Research on On-Line Monitoring System of Flexible DC Converter Valve Submodule Based on Machine Vision

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Abstract:
In this paper, a flexible DC converter valve sub-module online monitoring system based on machine vision is designed and implemented. The system uses machine vision technology to acquire and analyze the surface state and operating parameters of the flexible DC converter valve submodule in real time. By introducing Lesit life model and linear damage accumulation algorithm, the system can accurately evaluate the fatigue damage of submodules and predict their remaining service life. This paper discusses the algorithm design of the monitoring system in detail, including image processing, feature extraction, damage recognition and life prediction module, and verifies the effectiveness of the algorithm through system simulation. The simulation results show that the designed system can accurately identify the minor damage of the submodule and predict its development trend under various working conditions, and the prediction error is controlled within a reasonable range. Through accurate data analysis, the advantages of the monitoring system in real-time, accuracy and reliability are verified. The application of this system not only improves the safety and stability of the flexible HVDC system, but also provides a new idea and method for the on-line monitoring technology of power equipment.

Keywords: Machine Vision, Flexible DC Converter Valve, On-Line Monitoring System, Lesit Life Model and Linear Damage Accumulation Algorithm

INTRODUCTION

In recent years, in the context of the joint response to global climate change, the main energy of human beings has become an irreversible trend from fossil energy to non-fossil energy, from high carbon to low carbon transition, and finally to achieve green and clean development. Under the guidance of the "double carbon" goal, China's renewable energy continues to maintain a rapid growth trend, laying a solid foundation for the green low-carbon transformation of energy and electricity. Among them, the western region of China contains rich wind and light renewable energy, the regional wind power can be developed capacity of 348 million kilowatts, the total annual radiation of light between 5300~6950 megajoules/square meter. By the end of 2022, China's renewable energy installed capacity exceeded 1.2 billion kilowatts, historically surpassing the national coal power installed capacity. From January to April this year, the country's new installed capacity of wind power photovoltaic power generation was 62.51 million kilowatts, accounting for 74% of the country's new installed power generation capacity. With the increasing proportion of renewable energy generation, the complexity of power grid also increases. In order to restrain the influence of high proportion of renewable energy volatility and output instability on power grid stability, flexible DC transmission technology came into being. Flexible DC power transmission is a new generation of transmission technology after AC power transmission and conventional DC power transmission. It can realize the independent regulation of active and reactive power without the problem of commutation failure. It is easy to build a multi-terminal DC network, which can improve the wind power access performance and greatly improve the low voltage crossing ability and system stability.

In the western region of China, due to the large-scale new energy can not be consumed locally, and limited by delivery capacity, large-scale new energy can not be transported to the load center in the east of China, and the restriction of new energy delivery channel has become the main bottleneck of new energy construction and development. In order to improve the transmission capacity, flexible DC transmission technology is rapidly developing in the direction of high voltage and large capacity. At present, many UHV DC transmission projects such as the soft direct power grid project represented by the Zhangbei Project and the Kunliulong Hybrid DC project have been built. Up to now, more than ten projects have been completed and put into operation in China, and flexible DC transmission technology has been fully mastered, but there is still a certain gap in the overall performance of the valve control level compared with foreign countries: the number of communication fibers between the valve control and the converter valve is huge, and the compact design degree of the valve control equipment is low. The design status quo has caused the following problems: site construction and late operation and maintenance work is difficult: taking the Zhangbei soft and straight project as an example, the number of long-distance optical fibers above 200m required for the converter valve and valve control connection is more than 3,000, and the communication cable corridor occupies a large space. The reliability of the submodule caused by the communication fiber is low: In the point-to-point communication mode, the communication fiber of any submodule of the converter valve or the communication fiber of two submodules in the cross-communication architecture of adjacent submodules is faulty, and the corresponding module finally stops running. Large volume of valve control equipment: a large number of converter valve communication optical fibers cause the valve control hardware design is complicated, and the communication port is huge. In order to solve the above problems, it is urgent to carry out the research on the key technologies of the network and pulse distribution of the flexible DC converter valve submodule to reduce the number of optical fibers in the communication between the converter valve and the valve controller. The UHV flexible direct converter valve is the core of the whole flexible DC transmission system, and the valve control equipment is the key equipment directly connected with the converter valve sub-module to realize the control and protection of the converter valve, and its safe and reliable operation is directly related to the stability of the transmission system. The key technologies of DC converter valve submodule networking and pulse distribution proposed in this project will have an important impact on improving the reliability and economy of flexible DC transmission.

