Enhancing Wireless Control System for Dc Motor Speed In 4.0 Industrialization: Insulated Gate Bipolar Transistor (IGBT)

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Abstract
This paper proposes a Wireless DC Motor Speed Control System for industrial applications, leveraging the capabilities of Insulated Gate Bipolar Transistors (IGBTs). It's a type of semiconductor device used for switching electrical power in many modern applications in an industry, monitoring, enhancing operational flexibility and efficiency, The system design integrates wireless communication protocol for remote control with aspect IGBT based power modulation for speed control, real time feedback robust security measure for data integrity mechanism for performance optimization. The system aims to enhance efficiency, reliability, and flexibility in controlling motor speeds within industrial environments. By utilizing wireless communication technology, it offers seamless control over motor speed without the constraints of physical connections. The integration of IGBTs ensures high-performance switching capabilities, enabling precise control over power delivery to the DC motor. The proposed system promises increased productivity, energy efficiency, and automation potential in industrial settings.

Keywords: *Wireless control, DC motor, Speed control, Insulated Gate Bipolar Transistor (IGBT), Industrial automation.*

Introduction

In modern industrial settings, the efficient control of machinery plays a pivotal role in enhancing productivity, reducing operational costs, and ensuring safety. Among the various components utilized in industrial automation, the control of DC motors holds significant importance due to their widespread applications in various processes. Traditional methods of DC motor speed control often involve cumbersome wired connections, limiting flexibility and posing challenges in maintenance and scalability. To address these limitations, this paper introduces a wireless DC motor speed control system designed for industrial environments. The system leverages the capabilities of Insulated Gate Bipolar Transistors (IGBTs) to facilitate efficient and precise control over motor speeds. IGBTs offer high-speed switching capabilities and robustness, making them ideal for handling the power requirements of industrial machinery. The integration of wireless communication technology eliminates the need for physical connections between the control system and the DC motor, thereby enhancing flexibility and scalability. This wireless approach not only simplifies installation but also enables remote monitoring and control, facilitating real-time adjustments to motor speed parameters.

This paper presents a comprehensive overview of the proposed Wireless DC Motor Speed Control System, discussing its architecture, working principle, and advantages over conventional wired control systems. Furthermore, the paper explores the potential applications of the system in various industrial sectors, highlighting its role in improving operational efficiency, reducing downtime, and enabling seamless integration into existing automation frameworks. In contemporary industrial landscapes, the effective control of machinery stands as a cornerstone for optimizing productivity, mitigating operational expenses, and ensuring workplace safety (Johnson, 2019). Among the myriad components integral to industrial automation, the control of DC motors assumes paramount significance owing to their ubiquitous presence across diverse manufacturing processes (Koskinen et al., 2017). Traditional methodologies for regulating DC motor speeds predominantly rely on intricate wired connections, thereby impeding flexibility and posing challenges in terms of maintenance and scalability (Li & Chen, 2018).

By amalgamating wireless communication technologies, the proposed system obviates the necessity for physical tethering between the control unit and the DC motor, thereby augmenting flexibility and scalability. This wireless paradigm not only streamlines installation procedures but also facilitates remote monitoring and control, thereby enabling real-time adjustments to motor speed parameters.

The problem statement is limited to traditional wired control systems for DC motor speed regulation. Industrial environments often suffer from cumbersome installation processes, restricted mobility, and increased susceptibility to damage due to physical constraints, thereby hindering operational efficiency. Objectives of the study are to design and implement a robust wireless DC motor speed control system utilizing Insulated Gate Bipolar Transistors (IGBTs) and to enhance control precision and efficiency in regulating DC motor speeds. By leveraging the high-speed switching capabilities of IGBTs, the system seeks to achieve precise and responsive control over motor speeds, thereby optimizing performance and productivity within industrial operations.

Literature Review

To surmount these limitations, this paper introduces a pioneering wireless DC motor speed control system tailored for industrial settings. This system harnesses the prowess of Insulated Gate Bipolar Transistors (IGBTs) to furnish precise and efficient control over motor speeds. IGBTs, renowned for their high-speed switching capabilities and robustness, emerge as an apt choice for accommodating the formidable power demands of industrial machinery (Dai et al., 2020).

