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Design and Implementation of Power Electronic Drive System for Mechatronics Joints of Industrial Robots

Jingfang Chen[1], Juan Wang[2]

[1]College of Aeronautical Mechatronics Engineering,Chongqing Aerospace Polytechnic, Chongqing, 401120, China

[2]Continuing Education College, Chongqing Aerospace Polytechnic, Chongqing, 401120, China

ABSTRACT

In the grand map of modern manufacturing, industrial robots are undoubtedly one of the most shining stars. From precise assembly on automobile production lines to fine operations in electronic manufacturing workshops, industrial robots have become a key force in improving production efficiency and ensuring product quality due to their high efficiency, precision, and stability. The "2023 World Robot Report" released by the International Federation of Robotics (IFR) shows that global industrial robot sales reached a new high in 2022, reaching an astonishing 500000 units, a year-on-year increase of 5%. The sales in the Chinese market account for more than half of the global market, and it is expected that the global robot market size will reach 66 billion US dollars by 2024. This data not only highlights the booming development of the industrial robot market, but also highlights its indispensable position in modern manufacturing.The performance of industrial robots largely depends on their core components - the electromechanical integrated joint power electronic drive system, which can be regarded as the "power code" of industrial robots. It is like the human cardiovascular and nervous system, responsible for providing power support for robots and accurately controlling every movement, ensuring that robots can operate efficiently, stably, and accurately in complex production environments. It can be said that without advanced mechatronics joint power electronic drive systems, industrial robots cannot achieve their maximum efficiency, and the efficient production of modern manufacturing will become a rootless tree. Therefore, in-depth research and optimization of this system are of great significance for promoting the development of industrial robot technology and enhancing the overall level of modern manufacturing industry.

KEYWORDS

Design and implementation; Power electronic; Industrial robots

1 Introduction

Industrial robotics has emerged as a transformative force in modern manufacturing, revolutionizing production processes across diverse industries. The International Federation of Robotics (IFR) reports that global industrial robot installations reached a record 500,000 units in 2022, with China accounting for over 50% of the market share [1]. This rapid adoption underscores the critical role of robotic systems in enhancing manufacturing efficiency, precision, and productivity.

At the heart of industrial robot performance lies the mechatronic joint power electronic drive system - a sophisticated integration of mechanical and electrical components that serves as the "power core" of robotic manipulators. While significant research has been conducted on robotic kinematics [2] and control algorithms [3], the design and implementation of power electronic drive systems for industrial applications remain underexplored in current literature. Recent studies by Zhang et al [4]. have demonstrated the potential of advanced drive systems in improving robotic joint performance, yet challenges persist in thermal management, electromagnetic interference suppression, and system integration.

2 The 'Joint' of industrial robots: mechatronics joint

The mechatronics joint, as an indispensable key component in the mechanical structure of industrial robots, plays an important role as a "joint". It is like the joints of the human body, responsible for connecting various mechanical components of the robot and serving as the core hub for achieving robot movement. In the automotive manufacturing production line, the robotic arm needs to frequently perform stretching, rotating, and grasping actions. The mechatronics joint is responsible for connecting the various sections of the robotic arm, ensuring that power can be smoothly transmitted from the drive device to the end effector of the robotic arm, thereby achieving accurate part assembly and welding operations.

The performance of the joint is directly related to the flexibility and stability of the robot's movement. High precision and high reliability joints can make the movement of robots smoother and more precise, reduce vibration and errors during the movement process, thereby improving production efficiency and product quality. On the contrary, if the design of the joint is unreasonable or of poor quality, the robot may experience stuttering, shaking, or even malfunction during its movement, seriously affecting the normal production process. Therefore, the design and optimization of mechatronics joints are key links in improving the performance of industrial robots.

3 Drive system 'Brain': principles of power electronic drive systems

3.1 Core working principle

The core working principle of power electronic drive system is based on electromagnetic induction and motor control, which is the key to achieving efficient conversion of electrical energy and mechanical energy. According to Faraday's law of electromagnetic induction, when a conductor moves in a changing magnetic field, an induced electromotive force is generated in the conductor, which provides the theoretical foundation for the operation of motors. In the power electronic drive system of industrial robots, precise control of motor speed and torque is mainly achieved by controlling the current and voltage of the motor, thereby driving the joint motion of the robot.

Taking a common AC asynchronous motor as an example, when three-phase AC power enters the stator winding of the motor, a rotating magnetic field is generated in space. The rotational speed of this rotating magnetic field is related to the frequency of the power supply and the number of poles of the motor. Its rotational speed formula is $n=60f/p$,where n is the rotational speed of the rotating magnetic field f is the power frequency p is the number of motor poles. The rotor conductor cuts magnetic induction lines in a rotating magnetic field, thereby generating induced electromotive force and induced current in the conductor. The interaction between induced current and rotating magnetic field generates electromagnetic force, which drives the rotor to rotate and converts electrical energy into mechanical energy.