In recent years, machine vision technology has been gradually applied in the field of industrial inspection because of its high efficiency, non-contact and high degree of automation. Literature [1] proposes a steel surface defect detection method based on machine vision, which effectively solves the problem of low recognition rate of complex surface defects by traditional detection methods through feature extraction and classification algorithms. For the fault monitoring of mechanical equipment, literature [2] adopted the method of combining machine vision and deep learning to realize the automatic identification of surface cracks of equipment and improve the accuracy and real-time monitoring. In literature [3], machine vision technology was introduced into the health monitoring of wind turbine blades, and the online detection of tiny cracks in blades was successfully realized through image processing algorithms. In the monitoring of DC transmission system, the operation condition monitoring of flexible DC converter valve has been widely concerned. Literature [4] proposes a DC converter valve monitoring system based on sensor network, which realizes multi-parameter real-time monitoring of converter valve through multi-sensor data fusion technology, and solves the problem of single information in traditional monitoring system. Literature [5] studied the damage mechanism of flexible DC converter valve under high pressure environment, and proposed a damage assessment method based on stress analysis, which provided a theoretical basis for the life prediction of converter valve. Literature [6] developed a DC converter valve monitoring system based on thermal imaging technology. Through thermal image analysis, real-time monitoring of the internal temperature field of the converter valve was realized, thus improving the accuracy of fault diagnosis. As for the life prediction model, Lesit life model is widely used to predict the fatigue life of materials. Literature [7] proposed a metal fatigue life prediction method based on Lesit life model, and verified the prediction accuracy of the model under high stress environment through experimental data. Based on Lesit life model and finite element analysis, literature [8] studied the fatigue life of aero engine blades and proposed an accurate evaluation method for blade service life. Literature [9] combined Lesit life model and machine learning algorithm to develop a life prediction system for complex structural parts, which significantly improved the accuracy and efficiency of prediction. In addition, linear damage accumulation algorithm, as an important tool for fatigue life prediction, has been widely studied and applied. Literature [10] proposes an improved linear damage accumulation algorithm to solve the prediction error problem of traditional algorithms in the case of nonlinear fatigue damage. Literature [11] studies the fatigue life of bridge structures based on linear damage accumulation algorithm, and proposes a fatigue life assessment method considering the influence of multiple factors, which provides theoretical support for the health monitoring of bridge structures. Literature [12] combined with linear damage accumulation algorithm and acoustic emission technology, studied the fatigue damage mechanism of composite materials, and proposed an online fatigue life assessment method for composite materials.

In summary, the existing research provides important theoretical and technical support for the monitoring and life prediction of FDC converter valve submodules, but there are still some challenges in practical application. For example, how to improve the damage identification accuracy of converter valve submodule and how to achieve efficient life prediction under complex working conditions still need further research. This paper presents an on-line monitoring system of flexible DC converter valve submodule based on machine vision. The system uses machine vision technology to monitor the surface state of the converter valve submodule in real time, and combines Lesit life model and linear damage accumulation algorithm to identify fatigue damage and predict life of the submodule [13]. The main contents of this paper include: Firstly, the monitoring system architecture based on machine vision is designed, and each module of the system is designed and optimized in detail; Secondly, the fatigue life prediction algorithm combined with Lesit life model is developed, and the effectiveness and accuracy of the algorithm are verified by system simulation. Finally, the performance of the monitoring system is evaluated through the method of combining experiment and simulation, and the monitoring effect and prediction accuracy of the system under different working conditions are analyzed.

INTRODUCTION TO MONITORING OBJECTS

For flexible HVDC projects, the commonly adopted architecture is the Modular multilevel converter (MMLC), whose arms are composed of a series of energy units, each of which can be hundreds of units, and the number of units at the entire conversion site will climb to thousands. Figure 1 depicts an overview of the core circuit layout of a three-phase modular multilevel converter (MMLC) consisting of six arms, each consisting of n energy units (SU) and a conversion inductor in series [14]. At the current level of science and technology, the voltage carried by a single energy unit usually does not exceed 3000 volts, and the number of energy units connected to each arm of the flexible DC transmission conversion valve in the project is generally several hundred. In engineering practice, the energy unit of the half-H bridge structure is usually chosen, and its structure is shown in Figure 1. The insulated gate bipolar transistor (IGBT) is generally used for power electronic switching components, and there are also cases using IEGT or IGCT. This paper takes IGBT energy unit as the research object. The IGBT is in parallel with a DC capacitor, two IGBTs form a half H-bridge, and each IGBT is in reverse parallel with a diode. By adjusting the gate control signals T1 and T2 of IGBT, the energy unit can realize the switch of different operating states. In addition, the input of each energy unit is equipped with a thyristor and bypass switch S for bypass protection in case of module failure. When charging the transfer valve, the resistance R can make the resistance value between the units basically the same to ensure the voltage balance between the units.