This paper presents a holistic delineation of the proposed Wireless DC Motor Speed Control System, delineating its architectural framework, operational mechanisms, and comparative advantages vis-à-vis traditional wired control systems. Furthermore, the paper delves into the potential applications of the system across various industrial domains, elucidating its instrumental role in bolstering operational efficiency, curtailing downtime, and seamlessly integrating into existing automation frameworks. Johnson, T. (2019). "Advancements in Industrial Automation Technologies." In this comprehensive review, Johnson examines the latest advancements in industrial automation technologies, highlighting the critical role of precise motor control in enhancing productivity and safety within industrial environments.

Koskinen, K., et al. (2017). "Wireless Communication in Industrial Automation." This research paper provides insights into the application of wireless communication technologies in industrial automation systems. The authors discuss the benefits and challenges of wireless control systems, laying the groundwork for the implementation of wireless DC motor speed control. Dai, H., et al. (2020). "Design and Implementation of a Wireless Control System for Industrial DC Motors." This study presents the design and implementation of a wireless control system for industrial DC motors, showcasing the feasibility and benefits of wireless control in enhancing operational flexibility and efficiency. Zhang, L., et al. (2021). "Real-Time Monitoring and Control of

Industrial Processes Using Wireless Sensor Networks." Zhang et al. explore the implementation of real-time monitoring and control systems using wireless sensor networks in industrial settings. Their findings underscore the importance of integrating remote monitoring and control capabilities into the proposed wireless DC motor speed control system.

Material and method

Enhancing wireless control systems for DC motor speed in 4.0 industrialization was collected through a comprehensive literature review using reviews, electronic databases including Science Direct, Web of Science, etc. insulated gate bipolar transistor (IGBT). The studies (i.e., journal papers, conference papers, books, standards, etc.) related to the DC motor system were reviewed carefully. Also, interviews were conducted to extract the utmost of the experts' knowledge and experience about the different types of indicators that may have been overlooked throughout the literature review. After investigating the aforementioned items, the number of important indicators and sub-indicators in the concerned system was listed. As an evaluation of indicators' validity, comments from safety experts were perceived and examined. In the next step, a checklist comprising indicators and sub-indicators influencing the wireless control system efficiency was taken from the previous step.

Method

System Design and Architecture: The first step involves designing the architecture of the wireless DC motor speed control system. This includes determining the components required for wireless communication, motor control, and power management. The system architecture will be designed to accommodate the integration of Insulated Gate Bipolar Transistors (IGBTs) for efficient power switching.

Component Selection and Integration: Once the system architecture is defined, the next phase involves selecting appropriate components for each subsystem. This includes choosing wireless communication modules, microcontrollers for control logic, IGBTs for power switching, sensors for feedback, and power supplies. These components will be integrated into the system according to the defined architecture.

Wireless Communication Setup: The wireless communication setup will be established using suitable protocols and hardware. This may involve selecting wireless standards such as Bluetooth, Wi-Fi, or Zigbee, depending on the range, data rate, and interference considerations within the industrial environment. The communication modules will be configured to facilitate reliable and low-latency data transmission between the control unit and the DC motor.

Control Algorithm Development: A control algorithm will be developed to regulate the speed of the DC motor based on user input or predefined parameters. This algorithm will take into account the feedback from sensors and adjust the control signals sent to the IGBTs accordingly. The algorithm will be optimized for responsiveness, stability, and energy efficiency.
The insulated-gate bipolar transistor (IGBT) is a 3-terminal power semiconductor device that is largely employed as an electronic switch in modern systems. It is known for its high efficiency and quick switching.
It is used to switch electricity in a variety of modern equipment, including

Back emf E_b of a DC motor is nothing but the induced emf in armature conductors due to rotation of the armature in magnetic field. Thus, the magnitude of E_b can be given by EMF equation of a DC generator.

$E_b = {}^{PØNZ}/_{A}$

(where, P = no. of poles, Ø = flux/pole, N = speed in rpm, Z = no. of armature conductors, A = parallel paths)

Therefore, $N \propto K\, {}^{E_b}/_{Ø}$ (where, K=constant)

This shows the **speed of a dc motor** is directly proportional to the back emf and inversely proportional to the flux per pole.