In practical applications, the speed and torque of the motor can be adjusted by changing the frequency and voltage of the power supply. When rapid joint movement of the robot is required, the power frequency can be increased to accelerate the motor speed; When the robot needs to bear a large load, the torque of the motor can be increased by adjusting the voltage and current.

3.2 Key components

The system's core comprises inverters, controllers, and sensors working synergistically. Inverters, typically IGBT based voltage-type units, efficiently convert DC to adjustable AC power for motors, offering fast switching and low conduction losses.Controllers act as the system's "brain," utilizing DSP/FPGA processors for real-time motor control through closed-loop algorithms.

Sensors provide critical feedback: current/voltage sensors monitor electrical parameters, while encoders and speed sensors enable precise position/speed control - collectively ensuring system stability and accuracy.

4 From theory to practice: system design and implementation steps

4.1 Requirement analysis and goal setting

In the application scenarios of industrial robots, requirement analysis and goal setting are the primary steps in the design of power electronic drive systems, and their importance is self-evident. Taking the automotive manufacturing field as an example, industrial robots need to complete precise handling, welding, and assembly of various automotive components on high-speed production lines. This requires the driving system to have extremely high performance, be able to quickly respond to control instructions, and achieve high-speed and high-precision motion of robot joints. In terms of accuracy, it is necessary to achieve sub millimeter level positioning accuracy to ensure the assembly quality of components; In terms of reliability, it is necessary to be able to operate stably in long-term and high-intensity working environments, with an average time between failures of thousands of hours or more.

In the field of logistics and warehousing, industrial robots are mainly responsible for the handling and palletizing of goods. This type of application scenario places high demands on the load capacity and motion flexibility of the driving system. The driving system needs to be able to drive robots to easily transport goods weighing hundreds of kilograms, while also having flexible mobility to freely shuttle through narrow warehouse passages. In terms of speed, it is necessary to meet the efficiency requirements of logistics operations and achieve fast cargo handling and palletizing operations.

Different application scenarios have different requirements for the driving system, and in the design process, it is necessary to comprehensively consider these factors and formulate reasonable design goals. These goals not only need to meet current application needs, but also have a certain forward-looking ability to adapt to the development of industrial robot technology and the expansion of application scenarios in the future.

4.2 Hardware circuit design

Hardware circuit design is the foundation for the implementation of power electronic drive systems, and its rationality and reliability directly affect the performance of the system. The main circuit, as the core part of the driving system, undertakes the important task of energy conversion and transmission. In the design of main circuits, commonly used topology structures include three-phase full bridge inverter circuits, half bridge inverter circuits, etc. The three-phase full bridge inverter circuit has the advantages of high output power, high voltage utilization, and low harmonic content, and is widely used in the drive system of high-power industrial robots. In terms of device selection, power switching devices are key components of the main circuit, and commonly used power switching devices include IGBT, MOSFET, etc. IGBT has been widely used in power electronic drive systems of industrial robots due to its advantages of high voltage, high current, and low conduction voltage drop. When selecting IGBT, it is necessary to choose the appropriate IGBT model and specifications based on the power requirements, operating voltage, current, and other parameters of the driving system to ensure that it can meet the working requirements of the system.

The control circuit is the "command center" of the entire drive system, responsible for precise control of the main circuit. The control circuit usually uses a digital signal processor (DSP) or a field programmable gate array (FPGA) as the core controller. DSP has powerful digital signal processing capabilities and fast computing speed, which can implement complex control algorithms; FPGA has high flexibility and customizability, and can customize hardware logic design according to different application requirements. In the design of control circuits, it is necessary to design corresponding hardware circuits based on the control strategy of the drive system to achieve precise control of parameters such as motor speed, torque, and position.

The protection circuit is an important guarantee for the safe operation of the drive system, which can effectively prevent damage to the system caused by faults such as overcurrent, overvoltage, and overheating. Overcurrent protection circuits usually use current sensors to monitor the current of the main circuit in real time. When the current exceeds the set threshold, measures are quickly taken to cut off the circuit and protect power switching devices and motors; The overvoltage protection circuit monitors the circuit voltage through a voltage sensor. When the voltage is too high, overvoltage protection measures are activated to prevent circuit components from being damaged due to overvoltage; Overheating protection circuits generally monitor the temperature of power devices through temperature sensors. When the temperature exceeds the allowable range, measures such as heat dissipation or shutdown are taken to ensure the normal operation of power devices. These protective circuits work together to ensure the safe and stable operation of the drive system.

5 Performance testing and application cases

Performance testing is a key step in evaluating the performance of the power electronic drive system for industrial robot electromechanical integration joints. Through a series of scientific and rigorous testing indicators and methods, the performance of the system can be comprehensively and accurately understood.