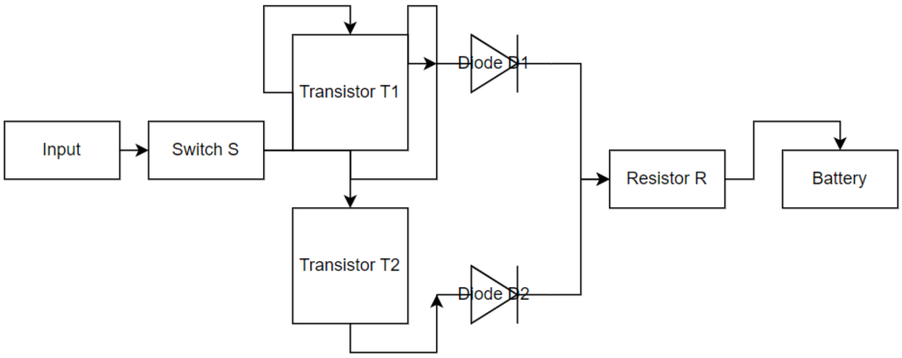

Figure 1: Circuit layout of modular multilevel converter energy unit

In addition to the key power components, the energy unit also integrates: IGBT drive circuit, unit control protection equipment, high voltage energy supply, cooling water system, etc. The operating stability of the energy unit directly affects the reliability of the overall transmission system. The common fault types of the energy unit are as follows: 1) The DC capacitance voltage is too high or too low. 2) IGBT driver fault, including IGBT driver control abnormal or driver feedback abnormal. IGBT drive control anomaly refers to the input or disconnect instruction issued by the energy unit controller, but the IGBT does not respond; IGBT drive feedback anomaly refers to that the IGBT can accurately execute the input or disconnect instruction issued by the energy unit controller, but the IGBT feedback signal does not match the actual state. 3) IGBT direct short circuit fault, refers to IGBT breakdown or upper and lower pipe direct conduction. 4) Energy supply failure, the energy unit controller (SMC) needs to draw power from the capacitor through the energy supply, when the output voltage of the energy supply can not meet the normal operation of the SMC, it is judged as an energy supply failure. 5) Communication failure refers to the interruption of optical fiber communication between the energy unit and the valve controller. 6) The bypass switch works incorrectly or refuses to work. 7) The temperature of the energy unit IGBT exceeds the standard.

ONLINE MONITORING DEVICE DESIGN

3.1 Overall Design

The core components of real-time monitoring equipment conceived in this paper include: information collection module, core arithmetic device, storage module, digital to analog conversion module, monitoring front end and so on. The architecture overview is shown in Figure 2. The information collection module is responsible for obtaining the operating parameters of the converter valve in real time, and the sampling rate is more than 10kHz. In order to avoid the signal disturbance caused by the high pressure on the converter valve, the real-time monitoring system connects the control system, water cooling system and valve tower environment detection system of the converter valve through the optical cable port [15]. The information parsing module is responsible for processing the collected information, such as feature extraction, state assessment, storage format transformation, etc., and input the operation parameters into the human-computer interaction platform and display them according to the front-end instructions.

The submodule of converter valve is the smallest control unit of the whole converter. Redundant configuration of pulse distribution link will greatly increase the cost of flexible DC pulse distribution fiber and the difficulty of operation and maintenance [16]. On the premise of not further increasing the number of pulse distribution fibers, in order to solve the problem of non-redundancy of pulse distribution links, how to carry out network interactive networking on the converter valve body, so that after networking, the communication length of the valve control to the submodule can be reduced, and the communication reliability of the submodule can be improved.