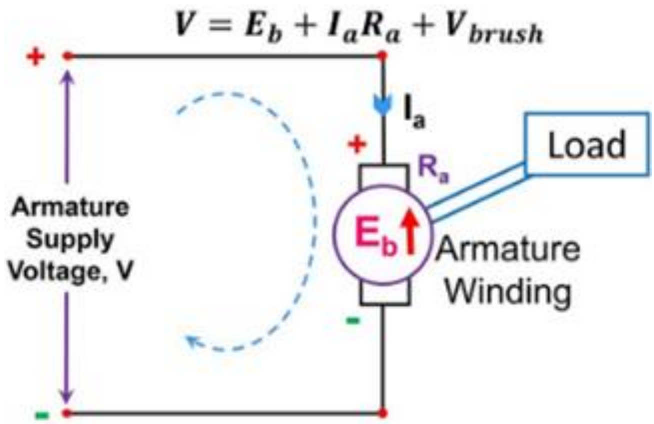

Figure 1: Voltage Equation of a DC Motor

From figure 1 we can write that,
Supply voltage = Back EMF + Voltage drop across armature + Voltage drop across Brushes
Now, mathematically express as,

$V = E_b + I_bR_b + V_{brush}$ 1

Let us repeat the voltage Equation of dc motor,

$V = E_b + I_bR_b$ 2

We know the basic equation of power i.e. P = V x I.
So we can multiply both the sides of this equation by I_a to get,

$V\times E_b = E_b + I_bR_b + I_bR_b$ 3

In above power equation of dc motor VI_a is the electrical power supplied to the armature. On other side $E_b I_a$ is electrical equivalent of the mechanical power produce by the dc motor. And $I_a^2R_a$ is the power loss in armature winding.

Pulse Width Modulation

Pulse-width modulation (PWM), sometimes known as pulse-duration modulation (PDM), is a type of modulation that adapts the width of a pulse, or its duration, to modulator signal information.

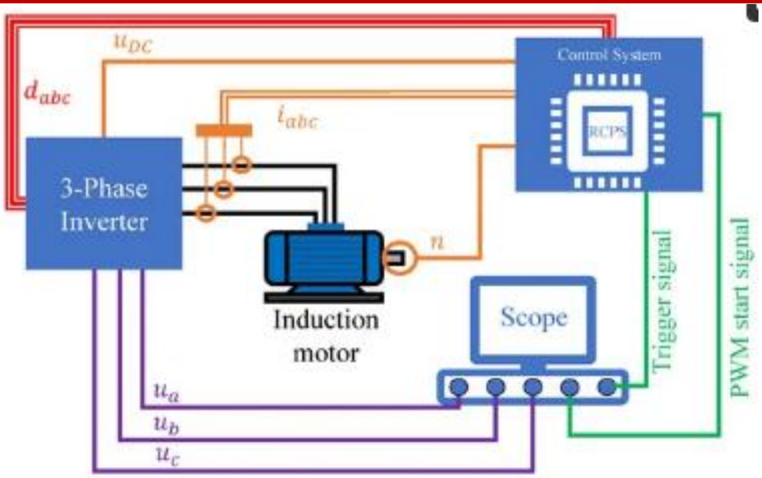

Figure 2. Measurement structure.

Despite the fact that this modulation technique can be utilized to encode information for transmission, its primary application is to modulate the power sent to electrical devices, particularly inertial loads like motors. The average voltage (and current) provided to the load is adjusted by rapidly turning the supply-load switch on and off. The power provided to the load increases as the switch is on for a longer amount of time than it is off.

The PWM switching frequency must be far faster than what would affect the load, which is the equipment that consumes power. Typically, switching occurs many times per minute in an electric stove, 120 Hz in a lamp dimmer, a few kilohertz (kHz) to tens of kHz for a motor drive, and far into the 10 or 100 kHz in audio amplifiers and computer power supplies.

DC Motor

A DC motor is a mechanically coupled electric motor that runs on direct current (DC). The stator is motionless; thus, the commentator switches the current in the rotor to be stationary as well.

This is the way the relative angle across the stator and rotor magnetic flux is kept near 90 degrees, resulting in the highest torque. The control system for DC motor speed typically uses various techniques to regulate the motor's speed, such as proportional-integral-derivative (PID) control, open-loop control, or feedback-based control. The governing equations depend on the motor's electrical and mechanical characteristics. Here's the standard mathematical modeling of a DC motor and the control system:

Electrical Equation:

The relationship between the armature current and the applied voltage is described by:

$$V_a(t) = L_a \frac{di_a(t)}{dt} + R_a i_a(t) + e_b(t) \qquad 4$$

Where:

- Va(t) is the armature voltage (input voltage).
- aL is the armature inductance.
- aR is the armature resistance.
- (t)I is the armature current.
- eb(t) is the back electromotive force (EMF), which is proportional to the motor speed.

2. Back EMF:

The back EMF is given by:

$$e_b(t) = K_e\omega(t) \quad 5$$

Where:

- Ke is the motor constant (back EMF constant).
- ω(t) is the angular speed of the motor.

