.

2.2 Experimental Setup

As depicted in Figure 1, the experiment setup is mainly constructed by a mechanical system, in which the roller is driven by a 1.5 kW motor through a coupling. The roller has a diameter of 360 mm. According to Gretzschel and Jaschinski scaling method [3], roller dimension determines scaling factors velocity profile and acceleration profile. As for velocity and acceleration measurement purposes, an optical encoder and a frequency to voltage converter are installed, thus they provide actual speed signals for the data acquisition system. To check the control system in terms of disturbance rejection, the roller is coupled with a braking system which involves disk brake, caliper, strain-gauge based load cell, and amplifier. This braking system provides a disturbance signal for the data acquisition system. The data acquisition system comprises a National Instrument NI6008 and a computer. The computer accommodates the operator to perform several tasks, which are receiving desired speed information, collecting speed and load data, as well as generating control action signals. This signal is delivered to the master of V/f control, i.e, the Programmable Logic Controller (PLC) through an ethernet connection. The PLC transforms the signal into a data frame that is ready to be read by the inverter as a slave of V/f control. This data frame is sent through a Modbus protocol. Finally, based on the received data frame, the inverter modifies the 50 Hz three-phase electrical grid to be another three-phase electrical grid that is required by the motor to achieve the desired speed.

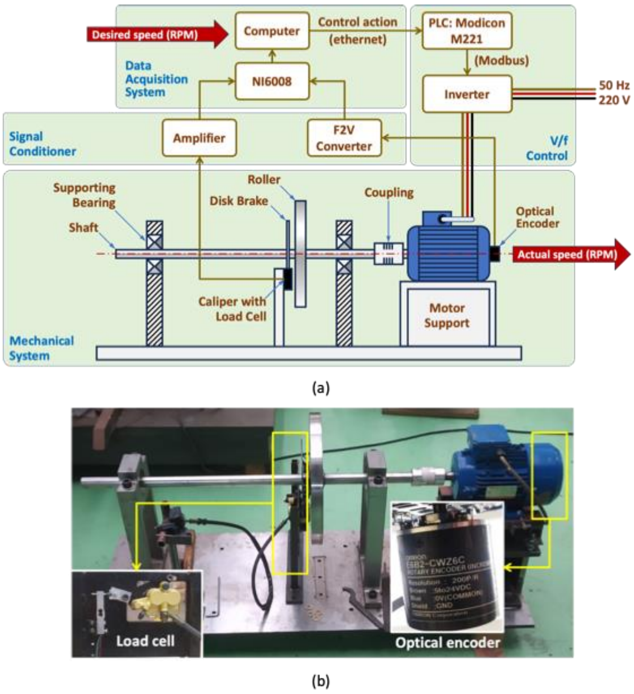

Figure 1 Experimental setup for induction motor control on a scaled roller-rig: (a) schematic diagram, and (b) the actual experimental setup.

To identify dynamic characteristics of the system, the system is to be tested using a step function fulfilling roller-rig criteria. In this research, the criteria are based on full-scale roller-rig specification developed at National Traffic Safety and Environment Laboratory (NTSEL), as well as Gretzschel and Jaschinski rules [3], [19]. The full-scale roller-rig has a diameter of 1200 mm, while the roller-rig employed in this research has a diameter of 360 mm. Thus, the geometry scaling factor calculated from Eq. (1) is 3.33.

$$\eta = \frac{D_f}{D_S} \tag{1}$$

were η is the geometry scaling factor, D_f is the diameter of full-scale roller-rig, D_s is the diameter of scaled roller-rig. The Gretzschel and Jaschinski rule governs the speed scaling factor based on the Eq. (2),

$$v_f = \sqrt{\frac{D_f}{D_s}} \times v_s \tag{2}$$

where V_s is roller speed on the scaled roller-rig, while V_f is roller speed on the full-scale roller-rig. On the other hand, the rule says that the acceleration scaling factor is 1. Since the reference speed and reference acceleration are respectively 250 km/h and 1.1 m/s^2, the speed and acceleration designed in this research are 137 km/h and 1.1 m/s^2, respectively. All scaling results are summarized in Table 1. This roller speed design corresponds with angular speed of 2019 RPM. To ease discussion and analysis, the roller is operated with a final speed of 2000 RPM. On the other hand, to achieve acceleration of 1.1 m/s^2, the final speed should be reached within 34 seconds.

