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CONTENTS

Analysis and Application of Water Control Fracturing Technology in Tight Sandstone Gas Reservoirs

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Abstract: Tight sandstone gas reservoirs have a huge amount of resources, but the complex gas-water relationship in some tight sandstone reservoirs severely limits the effective development of natural gas. Previous studies have developed water control fracturing schemes combining multiple techniques such as multi-stage sanding, nitrogen injection, and artificial barriers, which are beneficial for controlling water production and increasing natural gas yield. This paper analyzes the effectiveness of current water control fracturing technology, examines the impact of fracturing construction parameters, and selects a well in a certain block of the Sulige Gas Field. By improving the pumping stop time, perforation position, and construction parameters of secondary sanding, and optimizing the fracture morphology through a quasi-three-dimensional fracture morphology model, the extension of fracture height is suppressed, resulting in an optimized water control fracturing scheme suitable for the reservoir characteristics of the block.

Keywords: Tight Sandstone Gas Reservoirs; Water Control Fracturing; Fracturing Technology; Construction Parameters; Fracture Morphology

1. INTRODUCTION

The Sulige Gas Field is a complex tight sandstone gas reservoir that has been discovered for 20 years since 2001. Research on reservoir geology, engineering, and technology has been continuously carried out with the themes of deepening reservoir understanding and efficient development, making it a model for the development of tight gas reservoirs in China[1]. The well area is located in the western part of the Sulige Gas Field, and the most typical feature of the He 8 gas reservoir is the co-production of gas and water [2]. The reservoir has characteristics of "small pore throats, poor sorting, high displacement pressure, low continuous phase saturation, and small main contributing pathways" in terms of pore structure, and its physical properties are characterized by extremely low porosity and permeability. The co-production of gas and water in the same layer is mainly related to the late-stage uplift of the structure and the heterogeneity of the sand body[3]. With the development of the western part of the Sulige Gas Field, the reservoir properties have deteriorated, and the fracturing effect is significantly influenced by parameters such as the mechanical properties of barrier rocks. Therefore, it is necessary to analyze the effectiveness of current water control fracturing technology and develop an optimized water control fracturing scheme suitable for the reservoir characteristics.

2. WATER CONTROL FRACTURING SUPPORTING TECHNIQUES

Water control fracturing supporting techniques are relatively mature, but they have been less applied in tight sandstone gas reservoirs due to the complexity of gas-water relationships. In 2013, Cai et al.[4] proposed the concept of diversion fracturing technology, which achieved integration of water control and fracturing, and initial field applications showed promising results. In the same year, He et al. [5] conducted field experiments in the Sulige Gas Field using techniques such as relative permeability modification and variable displacement to control fracture height, and achieved good water control fracturing effects. Zhu et al.[6] used coated sand fracturing technology for water control fracturing in the Pudong Oilfield, reducing the water content by 11%. In 2014, Li Jiarui[7] conducted pilot experiments on artificial barriers and selective water control proppants, which provided guidance for water control fracturing in low-permeability reservoirs. In 2016, Luo Mingliang et al.[8-9] prepared RPM water control fracturing fluids using polysiloxane and MES as the main additives, forming suitable conditions for the formation of nanoscale emulsions for water control in tight gas wells. In 2017, Hao Guixian[10] used hydraulic jet fracturing technology for G82-44-1 well reservoir characteristics, resulting in a 4.7% decrease in water content and a daily oil increase of 7.24 tons, achieving the goal of increased oil production and water control. Yang Zhihao[11] developed software for water control selection in horizontal well fracturing sections of bottom-water reservoirs, and practical examples demonstrated its guiding role in on-site fracturing construction. In 2019, Feng Xingwu [12] studied the influencing factors of artificial fracture height and the characteristics of oil-water relative permeability, forming a process technology for controlling artificial fracture height in thin interlayers. In 2020, Zhao Jun et al. [13] used plugging proppant pack fluid for water control fracturing in fractured tight sandstones in the Sulige Gas Field, resulting in an average daily production increase of around 10% per well.

For water control fracturing supporting techniques applied to gas-water co-production in tight gas reservoirs, there are multiple techniques such as multi-stage sanding, liquid nitrogen injection, and artificial barriers[14].

2.1 Multi-stage Sanding Technique

The multi-stage sanding technique involves injecting the designed total proppant volume into the formation through several stages of pumping. During the fracturing process, low-rate pumping of pre-flush fluid and slurry is done initially to form a sand barrier. Then, the pumping rate is gradually increased while maintaining the sand barrier, slowly increasing the sand concentration until the reservoir is fully stimulated. This technique effectively controls the extension of fracture height and avoids communication with high-water layers in gas-water co-production sand bodies[15].

2.2 Liquid Nitrogen Injection Technique

The use of liquid nitrogen energizes and enhances the displacement process during proppant fracturing, compensating for the insufficient energy of reservoir fluid flowback. It significantly improves the flowback rate of low-pressure oil and gas wells, thereby enhancing the fracturing effect[16]. The liquid nitrogen injection technique is often combined with forced closure techniques to calculate the flowback rate of fracturing fluid. The results show that the lower the formation permeability, the longer the closure time of the fracture [17]. In the western part of the Sulige Gas Field, the liquid nitrogen injection technique can be used to improve the flowback rate, optimize the proppant distribution, and create high-conductivity gas-water flow channels.

2.3 Artificial Barrier Technique

During fracturing operations, if the barrier's blocking capacity is weak, it can lead to fractures crossing the barrier. For example, when the water-bearing layer is close to the production layer, it can cause water production and affect the fracturing effect[18]. By pumping low-viscosity fracturing fluid with high-density quartz sand and gel, a low-permeability artificial barrier is created to inhibit the extension of fractures along the fracture height direction[18-19]. When hydraulic fracturing gas-water co-production reservoirs in tight sandstone formations, using support agents with different densities and small particle sizes to control the fracture height extension can effectively increase the stimulated reservoir volume and delay the water breakthrough time in gas wells.

2 Analysis of the Effectiveness of Water-Controlled Fracturing Techniques

By combining the aforementioned water-controlled fracturing techniques, water-controlled fracturing operations were conducted on the sandstone reservoir interval of Well A, which ranges from 3336m to 3352m. This sandstone interval represents a low-permeability and low-porosity reservoir. According to the interpretation of well logging results, the reservoir is adjacent to a water-bearing layer and does not exhibit any significant barrier, indicating a gas-water co-production scenario.

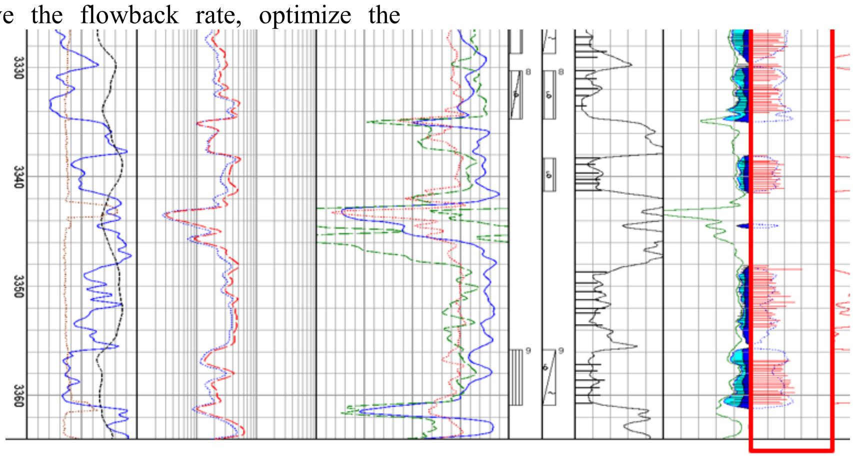

Figure 1 Well A Formation Logging Curve

After hydraulic fracturing, the gas production of Well A has increased, see Figure 1. However, the water production remains high, with a daily gas production rate of $1.38\times10^4 m^3/d$ and a daily water production rate of $28.8 m^3/d$. The movement of formation water could not be effectively controlled, indicating that hydraulic fracturing has penetrated the water-bearing layer.

To address this issue, numerical simulation of fracture extension was conducted, and the results confirmed that hydraulic fracturing has penetrated the water-bearing layer[20].

4. OPTIMIZATION OF FRACTURING PROCESS PARAMETERS

Considering the fracturing parameters used in Well A, there is room for improvement in the water-controlled fracturing process. The fracture geometry can be optimized, and the vertical extension of fractures can be suppressed by improving the shut-in time for secondary proppant injection, optimizing the location of the perforations, and adjusting other construction parameters.

A quasi-three-dimensional model is employed to calculate the geometric dimensions of the fractures. The model assumes a homogeneous formation, with the reservoir and cap rock having the same elastic modulus and Poisson's ratio. Fluid flow within the fractures is assumed to be laminar, and the vertical profile of the fractures is elliptical.

The fracture width in the quasi-three-dimensional model is obtained by applying a two-dimensional calculation method along the vertical direction at various points along the length of the fracture. Therefore, the fracture width is a function of net pressure and fracture height [21]:

$$W_{fe}=\frac{4(1-\nu^2)}{\pi E}H(x)\int_{fl}^{1}\frac{f_2 df_2}{\sqrt{f_2^{\,2}-fl^2}}\int_{0}^{f_2}\frac{p(f_1)df_1}{\sqrt{f_2^{\,2}-fl^2}} \quad (1)$$

The proppant volume has little effect on the variation of fracture length. However, in the multi-stage proppant injection process, the shut-in time significantly influences the hydraulic fracture morphology. With an increase in shut-in time, the hydraulic fracture length shows a decreasing trend followed by an increasing trend. At a shut-in time of 40 minutes, the hydraulic fracture aligns closely with the propped fracture. It can be observed that for different reservoir characteristics, such as the horizontal principal stress of the barrier layer, rock mechanical parameters, reservoir properties, and the position of adjacent water layers, targeted optimization should be carried out.

5. APPLICATION OF OPTIMIZED WATER-CONTROLLED FRACTURING PROCESS

Based on the analysis of factors influencing the water-controlled fracturing process, the sandstone interval at depths of 3389-3403m in Well B was selected for fracturing. The average porosity of the gas-water layer is 13.2%, with an average permeability of 0.27 mD and an average water saturation of 72.3%. There is no apparent barrier between the gas and water layers, see Figure 2.

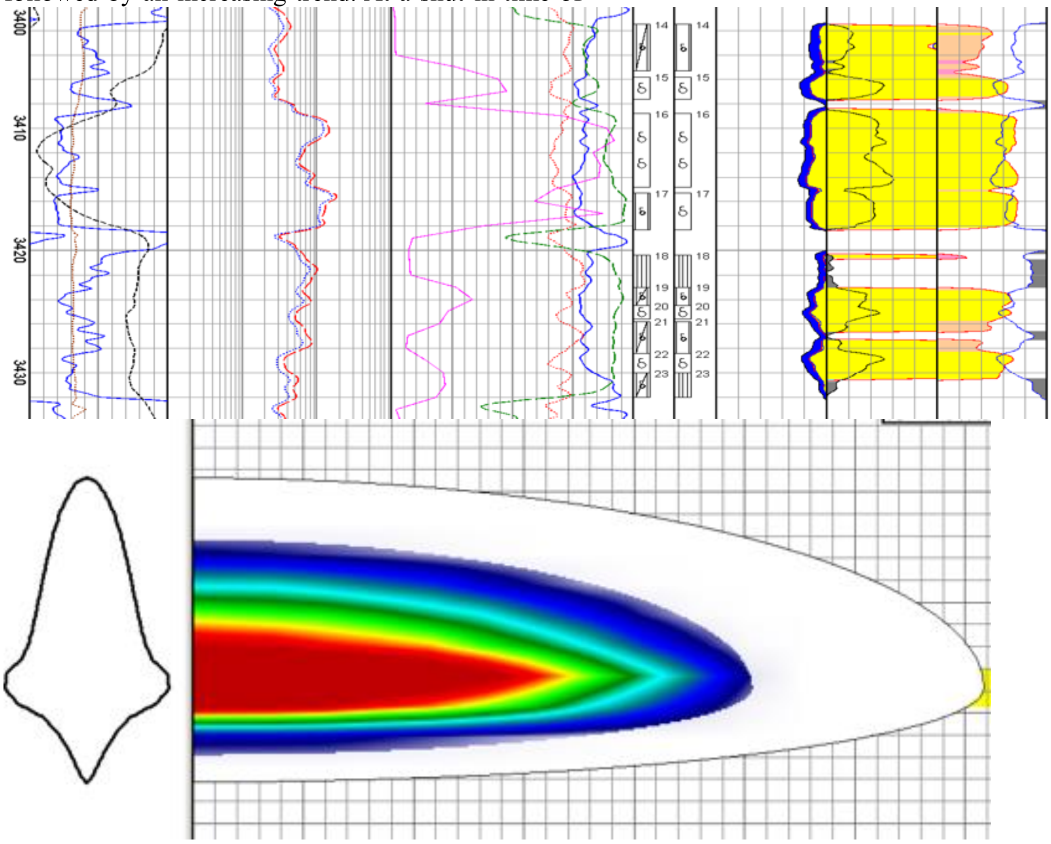

Figure 2 Well B's Production Log and Fracture Morphology

Based on the rock mechanics parameters and physical characteristics, the perforation interval in the upper section of the reservoir was determined to be 3593-3596m. The main pumping rate was set at 6 m3/min, with a net fluid volume of 553.8 m3, a proppant volume of 45 m3, and a pre-flush ratio of 37.9%. The shut-in time was set at 50 minutes. After the fracturing operation, the well's daily gas production reached 4.4×10^4 m^3/d, with a daily water production of 5.2 m^3/d. The unobstructed flow rate was measured at 129.78 m^3/d.

6. SUMMARY

In the water-controlled fracturing process of tight sandstone gas reservoirs, the shut-in time and perforation location during the secondary proppant injection significantly affect the water control effectiveness.

Significant differences in water control effectiveness were observed among the two wells that implemented the water-controlled fracturing process in the Sulige West area. Therefore, targeted optimization of water control fracturing schemes should be carried out based on different reservoir characteristics.

After optimizing the water-controlled fracturing scheme for Well B, the recommended construction parameters were as follows: a main pumping rate of 6 m3/min, a net fluid volume of 553.8 m3, a proppant volume of 45 m3, a pre-flush ratio of 37.9%, and a shut-in time of 50 minutes. The post-fracturing production results showed a daily gas production of 4.4×104 m3/d, a daily water production of 5.2 m3/d, and an unobstructed flow rate of 129.78 m3/d.

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Analysis of Fracture Width in Hydraulic Fracturing based on ANSYS

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Abstract: The width of hydraulic fractures determines their conductivity, and when the width is too small, proppant-laden fluid cannot flow through, resulting in a sharp increase in construction pressure beyond the operational limit, leading to the failure of hydraulic fracturing operations. Additionally, fracture width also affects the post-fracturing production of the well. In this study, an ANSYS finite element analysis software was utilized, along with the finite element method of fracture mechanics, to establish a finite element model for predicting fracture width. The elastic-plastic fracture mechanics finite element method was employed to determine the width of the fracture and the stress intensity factor at the crack tip, while also capturing the stress variation surrounding the fracture. By simulating different wellhead pressures, the study reveals the relationship between the stress intensity factor at the crack tip, fracture width, and wellhead pressure. It is observed that as the wellhead pressure increases, the stress intensity factor and fracture width also increase. Furthermore, by simulating different elastic moduli of the formation, the study demonstrates that the hydraulic fracturing width gradually decreases with an increase in elastic modulus. Through analyzing the factors influencing hydraulic fracture width, this research provides valuable insights for the design and construction of hydraulic fracturing operations.
Keywords: Hydraulic Fracturing, ANSYS Finite Element, Elastic Modulus, Fracture Width, Stress Intensity

1. INTRODUCTION

Hydraulic fracturing is currently the most effective method for extracting hydrocarbons from low-permeability reservoirs, and accurately understanding and evaluating the effectiveness of fracturing operations plays a crucial role in improving the ultimate oil and gas recovery. Currently, there are various methods for simulating hydraulic fracturing, including finite element methods, discrete element methods, boundary element methods, etc. Among them, the finite element method is considered an effective approach for simulating hydraulic fracturing, providing both computational accuracy and relatively ideal calculation speed. Numerical simulation studies using the finite element method to analyze the dynamic process of hydraulic fracturing have important guiding implications for on-site fracturing operations. Construction parameters for hydraulic fracturing, such as the volume of fracturing fluid, number and orientation of perforations, all have significant impacts on the width of reservoir fractures. Therefore, accurately simulating the influence of construction parameters on reservoirs is of great value for on-site oilfield operations. In this study, an in-depth analysis of fracture width in hydraulic fracturing is conducted to provide valuable insights for on-site fracturing operations in oilfields[1].

2. BASIC THEORY AND CRITERIA FOR FRACTURE PROPAGATION

2.1 Criteria for Fracture Initiation and Propagation

The process of hydraulic fracture propagation is generally accompanied by shear slip effects, resulting in a complex fracture pattern. ANSYS employs the cohesive zone model to study the initiation and propagation criteria for this type of fracture. The main content includes the functional response relationship between interfacial tensile stress and relative displacement and the relationship between interfacial energy during the fracture process. Regarding the determination of initial fracture, stress-strain relationships are considered, and ANSYS provides several standard approaches. In this study, the widely used secondary stress failure criterion is selected, which states that initial fracture occurs when the sum of the squares of stress ratios in three directions reaches 1, i.e.