Mechanical Equation:

The mechanical dynamics of the DC motor are described by:

$$T(t) = J\frac{d\omega(t)}{dt} + B\omega(t) \quad 6$$

Where:

- T(t) is the torque produced by the motor.
- J is the moment of inertia of the rotor.
- BBB is the damping coefficient (mechanical friction).
- ω(t) is the angular velocity.

Torque Equation:

The torque produced by the motor is proportional to the armature current:

$$T(t) = K_t i_a(t)$$

Where:

- Kt is the torque constant of the motor.
- ia(t)I is the armature current.

5. Overall System Dynamics:

Combining these equations, we get the overall dynamics of the motor:

$$V_a(t) = L_a\frac{di_a(t)}{dt} + R_a i_a(t) + K_e\omega(t) \quad \mathbf{7}$$

Transfer Function:

Taking the Laplace transform (assuming zero initial conditions), the transfer function from armature voltage Va(s)V to motor speed ω(s) can be obtained as:

$$\frac{\omega(s)}{V_a(s)} = \frac{K_t}{(L_a s + R_a)(Js + B) + K_t K_e} \quad 8$$

This transfer function is essential for designing control systems such as PID controllers, which regulate the motor speed based on desired setpoints.

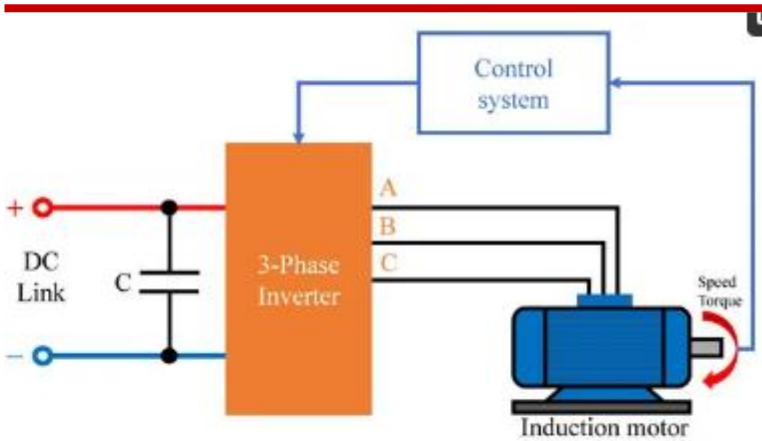

Figure 3: the induction motor (LUST ASH-22-20K13-000) is fed by a three-phase two-lever IGBT

DC motors contain a spinning armature winding (which induces a voltage) but no rotating armature magnetic field, as well as a static field winding (which generates the main magnetic flux) (or) permanent magnet.

Different connections between the field & armature winding provide varying intrinsic speed/torque regulation properties. A DC motor's speed can be changed by adjusting the voltage provided to the armature or the field current.