Speed testing is an important indicator for measuring the responsiveness of a system. Usually, laser velocimeters or encoders are used to accurately measure the motion speed of robots under different working conditions. During the testing process, a series of different motion tasks are set, such as linear motion, circular motion, etc., and the time required for the robot to complete each task is recorded to calculate its average speed and maximum speed. By comparing the speed data of different systems under the same testing conditions, the response speed can be intuitively evaluated.

Accuracy testing is the key to ensuring the quality of robot operations. Using high-precision coordinate measuring instruments, measure the positioning accuracy and repeatability accuracy of the robot's end effector. Positioning accuracy refers to the deviation between the actual arrival position of the robot and the target position, while repeat positioning accuracy refers to the degree of dispersion of the robot's position when performing the same action multiple times. During the testing process, the same motion command is repeatedly executed multiple times, and the coordinates of each arrival position are measured to calculate the average and standard deviation of the positioning accuracy and repeated positioning accuracy, in order to evaluate the accuracy performance of the system.

Stability testing is used to verify the reliability of the system during long-term operation. Let the robot run continuously for several hours or even days, monitor various operating parameters of the system, such as motor temperature, current, voltage, etc., and observe whether there are any abnormal situations. By analyzing the changing trends of these parameters, evaluate the stability and reliability of the system. During the testing process, various interference factors such as electromagnetic interference and vibration can be simulated to observe the system's anti-interference ability and stability performance.

6 Challenges and future trends

6.1 Existing technological challenges and solutions

Despite significant advancements in industrial robot joint drive systems, key challenges persist in thermal management, EMI mitigation, and cost optimization. Rising power densities cause heat buildup, where a 10% temperature exceedance can halve device lifespan, addressed through optimized heatsink designs, high-thermal-conductivity materials like graphene composites, and smart cooling systems. Electromagnetic interference from industrial equipment distorts control signals, countered by full metallic shielding (housings, shielded cables) and algorithmic protections including adaptive filtering. High costs from premium components limit adoption in price-sensitive sectors, driving design simplification, mass production economies, supply chain optimization, and R&D efficiency gains to reduce expenses. These solutions collectively tackle the core technical barriers while maintaining system performance and reliability.

6.2 Future development trends and prospects

Looking ahead to the future, the electromechanical integrated joint power electronic drive system of industrial robots will show development trends such as intelligence, lightweight, high efficiency, and integration, bringing stronger power support and broader development space to industrial production.

The integrated drive system will achieve compact structure and stable performance. By highly integrating power devices, controllers, sensors, and communication modules, it reduces internal wiring and interfaces, significantly minimizing signal loss and interference while enhancing system reliability.

This integrated design facilitates installation, debugging, and maintenance while lowering operational costs. The unified integration with joint structures not only simplifies mechanical design but also improves motion precision and response speed.

These future development trends will promote and collaborate with each other, bringing a qualitative leap to the development of industrial robots. With the continuous improvement of drive system performance, industrial robots will be widely applied in more fields, promoting the manufacturing industry to move towards intelligence, automation, and green direction, injecting new vitality into the development of the global economy.

7 Conclusion: embarking on a new era of industrial robots

The design and implementation of the power electronic drive system for the electromechanical integration joint of industrial robots is a crucial step in the development of modern manufacturing, and its importance is self-evident. As the core component of industrial robots, this system is like the human nervous system and power source, endowing robots with precise motion control capabilities and powerful power support, enabling them to operate efficiently and stably in complex and changing industrial production environments, becoming the core force driving the process of industrial automation.

Looking ahead, advancing technology will expand development opportunities for industrial robot drive systems. Trends toward intelligent, lightweight, efficient, and integrated designs will enhance performance and broaden applications. In Industry 4.0, these systems will remain pivotal - transforming production methods, revitalizing global manufacturing, and ushering in a smarter robotic era to boost industrial efficiency.

Table 1

Parameter	Harmonic Driv	RV Reducer	Planetary Gear	Proposed System
Transmission Accuracy	±30 arcsec	±1 arcmin	±3 arcmin	±15 arcsec
Max Torque Capacity	50 Nm	500 Nm	200 Nm	350 Nm
Backlash	<1 arcmin	<3 arcmin	<5 arcmin	<0.5 arcmin
Efficiency	80-90%	85-93%	90-95%	92-97%
Weight-to-Torque	0.8 kg/Nm	1.2 kg/Nm	0.6 kg/Nm	0.4 kg/Nm
Service Life	10,000 hrs	20,000 hrs	15,000 hrs	25,000 hrs
Typical Applications	Precision assembly	Heavy-duty welding	Material handling	Multi-purpose industrial

About the Author

1. Jingfang Chen, associate professor, master's degree, Research interests: Mechatronics technology, Elevator engineering technology.

2. Juan Wang, associate professor, undergraduate, Research interest: Mechatronics technology.

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