2.2 Stress Intensity Theory at the Crack Tip

The crack tip refers to the region near the tip of the crack, which is also referred to as the crack front or apex in some literature. The stress field and displacement field at the crack tip are fundamental for studying rock fracture. Therefore, investigating the stress field and displacement field at the crack tip is crucial as it controls the fracture process in that vicinity. Assuming the crack body is linear elastic, the stress field and displacement field for different types of cracks can be obtained using elastic theory. This leads to the introduction of the concept of stress intensity factors[2].

In the vicinity of the crack tip, within a sufficiently small region called the KI-dominant zone or control zone, for each loading mode, regardless of the geometric shape and load conditions, as long as they have the same value of KI, the distribution of stress, displacement, and strain is exactly the same, and their magnitudes are directly proportional to KI. Therefore, KI is a measure of the intensity of the stress field at the crack tip in linear elastic materials, and it is called the stress intensity factor. It is a significant parameter in linear elastic fracture mechanics and is essential for analyzing or solving the stress field and displacement field near the crack tip in geological formations, which involves calculating the stress intensity factor[3].

2.3 Physical Model

2.3.1 Basic Assumptions

a) The rock is assumed to be homogeneous, linear elastic, and isotropic.

b) The fracture height is assumed to be constant.

c) The flow of fracturing fluid in the cross-sectional direction of the fracture is neglected, The fluid flows one-dimensionally along the length of the fracture.

d) The fracture undergoes two-dimensional failure in terms of crack length and width.

e) The fracture surface is assumed to be planar.

3. FINITE ELEMENT ANALYSIS

3.1 Element Properties

In previous studies, most finite element models of cracks were established using modeling methods for symmetric half cracks. In this study, the PLANE183 eight-node quadrilateral solid element with plane strain is used. The finite element model is established by creating coincident keypoints near the crack tip[4].

3.2 Mesh Generation

The element size near Key Point 1 is set to 20mm, and the element size near Key Point 6 is also set to 20mm. The remaining element sizes are controlled at 500mm. The A1 plane is meshed using the Meshing-Mesh-Areas-Free command, as shown in Figure 1.

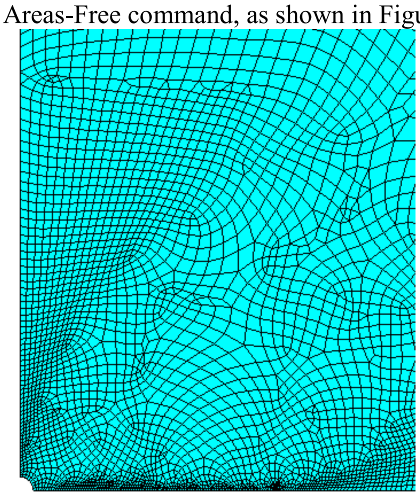


Figure 1 Unit Grid Division

3.3 Application of Boundary Conditions

The wellbore fracturing pressure, Pj, is applied to the AB and AF edges, i.e., L1 and L6. Based on the distribution of the stress field around the wellbore, the minimum in-situ stress is applied to the L4 edge, and the maximum in-situ stress is applied to the L3 edge. According to the theory of elastic mechanics, the displacement at the L3 edge, far from the stress concentration zone, has a negligible effect. Therefore, the x and y-direction displacements at the L3 edge are constrained to zero using the Define Loads-Apply-Structural-Displacement-Symmetry B.C.-OnLine command. The symmetric displacement constraints are applied to the L2 and L5 edges using Define Loads-Apply-Structural-Displacement-Symmetry B.C.-OnLine[5].

3.4 Solution Settings

To visualize the distribution of Von Mises stress, the contour plot for nodal solutions can be generated by selecting Plot Results-Contour plot-Nodal solu-Stress-Von Mises stress. An example of the Von Mises stress contour plot is shown in the figure 2 below:

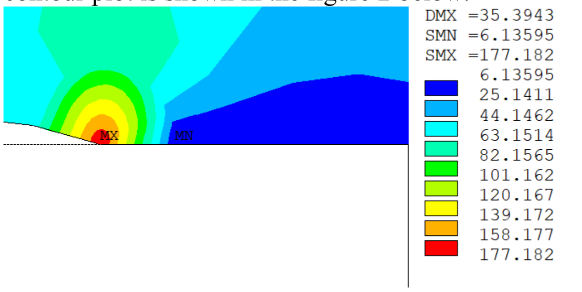


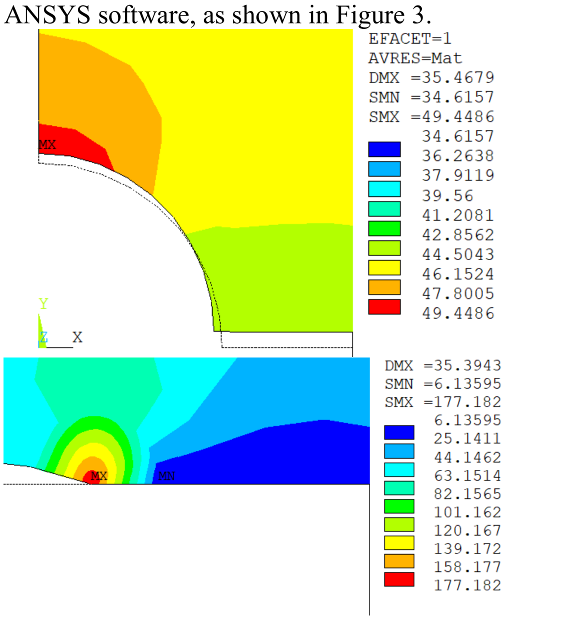
Figure 2 The Von Mises Stress Contour Plot

To establish a local coordinate system at the crack tip, enter the following command in the command window: LOCAL,11,0,r+length. Refer to Figure 3-9 for the visualization of the local coordinate system. Next, create a stress intensity factor path as shown in Figure. Use a symmetric model to calculate KI as KI1. Obtain the stress intensity factor KI1 by entering the command *get,KI1,Kcalc,K,1 in the command window. Check the variable data by navigating to Parameters-Scalar Parameters[6].

To establish a crack width path, enter the command path, Dy,2,100 in the command window. Create paths n4 and n5. Set up Path Operations to obtain the crack width on the paths. Finally, use Map onto Path and select UY to display the crack width curve.

3.5 Simulation of Different Wellbore Pressures

Based on the established hydraulic fracturing finite element model, simulate the variations in the stress intensity factor and crack width curve for wellbore pressures of 40 MPa, 50 MPa, and 60 MPa using ANSYS software, as shown in Figure 3.



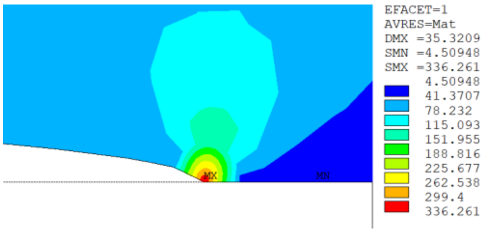


Figure 3 Stress Intensity Factor and Crack Width Curve

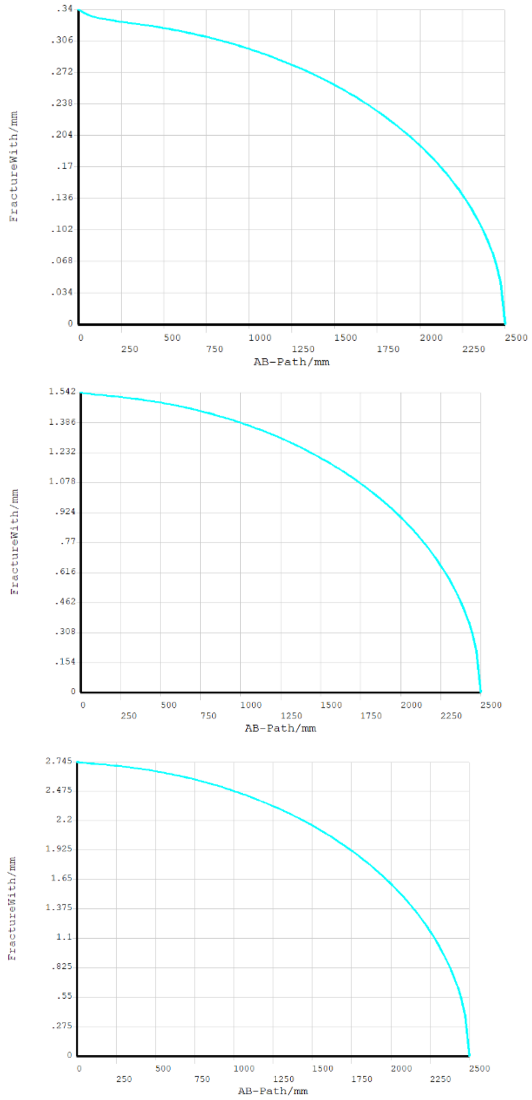


Figure 4 Relationship between Fracture Width and Wellbore Pressure Path under different Pressures

Figure 4 Relationship between crack width and path for wellbore pressures of 40 MPa, 50 MPa, and 60 MPa

Simulation of different wellbore pressures reveals that as the wellbore pressure increases, the Von-Mises stress also increases, and the location of the maximum Mises stress gradually moves closer to the crack tip from the crack width direction. Additionally, the stress intensity factor at the crack tip increases with increasing wellbore pressure. From Figure 3, it can be observed that the relationship between crack width and path is nonlinear, and the crack width continuously increases with increasing wellbore pressure[7].

4. CONCLUSION

(1) As the wellbore pressure increases, the Von-Mises stress increases, and the location of the maximum Mises stress gradually moves closer to the crack tip from the crack width direction. The stress intensity factor at the crack tip also increases with increasing wellbore pressure. The relationship between crack width and path is nonlinear, and the crack width continuously increases with increasing wellbore pressure.

(2) Analyzing the hydraulic fracturing finite element and its influencing factors provides valuable guidance for optimizing fracturing design.

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Numerical Modeling of Hydraulic Fracture Propagation in Horizontal Wells Based on Geological Parameters

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Abstract: Tight sandstone gas reservoirs are unconventional oil and gas resources with significant exploration and development potential. Hydraulic fracturing in horizontal wells is an effective method to enhance the productivity of these reservoirs. Multi-stage hydraulic fracturing in horizontal wells can create a stable network of primary fractures and fracture systems in low-permeability and homogeneous tight rock formations, successfully addressing issues such as low oil and gas production in tight reservoirs. However, in practical engineering, many of the perforations and fracture extensions in horizontal wells are ineffective, with some fractures deviating or even changing direction from their intended path. This study utilizes a finite element numerical simulation approach to investigate the fracture propagation behavior under different geological parameter conditions in this area. The results indicate that with a Poisson's ratio of 0.25 and an elastic modulus of 15 GPa, lower fracturing pressures and wider hydraulic fracture apertures are generated, which are beneficial for improving the effectiveness of hydraulic fracturing. The findings of this study will provide a scientific basis for the development of tight sandstone gas reservoirs in the Ordos Basin.
Keywords: Horizontal Wells; Fracture Propagation; Tight Sandstone; Geological Parameters

1. INTRODUCTION

China's onshore tight gas reserves cover an advantageous exploration area of 32.46×10^4 km^2 with estimated resources of 21.85×10^{12} m^3, mainly distributed in the Ordos Basin, Bohai Bay, and Sichuan Basin. Among them, the tight sandstone gas resources in the Ordos Basin exceed 12×10^{12} m^3, accounting for approximately 83% of the total natural gas resources in basin and mainly concentrated in the Sulige area [1]. Horizontal well fracturing is an effective method to increase the production of tight sandstone gas reservoirs[2]. However, the overall development of tight sandstone gas reservoirs in the Ordos Basin faces challenges due to the rapid lateral variations and vertical multilayer development of reservoirs. Deepening the understanding of fracture propagation in horizontal well hydraulic fracturing in the target blocks can help predict the post-fracturing fracture expansion patterns and provide theoretical guidance for optimizing construction parameters. This paper conducts numerical simulation experiments on multi-stage hydraulic fracture propagation in the northern and southeastern replacement areas of Block S, aiming to provide theoretical guidance for the design of multi-stage fracturing in field horizontal wells[3].

2. FRACTURE PROPAGATION MODEL

During the hydraulic fracturing process, the propagation of fractures is one of the key issues in rock mechanics. To address this problem, the basic governing equations consist of the rock mass equation, the fluid flow equation (i.e., continuity equation) for the fracturing fluid, and the propagation criteria. In particular, rock deformation is primarily based on linear elastic fracture mechanics theory, while plastic deformation characteristics require the use of the B-matrix method to modify the elemental stresses based on plastic criteria[4-5]. To solve the fracture propagation, a hybrid method combining the finite element method (FEM) and the discrete element method (DEM) is employed. Specifically, the computational domain is divided into multiple solid elements, which are connected by virtual springs to transmit interaction forces, and the fracture of the springs represents the rock fracturing process. Additionally, there exists a fracture element between every two solid elements to compute the flow of the fracturing fluid and the distribution of fluid pressure. The fluid pressure acts as an external load on the fracture surfaces (i.e., contact surfaces between the solid elements). The deformation of the continuous solid elements is solved using the finite element method, while the fracture of the springs is calculated using the discrete element method. The conditions for fracture propagation are determined by the maximum tensile stress criterion and the Mohr-Coulomb criterion. These criteria need to be modified and optimized based on the specific circumstances to meet engineering requirements. In summary, the fracture propagation problem in hydraulic fracturing is a complex multi-physics coupling problem that requires the integration of knowledge from various fields such as rock mechanics, fluid mechanics, and mechanics. By employing a hybrid method that combines the finite element method and the discrete element method, the process of fracture propagation can be simulated more accurately, providing strong support and assurance for engineering practice. In the fracture propagation model for hydraulic fracturing, the following assumptions are made: (a) the reservoir matrix is homogeneous and isotropic; (b) the rock mass equation includes an inertial term to make the mechanical behavior dynamic, but an artificial damping term is introduced to make it a quasi-static process; (c) the influence of proppants on fracture propagation is not considered; (d) fractures only occur and extend along the interfaces between the elements, and it is assumed that the number of mesh elements is large enough to provide a stochastic path for fracture propagation[6-7].

3. NUMERICAL SIMULATION STUDY ON FACTORS AFFECTING CRACK PROPAGATION

This section analyzes the influence of Poisson's ratio and rock elastic modulus formation parameters on the fracture propagation pattern of staged fracturing in horizontal wells, providing theoretical guidance for fracturing construction in the replacement area of Block S.

3.1 Poisson's ratio

Model parameters: fracturing 3 sections, horizontal stress difference 5MPa, Young's modulus 20GPa, fracture height 40m, section spacing 60m, construction displacement 10m^3/min, Poisson's ratio set to 0.1, 0.15, 0.2, 0.25, 0.3, 0.35. The simulation results are shown in Figure 1.

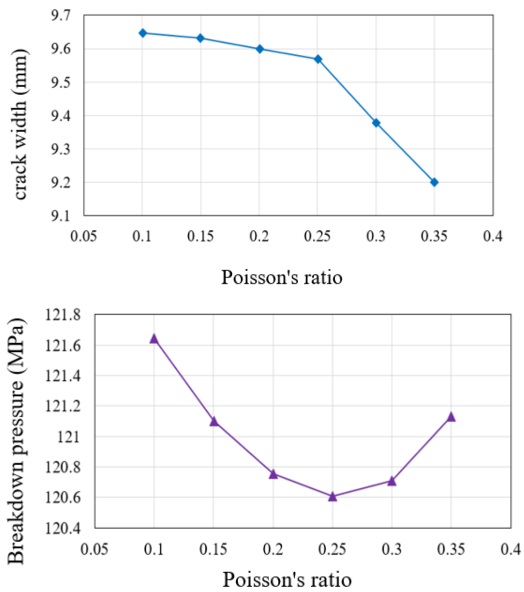

Figure 1 Variation of Crack Width and Fracture Pressure under Different Poisson's Ratio

The results show that the crack width decreases with the increase of Poisson's ratio. When μ≤ At 0.25, the crack width slightly decreases; and μ≥ At 0.25, the trend of crack width decreasing increases.

μ< At 0.25, with the increase of Poisson's ratio, the fracture pressure of reservoir sandstone decreases, and the decreasing trend gradually weakens to μ= At 0.25, the fracture pressure of sandstone is the smallest. When μ> At 0.25, the fracture pressure of sandstone increases with the increase of Poisson's ratio, and the increasing trend is strengthened. According to the comprehensive change of fracture width, when the Poisson's ratio is about 0.25, the fracture pressure is small and the hydraulic fracture width is large, which is conducive to improving the fracturing effect.

3.2 Elastic modulus

Model parameters: fracturing 3 sections, horizontal stress difference of 5MPa, Poisson's ratio of 0.25, fracture height of 40m, interval of 60m, construction displacement of 10m^3/min, elastic modulus of 10GPa, 15GPa, 20GPa, 25GPa, 30GPa. The simulation results are shown in Figure 2.