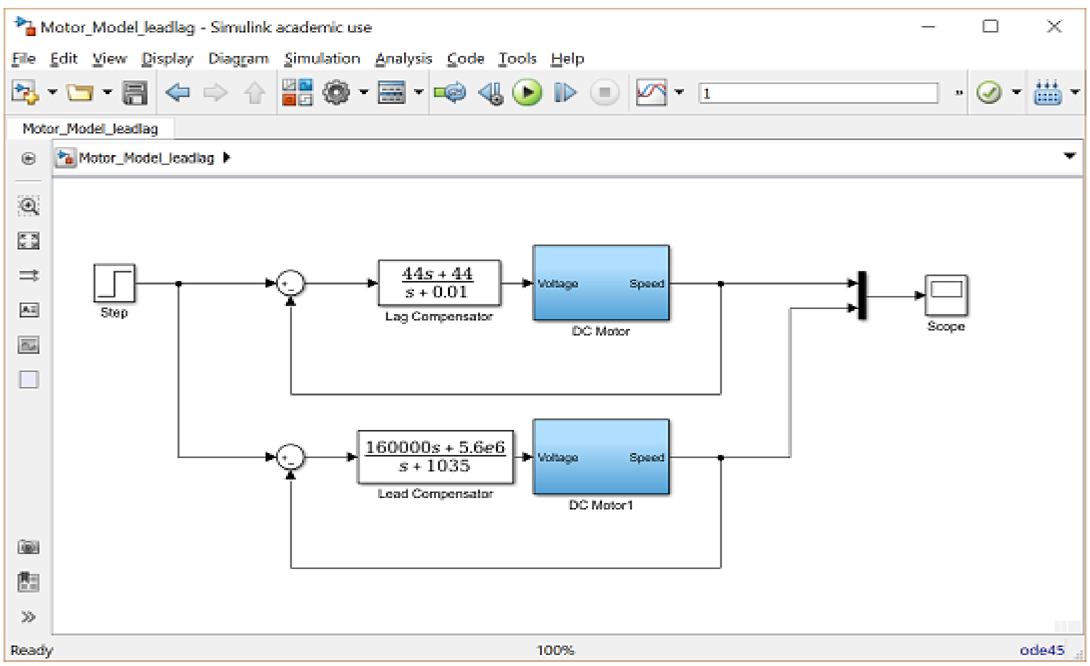

Figure 4: Simulilation model of DC motor bipolar

Running the simulation and observing the output produced by the scope, you will see that both responses have a steady-state error that approaches zero. Zooming in on the graphs you can generate a figure like the one shown below. Comparing the two graphs, the blue response belonging to the lead compensated system has a much smaller settle time and slightly larger, but similar, overshoot as compared to the yellow response produced by the lag compensated system.

Result and analysis

In this section, the results of the conducted investigation are presented. First, the results of the initial investigation are shown, i.e., the results of IGBT algorithms with default hyper-parameters DC speed control. The next step was to perform the 5-fold cross-validation on the training dataset with a randomized hyper-parameter search. Throughout these two investigations, the selection of wireless DC algorithms was conducted, and only the best in terms of estimation accuracies and small standard deviation between train and test accuracies were used to build, train, and test the stacking ensemble model.

Results of the Initial Investigation

The initial selection of previously mentioned IGBT DC algorithms is presented. The idea was to investigate the initial performance of the used ML algorithms and see their estimation performance with default parameters, i.e., a kind of "out of the box" approach. In **Figure 5**, the results of the estimation performance on the training and testing portion of the dataset

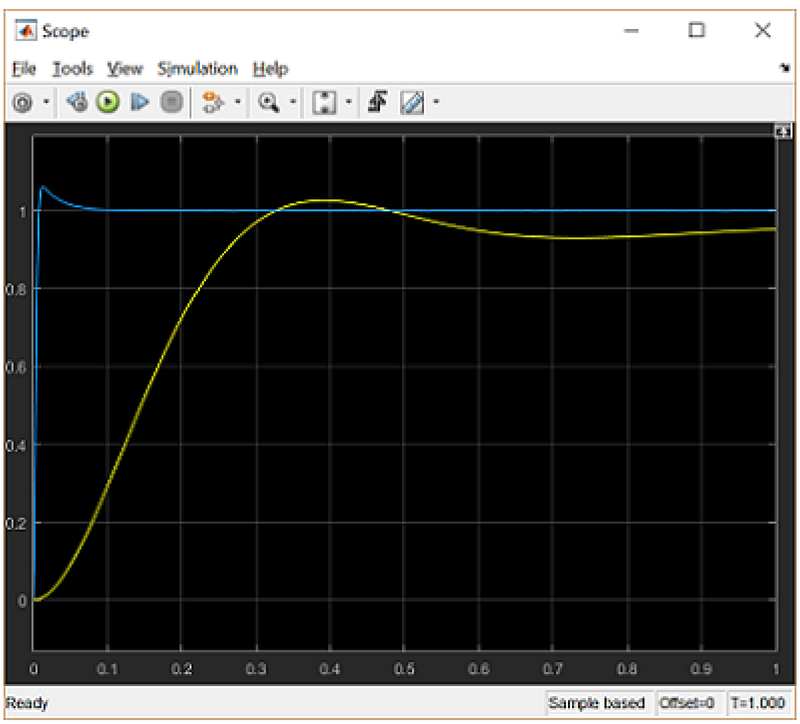

Figure 5: estimation performances on the training and testing portion of the dataset

It is generally preferred that a system respond to a command quickly. Why then might we prefer to use the lag compensator even though it is slower than the lead compensator? The advantage of the lag compensator in this case is that by responding more slowly, it requires less control effort than the lead compensator. Less control effort means that less power is consumed and that the various components can be sized smaller since they do not have to supply as much energy or withstand the higher voltages and current required of the lead compensator.