Table 1 Summary of physical parameters.

Scaling factor	Reference [19]	Scaling factor value	Experiment value
Roller diameter	1200 mm	3.33	360 mm
Speed	250 km/h	1.83	137 km/h
Acceleration	1.1 m/s2	1.00	1.1 m/s2

3 Result and Discussion

Figure 2 shows the step response of the open-loop system. The response of the open-loop system is then used for the identification of dynamic characteristics. This identification includes transient response parameters such as time constant, rise time, settle time and overshoot. The calculations summarized in Table 2 show that the time constant is 4.104 seconds obtained when the speed reaches 63% at 1255 RPM; the rise time is 5.08 seconds obtained when the speed reaches 80% at 1594 RPM; the settle time is 7.294 seconds obtained when the speed reaches 98% at 1953.

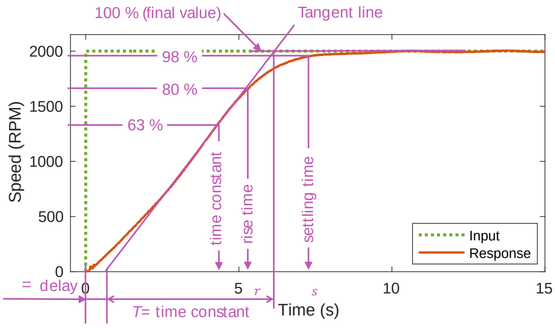

Figure 2 The speed response of open-loop test with step function input.

In addition, the respons signal provides Ziegler-Nichols constants, including T and L. These constants are then employed to calculate controller coefficients, based on Ziegler Nichols method. All constants are summarized in Table 3.

Table 2 Dynamic characteristics of open loop test with step function input.

Dynamic characteristics	Value
Rise time (s), t_r	5.08
Settling time 2 % (s), t_s	7.294
Time constant (s), τ	4.104
Overshoot (%)	0
ZN time constant (s), T	5.46
Delay time (s), L	0.68

Table 3 The coefficients of PID controller

Controller	K_p	τ_i	τ_d
P	$\frac{T}{L} = 8.02$	∞	0
PI	$0.9\frac{T}{L} = 7.22$	$\frac{L}{0.3} = 2.05$	0
PID	$1.2\frac{T}{L} = 9.62$	$2L = 1.36$	$0.5L = 0.34$

The open loop system is then turned into a closed-loop system by employing a feedback signal from the optical encoder. The feedback signal is delivered to a controller unit, which can be programmed using two different control strategies: PI and PID. We tuned both controllers using the coefficients in Table 3 and showed their step responses in Figure 3 (a). The PI controller has the best rise time (4.73 sec) and overshoot (11.1 %) among the responses. The PID controller, on the other hand, had the shortest settling time (12.36 sec). Moreover, the closed-loop system eliminates the steady-state error that the open-loop system do not, regardless of the control strategy used.

Figure 3 (b) presents the ramp responses of the open-loop and closed-loop systems. The results show that both the open and closed loop systems track the speed during acceleration. However, unlike the others, the open-loop system produces no overshoot. Thus, it can be concluded that the open-loop system performs the most accurate speed tracking during acceleration, but it performs the worst speed accuracy under steady state condition. In contrast, the closed-loop system has lower accuracy under transient conditions as it still leads overshoot, but totally removes the steady-state error. In terms of overshoot, the closed-loop system with PID controller generates lower overshoot than PI controller and recovers the response faster during the overshoot.

The last control performance evaluated in this study is disturbance rejection. An amount of disturbance torque is applied to the mechanical system by braking the disc. Figure 4 illustrates the results of the disturbance rejection test.