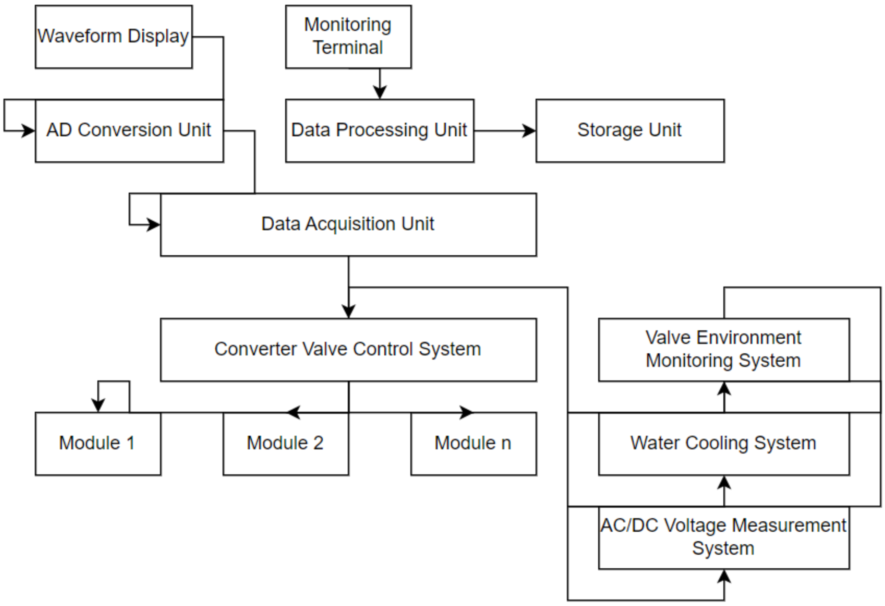

Figure 2: Schematic diagram of on-line monitoring system

3.2 Hardware Implementation

Flexible converter valve real-time monitoring system needs high sampling rate, large amount of information, fast processing, so it needs multiple processors to work together to achieve [17]. It is generally implemented in FPGA+CPU mode, using the advantages of FPGA parallel computing to complete information collection, and using high-performance CPU chips to complete information processing and algorithm execution. The ZYNQ series is the industry's first system-on-chip (SoC) processor launched by Xilinx, which integrates the CPU core and FPGA core in a single chip, and exchanges information between cores through the high-speed AXI bus in the chip, which greatly accelerates the speed of information interaction between FPGA and CPU core, and helps the hardware layout of the board. The ZYNQ7030 SoC processor selected in this paper integrates dual ARMCortexA9 core and a 28nm high-density programmable logic FPGA core in one chip, which has excellent information processing capability. The hardware architecture of the real-time monitoring system designed in this paper is shown in Figure 3.

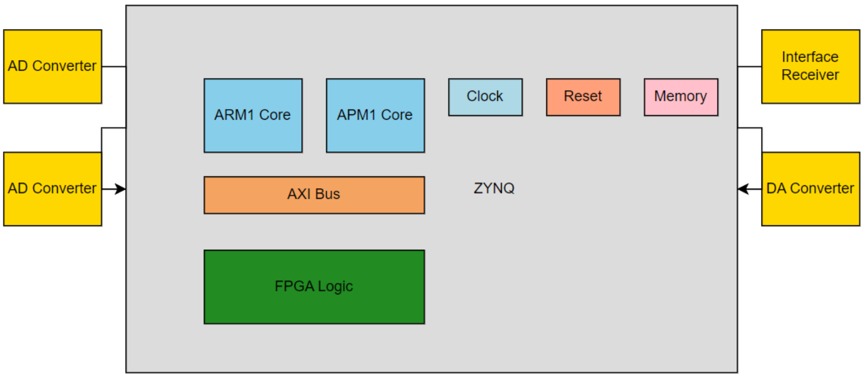

Figure 3: Hardware block diagram

The real-time monitoring system includes analog input and digital input ports, in which the analog input uses the electrical port to directly measure the voltage, and the digital input uses the high-speed optical cable communication port, the rate of up to 2.5Gbit/s. The output port includes an analog output port and an Ethernet port. The analog output port, through digital-to-analog conversion, outputs the digital information collected by the high-speed cable port in real time in an analog form, and the Ethernet port is used to connect the human-computer interaction platform to realize the access to the output information [18]. Signal conversion devices such as photoelectric conversion, analog-to-digital conversion and level conversion are configured between ZYNQ core and peripheral ports to complete signal matching and drive amplification functions. In view of the limited internal storage space of the ZYNQ chip and the large amount of information about the operation status of the converter valve monitored, the hardware is configured with a dedicated high-capacity memory for the temporary storage buffer of monitoring information.

3.3 Software Process

3.3.1 Energy unit status real-time monitoring software program

The capacitor voltage, IGBT switching frequency, temperature and communication status of all energy units are continuously monitored. The sampling interval reaches 10kHz, and the transient process of energy unit status changes can be recorded in real time. By continuously monitoring the abnormal changes of the state of the energy unit, the fault progression of the energy unit can be forewarned [19]. The software calculates the average value of the monitoring data of all energy units of each arm in real time, sorts the values according to the value size, selects the smallest five and the largest five monitoring values, and transmits them to the human-computer interaction platform in real time for operation and maintenance personnel to check. The software program for condition monitoring is shown in Figure 4.