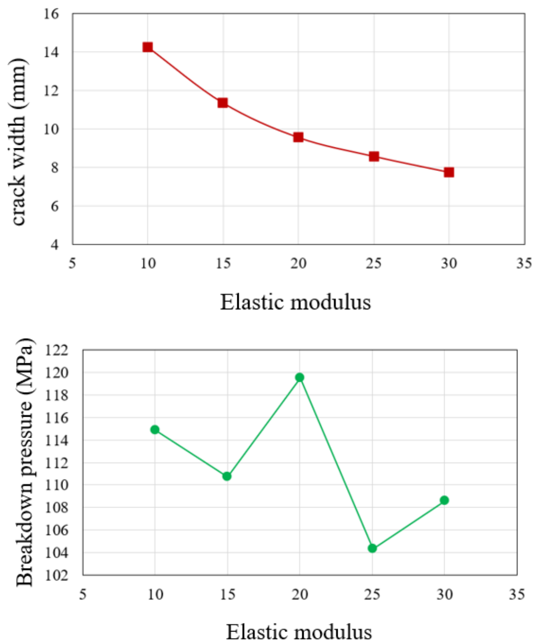

Figure 2 Changes in Crack Width and Fracture Pressure under Different Elastic Moduli

As the elastic modulus increases, the length of hydraulic cracks tends to increase while the width of cracks gradually decreases. The elastic modulus of reservoir rocks is negatively correlated with the width of hydraulic fractures. The width of hydraulic fractures decreases with the increase of rock elastic modulus, and the decreasing trend gradually decreases. The higher the Young's modulus of rocks, the stronger their brittleness, and the less likely they are to undergo significant deformation. Therefore, staged fracturing of horizontal wells in formations with stronger Young's modulus is more likely to form narrow and long fractures.

4. CONCLUSION

The numerical simulation experiment of multi-stage fracturing fracture propagation of horizontal wells was carried out in the northern and southeastern replacement areas of Block S, and a set of multi-stage and multi cluster fracturing fracture propagation model was established by comprehensively considering the stress interference, Fluid–structure interaction, and multi fracture flow distribution. By analyzing the influence of different formation parameters on the multi cluster fracture propagation, when the Poisson's ratio is about 0.25 and the elastic modulus is about 15GPa, the small fracturing pressure and the large hydraulic fracture width generated are beneficial for improving the fracturing effect.

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Non-Contact Fan Control Device Integrated with Gesture Recognition

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Abstract: This system uses STC's Ai8051U microcontroller as the core controller, with DWIN intelligent serial screen, to build a non-contact fan control system based on gesture recognition. The system realizes the start-stop, steering and speed control of the fan by detecting the waving action through the diffuse reflection photoelectric switch. At the same time, the system uses a self-made distance measurement module based on the principle of ultrasonic echo ranging to monitor the operating distance in real time. The fan's operating voltage is precisely regulated using PWM technology, and the system status parameters are displayed in real time on the DWIN LCD screen. In addition, the system supports a combination operation mode, which can store and execute eight sets of preset action sequences. Users can set the operating time and preset operating voltage, and achieve multi-action interlocking control.
Keywords: Gesture Recognition; Non-contact Fan Control; Ultrasonic Distance Measurement; PWM

1. INTRODUCTION

With the rapid development of IoT technology and the smart home industry, contactless interaction technology has become a hot topic in human-computer interaction research due to its significant advantages in terms of hygiene safety and ease of operation. In scenarios such as public facilities, medical equipment, and smart homes, traditional contact-based control methods can easily lead to the cross-transmission of bacteria and are inconvenient to operate in special environments. Non-contact control technology, which uses gesture recognition and distance sensing, can effectively solve these problems and meet users' needs for convenient and hygienic operation[1-2].

Currently, non-contact control technology is mainly based on infrared sensing, ultrasonic ranging, machine vision and other principles[3-4]. Infrared sensing technology is relatively low in cost, but is easily affected by ambient light and has limited recognition accuracy. Although machine vision solutions can achieve complex gesture recognition, they are characterised by high algorithm complexity, expensive hardware costs, and high computing resource requirements, making them difficult to popularise in low-cost embedded devices[5]. Ultrasonic ranging technology, on the other hand, has unique advantages in medium- and short-range non-contact control scenarios due to its strong anti-interference capabilities, fast response speed, and moderate cost. However, its ranging accuracy is easily affected by environmental factors such as temperature, and technical optimisation is required to improve stability[6].

In response to the issues of existing non-contact control devices, such as limited functionality, insufficient precision, and high cost, this paper designs a non-contact intelligent control device with a fan as the control object.The system is based on a high-performance microcontroller and integrates ultrasonic distance measurement modules, photoelectric switch modules, display modules, and drive circuits to achieve non-contact fan start-stop, forward and reverse switching, speed adjustment, timing control, and combination operation functions. Temperature compensation algorithms are used to optimise distance measurement accuracy, while PWM pulse width modulation and PID closed-loop control are used to achieve precise voltage adjustment. Modular programme design is also used to improve system stability and expandability.

2. SYSTEM CIRCUIT ANALYSIS

2.1 Ultrasonic Distance Measurement Analysis

The self-made ultrasonic distance measurement module based on the CS100A chip is the core component for non-contact distance detection, and its working principle is based on the echo ranging method. The module continuously emits eight 40 kHz pulse signals toward the palm using the transmitter probe, while simultaneously starting the timer on the Ai8051U. The ultrasonic waves propagate through the air to the palm and are reflected back, captured by the receiver probe. At this point, the timer stops, yielding the round-trip propagation time t of the ultrasonic waves. The distance calculation formula is as follows:

$$d = \frac{v \times t}{2} \quad (1)$$

Among them, v is the speed of sound propagation in air.

However, temperature affects the speed of sound, i.e., the speed of sound changes with the ambient temperature. A temperature compensation formula must be introduced to improve accuracy，

$$c = 331.45 + 0.61 \times \mathrm{T} \quad (2)$$

Among these, T represents the ambient temperature. At 0℃, the speed of sound is 330.45m/s; at 20℃, it is

332.62m/s; and at 40℃, it is 354.85m/s.

2.2 Fan Drive and Voltage Regulation Analysis

The fan's operating voltage range is 3-10V, and voltage regulation is achieved using PWM pulse width modulation. The working principle is as follows: with 12V as the input voltage, a MOSFET is used as the switching device to control the on/off state of the fan's power supply. The relationship between the output voltage and the PWM duty cycle is as follows:

$$U_{out} = U_{in} \times D \quad (3)$$

Among them, D is the duty cycle, $0 \leqslant D \leqslant 1$.

The sources of error are the accuracy of the PWM duty cycle and the conduction voltage drop of the MOSFET. In this design, a MOSFET with low conduction resistance is selected, and voltage feedback is added to the software. Specifically, the fan voltage is collected via an ADC, and a PID algorithm is used to dynamically adjust the duty cycle, keeping the error within 0.1V.

2.3 Analysis of Photoelectric Switch Signal Processing

The core of diffuse reflection photoelectric switch processing is interference resistance and direction recognition. The photoelectric switch outputs high and low level signals, and the waving direction is determined by the timing sequence of 'first blocking and then restoring'. To avoid interference from ambient light, software anti-shake is used, which continuously detects the signal three times (each time with an interval of 20 ms), and only when all three are in a valid state is it determined to be a valid operation.

3. CIRCUIT AND PROGRAM DESIGN

3.1 Circuit Design

The overall block diagram of the designed system is shown in Figure 1.

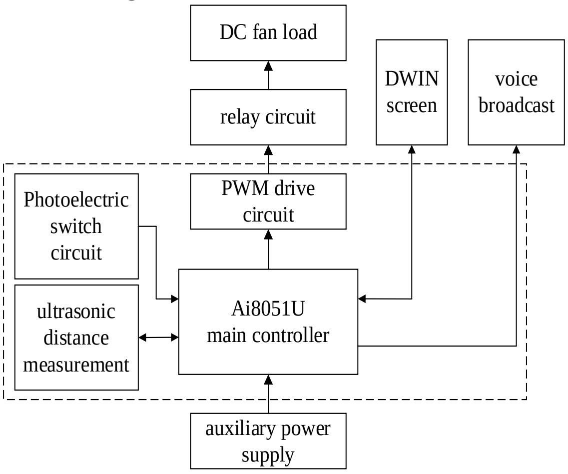

Figure 1 System block diagram

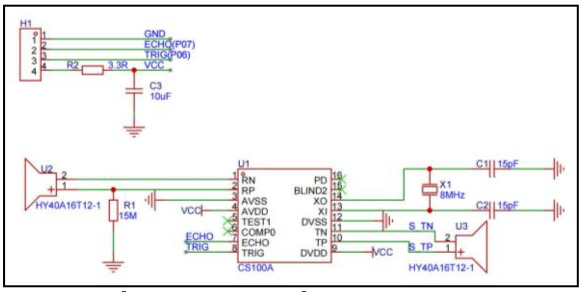

Figure 2 Ultrasonic circuit diagram

The principle of the ultrasonic ranging circuit is as described above. The CS100A chip integrates an ultrasonic transmission circuit, an ultrasonic reception circuit, and a digital processing circuit, enabling ultrasonic ranging to be performed with a single chip. The ranging results are output in the form of pulse widths. This chip is used in conjunction with a 40 kHz open ultrasonic probe, connected to a 15 MΩ pull-down resistor and an 8 MHz crystal oscillator to achieve high-performance ranging functionality.

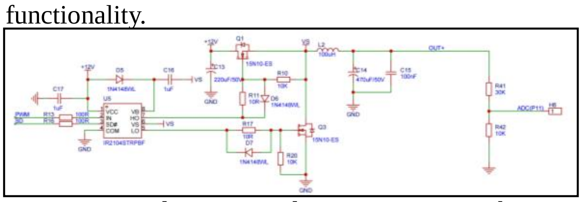

Figure 3 Voltage Regulation Circuit Schematic Diagram

The principle of the voltage regulation circuit is as described above. The IR2104 in the circuit is a high-voltage, high-speed power MOSFET and IGBT driver that works with MOSFETs and other circuits to provide drive voltages of varying amplitudes for the fan.

The auxiliary power supply is provided by an MC7805 three-terminal voltage regulator, which supplies 12V and 5V operating voltages to the MOS driver chip and measurement and control circuitry.

3.2 Program Design

(1) Program Function Description

This system uses the Ai8051U series microcontroller as the core controller. It coordinates gesture recognition, ultrasonic distance measurement, motor control, and display modules to achieve non-contact fan control. The program must complete the following core functions:

① Gesture recognition and analysis: Real-time detection of the trigger sequence of the diffuse reflection photoelectric switch, recognition of the direction of the wave, and triggering of the corresponding operation.

② Ultrasonic distance measurement: Drive the self-made ultrasonic module to measure the distance between the module and the palm.

③ Motor control: Control the fan start/stop, forward/reverse rotation, and voltage speed regulation through PWM output. Adjust the PWM duty cycle according to the gesture to achieve voltage stepping.

④ Parameter settings and countdown: Set the running time according to the distance as required by the question. Display the countdown and control the indicator light status.
⑤ Combination operation mode: Supports users to arrange and store more than 8 action sequences. Automatically executes fan actions (direction, voltage, duration) according to the stored sequence.
⑥ Display management: Displays real-time information such as operating distance, set voltage, countdown, fan direction, and status indicators.
(2) Design Concept
The system operates based on a closed-loop logic of ‘real-time detection - command parsing - parameter adjustment - status feedback.’ During the initialisation phase, peripherals are configured, parameters are preset, and the combination operation storage area is cleared. The main loop runs at a 10 ms cycle: the ultrasonic module measures the distance at regular intervals to calculate the operating distance, and the photoelectric switch captures signals through external interrupts and analyses the direction of the wave. Subsequently, processing is carried out according to the command mode: in basic mode, the fan direction is identified as forward or reverse and started; when a voltage command is identified, the PWM duty cycle is adjusted, and the voltage is corrected through ADC sampling in a closed loop; in combination mode, the action sequence is recorded and stored, and when started, it is executed in sequence and controlled by a timer interrupt countdown. After parameters or status are updated, the display is immediately refreshed, and the indicator light flashes when an operation error is triggered.

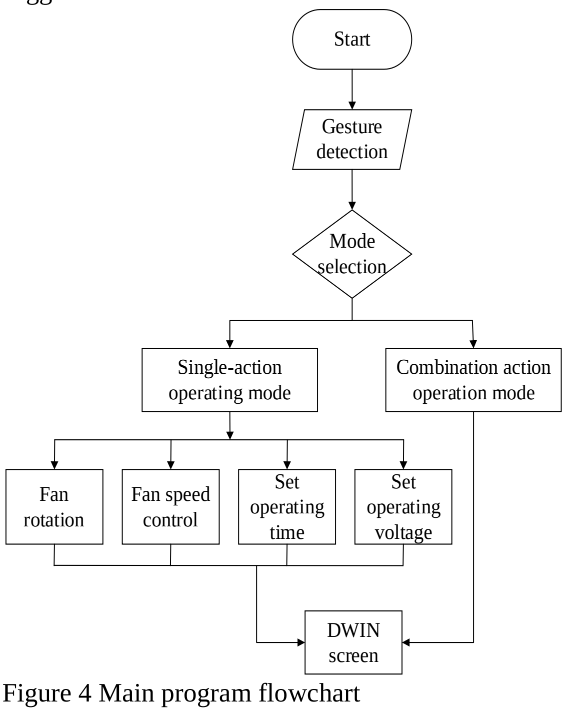

Figure 4 Main program flowchart

4. THE SYSTEM TESTING
To verify system performance, comprehensive testing was conducted under standard conditions (25°C). The operating distance error test showed that within the effective range of 5-30 cm, the maximum deviation of the system measurement was 0.08 cm (at 30 cm), with an average absolute error of 0.038 cm. In the running time control accuracy test, when the operating distance varies from 5 cm to 20 cm, the actual execution error range of the preset running time (15-30 s) is 0.026-0.907 s, with 90% of the test points having an error of less than 0.5 s. The working voltage regulation test shows that within the output range of 3-10V, the maximum deviation between the set voltage and the actual voltage is 0.081V (at 3V).
Functional verification testing confirmed that the system can reliably recognise hand gestures to start and stop the fan and switch between forward and reverse rotation, with the rotation speed responding linearly to the PWM duty cycle. In combined operation mode testing, the execution success rate of the eight preset action sequences reached 100%, and no cumulative errors occurred in the multi-parameter linkage. The addition of the voice broadcast module has significantly improved the human-machine interaction experience. No false triggers or response delays were observed during testing. All test items were verified using instruments such as the UNI-T UT89X multimeter and GWinstek GDS-1152E oscilloscope, confirming that the system fully meets the design objectives in terms of accuracy, real-time performance, and functional completeness.
5. CONCLUSIONS
This paper successfully constructed a non-contact fan control system based on gesture recognition and ultrasonic distance measurement fusion. Through the Ai8051U microcontroller working in conjunction with the self-developed CS100A distance measurement module, diffuse reflection photoelectric switch, and PWM closed-loop voltage regulation architecture, high-precision non-contact operation was achieved. This achievement not only solves the limitations of traditional contact-based control in hygiene and safety scenarios, but its modular design also provides an expandable technical paradigm for non-contact interaction in fields such as smart homes and medical clean environments. Future research will further optimise multi-gesture parallel recognition capabilities and explore machine learning-based environmental adaptation mechanisms to improve robustness in complex scenarios.

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Electrical Automation System Integration and Optimization in Smart Factories

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Abstract: Driven by Industry 4.0 and the 'Made in China 2025' strategy, smart factories have become the core direction for the transformation and upgrading of manufacturing. As the 'nerve center' of smart factories, the integration and optimization level of electrical automation systems directly determine production efficiency, flexibility, and safety reliability. This paper first elucidates the essence and core value of electrical automation system integration within smart factories. It then analyses key integration technologies and hierarchical architecture design, followed by proposing optimization strategies[1]. Finally, it validates the practical effectiveness of the integration and optimization solutions through a case study of an automotive components smart factory.
Keywords: Smart Factories; Electrical Automation; System Integration; Optimization Strategies;

1. INTRODUCTION

With the deep integration of information technology and manufacturing, the "smart factory"has evolved from concept to practice. Its core characteristic lies in achieving transparency, flexibility, and intelligence throughout the entire production process through data-driven approaches. As the core execution vehicle within smart factories, electrical automation systems span the entire chain — from field device control (sensors, actuators) to production process monitoring (SCADA), and on to management-level data interaction (MES/ERP). They serve as the vital link connecting the "physical factory" with the "digital factory"[1].

However, the electrical automation systems of most manufacturing enterprises currently suffer from fragmentation: incompatible protocols between PLCs, variable frequency drives, and sensors from different manufacturers prevent equipment collaboration; data silos between SCADA and MES systems hinder production scheduling optimisation; and traditional control logic reliant on manual adjustments fails to adapt to the dynamic demands of multi-variety, small-batch orders. According to the China Smart Factory Development Report (2023), only 30% of manufacturing enterprises have achieved partial integration of their electrical automation systems, while fewer than 15% have attained the level of "data connectivity and intelligent regulation"[4].