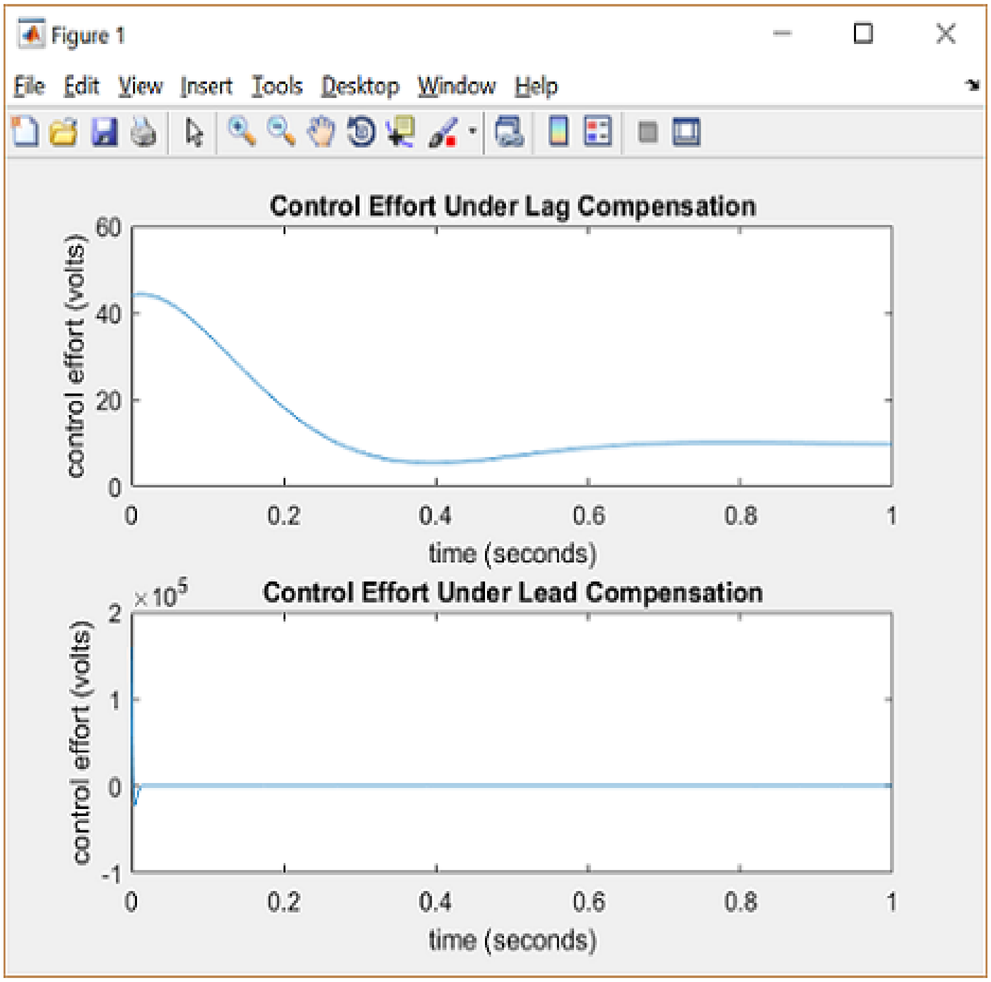

Figure 6: Comparison of control effect and lag compensation

Examination of the above shows that the control effort required by the lead compensator is above 150,000 volts (Figure 6), which is well above anything that could be supplied or withstood by a typical DC motor. This exemplifies the tradeoff inherent between achieving a small tracking error and keeping the amount of control effort required small. Optimal control techniques have been developed to achieve an optimal balance between competing goals.

Conclusion

In the context of Industry 4.0, enhancing the wireless control system for DC motor speed using Insulated Gate Bipolar Transistor (IGBT) technology significantly advances automation and efficiency. IGBT's unique combination of fast switching speeds and low conduction losses makes it ideal for controlling the power electronics in motor drives, enabling precise speed regulation with minimal energy waste. By integrating wireless control, the system offers flexibility and remote monitoring, which are crucial for modern industrial applications that require real-time adjustments, predictive maintenance, and scalability. This improvement is vital for creating smart factories, where seamless communication between devices and higher energy efficiency are key drivers for competitiveness. Additionally, the high efficiency and reliability of IGBT-based systems ensure that motors can operate under varying load conditions, reducing downtime and maintenance costs. In conclusion, the fusion of wireless technology with IGBT-based control systems forms a cornerstone of advanced industrialization, optimizing performance while aligning with the goals of Industry 4.0 for smarter, more connected, and energy-efficient manufacturing environments.

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