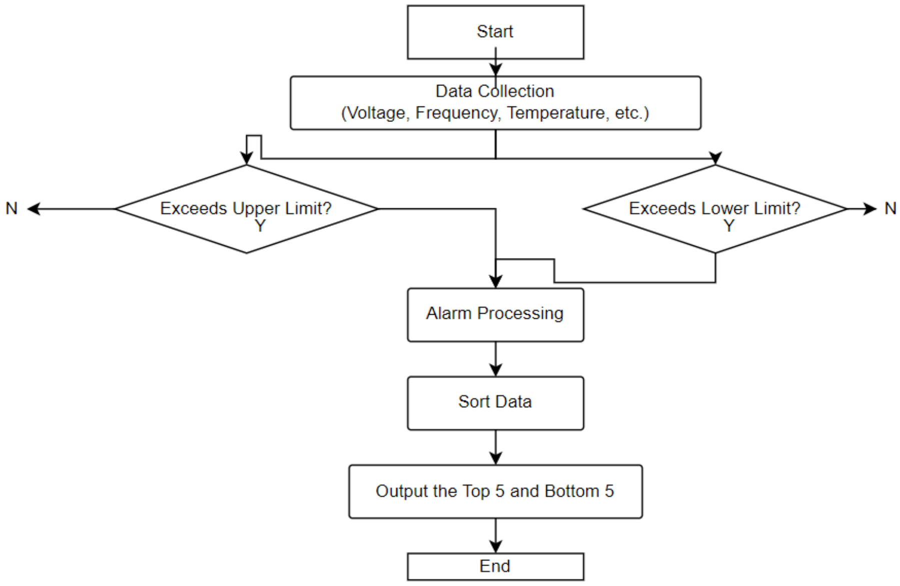

Figure 4: Software flow of online monitoring of sub-module status

3.3.2 Early warning and prediction software program

By constructing the mathematical model of the flexible HVDC system, the theoretical values of the operating parameters of the converter valve can be calculated. The flexible HVDC system simulation model is built, and various operation scenarios are simulated and analyzed to verify and adjust the accuracy of theoretical calculation parameters. At the same time, by tracking and monitoring the operation parameters of the converter valve on the engineering site for a long time, and conducting analysis and statistics, the expert database of the flexible DC converter valve can be continuously enriched and improved. The information processing unit extracts fault features from all kinds of information collected, and then compares the real-time status of the energy unit and valve control with the expert database. If the real-time status of the energy unit and valve control matches a certain condition in the fault signature database, the unit or valve control will be predicted to fail, and the fault warning signal will be output through the human-computer interaction platform. Operation and maintenance personnel can take manual intervention or prepare corresponding emergency plans according to the warning signals [20]. The early warning and prediction software also calculates and diagnoses the change rate of the parameter in real time. When the change rate is too high for a certain period of time, the abnormal running condition represented by the parameter is predicted. The software processing program of early warning prediction is shown in Figure 5.

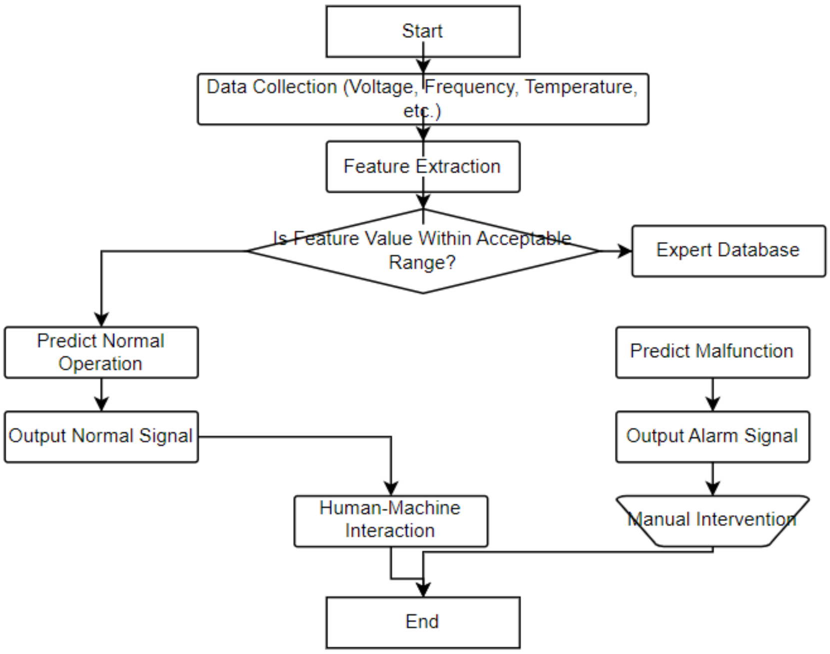

Figure 5: Flow chart of fault prediction software

DATA MONITORING PRINCIPLE OF POWER DEVICES

4.1 Loss calculation of power devices

For the converter valve, in view of the relatively low switching frequency of the IGBT, the effective number of on-offs of each power component is only several times in a power frequency cycle. The energy consumption of IGBT includes conduction energy consumption P_{α} , start-up energy consumption P_{on} , and cut-off energy consumption P_{off} .