Against this backdrop, the "integration" and "optimization"of electrical automation systems have become pivotal to overcoming bottlenecks in smart factory development. This paper examines the practical requirements of smart factories through four dimensions: the essence of integration, key technologies, existing challenges, and optimisation strategies. It validates the effectiveness of proposed solutions through case studies, aiming to provide manufacturing enterprises with actionable technical pathways while offering reference for teaching and research in relevant academic disciplines (Electrical Engineering and Automation, Intelligent Manufacturing Engineering) at higher education institutions.

2. THE ESSENCE AND VALUE OF ELECTRICAL AUTOMATION SYSTEM INTEGRATION IN SMART FACTORIES

2.1 The Core Essence of Integration

The integration of electrical automation systems within smart factories is not merely a matter of connecting equipment or layering functions, but rather a three-tiered convergence based on: - Data interoperability - Control coordination - Management linkage[1].

(1)Equipment Layer Integration:Achieve interoperability among on-site heterogeneous devices, including sensors, actuators, PLCs, frequency converters, and others. Resolve protocol compatibility issues between equipment from different manufacturers to ensure the real-time transmission and execution of control commands.

(2)Control Layer Integration:Break down the collaborative barriers between PLC (discrete control), DCS (process control) and SCADA (supervisory control and data acquisition) systems, forming an integrated architecture of "distributed control + centralised monitoring"to achieve dynamic regulation of production processes[1].

(3)Data Layer Integration:By interfacing control layer data (such as equipment operating parameters and production progress) with management layer systems (MES, ERP, PLM) via standardised protocols (e.g., OPC UA), data support is provided for production scheduling, quality traceability, and cost accounting, thereby establishing a closed-loop system of "data - decision-making – execution"[6].

2.2 The Core Value of Integration

(1)Enhancing production efficiency: By coordinating equipment and optimising processes, manual intervention and waiting times are reduced. In machining scenarios, coordinated control logic between PLCs and SCADA systems enables automatic adaptation of machine tool parameters (such as rotational speed and feed rate) for different workpieces. Combined with pre-loading parameters based on production orders, this reduces changeover time per production line from 120 minutes to 30 minutes, achieving a 75% efficiency gain[1].

(2)Enhanced Flexible Manufacturing Capabilities: The integrated system enables rapid response to order variations by automatically adjusting PLC control logic via production schedules issued through the MES, thereby meeting the demands of multi-variety, small-batch production. For instance, automotive component factories can utilise system integration to switch production between 3-5 different products on the same production line[1].

(3)Ensuring production safety and reliability: Centralised monitoring and data alert functions enable real-time identification of equipment anomalies (such as motor overloads or excessive temperatures), triggering emergency shutdowns or maintenance instructions to mitigate safety incident risks.

(4)Reducing energy consumption and costs: By integrating and analysing data to identify energy consumption hotspots within production processes (such as air compressors and cooling systems), optimising equipment operating parameters achieves energy savings of 10 – 15%. This simultaneously minimises losses arising from unplanned equipment downtime.

3. KEY TECHNOLOGIES AND ARCHITECTURAL DESIGN FOR ELECTRICAL AUTOMATION SYSTEM INTEGRATION IN SMART FACTORIES

3.1core Integration Technology

(1)Industrial Communication Technology: The Lifeblood of System Integration. Industrial communication forms the foundation for data transmission between equipment and systems, necessitating real-time performance (millisecond-level latency), reliability (packet loss rate < 0.1%), and compatibility. A comparison of current mainstream technologies is presented in Table 1.

Table 1 Current Mainstream Technologies

Communication technology	Transmission rate	Real-time capability	Compatibility	Applicable scenarios
Profinet	100Mbps-1G	1-10ms	Primarily Siemens equipment	Discrete manufacturing (automotive, machinery)
EtherNet/lP	100Mbps-1G	10-100ms	Primarily Rockwell equipment	General for Discrete/Process Manufacturing
OPC UA	Adapt as required	flexible adjustment	Cross-vendor, cross-platform	Data Layer Integration (SCADA-MES)
5G-Industrial	1Gbps+	Less than 1ms	Wireless connectivity	mobile devices(AGV, robotic arm)

Among these, the OPC UA protocol serves as the core for achieving data layer integration: its object-oriented architecture unifies data models (such as device parameters and production orders), supports cross-vendor and cross-system data exchange, and has become the international standard for smart factory data integration (IEC 62541) [6]. OPC UA over TSN (Time-Sensitive Networking) technology further optimises real-time performance. TSN enables microsecond-level time synchronisation for industrial Ethernet. Combined with OPC UA's cross-platform capabilities, this effectively resolves real-time communication challenges between heterogeneous devices [2][3].

(2)PLC/SCADA/DCS Collaborative Technology: The “Brain”of the Control Layer. PLC (Programmable Logic Controller): Responsible for real-time control of discrete field equipment (such as machine tool start/stop and valve actuation), requiring closed-loop control via industrial Ethernet in conjunction with sensors and actuators; SCADA (Supervisory Control and Data Acquisition): Enables centralised monitoring of production processes, displaying equipment operational status and production data via human-machine interfaces (HMIs), whilst supporting remote operation; DCS (Distributed Control System): Suitable for process industries (such as chemical and metallurgical), enabling precise multi-variable control (temperature, pressure, flow) through distributed controllers[1].

The synergy among these three components is achieved through bidirectional interaction via “control commands – data feedback”: for instance, SCADA disseminates production schedules to PLC/DCS, which then execute tasks and relay real-time data (such as output volume and energy consumption) back to SCADA, thereby forming a closed-loop control system.

(3)Data Acquisition and Edge Computing Technology: The “Front End”of Data Processing. In traditional systems, the bulk of field data is uploaded directly to the cloud, which can easily lead to network congestion and latency. The introduction of edge computing technology enables data pre-processing (such as filtering redundant data and detecting anomalies) to be performed at “edge nodes” (e.g., edge gateways) close to the equipment. Only critical data (such as fault alerts and production reports) is then uploaded to the cloud, thereby reducing network load while enhancing real-time control capabilities. For instance, a steelworks utilised edge computing to conduct real-time analysis of blast furnace temperature data, achieving temperature control precision of ±1°C. This represents a significant improvement over the ±5°C accuracy achievable through traditional cloud-based processing[1].

3.2LAYERED INTEGRATED ARCHITECTURE DESIGN

The four-tier architecture comprising the field device layer, control layer, monitoring layer, and management layer represents the mainstream solution for electrical automation system integration in smart factories. The functions and core equipment for each layer are as follows:

(1)Field Device Layer:Core Equipment: Sensors (temperature, pressure, displacement), Actuators (motors, valves, robotic arms), Smart Instrumentation; Function: Acquires physical quantities from the production site (e.g., equipment temperature, product dimensions) and executes commands issued by the control layer;Communication: Utilises real-time protocols such as Profinet/EtherNet/IP to establish connectivity with the control layer.

(2)Control Layer:Core Equipment: PLCs, DCS systems, edge gateways;Functions: Executes production logic control (e.g., production line start/stop, parameter adjustment), performs data pre-processing via edge gateways;Communication: Interacts with the monitoring layer via OPC UA upwards, connects to field devices via industrial Ethernet downwards.

(3)Monitoring Layer:Core Equipment: SCADA systems, HMIs, data servers;Functionality: Centralised monitoring of production processes, generation of real-time reports (e.g., output volume, equipment utilisation), triggering of anomaly alerts;Communication: Interfaces upwards with management layers via database interfaces (e.g., ODBC), connects downwards to the control layer via OPC UA [6].

(4)Management Layer: Core Equipment: MES (Manufacturing Execution System), ERP (Enterprise Resource Planning), PLM (Product Lifecycle Management); Functions: Formulating production schedules, conducting quality traceability, calculating costs, and providing data support for corporate decision-making; Communication: Receiving monitoring layer data via standardised interfaces and issuing production instructions to the monitoring layer.

4.THE PRINCIPAL CHALLENGES CURRENTLY FACING ELECTRICAL AUTOMATION SYSTEM INTEGRATION

4.1EQUIPMENT HETEROGENEITY AND PROTOCOL INCOMPATIBILITY

Equipment from different manufacturers and eras employs disparate protocols (such as Siemens' Profinet and Schneider's Modbus), preventing direct communication between devices. Research indicates that a certain automotive components factory requires over eight distinct gateways to connect more than twenty types of equipment, not only increasing hardware costs but also compromising system real-time performance[1].

4.2THE PHENOMENON OF DATA SILOS IS SEVERE

Most enterprises' SCADA, MES, and ERP systems are developed by different vendors, resulting in inconsistent data models (e.g. “production order” is termed “task number” in SCADA and“work order ID” in MES), which prevents seamless data integration. For instance, an electronics factory's SCADA system can collect equipment output data but cannot link it to MES quality data, necessitating manual data entry—a process that is both time-consuming and prone to errors.

4.3INSUFFICIENT SYSTEM RELIABILITY AND SECURITY

Reliability concerns: Increased system complexity following integration heightens the risk of single points of failure triggering cascading failures (e.g., PLC malfunction causing entire production line shutdowns) [1].Security concerns: Connecting industrial networks to the internet amplifies cyberattack risks. In 2022, global manufacturing losses from attacks on industrial control systems (ICS) exceeded US$5 billion, with primary attack vectors including virus injection and data tampering.

4.4HIGH COST AND TECHNICAL BARRIERS

System integration requires investment in hardware (gateways, servers), software (OPC UA servers, MES modules) and labour (scheme design, commissioning), costs which small and medium-sized enterprises struggle to bear. Furthermore, a shortage of multi-skilled personnel (proficient in both electrical control and industrial software/networking) leads to inadequate operational and maintenance capabilities post-integration.

5.OPTIMISATION STRATEGIES FOR ELECTRICAL AUTOMATION SYSTEMS IN SMART FACTORIES

5.1TECHNICAL OPTIMISATION: ADDRESSING CORE PAIN POINTS THROUGH STANDARDISATION AND INTELLIGENT SOLUTIONS

(1)Unified Communications and Data Protocol Promotion: OPC UA over TSN (Time-Sensitive Networking) Technology: TSN enables time synchronisation on industrial Ethernet (with microsecond-level precision) [3]. Combined with OPC UA's cross-platform capabilities [6], it resolves real-time communication challenges between heterogeneous devices [2]; Establishing enterprise-level data standards: Unified data models (e.g., device coding, parameter definitions), such as defining ‘device temperature’ as ‘DEV-TEMP-XX (where XX denotes the device identifier)’, ensure consistent data semantics across systems [1].

(2)Implementing intelligent optimisation through AI and machine learning: Predictive maintenance: By collecting equipment vibration, temperature, current and other data via edge computing, AI algorithms (such as LSTM neural networks) establish fault prediction models to identify equipment anomalies in advance. For instance, a wind turbine manufacturer reduced equipment failure rates by 30% and maintenance costs by 25% through AI-driven predictive maintenance[5]. Production Scheduling Optimisation: Dynamically adjust production plans by analysing historical manufacturing data (order volumes, equipment efficiency) via machine learning. For example, a food processing plant enhanced equipment utilisation by 18% through reinforcement learning algorithms optimising production line scheduling.

(3)Modular and flexible design: Employing modular electrical equipment (such as modular PLCs and reconfigurable sensors) to facilitate rapid device replacement and expansion. For instance, a new energy battery factory achieved a reduction in production line changeover time from four hours to one hour through modular design, thereby meeting the production requirements for different battery models.

5.2MANAGEMENT OPTIMISATION: IMPLEMENTING SYSTEMS THROUGH COLLABORATION AND TALENT SUPPORT

(1)Establish a cross-departmental coordination mechanism: Form a “Smart Factory Task Force” comprising electrical engineers (responsible for equipment commissioning), IT engineers (responsible for system integration), and production managers (responsible for requirements analysis). This prevents “disconnect between electrical and IT systems”and “disparities between production and operations”. For instance, a machinery factory reduced its system integration cycle from six months to three months through cross-departmental collaboration[1].

(2)Enhancing the cultivation of multi-skilled professionals: University-enterprise collaborative education: Higher education institutions may introduce courses in“Industrial Software” and“Industrial Networking” within the “Electrical Engineering and Automation” programme[1], while enterprises provide internship placements to develop talent proficient in both electrical control and industrial internet technologies; Internal Training System Development: Regularly conduct training programmes on OPC UA[6], MES, and AI operations and maintenance[5]. Upon successful completion and assessment, issue certification for on-the-job readiness to enhance the technical capabilities of existing staff.

(3)Full lifecycle cost management: Design phase: Prioritise cost-effective modular equipment to avoid overinvestment; Operations and maintenance phase: Reduce unplanned downtime costs through predictive maintenance, and lower on-site maintenance expenses by utilising remote operations (such as VPN remote debugging).

5.3SECURITY OPTIMISATION: ENSURING SYSTEM STABILITY THROUGH REDUNDANCY AND PROTECTION

(1)Hardware redundancy design: Critical equipment such as PLCs, power supplies, and communication modules are configured redundantly, for instance in a “one active, one standby” arrangement. Should the primary device fail, the standby unit can switch over within milliseconds, thereby preventing production line downtime.

(2) Deploy industrial firewalls and intrusion detection systems (IDS) to block unauthorised access (e.g., unauthorised PLC programme modifications); • Implement data encryption technologies (e.g., SSL/TLS) to safeguard industrial network data transmission, preventing data tampering or theft[1]; • Conduct regular industrial cybersecurity audits to identify security vulnerabilities (e.g., weak passwords, outdated firmware).

(3) Fault Emergency Drills: Develop contingency plans for system failures (e.g., PLC malfunctions, network outages), conduct quarterly emergency drills to enhance operational staff's fault-handling capabilities, and reduce average fault recovery time from 4 hours to under 1 hour.

6.CASE STUDY: INTEGRATION AND OPTIMISATION PRACTICES AT AN AUTOMOTIVE COMPONENTS SMART FACTORY

6.1FACTORY BACKGROUND AND PRE-INTEGRATION ISSUES

A certain automotive component factory primarily manufactures engine cylinder blocks. Prior to integration, it faced the following issues: Equipment heterogeneity: Utilised three types of PLCs—Siemens, Schneider, and Rockwell—requiring five different gateways for communication, resulting in poor real-time performance (latency > 100ms); Data silos: SCADA could collect equipment output but failed to link with MES quality data, necessitating manual calculation of product pass rates; Reactive maintenance: Faults were only detected after equipment breakdowns, resulting in 80 hours of unplanned downtime annually and losses exceeding ¥2 million.

6.2INTEGRATION AND OPTIMISATION SOLUTIONS

(1)Architectural Refactoring: Adopting a four-tier architecture comprising the Field Device Layer, Control Layer, Monitoring Layer, and Management Layer[1], with core equipment including: Field Layer: 200 sensors (temperature, displacement), 50 servo motors; Control Layer: Siemens S7-1500 PLC (with OPC UA server), edge gateway (Advantech UNO-2484G); Monitoring Layer: Siemens WinCC SCADA system, HMI workstations; Management Layer: SAP MES system, ERP system.

(2)Protocol Unification: Utilising OPC UA over TSN technology [2][3] to enable real-time communication between PLCs, SCADA systems, and MES, reducing latency to under 10 milliseconds; implementing a unified data model [6] that defines metrics such as "equipment output"and "yield rate" as standardised fields.

(3)Intelligent Optimisation: Deploying an AI Predictive Maintenance System[5]: Collecting motor vibration and current data via edge gateways, utilising LSTM algorithms to predict faults and issue maintenance alerts 1-2 weeks in advance; Optimising Production Scheduling: Analysing order data through machine learning to dynamically adjust PLC processing parameters, thereby reducing changeover times.

(4)Security reinforcement: Implement redundant configurations for core PLCs and servers[1], deploy industrial firewalls and IDS systems, and conduct regular security drills.

6.3OPTIMISATION RESULTS

(1)Production efficiency: Production line changeover time reduced from 2 hours to 30 minutes, with overall production efficiency increasing by 18%[1];

(2)Equipment reliability: Equipment failure rate decreased by 25%[5], unplanned downtime reduced from 80 hours to 20 hours, resulting in annual savings of ¥1.5 million;

(3)Data Integration: Real-time synchronisation between SCADA and MES systems[6] reduced manual product pass rate calculation from 2 hours to automated 5 minutes, achieving 100% data accuracy.

(4)Energy Optimisation: AI-driven optimisation of motor operating parameters[5] lowered energy consumption by 12%, yielding annual electricity cost savings of ¥300,000.

7.CONCLUSIONS AND OUTLOOK

7.1CONCLUSIONS

This paper, through research into the integration and optimisation of electrical automation systems in smart factories, draws the following conclusions:

(1)The core of system integration lies in ‘interconnected equipment, seamless data flow, and coordinated control’, necessitating the use of layered architectures [1] and standardised protocols (such as OPC UA over TSN [2][3]) to overcome the challenges of heterogeneous devices and data silos [6];

(2)Optimisation must integrate technology (AI predictive maintenance [5], edge computing [1]), management (cross-departmental collaboration, talent development [1]), and security (redundancy design [1], network protection) to achieve a trinity of "integration – optimisation – security";

(3)Case studies demonstrate that well-designed integration and optimisation solutions can significantly enhance production efficiency and reduce costs, providing an effective pathway for manufacturing enterprises' transformation and upgrading.