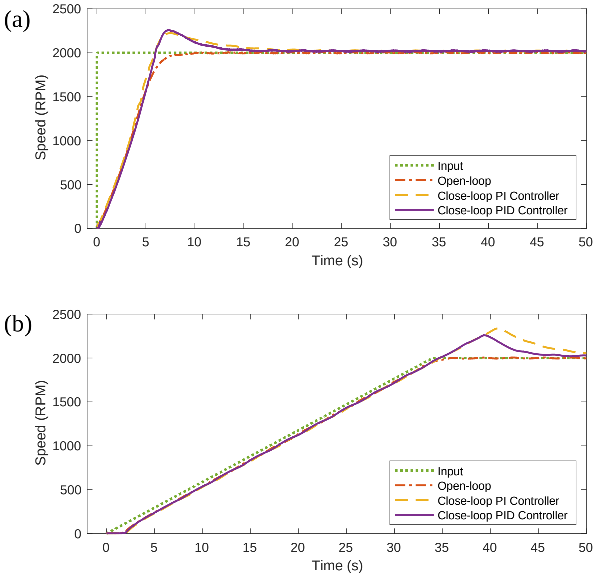

Figure 3 Speed response comparison between open-loop and close-loop with (a) step function input command, and (b) ramp function input command.

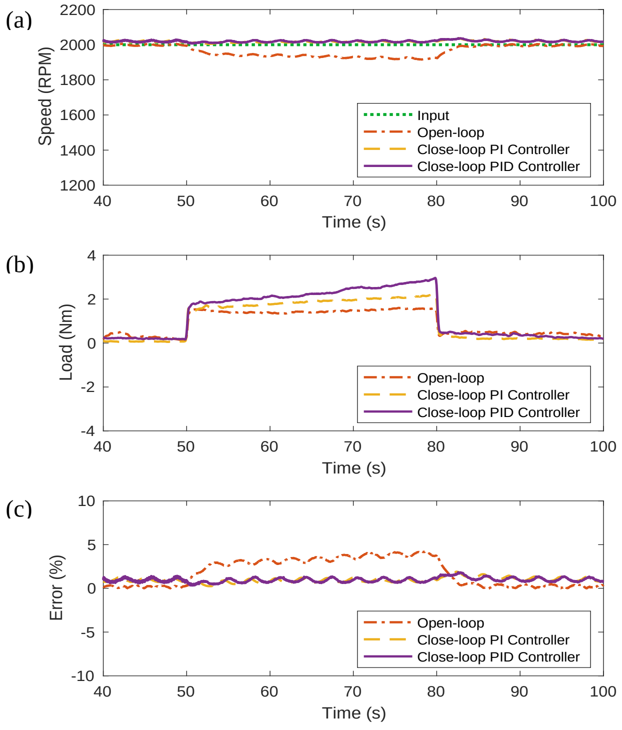

Figure 4 Comparison of (a) speed response, (b) disturbance torque profile, and (c) speed error between closed-loop and open-loop systems.

Figure 4 (a) shows the velocity profile when the load torque is applied, whereas Figure 4 (b) shows the load profile as a nearly rectangular function with magnitude of 2 Nm and pulse width of 30 seconds. The results confirm that the open-loop system does not reject the disturbance, as shown graphically in Figure 4 (c). The steady-state error of the open-loop system increases as the load is applied, but that of the closed-loop system remains constant.

Overall, the results of this study demonstrate that the proposed induction motor speed control system effectively meets the operational requirements of the roller-rig. The system successfully achieves low settling time and minimal steady-state error, which are critical performance indicators for roller-rig applications. Additionally, the system's ability to reject disturbances highlights its strong stability under varying load conditions, ensuring consistent and reliable performance in actual applications. These findings suggest that the approach adopted in this research provides an effective and efficient solution for traction motor control in roller-rigs, fully complying with stringent operational demands.

4 Conclusion

An experimental study on speed control of a roller driven by an induction motor has been conducted. It is found that the open-loop system had the best speed tracking accuracy during acceleration, but it fails to reject disturbances and fails to eliminate steady-state errors under no-load condition. The closed-loop system, on the other hand, is fairly accurate in speed tracking during acceleration and rejects disturbances unlike the open-loop system. However, the closed-loop system also has a faster response time, which results in more overshoot. Among the closed-loop systems, the one with PID control has lower overshoot and faster speed recovery than the one with PI control. Therefore, it can be concluded that the PID control strategy was the most suitable for the induction motor control system as a scaled roller-rig drive.

For future work, the use of system identification method, mathematical models and software is suggested to fine-tune the controller parameters and reduce the overshoot. The identification method is employed to obtain the mathematical model of the controlled system based on the experimental data, while a software-assisted method is utilized to optimize the controller settings and achieve the best control system performance.

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