4.2 Calculation of node temperature rise of power components

PR_1, PR_2, PS_1, PS_2 is the cumulative energy consumption of IGBT and DIODE; $PR_{1z}, PR_{1w}, PR_{2z}, PR_{2w}, PS_{1b}, PS_{1t}, PS_{2b}, PS_{2t}$ is the share of energy consumption borne by different pole components; R_w, R_z, R_b, R_t is the thermal impedance of different pole components; R_{ai}, R_{ab} is the thermal impedance from the radiator shell to the IGBT and DIODE; $T_{in1}, T_{in2}, T_{in3}$ is the temperature rise of the cooling housing [21]. Refer to the parameters listed in the IGBT component manual, as shown in Table 1, and set PR_{1w} as 85% of the total energy consumption PR_1 combined with actual operation experience; Set PR_{1z} as 15% of the total energy consumption PR_1 R_z is 85% of R_{jc_IGBT} thermal resistance; R_w is 15% of the thermal resistance of R_{jc_IGBT} .

Table 1: Thermal resistance parameters in the data sheet

R_{jc_IGBT}	5.2K/kW	R_{ai}	1.2K/kW
R_{jc_diode}	8.4K/kW	R_{ab}	2.4K/kW

Define state variables as follows:

$$\begin{aligned} U_0 &= [T_{in1} \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T \\ U_1 &= [PR_{1w} \quad PR_{1z} \quad PR_{2w} \quad PR_{2z} \quad PS_{1t} \quad PS_{1b} \quad PS_{2t} \quad PS_{2b}]^T \\ F_1 &= [W_1 \quad W_2 \quad T_{c2} \quad T_{c3} \quad TD_1 \quad TD_2 \quad T_{c2} \quad T_{c3}]^T \end{aligned} \quad (1)$$

T_{in1} is the temperature rise of heat dissipation device 1; W_1 is the node temperature rise of IGBT1. TD_1 is the temperature rise of DIODE1 node. U_0, U_1 is the parameter that can be obtained by operation or detection; F_1 indicates the parameter to be evaluated.

$$F_1 = [B_0 \quad B_1]\begin{bmatrix} U_0 \\ U_1 \end{bmatrix} \quad (2)$$

Among them:

$$B_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B_1 = \begin{bmatrix} R_{ai}+R_w & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{ai}+R_w & -R_{ai}-R_z & R_{ai}+R_w & 0 & 0 & 0 & 0 & 0 \\ R_{ai}+R_w & -R_{ai}-R_z & 0 & 0 & 0 & 0 & 0 & 0 \\ R_{ai}+R_w & -R_{ai}-R_z & R_{ai}-R_w & -R_{ai}-R_z & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{ab}+R_t & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{ab}+R_t & -R_{ab}-R_b & R_{ab}+R_t & 0 \\ 0 & 0 & 0 & 0 & R_{ab}+R_t & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{ab}+R_t & -R_{ab}-R_b & R_{ab}+R_t & -R_{ab}-R_b \end{bmatrix} \quad (3)$$

At this time, the junction temperature of each device can be calculated.

$$\begin{aligned} W_1 &= T_{in1} + PR_{1w}(R_{ai} + R_w) \\ W_2 &= T_{in1} + PR_{1w}(R_{ai} + R_w) + PR_{2w}(R_{ai} + R_w) - PR_{1z}(R_{ai} + R_z) \\ TD_1 &= T_{in1} + PS_{1t}(R_a + R_t) \\ TD_2 &= T_{in1} + PS_{1t}(R_a + R_t) + PS_{2t}(R_a + R_t) - PS_{1b}(R_a + R_b) \end{aligned} \quad (4)$$

4.3 Durability estimation of power components

At present, durability prediction models for IGBTs are mainly divided into two categories: 1) Durability prediction models based on node temperature rise; 2) IGBT durability prediction model based on multiple factors. This paper focuses on Lesit model, a prediction model based on node temperature rise, and proposes a durability prediction method for IGBT. The Lesit model covers two elements ΔT_j and T_m.