7.OUTLOOK

The development of electrical automation systems in future smart factories will exhibit the following trends:

(1)Deep integration of digital twins: Constructing digital twin models for electrical automation systems to achieve real-time mapping between physical systems and digital models. Optimising control logic through virtual commissioning reduces on-site debugging time;

(2)Human-Machine Collaborative Intelligence Enhancement: Integrating Industry 5.0's ‘human-machine collaboration’ philosophy, AI algorithms dynamically allocate tasks between humans and machines (e.g., complex operations performed by humans, repetitive tasks handled by robots);

(3)Green and Low-Carbon Optimisation: Incorporating energy consumption optimisation into system integration objectives. Achieving dual ‘intelligent + green’ goals through smart regulation (e.g., photovoltaic-grid power supply coordination, staggered equipment operation).

Subsequent research may focus on the coupling mechanisms between digital twins and electrical automation systems, alongside low-cost integration solutions for small and medium-sized enterprises, thereby advancing the inclusive application of smart factory technologies.

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Intelligent Transformation of Automatic Loading and Unloading Of CNC Machine Tools Based On Industrial Robots

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Abstract: With the development of the times and advances in science and technology, intelligent manufacturing has become one of the important directions for the development, transformation, and upgrading of the global manufacturing industry. Nowadays, in the processing of multi-process workpieces by traditional CNC machine tools, most enterprises still adopt the method of manual loading and unloading of workpieces. Aiming at the problem of manual professional loading and unloading of traditional CNC machine tools, this paper takes the CNC machine tool equipment used for training as an example to carry out intelligent transformation of automatic loading and unloading of CNC machine tools based on industrial robots. By configuring and debugging industrial robots, combined with the interconnection between FANUC 0iMF series CNC machine tools and industrial robots, the process of automatic loading and unloading of CNC machine tools by industrial robots instead of manual labor is realized.

Keywords: Industrial Robots, CNC Machine Tools; Automatic Loading and Unloading; Intelligent Transformation

1. INTRODUCTION

With the rapid development of science and technology, intelligent manufacturing technology has become an important direction for the transformation and upgrading of the global manufacturing industry. Intelligent manufacturing realizes the automation, efficiency and precision of the production process through integration, digitization, intelligence and other means [1]. As CNC machine tools are constantly updated, the intelligent transformation of CNC machine tools is also under continuous exploration and research. In addition to improving the precision and processing efficiency of CNC machine tools themselves, how to realize the intelligent manufacturing of CNC machine tools is also an important research direction [2-3].

Traditional CNC machining requires manual loading and unloading of workpieces. With the further increase of labor costs, manual loading and unloading has low efficiency. However, the method of using industrial robots to assist CNC machine tools in loading and unloading can not only replace manual labor in loading and unloading, but also ensure the stability and efficiency of production in a more economical and safe way [4-5].

Industrial robots for loading and unloading can automatically perform material loading and unloading according to preset programs. Compared with manual operation, it does not need rest, will not make mistakes, has faster operation speed and better continuity, thus improving production efficiency. Traditional loading and unloading work requires special personnel to operate. With the continuous rise of social labor costs, the labor costs of enterprises are also increasing. Industrial robots can replace part of the labor force and reduce the labor costs of enterprises. Loading and unloading work is a high-risk job, and manual operation is easy to cause injuries. The operation of the robot is controlled by a preset program, and there is no human error, thus reducing safety risks.

Industrial robots have high precision in loading and unloading operations, and will not cause errors due to fatigue and other problems. They can accurately complete the work of loading and unloading materials, thus improving product quality. Loading and unloading work is mainly concentrated on the workshop production line, which not only has a lot of dust, but also has high noise, and there are problems such as manual injury and work delay. The use of loading and unloading robots can reduce the exposure time of personnel in these environments, thus improving the quality of the working environment. To sum up, loading and unloading robots have the advantages of improving production efficiency, reducing costs, reducing safety risks, improving product quality and improving the quality of working environment.

At the same time, with the transformation and upgrading of the manufacturing industry, it is an inevitable trend to realize automatic loading and unloading of CNC machine tools. This project takes the training FANUC 0iMF series CNC machine tools and FANUC industrial robot equipment as the benchmark, and realizes the intelligent transformation of automatic loading and unloading of CNC machine tools by industrial robots through the interconnection between CNC machine tools and industrial robots.

2. INDUSTRIAL ROBOT AUTOMATIC LOADING AND UNLOADING TRANSFORMATION SCHEME

This transformation requires the coordinated operation of CNC machine tools and industrial robots to realize the automation of basic functions such as automatic loading and unloading of equipment, and to add safety protection measures. It mainly involves the transformation of the CNC machine tool door, the bench vice inside the machine tool, and the compilation of the corresponding PMC ladder diagram.

2.1 Transformation of CNC Machine Tool Door

The opening and closing of the door of traditional CNC machine tools need to be done manually. Therefore, in order to realize the automatic opening and closing of the machine tool door, an air pressure rod is installed on the door, and the control of the opening and closing signals is realized through PMC signals. When the PMC sends a door-closing signal, the air pressure rod is pushed out through the air valve to close the door. Similarly, when an opening signal is sent, the air rod drives the machine tool door to retract, opening the machine tool door.

2.2 Transformation of CNC Machine Tool Bench Vice

In order to fix the position of the machine tool for loading and unloading by the industrial robot, a bench vice is used for clamping, and the bench vice is pneumatically transformed to realize the automatic opening and closing of the bench vice, so as to realize automatic clamping during loading and unloading. The opening and closing of the bench vice is controlled by PMC. The bench vice is fixed on the machine tool workbench with bolts, and an air pipe is inserted to realize the automatic opening and closing of the bench vice through the air circuit control valve.

2.3 Transformation of PMC Control Function

Devices that input signals (such as buttons and switches) are connected to the input terminals of the PMC, and controlled devices that receive output signals (such as contactors and solenoid valves) are connected to the output terminals of the PMC. This transformation uses PMC programming to realize the linkage control of CNC machine tools and robots. The compilation of the PMC ladder diagram program is based on the wiring schematic diagram of each input and output point. The signal list for the development of industrial robot application functions of the control system PMC is shown in Table 2.1. It mainly involves the compilation of the automatic door opening and closing of the machine tool, the loosening and clamping of the bench vice, and the start and completion of processing.

Table 1 Signal Table for the Development of Industrial Robot Application Functions

CNC	PMC	Robot	ROBOT	IO
Machine tool door open in place1	X9.0	DI[121]	Quick change	RO[1]
Machine tool door open in place 2	X9.1		Gripper	RO[2]
Machine tool door closed in place 1	X9.2	DI[123]	Gripper	RO[3]
Machine tool door closed in place 2	X9.3		Nozzle	RO[4]
Processing completion signal	F9.4,	DI[124]		
Machine tool pick - and - place in	F96.0,	DI[125]		
Machine tool door open	Y8.0	DO[101]	Gripper	RI[1]
Machine tool door close	Y8.1	DO[102]	Gripper	RI[2]
Flat - jaw pliers open	Y8.2	DO[103]	Gripper at	RI[3]
Flat - jaw pliers clamp	Y8.3	DO[104]		
Start processing	G7.2	DO[105]		
Robot outside machine tool		DO[106]		

2.3.1 Compilation of PMC Ladder Diagram for Automatic Door Opening and Closing of Machine Tool

This transformation aims to realize the automatic loading and unloading process of industrial robot CNC machine tools. Therefore, according to Table 2.1 Signal List for Industrial Robot Application Function Development, the ladder diagram for PMC control of automatic door opening and closing of CNC machine tools is compiled.

As shown in Figure 2.1, which is the ladder diagram for machine tool door opening and closing, R signals are mainly used in the compilation of the ladder diagram to control the door opening and closing in manual state and the M command code in automatic state, so as to realize the output of machine tool door opening (Y8.0) and machine tool door closing (Y8.1). There are two in-place signals: door opening in place 1 (X9.0) and door opening in place 2 (X9.1).

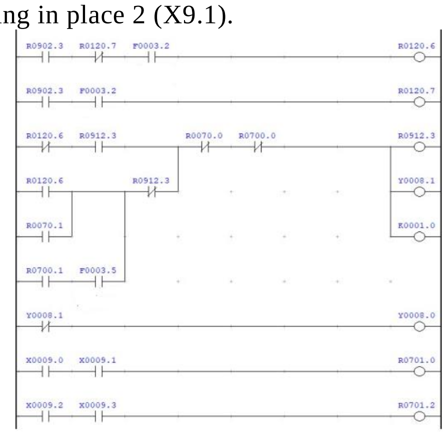

Figure 2 Ladder Diagram of Machine Tool Door Opening and Closing

2.3.2 Compilation of PMC Ladder Diagram for Loosening and Clamping of Parallel Jaw Vice

To enable the robot to fix and clamp workpieces during loading and unloading on the CNC machine tool, the PMC ladder diagram for the clamping and loosening of the parallel jaw vice is compiled according to Table 2.1 Signal List for Robot Application Function Development.

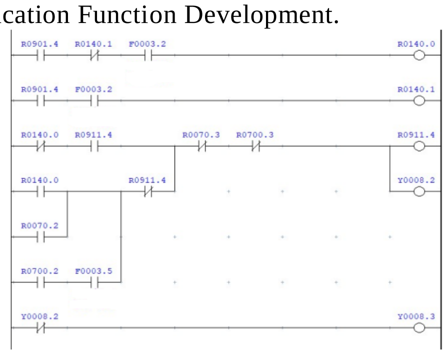

Figure 3 Ladder Diagram for Releasing and Clamping Of Parallel Jaw Vice

As shown in Figure 2.2, consistent with the compilation idea of the machine tool door opening and closing, R signals are used as the intermediate signals for the key signals of the parallel jaw vice in the manual state and the M code command control in the automatic state. Y8.2 and Y8.3 correspond to the output signals for the loosening and clamping of the parallel jaw vice respectively.

3. AUTOMATIC LOADING AND UNLOADING TRANSFORMATION OF INDUSTRIAL ROBOTS

3.1 Compilation of the Initialization Program for Industrial Robot Loading and Unloading

The compilation of the initialization program for industrial robot signals. This section of the program is for writing the initial state of the robot, which is also the initial state of the robot's actions. The program is as follows:

RO【1:ON】=ON
RO【3:0FF:Gripper Clamping】=OFF
RO【3:0FF:Gripper Clamping】=OFF
RO【2:0FF:Gripper Release】=ON
RO【2:0FF:Gripper Release】=0FF
DO【102:OFF】=OFF
DO【101:OFF】=PULSE
DO【104:ORF】=OFF
DO【103:0FF】=PULSE

3.2 Compilation of the Robot's Workpiece Gripping Program for Loading and Unloading

3.2.1 Compilation of Gripper Retrieval Program

After the robot completes its initial state, it performs the action of retrieving the gripper, so it is necessary to teach the coordinate points for gripper retrieval. First, it needs to quickly move to a position above the safety plane. Reduce the speed to the safety plane 30mm above the gripper. Finally, move to the gripper retrieval position. The program written according to the robot's gripper retrieval action is as follows:

J P【1】35% FINE Offset,PR【2:z300】
L P【2】500mm/sec FINE Offset,PR【3:z30】
L P【3】100mm/sec FINE
RO【1:ON】=OFF
L P【4】100mm/sec FINE Offset,PR【3:z30】
L P【5】600mm/sec FINE Offset，PR【2:z300】
J P【6】35% FINE

3.2.2 Compilation of Workpiece Gripping Program

After the gripper is installed, the robot performs the setup for gripping the workpiece. First, teach and reach the coordinate point of the workpiece gripping safety plane, then teach the coordinate point of the workpiece gripping bottom to grip the workpiece, and finally get ready for transporting the workpiece. The program compiled according to the robot's workpiece picking action is as follows:

J P【7】35% FINE
L P【8】300mm/sec FINE
RO【3:OFF:Gripper Clamping】=ON
WAIT 1.00(sec)
L P【9】100mm/sec FINE

Offset, PR【3:Z30】
L P【10】600mm/sec FINE
Offset. PR【4:-Y150】
J P【11】35% FINE
J P【12】35% FINE

3.3 Compilation of the Workpiece Machining Process Program

3.3.1 Compilation of the Program for Placing Workpieces in Parallel Jaw Vise

The robot moves the workpiece to the taught coordinate point in front of the machine tool door and places it at the taught coordinate point of the parallel jaw vice. At this time, in conjunction with the parallel jaw vice clamping command, the workpiece is clamped, and finally the gripper is released. The program compiled according to the robot's action of placing the workpiece is as follows:

J P【1】35% FINE
J P【2】35% FINE
J P【13】35% FINE Offset,PR[3:z30]
L P【14】100mm/sec FINE
RO【3: 0FF: Gripper Clamping】=0FF
RO【2: 0FF: Gripper Release】=PULSE
WAIT1.00(sec)
DO【104:0FF】=PULSE
WAIT 1.00(sec)
L P【15】100mm/sec FINE
J P【16】35% FINE
J P【17】35% FINE

3.3.2 Compilation of the Linked Machining Program

In the part of the linkage between the robot and the CNC machine tool, the robot program is mainly written to first move the gripper out, exit to the safe teaching point outside the machine tool door, issue the machine tool door closing command, and start the machining program after waiting for 2 seconds. The program compiled according to the robot's linked machining is as follows:

DO【102:0FF】=PULSE
WAIT DI【123:OFF】=ON
DO【105:0FF】=PULSE
WAIT 2.00(sec)
WAIT DI【124:=ON】=ON
DO【101:0FF]=PULSE
WAIT DI【121:ON】=ON

3.3.3 Compilation of the Program for Gripping Workpieces After Machining

After the machine tool finishes machining and the M30 program ends, it issues a machine tool door opening command. The robot acts to grip the workpiece, then the parallel jaw vice is released, and finally the workpiece is moved out of the machine tool. The program compiled according to gripping the workpiece after machining is as follows:

J P【18】35% FINE
J P【19】35% FINE
RO【4:OFF】=ON
WAIT 5.00(sec)
RO【4:OFF】=ON
L P【20】100mm/sec FINE
RO【3:OFF: Gripper Clamping】=ON
WAIT 1.00(sec)
DO【103:0FF】=PULSE
WAIT 1.00(sec)
L P【21】100mm/sec FINE Offset，PR【3:z30】
J P【22】35% FINE
J P【23】35% FINE

3.4 COMPILATION OF THE ROBOT WORKPIECE PLACEMENT PROGRAM

3.4.1 Compilation of Placement Position Program

Move the workpiece to a position near the placement location for teaching coordinate points, reach the workpiece's safety plane point, reduce the moving speed to place the workpiece at the placement position, and finally move the gripper out. The program written according to the robot's placement position action is as follows:

J P【24】35%FINE
J P【25】35%FINE
J P【26】35%FINE
L P【27】300mm/secFINEOffset,PR【3:z30】
L P【28】100mm/secFINE
RO【3:OFF:Gripper Clamping】=OFF
RO【2:0FF:Gripper Release】=PULSE
L P【30】500mm/sec FINE Offset,PR【4:-Y150】
J P【31】35%FINE

3.4.2 Compilation of Gripper Placement Program

To place the gripper, the robot returns to the safety plane before fetching the gripper, reduces the speed to move to the gripper placement position, issues the gripper release command, places the gripper, and finally returns to the initial state. The program written according to the robot's gripper placement action is as follows:

J P【58】35% FINE Offset.PR【2:z300】
L P【59】500mm/sec FINE Offset,PR【3:z30】
L P【60】100mm/sec FINE
RO【1:ON】=ON
L P【61】100mm/sec FINE Offset，PR【3:z30】
J P【62】35% FINE

4. CONCLUSIONS

By transforming the existing FANUC 0iMF series CNC machine tools and FANUC industrial robot equipment for automatic loading and unloading of CNC machine tools based on industrial robots, the interconnection between CNC machine tools and industrial robots has been realized. The intelligent transformation of industrial robots for automatic loading and unloading of CNC machine tools has integrated the originally independent equipment units into systematic intelligent manufacturing equipment, forming a CNC machine tool automatic loading and unloading processing and manufacturing platform.

After compiling each action program segment of the robot and combining them for debugging, the transformation of industrial robot machine tool automatic loading and unloading under actual conditions has been verified, realizing the process: press the cycle start on the robot control cabinet→automatic door opens, fixture releases→robot grabs the blank and loads it into the machine tool→robot places the first blank, fixture clamps→robot retreats to the proper position→automatic door closes, the machine tool actually processes the part→after processing, the machine tool door opens, fixture releases→robot grabs the part→robot retreats to the proper position and places the workpiece→robot moves, grabs the second blank, and enters the next cycle until the processing is completed.

This paper carries out intelligent transformation on traditional CNC machine tool equipment according to the current status of technical equipment in the manufacturing industry. It not only meets the required cutting processing requirements of CNC machine tools, but also can complete simple tasks such as loading and unloading, which greatly reduces labor intensity and improves work efficiency.

Using advanced automation technology to transform and enhance the functions of traditional equipment so that they can meet the needs of intelligent equipment is the development direction of China's manufacturing industry in the future. In this transformation process, only robots and electrical control units were added, and only the robot loading and unloading function was simply realized, which is still far from "intelligence". In the future, components such as visual inspection units, grinding units, and MES systems will be added to truly realize the intelligence of CNC machine tools.

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Artificial Intelligence Empowers Factory Power Supply and Distribution Teaching

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Abstract: Imperial College London in the United Kingdom has developed a simulation teaching platform for factory power supply and distribution based on virtual reality and artificial intelligence technology. On this platform, students can wear virtual reality equipment and enter highly simulated factory power supply and distribution scenarios for practical operation. Artificial intelligence technology can not only provide real-time feedback on students' operations, but also automatically generate detailed evaluation reports and improvement suggestions based on students' operation steps and results, helping students quickly improve their practical skills.
Keywords: Artificial Intelligence; Factory Power Supply; Teaching

1. INTRODUCTION

1.1 Background and significance of the study

In the modern industrial system, the importance of factory power supply and distribution system as a key infrastructure to ensure stable production of factories is self-evident. The factory power supply and distribution system is responsible for introducing electricity from the grid into the factory and reasonably distributing and controlling it according to the needs of different production equipment to ensure the continuity and stability of the production process. Once the power supply and distribution system fails, it will not only lead to production interruptions and direct economic losses, but also cause a series of safety problems, posing a threat to personnel and equipment. Therefore, cultivating professionals with solid factory power supply and distribution knowledge and skills has become an urgent need for the development of the industrial field[1].

To sum up, it is of great practical significance to study the application of artificial intelligence technology in the teaching of factory power supply and distribution. By introducing artificial intelligence technology, we can break the limitations of traditional teaching models, improve the quality and effectiveness of teaching, cultivate professionals who are more suitable for the needs of modern industrial development, and provide strong talent support for technological innovation and development in the field of factory power supply and distribution. At the same time, this research will also help promote the deep integration of education and artificial intelligence technology, explore more innovative teaching models and methods, and provide reference for the teaching reform of other professional courses.

1.2 Research status at home and abroad

In foreign countries, the application research of artificial intelligence in the field of education started early and developed relatively maturely. Many developed countries have actively explored the integration of artificial intelligence technology into the teaching of various disciplines and have achieved a series of remarkable results. In terms of factory power supply and distribution teaching, some foreign universities and research institutions are committed to developing intelligent teaching systems based on artificial intelligence. Purdue University in the United States uses machine learning algorithms to analyze students' behavior data during the learning process of factory power supply and distribution courses, including learning time, answering questions, and participation in discussions, so as to achieve real-time monitoring of students' learning status and accurate evaluation of learning effects. According to the evaluation results, the system provides students with personalized learning suggestions and resource recommendations, effectively improving students' learning enthusiasm and academic performance[2].

1.3 Research methods and innovations

This paper adopts a variety of research methods to comprehensively and deeply explore the application of artificial intelligence technology in factory power supply and distribution teaching. The literature research method is the foundation, and through extensive review of relevant literature at home and abroad, including academic journal papers, dissertations, research reports, etc., the research status, development trend and existing problems of artificial intelligence technology in the field of education, especially in factory power supply and distribution teaching, are sorted out, and theoretical support and research ideas are provided for subsequent research. Through the analysis of these literatures, we understand the current research hotspots and priorities in this field at home and abroad, such as the development of intelligent teaching systems, the realization of personalized learning, and the innovation of practical teaching, and also find the shortcomings of existing research, which provides an entry point for the research of this paper[3].

The innovation points of this paper are mainly reflected in the following aspects. In terms of teaching mode innovation, a hybrid teaching mode based on artificial intelligence is proposed, which organically combines online teaching and offline teaching. The online artificial intelligence teaching platform provides students with rich learning resources, including multimedia courseware, virtual experiments, intelligent tutoring, etc., and students can learn independently according to their own learning progress and needs. offline, through classroom discussions, group projects, practical operations and other activities, strengthen communication and cooperation among students, and cultivate students' teamwork and practical skills. This hybrid teaching model gives full play to the advantages of artificial intelligence technology, while retaining the interactivity of traditional teaching, which can effectively improve the quality of teaching.

2. OVERVIEW OF ARTIFICIAL INTELLIGENCE TECHNOLOGY AND FACTORY POWER SUPPLY AND DISTRIBUTION TEACHING

2.1 Foundation of Artificial Intelligence Technology

Deep learning is a subfield of machine learning that builds multi-layer model structures based on artificial neural networks, which can automatically extract high-level abstract features from data, especially suitable for processing complex data such as images, speech, and text. The core models of deep learning include convolutional neural networks (CNNs), recurrent neural networks (RNNs) and their variants, long short-term memory networks (LSTMs), gated recurrent units (GRUs), and transformer architectures. CNN is mainly used in image recognition tasks, and it can automatically extract local and global features of images through structures such as convolutional layers, pooled layers, and fully connected layers. In the image monitoring of power supply and distribution equipment in factories, CNN can be used to identify the appearance of equipment and detect whether there is abnormal wear and overheating. RNNs and their variants, LSTM and GRU, are primarily used to process data with sequence characteristics, such as speech signals and time series data. In the load prediction of the factory power supply and distribution system, due to the time series characteristics of the load data, the LSTM network can be used to learn from the historical load data to predict the future load change trend and provide a basis for power dispatch and equipment maintenance. The Transformer architecture has achieved great success in the field of natural language processing, based on a self-attention mechanism, which can better capture long-distance dependencies between words in text, thereby achieving more accurate natural language understanding and generation. In the teaching of factory power supply and distribution, an intelligent tutoring system can be developed using a language model based on the Transformer architecture to answer questions about power supply and distribution knowledge for students.

Natural language processing aims to enable machines to understand and generate human natural language, enabling natural language interaction between humans and machines. Natural language processing involves several key tasks and techniques, including text classification, machine translation, question-answering systems, sentiment analysis, and more. In the teaching of factory power supply and distribution, text classification technology can be used to classify and organize a large number of power supply and distribution technical documents, making it easier for students to find and learn relevant materials. Machine translation technology can translate foreign advanced power supply and distribution technology literature into Chinese, promoting international technical exchanges and learning. The Q&A system can answer questions raised by students in real time during the learning process, providing immediate help and guidance. Sentiment analysis can be used to analyze students' feedback on the teaching content and teaching methods of power supply and distribution, so that teachers can adjust teaching strategies in time and improve teaching quality. Natural language processing technology usually combines deep learning models and traditional natural language processing methods, such as word embedding, syntactic analysis, semantic understanding, etc., to achieve effective processing and understanding of natural language. For example, BERT, a pre-trained language model based on the Transformer architecture, can perform deep semantic understanding of input text after being pretrained on large-scale text data, excelling in various natural language processing tasks.

2.2 Analysis of the Current Situation of Power Supply and Distribution Teaching in Factories

At present, the teaching content of factory power supply and distribution mainly focuses on the basic principles of power system, the structure and working mechanism of power supply and distribution equipment, power load calculation, short-circuit current calculation, relay protection, electrical lighting design, etc. These contents form the basis of the factory power supply and distribution curriculum system, aiming to enable students to master the basic concepts, operating principles, and basic methods of design and maintenance of factory power supply and distribution systems. In the basic principles of the power system, students learn the composition, operation mode and the process of power generation, transmission and distribution of electric energy, understand the basic structure and operation laws of the power system, and lay the foundation for subsequent learning of the relevant knowledge of the power supply and distribution system. The teaching content of power supply and distribution equipment covers transformers, high and low voltage switchgear, circuit breakers, disconnect switches, fuses and other major equipment, and students need to master the structure, working principles, selection principles, operation and maintenance methods of these equipment, so that they can correctly select and use power supply and distribution equipment in actual work.

Few practical opportunities are also a major dilemma faced by teaching. Factory power supply and distribution is a very practical course, and students need to improve their practical application ability through a lot of practical operations. However, due to many reasons such as safety, venue, and corporate cooperation, it is difficult for students to get enough practical opportunities. On the one hand, the operation of power supply and distribution systems involves high voltage and high current, and there are certain safety risks, and enterprises are often reluctant to let students participate in actual operation and maintenance. On the other hand, the cooperation between schools and enterprises is not close enough, and there is a lack of stable internship bases and practical projects, so students cannot have an in-depth understanding of the actual operation of the factory's power supply and distribution system and the needs of engineering applications. This makes it difficult for students to quickly adapt to the requirements of the actual job after graduation, and requires a long period of training and practice to be competent.

3. APPLICATION ADVANTAGES OF ARTIFICIAL INTELLIGENCE TECHNOLOGY IN FACTORY POWER SUPPLY AND DISTRIBUTION TEACHING

3.1 Provide Personalized Learning Experiences

In the traditional factory power supply and distribution teaching, the teaching content and progress are often uniformly arranged, which is difficult to meet the learning needs of each student. The introduction of artificial intelligence technology provides an effective way to solve this problem. With the help of advanced artificial intelligence algorithms, it is possible to conduct in-depth analysis of the vast amount of data generated by students during the learning process. These data include student participation in the classroom, such as the number of questions asked and the accuracy of answering questions; learning behaviors on the online learning platform, such as the duration of watching instructional videos, the number of pauses and replays; and the completion of assignments and exams, including answer time, scores, etc. Through the comprehensive analysis of these multi-dimensional data, the system can accurately understand each student's knowledge mastery, learning ability and learning habits.

3.2 Enhance the Intuitiveness And Interactivity Of Teaching Content

Factory power supply and distribution systems involve many complex equipment and abstract principles, and traditional teaching methods are difficult for students to intuitively understand and master. The use of artificial intelligence technology to build a virtual factory power supply and distribution scenario provides students with an immersive learning experience, effectively solving this problem. Through virtual reality (VR) and augmented reality (AR) technologies, combined with artificial intelligence graphics rendering and interactive algorithms, it is possible to create a highly realistic virtual environment for factory power supply and distribution. In this virtual environment, students feel like they are in a real factory, and can observe the appearance, internal structure and operating status of power supply and distribution equipment from all aspects and multiple angles. Students can get close to the transformer and observe the winding method of its winding, the structure of the core, and the working principle of the cooling system; You can also enter the interior of the high-voltage switchgear to understand the operating mechanism and electrical connection methods of circuit breakers, disconnect switches and other equipment.

In order to further enhance the interaction between teachers and students and students' learning participation, the introduction of intelligent interactive teaching tools such as intelligent chatbots and intelligent Q&A systems is an effective way. Intelligent chatbots can answer questions students encounter during the learning process at any time, providing immediate assistance and guidance. Whether it is questions about the theoretical knowledge of power supply and distribution or confusion in experimental operations, students can get answers by having a conversation with the chatbot. Utilizing natural language processing technology, chatbots can understand students' questions and provide accurate and detailed answers based on pre-set knowledge bases and artificial intelligence algorithms. When students ask, "How is the no-load loss of a transformer generated?" The chatbot can explain in detail the causes of no-load loss, including hysteresis loss and eddy current loss in the core, and explain it in combination with relevant formulas.

3.3 Improve Teaching Efficiency And Quality

In addition to automatically correcting homework, the artificial intelligence system can also conduct in-depth analysis of students' homework data and explore students' knowledge weaknesses and learning problems. Through the statistics and analysis of a large amount of homework data, the system can find out which knowledge points students are prone to error and which question types are not well mastered. For the homework of short circuit calculation of the power system, the system can analyze the students' problems in the selection of short-circuit current calculation methods, the value of parameters, and common errors in the calculation process. According to the analysis report provided by the system, teachers can adjust the teaching content and teaching methods in a targeted manner, focus on explaining and tutoring students' weak links, and improve the pertinence and effectiveness of teaching. At the same time, students can also understand their learning status based on the results of homework analysis, review and improve in a targeted manner, and improve their learning effectiveness.

The intelligent tutoring system can also actively push relevant knowledge points and cases according to students' problems to help students consolidate and expand their knowledge. If students ask about the fault handling method of a specific type of circuit breaker, the system can not only give specific processing steps, but also push analysis of the working principle of that type of circuit breaker, common fault types, and other similar fault cases, so that students can understand and master relevant knowledge from multiple perspectives. This intelligent tutoring and Q&A method can meet the needs of students to learn anytime and anywhere, and improve students' learning efficiency and enthusiasm. At the same time, it can also reduce the workload of teachers, so that teachers can devote more energy to teaching design and teaching innovation, and improve the quality of teaching.

4. CHALLENGES AND COPING STRATEGIES FACED BY ARTIFICIAL INTELLIGENCE TECHNOLOGY APPLIED TO FACTORY POWER SUPPLY AND DISTRIBUTION TEACHING

4.1 Challenges

System stability is also an important factor that must be considered when artificial intelligence technology is applied to factory power supply and distribution teaching. Artificial intelligence systems may be affected by various factors during operation, such as hardware failures, software vulnerabilities, network fluctuations, etc., which may cause system failures or abnormal behavior. In the intelligent teaching platform, if the server fails hardware, it may cause the platform to not operate normally, affecting students' learning and teachers' teaching. Moreover, AI algorithms themselves have certain uncertainties that may produce false results in some cases. In fault diagnosis, due to the inaccurate identification of fault characteristics by algorithms, it may lead to misjudgment and mislead teaching and practical application. Therefore, how to improve the stability and reliability of artificial intelligence systems and ensure that they can operate continuously and stably in the teaching process is an urgent problem to be solved.

The lack of students' independent learning ability also brings difficulties to the application of artificial intelligence technology in the teaching of factory power supply and distribution. The application of artificial intelligence technology emphasizes students' ability to learn and explore independently, and students need to independently acquire knowledge and solve problems through tools such as self-learning platforms and intelligent tutoring systems. However, in the traditional teaching model, students are often accustomed to passively accepting knowledge and lack the awareness and ability to learn independently. Some students do not know how to screen and utilize rich online learning resources, and lack effective learning methods and strategies. Moreover, some students lack self-discipline and initiative in the learning process, are easily disturbed by external factors, and it is difficult to maintain continuous learning motivation. This requires teachers to strengthen the cultivation of students' independent learning ability in the teaching process, guide students to master the correct learning methods, and improve students' awareness and ability of independent learning.

Data privacy protection is an ethical issue that must be paid attention to when applying artificial intelligence technology in factory power supply and distribution teaching. During the teaching process, the artificial intelligence system will collect a large amount of students' learning data, including basic personal information, learning behavior data, test scores, etc. This data contains students' private information, and if leaked, it may cause damage to students' personal rights and interests. Hacking can lead to student data breaches, and students' personal information may be used for illegal purposes, such as identity theft, fraud, etc. Moreover, some data collection and use processes may be opaque, and students may not be clear about how their data is used and shared, which also raises concerns about data privacy among students and parents. Therefore, how to ensure the security and privacy of student data and establish a sound data protection mechanism is an important problem that needs to be solved when artificial intelligence technology is applied to factory power supply and distribution teaching.

4.2 Coping Strategies

Encouraging universities and enterprises to carry out in-depth cooperation and jointly develop artificial intelligence technologies and products suitable for factory power supply and distribution teaching is an effective way to break through technical bottlenecks. Universities have rich scientific research resources and professional research talents, and have advantages in artificial intelligence theoretical research and algorithm innovation. Enterprises have rich practical experience and practical application scenarios, and can transform scientific research achievements from universities into practical products and solutions. Through school-enterprise cooperation, colleges and universities can have an in-depth understanding of the actual needs of factory power supply and distribution teaching, and carry out targeted scientific research. Enterprises can use the scientific research strength of universities to improve the technical content and competitiveness of products. The two parties can cooperate to carry out research on data processing and analysis technologies for plant power supply and distribution, develop efficient data acquisition, transmission and storage systems, and advanced data cleaning and preprocessing algorithms to improve data quality and availability. In terms of algorithm optimization, school-enterprise cooperation can jointly study and improve existing artificial intelligence algorithms, reduce the computational complexity of algorithms, and improve the adaptability and generalization ability of algorithms. For power system fault diagnosis algorithms, universities can study new algorithm models and optimization strategies from the theoretical level, while enterprises can test and verify the algorithms in practical application scenarios, and continuously optimize the algorithms according to actual feedback, so that they can better meet the needs of factory power supply and distribution teaching and practical application.

Formulating strict data usage norms is an important measure to protect student data privacy. Schools and educational institutions should clarify the principles and processes for data collection, storage, use, and sharing to ensure that the use of data complies with laws, regulations, and ethical requirements. In the data collection process, the principle of minimum necessity should be followed, and only necessary data related to teaching and learning should be collected, and excessive collection of students' personal information should be avoided. When collecting students' academic performance, only key data for instructional evaluation and analysis is collected, and personal privacy information that is not related to learning is collected. In terms of data storage, secure and reliable storage methods should be used to encrypt data and prevent data leakage. Encrypted storage of student data using encryption algorithms, allowing only authorized personnel to access and decrypt the data. In the process of data use, the purpose and scope of data use should be clarified, and data should not be used for other purposes without the consent of students and parents. For data sharing, a strict approval system should be established to ensure the security and legality of data sharing. Student data can only be shared with third-party institutions if certain conditions are met and subject to strict approval.