$$\begin{cases} \Delta T_j = T_{\max} - T_{\min} \\ T_m = \dfrac{T_{\max} + T_{\min}}{2} \end{cases} \quad (5)$$

Node temperature difference range ΔT_j and mean node temperature rise T_m are the core elements for establishing IGBT durability prediction model, Lesit model is as follows:

$$M_f = B \cdot (\Delta T_j)^{\alpha} \cdot \exp\left(\frac{E}{RT_m}\right) \quad (6)$$

In the above indicators, M_f represents the power cycle frequency of the module; B and α are fixed values associated with component properties; E is the activation energy related to the material; R is the gas constant. Igbts generate a large amount of data during operation, and need to perform purposeful estimates. Miner linear fatigue cumulative damage theory and rain-flow algorithm are introduced to manage the data of power module durability prediction [22]. Miner's rule reveals the general law of durability loss. Assuming that the component contains multiple microcycles in its service cycle, each corresponding to different ΔT_j, the cumulative durability loss of each stage can be calculated by selecting ΔT_j in n different stages:

$$R = \sum_{1}^{n} \frac{1}{M_f(\Delta T_j)} \quad (7)$$

Using the rain-flow counting method to select ΔT_j, focusing on the key stages can reduce the statistical burden on ΔT_j. Typically, the entire endurance curve is segmented into several equally spaced stress amplitude levels.

SIMULATION AND EXPERIMENTAL VERIFICATION

The test environment of the flexible DC pulse distribution system was built by using the prototype of the submodule in ring topology, and the start-up test of the flexible DC converter valve in different operating conditions was completed. All system indexes are normal during the test, and the module works normally after starting. Complete the continuous operation test of the flexible DC converter valve in the submodule network. Under different power conditions, the converter valve indicator is normal, the module voltage is normal, and the command execution time is consistent without delay. Complete the sub-module fault protection test of the flexible DC converter valve. Simulate different fault types of different modules, such as overvoltage faults, undervoltage faults, and communication faults [23]. When the number of sub-module faults is smaller than the number of redundant sub-modules, when one or more sub-modules are faulty, the system runs normally and the module protection is fast and without damage. The parameters in Table 2 were used to build the experimental system. Taking 6-towed 6-power module experimental platform as the object, the power modules of 6 half-bridges of the tested system are monitored online. The temperature, switching frequency and loss of IGBT are calculated in real time, and alarm functions such as overtemperature and overfrequency are set to provide detailed data for the operating status of the converter valve. At the same time, the PSCAD/EMTDC simulation model is established to verify the effectiveness of the online monitoring scheme.

Table 2: Experimental system parameters

Argument		Argument	
L	3.5mH	I_w	2000A (peak)
C	12mF	U_z	1500V ~ 2200V

In the starting stage, the supplementary power supply is set at a higher voltage to charge the detection and accompanying modules. After unlocking, replenish the power supply to keep the power module voltage stable at the predetermined voltage. Where L is an inductor; C represents the capacitance of the power module; U_z is the module voltage; I_w is the current reference value. The test and simulation results of the online monitoring system will be discussed below. The test data are shown in Figure 6 and Figure 7.

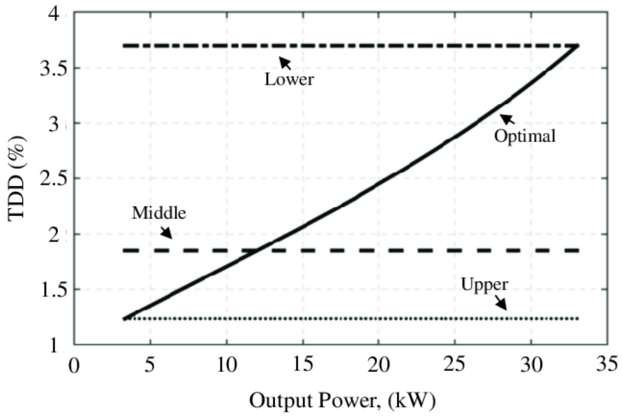

Figure 6: IGBT switching frequency and junction temperature curves of the power module

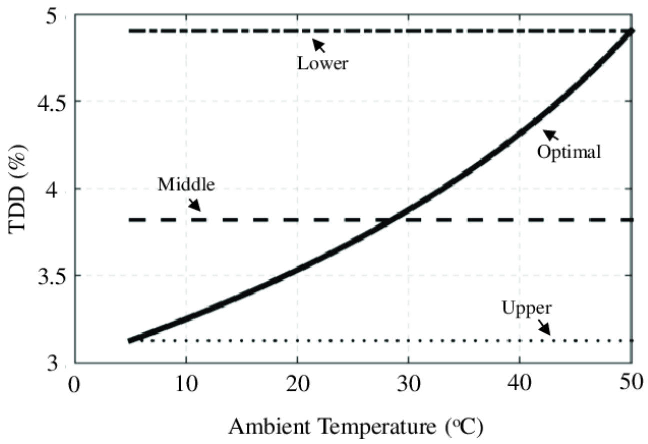

Figure 7: Voltage and loss information of the power module

Stable performance in 820A/1500V operating environment, did not reach the alarm threshold. The comprehensive loss meter of energy module 1 is 2.121kW; The temperature of T1 element node of energy module 1 rises to 70℃. The T1 component has a durability of 27.26. Stable performance in 920A/1700V operating environment, did not reach the alarm threshold. The comprehensive loss meter of energy module 1 is 3.214kW; The node temperature of T1 component of energy module 1 rises to 65℃. T1 components have a durability of 17.82. The comparison results of PSCAD simulation and experiment are shown in Figure 8. The experimental data and simulation results are roughly consistent, and the deviation between them is mainly concentrated in the range of 2% ~ 5%. This shows that the simulation results of the on-line monitoring system are basically consistent with the experimental results and have reliability.

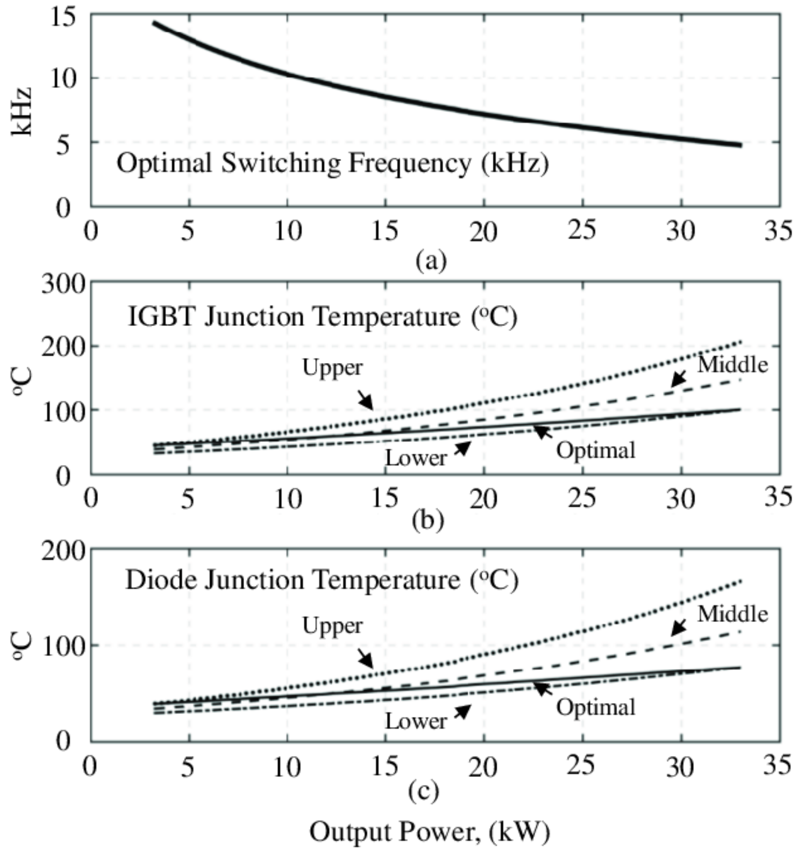

Figure 8: Comparison of PSCAD simulation and experimental results

CONCLUSION

This paper studies and implements an on-line monitoring system of flexible DC converter valve submodule based on machine vision. Through the introduction of machine vision technology, the system can monitor the surface state of sub-modules in real time, and combine Lesit life model and linear damage accumulation algorithm to effectively predict the fatigue life of sub-modules. The results show that the system can accurately identify the small damage of submodules under different working conditions, and predict the development trend of the damage. System simulation verifies the effectiveness and accuracy of the proposed algorithm, and simulation data analysis shows that the system has significant advantages in improving the monitoring accuracy and real-time performance. In addition, the life prediction function of the system can provide reliable decision support for the operation and maintenance of the flexible HVDC system, thus improving the safety and stability of the system. Overall, this study provides an innovative solution for online monitoring of power equipment, especially in complex working conditions, the reliability and practicability of the system has been fully verified.

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