5. RESEARCH SUMMARY

This study delves into the application of artificial intelligence technology in factory power supply and distribution teaching, and comprehensively analyzes the significant advantages of artificial intelligence technology in improving teaching quality and effectiveness. By introducing artificial intelligence technology, the provision of personalized learning experiences has been successfully achieved. With the help of artificial intelligence algorithms to analyze student learning data, it can intelligently plan the learning path for each student, adaptively adjust the learning progress according to the real-time learning situation of students, meet the learning needs of different students, and improve learning efficiency and learning enthusiasm. In terms of enhancing the intuitiveness and interactivity of teaching content, virtual simulation experimental scenarios built by virtual reality (VR) and augmented reality (AR) technology enable students to experience the operation process of the factory's power supply and distribution system immersively, enhancing their understanding and mastery of knowledge. The application of intelligent interactive teaching tools, such as intelligent chatbots and intelligent question-answering systems, effectively promotes interaction between teachers and students, and improves students' learning participation. Artificial intelligence technology also greatly improves teaching efficiency and quality, realizes automatic homework correction and analysis, provides teachers with detailed feedback on students' learning situation, and facilitates teachers to adjust teaching strategies; The intelligent tutoring and Q&A system provides students with a channel to get help at any time to meet their learning needs.

Looking forward to the future, the application of artificial intelligence technology in factory power supply and distribution teaching has broad prospects. With the continuous development of artificial intelligence technology, the development of teaching resources will become more intelligent and diversified. In addition to the existing virtual simulation experimental scenarios and intelligent interactive teaching tools, more innovative teaching resources based on artificial intelligence technology will be developed in the future. Using artificial intelligence generative technology, personalized teaching courseware, case analysis and practice questions are automatically generated according to students' learning needs and interests, providing students with richer and more accurate learning materials. With the deep integration of artificial intelligence technology, virtual reality and augmented reality technology, a more immersive and interactive learning environment will be created, allowing students to experience the actual operation of the factory's power supply and distribution system more immersively, further improving the learning effect.

The integration of artificial intelligence technology and factory power supply and distribution teaching is an inevitable trend in the development of education. Through continuous innovation and practice, giving full play to the advantages of artificial intelligence technology and overcoming the challenges faced in the application process will bring new vitality and change to factory power supply and distribution teaching, and cultivate more high-quality professionals who meet the needs of modern industrial development.

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Analysis of the Development Status and Trends of Metal Oxide Arrester (MOA) Technology

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Abstract: Surge arresters are indispensable overvoltage protection devices in power systems, and their technological development is directly related to the safety, stability, and reliable operation of the grid. This paper aims to systematically discuss the current development status and future trends of surge arrester technology. It begins by outlining the technological evolution of arresters from gap-type to modern Metal Oxide Arresters (MOAs). Subsequently, it provides a detailed comparative analysis of the current status of arrester technology domestically and internationally, covering aspects such as material systems, product design, intelligent applications, and standard setting. It points out that while domestic enterprises have achieved parallel and even leading positions in high-end fields like ultra-high voltage (UHV), gaps still remain compared to international giants in basic materials research and global market influence. Finally, the paper forecasts future trends where arrester technology develops towards high performance, intelligence, environmental sustainability, and deep digital integration. Research indicates that "intelligent arresters" integrated with sensing, big data, and artificial intelligence will become the mainstream direction for next-generation products.
Keywords: Metal Oxide Arrester (MOA); Zinc Oxide (ZnO) Resistor; Technology Status; Intelligence; Development Trend

1. INTRODUCTION

The stable operation of power systems is the cornerstone of a nation's economic vitality and social stability. Transient overvoltages, such as lightning strikes and switching overvoltages, have always been a major factor threatening the insulation of power equipment and causing system failures. As key protective devices for limiting overvoltages and discharging impulse currents, surge arresters are widely used throughout generation, transmission, substation, and distribution processes. Their performance directly determines the lightning withstand level and operational reliability of the power system.From the early 20th century to the present, arrester technology has undergone a revolutionary evolution from expulsion-type and valve-type arresters to the current mainstream Metal Oxide Arrester (MOA). The zinc oxide (ZnO) based resistor discs, renowned for their excellent non-linear volt-ampere characteristics (i.e., low resistance to discharge current at high voltage, high resistance to block current at low voltage), endow MOAs with a series of advantages such as being gapless, free from follow current, fast response, and superior protective performance, making them the absolute mainstream worldwide. This paper aims to systematically review the current development status of surge arrester technology, particularly MOA technology, both domestically and internationally, provide an in-depth analysis of its technological core and competitive landscape, and offer a forward-looking perspective on future development trends, hoping to provide a reference for technological innovation and industrial development in related fields [1].

2. CURRENT DEVELOPMENT STATUS OF ARRESTER TECHNOLOGY ABROAD

The power industries in developed countries such as those in Europe, America, and Japan have a long history. Their leading power equipment manufacturers have accumulated profound technical expertise in the field of arrester technology, long guiding the direction of its development.

Leadership in Materials and Basic Theory: International giants like Siemens, ABB, Toshiba, and General Electric (GE) invest heavily and possess deep foundation in basic materials science research related to ZnO resistors, including microscopic mechanisms, doping formulations, and sintering processes. Their products still represent the industry's highest standards in core performance indicators such as current-carrying capacity, energy withstand capability, and aging characteristics. For instance, in the field of Ultra-High Voltage Direct Current (UHVDC) transmission, their research on resistor performance under complex multi-stress conditions is more advanced [2].

High Performance and High Reliability: These companies have developed complete high-performance product lines for different application scenarios (e.g., station, line, distribution, renewable energy). Their products are designed for extreme reliability and long-term stability to meet the stringent lifecycle requirements (often demanding 40+ years) of European and American grids. They hold numerous patents in areas like composite housing materials, explosion-proof structures, and weather resistance [3].

Early Exploration and Application of Intelligent Technology: Foreign companies started the R&D and application of arrester condition monitoring technology relatively early. Their products often integrate or are compatible with modules for leakage current monitoring, operation counters, and online temperature monitoring, supported by advanced diagnostic algorithms and backend software systems. This facilitates a shift from "passive protection" to "active warning" and supports condition-based maintenance (CBM) [4].

Strong Standard-Setting Power and Brand Influence: These international giants actively participate in and dominate the setting of international standards such as those by the International Electrotechnical Commission (IEC), turning their technical solutions into globally accepted norms. This builds high technical barriers and brand moats, allowing them to hold a major share of the global high-end market [5].

3. CURRENT DEVELOPMENT STATUS OF DOMESTIC ARRESTER TECHNOLOGY IN CHINA

China's arrester industry has achieved a remarkable transformation from catching up, running in parallel, to leading in some areas, alongside the leapfrog development of China's power industry, particularly its UHV projects. It has become a major force in the global arrester technology landscape.

Leading Global Industrial Scale and Market Share: China boasts the world's largest arrester industry chain and market, nurturing numerous leading enterprises such as China XD Group, Pinggao Group, XJ Group Corporation, and Jinguan Electric. Domestic MOAs hold a very high market share within China and are extensively exported overseas under the "Belt and Road" initiative [6].

Major Breakthroughs and Leadership in UHV Technology: To meet the needs of China's "West-East Power Transmission" strategy, domestic enterprises and research institutes (e.g., Xi'an Electric Apparatus Research Institute) have jointly tackled key problems, successfully developing ±1100kV and 1000kV UHV AC/DC arresters with completely independent intellectual property rights. These products reach or even surpass international counterparts in voltage level, energy absorption capacity, and technical sophistication, ensuring the safety of the world's largest and most complex UHV grid. They represent a landmark achievement in the rise of China's arrester technology [7].

Accelerated Technological Innovation and IP Accumulation: Domestic companies continuously innovate in resistor disc formulations and structural design, with a surge in patent applications. For example, numerous innovative designs have emerged in multi-gap structures, explosion-proof technology, and anti-corrosion (evidenced by relevant patents from China Southern Power Grid, Dalian Beifang Surge Arrester, etc.). Domestic products already possess significant advantages in the lightweight, explosion-proof, and pollution resistance performance of composite-housed arresters [8].

Intelligent Upgrading and Increased Standard Participation: Domestic enterprises actively embrace the intelligent trend, launching smart arrester products integrated with various sensors and developing corresponding online monitoring systems. More importantly, Chinese experts and companies are actively participating in the revision and formulation of IEC international standards, integrating the experience and technical solutions from China's UHV projects into global standards, enhancing China's voice on the international stage.

Existing Gaps and Shortcomings: Despite achievements in engineering applications, certain gaps compared to the top international level remain, particularly in original innovation of basic materials and core processes for high-end resistor discs, and the accumulation of long-term operational data and the accuracy of life assessment models. Brand international influence and market share in high-end overseas markets still need further improvement.

4. FUTURE DEVELOPMENT TRENDS

Future arrester technology will no longer be limited to the single function of overvoltage protection but will develop multi-dimensionally towards deep integration with new power systems.

Continued Deepening of High Performance and High Reliability: The pursuit of core parameters like the energy density, gradient, and non-linear coefficient of resistor discs is endless. The exploration of new materials (e.g., new dopants) and new processes (e.g., low-temperature sintering, uniformity control) will continue to be the cornerstone of technological progress, meeting the future grid's demands for equipment miniaturization, lightweight design, and high reliability.

Comprehensive Integration of Intelligence and Condition Sensing: "Intelligent arresters" integrated with multi-dimensional sensors for current, temperature, mechanical stress, environmental parameters, etc., will become standard. Combined with edge computing technology, they will enable local data preprocessing and fault diagnosis. Using Internet of Things (IoT) technology to upload data to cloud platforms, and leveraging big data analytics and artificial intelligence (AI) algorithms, will enable accurate assessment of arrester health status, residual life prediction, and early fault warning, ultimately achieving predictive maintenance and significantly improving grid operational efficiency.

Environmental Protection and Green Manufacturing: Developing environmentally friendly resistor disc formulations (lead-free, cadmium-free, etc.), reducing energy consumption and emissions in the production process, and exploring alternatives to SF6 gas (for arresters in gas-insulated switchgear) will be inevitable trends in response to global environmental consensus.

Deep Integration into New Power Systems: Developing specialized, serialized arrester product solutions tailored to the specific overvoltage protection needs of new application scenarios like renewable energy generation (wind, solar), flexible HVDC transmission (VSC-HVDC), and energy storage systems will be a significant market growth area and direction for technological innovation.

5. CONCLUSIONS

Arrester technology, after a century of development, has entered a mature stage dominated by Metal Oxide Arresters. Currently, foreign enterprises, leveraging their profound technical 积累 (accumulation) and brand advantages, still maintain strong competitiveness in basic research and high-end markets. Meanwhile, domestic enterprises, building on the great practice of China's UHV projects, have achieved leapfrog technological development, reaching internationally advanced levels in many application areas and transitioning from "technology followers" to "standard setters."

Looking ahead, the development of arrester technology will be characterized by distinct features: pushing performance limits, integrating intelligent functions, adopting eco-friendly materials, and achieving deep integration. The next generation of arresters will no longer be "silent" protectors but will become intelligent nodes within the new power system, integrating protection, measurement, sensing, and decision-making. Continuously strengthening basic materials R&D, accelerating the deployment of intelligent technologies, and deeply participating in global competition and cooperation will be key for China's arrester industry to consolidate its advantages and move towards the high end of the global value chain.

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An Evaluation Method for Machining Production Efficiency of RBF Network based on Flocking

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Abstract: This paper proposes an evaluation methodology for assessing the production efficiency of Denso's intelligent manufacturing lines. The assessment framework evaluates three key dimensions: production quality, production costs, and production cycle duration. At its core, this efficiency evaluation system employs techniques such as critical factor analysis, metric quantification, and the Pigeon Swarm Improved RBF Network algorithm to establish computational models centered around target parameters. By selecting appropriate metric sets and training the model through production big data, the developed computational model achieves enhanced maturity. This ultimately results in an intelligent manufacturing production efficiency evaluation system with both assessment capabilities and predictive potential for Denso's smart manufacturing operations.
Keywords: Denso production line, production efficiency evaluation, production quality, RBF network algorithm

1. INTRODUCTION

Intelligent manufacturing is a comprehensive term for advanced manufacturing processes, systems, and models that are based on new-generation information technology, spanning all aspects of manufacturing activities including design, production, management, and service. These systems feature deep self-awareness of information, intelligent optimization decision-making, and precise self-execution control. The "China Manufacturing 2025" initiative explicitly identifies intelligent manufacturing as one of the five major government-guided projects [1].

The advanced nature of intelligent manufacturing is reflected in the digital design of products and intelligent full life cycle management, the full digital control of production processes, and the significant improvement in production efficiency [2]. Among these, the most evident benefits, the most intuitive impacts, and what enterprises care about most is the improvement in production efficiency.

Production efficiency refers to the effective output per unit of time under fixed inputs. The most critical influencing factors are distributed across three aspects: production quality, production cycle, and production costs. In the electrical assembly processing of aviation manufacturing systems, production quality stands out as the most crucial factor among these three [3]. Quality serves as the lifeline of products while also impacting production cycle duration and production costs.

The existing production quality, production cycle and production cost are calculated by measuring and statistics the quality data, cycle data and cost data generated in the actual production after the production line is built.

While the method of calculating production efficiency based on Denso's actual production data demonstrates certain accuracy, it lacks predictive capabilities and evaluation potential. In practice, after a production line is constructed and trial production begins, discrepancies between actual performance metrics and initial design plans often emerge. However, since the production line has already commenced operations, major modifications become impractical, forcing compromises to be accepted. Therefore, conducting production efficiency projections and evaluations during the design phase of production lines proves essential. This study analyzes historical production data from Denso products [4], examines how parameters across manufacturing processes influence efficiency, and forecasts changes in productivity caused by production line construction or intelligent transformation initiatives. These insights ultimately guide the design and implementation of intelligent production line systems.

2. ELECTRIC EQUIPMENT PROCESSING AND PRODUCTION EFFICIENCY EVALUATION METHOD

This paper proposes an evaluation framework for Denso's intelligent manufacturing production efficiency. The assessment methodology encompasses three key dimensions: production quality, operational costs, and production cycle optimization. At its core, the system employs techniques including critical factor analysis, quantitative metrics, and a Pigeon Swarm Improved RBF Network algorithm to establish computational models centered on target parameters. By selecting appropriate metric sets and training the model through production big data, the developed computational model achieves enhanced maturity. This ultimately results in a comprehensive evaluation system with both diagnostic capabilities and predictive potential for assessing Denso's intelligent manufacturing production efficiency.

The specific design route of the evaluation method for production efficiency of electric device processing intelligent manufacturing is shown in Figure 1.

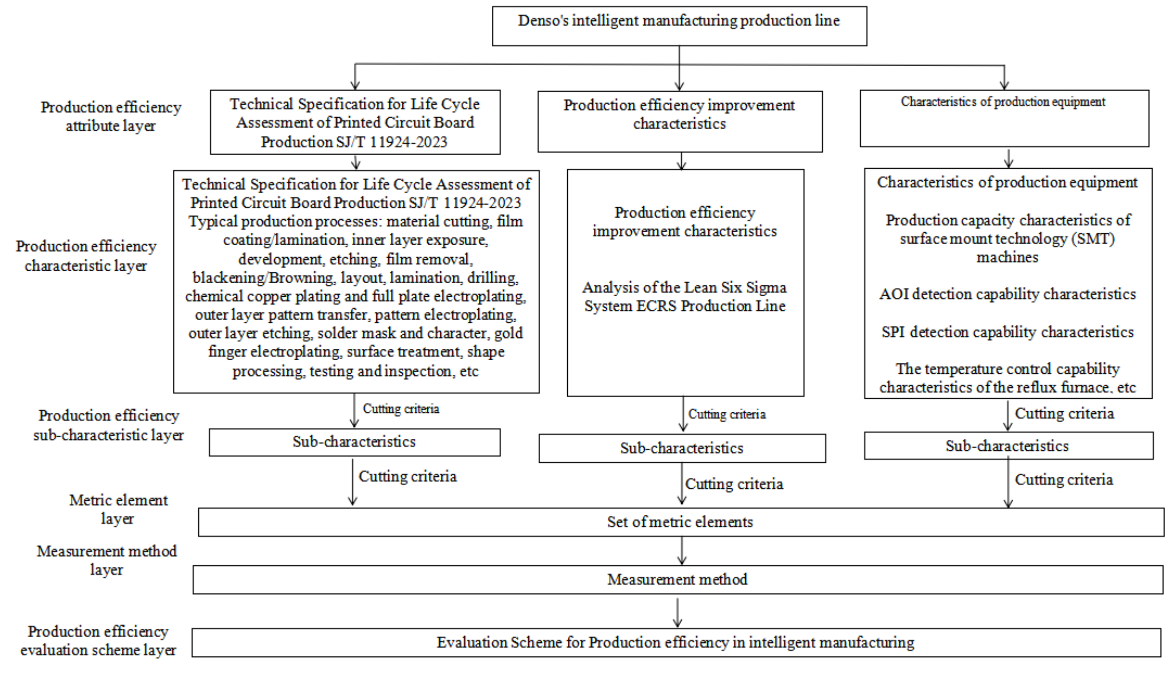

Figure 1 Schematic Diagram of Intelligent Manufacturing Production Efficiency of Electric Processing

The design route of the intelligent manufacturing production efficiency evaluation scheme shown in the figure contains six levels.

3. CONSTRUCTION AND OPTIMIZATION METHOD OF MULTI-DIMENSIONAL EVALUATION SYSTEM FOR INTELLIGENT MANUFACTURING PRODUCTION EFFICIENCY OF DENSO

3.1 Production Efficiency Attribute Layer

Research on the production efficiency attribute layer encompasses three key aspects: typical manufacturing processes and quality characteristics based on the SJ/T11924-2023 Technical Specification for Life Cycle Assessment of Printed Circuit Board Production (Product Classification Rules); improvement features incorporated into common production efficiency enhancement methods; and inherent characteristics of processing and inspection equipment. Furthermore, this attribute layer can be modified and expanded according to variations in product types, production processes, and practical requirements.

3.2 Production Efficiency Characteristics Layer

The characteristics affecting the processing and production efficiency of electrical equipment are as follows:

The study of production efficiency attributes encompasses processes specified in the SJ/T 11924-2023 Technical Specification for Life Cycle Assessment of Printed Circuit Board Production (Product Classification Rules), including: material cutting, film coating/adhesive application, inner layer exposure, development, etching, stripping, blackening/browning, layout, lamination, drilling, chemical copper plating and full-board electroplating, outer layer pattern transfer, pattern electroplating, outer layer etching, solder mask formation and character detailing, gold finger electroplating, surface treatment, formwork processing, testing and inspection; along with related quality characteristics such as material, energy, information, materials, resources, product, risk, monitoring, measurement, analysis, and evaluation.

The improvement characteristics of common production efficiency improvement methods: the production efficiency improvement characteristics in lean Six Sigma system and ECRS production line analysis method;

Processing characteristics of the processing equipment itself: surface mount machine production capacity characteristics, AOI detection capability characteristics, SPI detection capability characteristics, reflow furnace temperature control capability characteristics, etc.

The specific effects are shown in Table 1.

3.3 Production Efficiency Sub-Characteristics Layer

After the analysis and refinement of the above production efficiency related characteristics, a series of sub-traits are formed. The specific content is shown in Table 2.

Table 1 Productivity Characteristics Table

	GJB9001C-2017	Methods for improving production efficiency	Equipment/Production line characteristics

Quality of production	Process quality characteristics	Six Sigma system quality characteristics	Quality related characteristics of CNC machine tools Production line quality related characteristics
Production cycle	production cycle Quality control cycle	Lean production cycle characteristics ECRS method production cycle characteristics	Speed related characteristics of CNC machine tools Production line cycle related characteristics
Cost of production	cost of production Quality control costs Nonconforming product costs	Lean production cost characteristics ECRS method production cost characteristics	Machine tool cost related characteristics Production line cost related characteristics

Table 2 Production Efficiency Sub-Characteristics Table

	GJB9001C-2017	Methods for improving production efficiency	Equipment/Production line characteristics
Quality of production	Quality of raw materials Adhesion, hardness, wear resistance, weather resistance, chemical resistance Erosion rate, erosion selectivity, uniformity, erosion deviation, erosion angle Compression thickness, bonding, dimensional stability Electroplating: coating thickness, adhesion, corrosion resistance, surface quality Quality control method (automatic/artificial) Quality inspection frequency (full inspection/spot check)	Maturity of production process Degree of digitization of production lines	Mounting accuracy Component error rate Discard rate Adhesive size range Height of the patch Lamination pressure Temperature control accuracy Temperature control range temperature homogeneity Plugin accuracy Plugin success rate mean free error time mean repair time
Production cycle	Average quality control time	Maturity of production process Rationality of production scheduling plan Production line material time Logistics automation rate The distance from the warehouse to the work station The number of bottlenecks that hinder logistics Inter-process handling automation rate Average distance between processes	Maximum mounting speed Average mounting speed Preheat speed cooling velocity Plugin speed no-load speed Production line balance rate mean free error time mean repair time
Cost of production	Nonconforming product costs	Raw material costs administration cost Overall human costs	Fixed asset costs Energy cost

The details of the sub-features of production quality, production cycle and production cost in Table 2 are as follows.

3.3.1 Production quality characteristics

Some very common production quality characteristics are described below.

(1) Adhesion

Adhesion refers to the bonding strength between the coating and the substrate. Common testing methods include tensile method, peeling method, marking method, etc.;

(2) weather fastness

Weather resistance refers to the weather resistance of the coating film under long-term exposure to the external natural environment, such as ultraviolet, humidity, high temperature, low temperature and so on. The main test methods are Xenon lamp weather resistance test, hot and humid cycle test, salt spray test, etc.;

(3) Chemical resistance

Chemical resistance refers to the film does not react with chemicals and physical damage, with the effect of protecting objects. The main test methods are solvent wiping test, acid and alkali resistance test;

(4) etching rate

Etch rate refers to the rate at which material is removed during etching, usually expressed as the thickness reduction per unit time, typically in nanometers per second (nm/s) or angstroms per second (A/s). Thickness can be characterized by film thickness meters, step meters, or SEM.

(5) Engraving select ratio

In the etching process, the photoresist (such as photoresist) on the upper layer of the etched material or the substance in the lower layer of the material that should not be etched at the same time will be etched. Therefore, there needs to be a definition between the photoresist and the etching material, namely the etching selectivity ratio.

(6) Etching uniformity

Uniformity is commonly used to characterize the consistency of etching rates across a wafer. It measures the etching process capability across a wafer, across a batch, or between batches (within, between, and across batches).

(7) Erosion bias

The variation of line width or critical dimension spacing after etching. The variation of line width, pattern height, depth and other dimensions after etching process. As long as chemical reaction is involved, there will be some side etching to a certain extent. The effective use of side etching can achieve some special structures.

(8) Erosion angles

Etching Angle is usually defined as the angle between the vertical etching direction and the horizontal line of the surface during etching. The etching angle can be achieved by controlling the ratio of etching rates.

In the etching process, precise control of the etching angle is crucial for fabricating devices with specific geometries or structures. By adjusting the angle, engineers can regulate the material's etching rate in specific directions, enabling the creation of desired shapes or configurations [5]. For example, developing devices with inclined surfaces can be achieved through controlled etching angle adjustments.

(9) Coating thickness

The most fundamental quality standard in electroplating processes is coating thickness. Insufficient coating thickness not only leads to oxidation, corrosion, and peeling issues, but also fails to achieve the desired decorative or protective effects [6]. Therefore, coating thickness quality standards are a critical indicator in the industry.

(10) Adhesion

Adhesion is one of the very important quality indicators of the electroplating process, which determines the bonding between coating and substrate. If the adhesion is not strong enough, it is easy to produce peeling and falling off, which will also have a great impact on the protection and decorative effect of products.

(11) Corrosion resistance

Corrosion resistance is one of the important indicators to measure the quality of electroplating process. Good corrosion resistance can ensure that the electroplated parts are not easy to rust and corrode in special environments such as humidity, acid and alkali, so that the electroplated parts can maintain good appearance and performance for a longer time.

(12) Surface quality

Surface quality serves as a key indicator of electroplating process excellence, reflecting the surface's smoothness and flatness. Superior surface quality not only enhances the aesthetic appeal and decorative performance of plated components but also reduces friction between products and their environment, while providing enhanced corrosion resistance.

(13) Compression thickness

Provide relevant electrical insulation, impedance control, and filler between inner layers.

(14) Compatibility

Provide a bond with the inner black (brown) and outer copper foil.

(15) Dimensional stability

The size variation of each inner plate is consistent to ensure the alignment of holes and rings on each layer.

(16) Sub-characteristics related to production quality in electronic assembly equipment include placement accuracy, component error rate, material rejection rate, placement dimensional tolerance, placement height, placement pressure, temperature control precision, temperature regulation range, temperature uniformity, and component insertion accuracy. Among these, placement accuracy, component error rate, material rejection rate, and component insertion accuracy have particularly significant impacts on production quality. Mean Time Between Failures (MTBF) refers to the average duration a device remains operational between failures, calculated as Total Operating Time divided by Total Number of Failures. Average Repair Time (ATT) denotes the average duration required to restore equipment or production lines to normal operation after a failure occurs. These two metrics are used to evaluate equipment stability, which directly affects both production quality and production cycle efficiency.

3.3.2 Production cycle characteristics

Key performance metrics in electronic assembly systems include maximum assembly speed, average assembly speed, preheating rate, cooling rate, component insertion speed, no-load operation speed, production line balance rate, mean time between failures (MTBF), and mean time to repair (MTTR). Among these parameters, average assembly speed and component insertion speed demonstrate particularly significant impacts on production cycle efficiency.

Production process maturity not only affects product quality but also influences each product's production cycle. Production scheduling plan rationality is used to evaluate the generation method (manual/system), identify conflicts between multiple scheduling plans, and assess the validity of key performance indicators (KPIs) in scheduling outcomes. The quantitative methods for assessing scheduling plan rationality will be detailed in the next section.

Before mechanical processing, raw materials must be clamped onto fixtures. Similarly, after processing, finished or semi-finished products need to be removed from the fixtures. This process is typically manual, and when handling heavy products, additional operations like hoisting and auxiliary equipment are required. Consequently, fixture installation and removal often occupy a significant portion of production cycles, making them a critical factor that demands thorough attention.

The time of material cutting in production, the automation rate of logistics transfer, the distribution distance from warehouse to workstation, the number of stuck points hindering logistics, the automation rate of handling between processes and the average distance of handling between processes are all specific sub-features affecting the operation time of logistics. The shortening of the logistics cycle is also crucial for the optimization of the whole production cycle.

Production line balance (PLB) is a technical approach that analyzes load distribution across all production processes. By adjusting the workload allocation between operations to achieve capacity equilibrium (with processing times as close as possible), it eliminates idle waiting time and enhances overall production efficiency. This method of balancing process capacities is also known as "bottleneck improvement". The sub-characteristic can be quantified using the production line balance rate for evaluation, as detailed in the next section.

The spindle speed, feed speed, acceleration, coordinate stroke, tool magazine capacity, tool change time and so on are the important indicators that affect the processing speed and production cycle of CNC machine tools, which have an intuitive impact on the production cycle.

3.3.3 Production cost characteristics

The sub-characteristics of production equipment encompass various cost-related factors. The costs associated with quality inspection equipment, defective product rework, and processing expenses constitute operational costs within the quality management system. The comprehensive labor cost includes personnel expenses for production staff, quality inspectors, management personnel, technical staff, and other production-related personnel.

The average production cycle of products affects the production cost, raw material cost, logistics cost, management cost, fixed asset cost, energy consumption cost are the direct factors of production cost.

3.4 Measurement Layer

Most of the sub-features described in the previous section are quantitative features. These sub-features can be used directly as metric elements. Some complex sub-features still need to be analyzed and quantified, which will be detailed below.

(1) Process maturity level

Process maturity levels serve as a quantitative framework for evaluating manufacturing sophistication. These metrics are intrinsically linked to technological maturity, both serving to identify critical risks. When core technologies remain immature or designs lack stability, they inevitably compromise production processes. In such cases, establishing process maturity becomes impossible. Therefore, each defined process maturity tier inherently corresponds to a specific technological maturity level. Specifically, when a process reaches a particular maturity stage, its associated technological maturity must meet the corresponding technical standard. This relationship is formally defined as:

PRL1: discovery of basic principles of the process;

PRL2: Confirm the manufacturing process concept;

PRL3: Confirm the process plan and verify the feasibility of the process plan;

PRL4: The ability to produce a prototype of the principle, which has been validated in a laboratory environment;

PRL5: The capability to produce samples, install them on a subsystem-level prototype, and verify them in a simulated operating environment;

PRL6: The ability to produce and commission trial production units into system-level equipment that has been validated in typical operating environments;

PRL7: Have the ability to produce in small batches and verify the production line capability;

PRL8: capable of mass production on the production line;

PRL9: High efficiency, fast and flexible production capacity.

(2) Degree of digitization of production lines

This paper determines the degree of digitization of a production line according to the following conditions. The more conditions that are met, the higher the degree of digitization.

a) Data acquisition capability of intelligent equipment: Complete intelligent manufacturing equipment should have complete file information, including product number, product description, product status, product timestamp and other information. Key data in the production process can be collected through various sensors, scanners and other equipment.

b) Interconnection capability of intelligent devices: Based on information technology, the collected information can be uploaded to central management systems such as MES by connecting intelligent devices with communication networks.

c) Upper-level system control capability: Establish MES manufacturing execution system, using production scheduling management, process execution and management, process control management, scheduling management, quality management, equipment management and other modules, can manage and display the whole manufacturing process at any time.

d) Intelligent Integration of the Entire Production Line: Building upon automation capabilities, production equipment such as CNC machine tools and robots is further supported by management systems like ERP and MES. The system architecture integrates components including vision cameras, RFID tags, barcode scanners, and sensors, with control units utilizing NC numerical control systems or PLCs. Communication networks utilize fieldbus PROFIBUS, industrial Ethernet PROFINET, and MODUBUS to establish a comprehensive intelligent production line layout.

(3) Reasonability of production schedule

The rationality of the production scheduling plan mainly affects the production cycle, and also indirectly affects the production cost. This paper evaluates the rationality of the production scheduling plan by the following indicators.

a) Occupying capacity, indicating the occupied time of work orders on equipment within the planned scope;

b) Equipment cost, which is calculated according to the standard rate of equipment to calculate the use cost of equipment;

c) Idle time, indicating the working time of the equipment without work order within the plan;

d) Idle cost, which is calculated according to the standard rate of the equipment;

e) Process delay, the sum of the delay time of all processes;

f) Line change cost, after the static and dynamic line change time of all processes;

g) Labor costs, calculated at the standard rate for workers;

h) Work order delay, the sum of all work order delay time;

i) Waiting time, the sum of the transition time between the processes of each work order;

j) Work order cycle, the sum of the time between the start time of the first process and the end time of the last process of each work order.

The more indicators that are covered and optimized in the formulation of the production schedule, the more reasonable it is.

(4) Line balance rate

Production line balancing involves averaging all production processes and adjusting workloads to align operation times as closely as possible [7]. This constitutes the most critical consideration in production process design and standardization. The objectives of production line process balancing include: reducing preparation time between processes to shorten production cycles; minimizing work-in-progress (WIP) across operations and space occupation; shortening product assembly time to enhance output per unit time and reduce costs; while improving overall plant efficiency and minimizing various waste phenomena in the production environment.

Production line balance ratio is the measurement of the above sub-features, and its calculation formula is:

Balancing ratio = (total operation time of each process / (number of processes * bottleneck process time)) * 100%= (∑ti/(number of processes * CT)) * 100%

3.5 Measurement Method Layer

The measurement methodology layer investigates how predefined metrics can evaluate production efficiency. Specifically, the plan establishes evaluation models for quality control, production cycle optimization, and cost management metrics using a swarm-based improved RBF network. These models are then validated through airborne demonstrations of historical production data from smart manufacturing lines, with training conducted to calculate weighted indicators for each metric.

The Pigeon Improved RBF Network Technology, developed based on RBF neural network technology and the pigeon optimization algorithm, utilizes the Pigeon Optimization Algorithm to optimize structural parameters such as weights in the RBF network. This method can be employed to construct a computational model for evaluating production line efficiency in electrical equipment manufacturing. The specific algorithm design and training procedures of the Pigeon Improved RBF Network used in this study can be referenced from Tian Chuan et al.'s research on improving RBF for software quality prediction [3].

3.6 Production Efficiency Evaluation Scheme Layer

The research content of the production efficiency evaluation solution layer focuses on applying measurement methods to assess intelligent manufacturing production lines in airborne units. Field investigations are conducted at application-validated units to collect required production data and equipment parameters. Predictions are made about production efficiency after intelligent transformation of the production line, verifying whether all indicators meet the requirements of the transformation plan. As the application phase of efficiency evaluation methods, manufacturers utilize mature assessment models trained on historical data to evaluate Denso's production line efficiency. Based on these evaluations, new production line designs can be optimized or existing bottlenecks in production lines can be targeted for improvement.

4. CONCLUSIONS

This paper proposes an intelligent manufacturing efficiency evaluation method for Denso production systems based on a swarm optimization-enhanced radial basis function (RBF) network. Through hierarchical modeling, the approach achieves systematic quantitative analysis of production quality, cycle time, and cost. The study first establishes a four-dimensional evaluation framework comprising attribute layers, characteristic layers, sub-characteristic layers, and measurement dimensions, covering all elements from process parameters (e.g., etching uniformity, coating thickness) to management metrics (e.g., scheduling plan rationality, production line balance rate). For complex indicators like process maturity and digitalization level, the research designs quantifiable measurement methods and innovatively applies swarm optimization algorithms to refine RBF network weights, significantly enhancing the model's capability to fit nonlinear production data. Practical applications demonstrate that this method not only accurately evaluates existing production line efficiency but also predicts intelligent transformation outcomes, providing data-driven decision support for Denso's production line optimization in aviation manufacturing. The hierarchical modeling approach also shows potential for extension to other discrete manufacturing scenarios.

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