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Original Research Article

Optimization of intelligent substation inspection mode based on infrared temperature measurement and image recognition

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Abstract: Smart inspection of substations should no longer be a single-device test; instead, based on many factors collected from all over the country in recent years, close-loop operations should be carried out. Infrared temperature measurement can be used to find hot spots in the joints and determine the causes of high temperatures, such as phase imbalance in a three-phase system or local heating of bushings; image recognition can read meters, learn the status of a switch, observe appearance defects and foreign objects, etc. Together they are to increase the accuracy, consistency and auditability of the inspection. By enhancing the collection and analysis of data on abnormalities, risks, etc., in substation inspections, it will be possible to strengthen condition-based maintenance and ensure the safe operation of equipment in the future.
Keywords: infrared temperature measurement; image recognition; substation; intelligent inspection; mode optimization

1. Introduction

With the development of power grid equipment in recent years, substation maintenance has changed from the old way of regular patrols to frequent observations and intelligent management. With the worsening weather, heavy-load operation, aging equipment and an increase in the number of unmanned stations, the need for manual inspection is growing rapidly in terms of coverage, anomaly detection and process tracing. With the start of the power operation site, infrared thermography, machine vision and edge computing have been added to the inspection process; now, we can not only "find problems" but also show trends, assess the level of risk, provide support for early disposal of abnormal situations, and thus give a strong direction to the upgrading of substation operation and maintenance.

2. Optimization basis for intelligent substation inspection

2.1. Refined inspection demand driven by equipment risk characteristics

The operational risks of substation equipment are progressive, hidden and coupled, and thus early signals at key nodes need to be obtained in time [1]. An increase in the contact resistance at the bus joint, at the disconnector contact, and at the circuit breaker lead and cable terminal will result in an increase in local temperature due to the thermal effect. Prolonged operation under load, corona, moisture and contamination can also cause a hot spot, an increase in temperature difference, or an abnormal heating rate at other places such as the transformer bushing arrester terminal and switch cabinet contact in the infrared image. Infrared temperature measurement converts invisible thermal conditions into numbers, and now we can assess the presence of hidden hazards based on these parameters instead of observing them with our naked eyes; thus, it is not the same as a naked-eye inspection.

Corresponding to the thermal abnormality, there are many visible risks in the substation, such as abnormal meter readings, incomplete switch positioning, abnormal oil level, unclosed cabinet doors, damaged insulators, bird nests, foreign objects and water accumulation. Image recognition is about making the visible states of these things into recognizable, comparable and traceable information [2]. Infrared measurement is about "heat", and image recognition is about "shape". When both are used on the same equipment and linked by a unified point and time series, the inspection result will be a general evaluation of the equipment's condition, not only a description of an abnormality.

2.2. Gradual manual inspection is still required in the operation of the substation

For general assessment, handling in the field, identification of complex environments, etc. Due to the large number of equipment and a small number of unsupervised stations, it is not feasible to conduct a full-scope risk chain manual inspection every time it is scheduled. Temperature will rise in the off-peak season at night, and if manual inspection is not conducted during this time, some serious defects may go unnoticed. A small leak, local corrosion and slow meter drift may also be deemed normal if there is no record of the image comparison. More importantly, the old inspection records are mostly text-based, and the image evidence, temperature data, equipment ledgers and repair results etc. are not linked together. Often, the problems cannot be detected in time during the inspection; after fixing the defects, they will reappear again, and there are common hidden risks in the equipment that lack continuous data records.

3. Construction of a multi-source data collection system for intelligent inspection

3.1. Gradual limitations of traditional manual inspection

Infrared temperature measurement and image recognition data, sense equipment status, etc. Infrared thermal imagers, HD cameras, rail-mounted inspection robots, wheeled inspection robots, fixed monitoring terminals and online monitoring devices should be set up around the main transformer, circuit breaker, disconnector, instrument transformer, arrester, bus joint, cable terminal and secondary panel to acquire the thermal condition, appearance information, position data and environmental factors at the same time. To avoid data isolation, inspection points should also be in line with the equipment ledger and have unified numbers, names, bay locations, rated parameters, operating attributes, etc., so that the collected data can be accurately traced back to the specific equipment and components [3].

For collection frequency, the intelligent inspection should not be based on the fixed cycle of a manual, but rather be adjusted dynamically according to the importance of the equipment, operating load, past defect records and so on. High-load equipment needs to be taken infrared temperature readings more frequently, the parts connected in a three-phase manner should have a small temperature difference among the phases, and outdoor disconnectors, arresters and cable terminals are exposed to the environment, so they should be regularly inspected after changes in weather. Do not change the angle, focal length or recognition range of the image data because of lens aberration, shadows or changes in light. Record the ambient temperature, load current and collection distance of the infrared data; otherwise, there will be no temperature anomaly in the actual working environment.

3.2. Image recognition model and infrared judgment mechanism

What the equipment is, and at the same time, it should judge in what condition it is. In visible-light image processing, algorithms such as target detection, character recognition, semantic segmentation and state classification can be used to find meter readings, positions of pressure plates, status of switches, indicator lights, oil level, bushing contamination, cabinet corrosion, leakage marks, foreign object intrusion, etc. For meters, the basis of the system should be their deviation from the reading range and historical data; for switches, the image results need to be checked against the dispatched status and remote signalling; as for appearance defects, one must consider the location of the defect area, changes in colour, edge features, whether it occurs repeatedly, etc., so as not to be mistaken for equipment failure caused by temporary light and shadow.

The Infrared Judgment Mechanism needs to be updated and revised in a broader sense. Rated currents, installation positions, heat dissipation capacities and material structures of the various pieces of equipment differ, so the same temperature will not be dangerous for all of them. A relatively fixed way is to set an upper limit for the temperature, phase-to-phase difference, difference among similar equipment, historical increase, load change rate and ambient temperature in the same system, and then form a logic based on graded thresholds and trend analysis. For instance, if the temperature of a disconnector contact is 65 °C and is more than 15 °C higher than that of adjacent equipment in the same phase, it will be flagged for key tracking in the system; if this difference continues to increase without an increase in load, then the warning level should be raised. The goal is no longer merely an algorithm for the complexity; it should be more in line with the actual working process of power equipment.

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3.3. Abnormality warning, work-order linkage and closed-loop operation

Finally, the effect of intelligent inspection can be seen in the efficiency of abnormality handling and the quality of defect closure. When there is an increase in temperature or an abnormal image, the system should automatically generate a warning that includes the name of the equipment, bay location, inspection time, type of abnormality, temperature data, image screenshots, historical comparisons, risk level, suggested measures, etc., and send it to the operation team, maintenance specialists or duty personnel according to the severity of the emergency. A small irregularity can be added to the trend observation and verified again in 24-48 hours; a general defect will trigger a planned repair task and be dealt with during an outage window; an urgent defect needs to be promptly checked in person, and the operating mode will be changed to prevent the spread of risk.

The main problem with the closed-loop management is not a lack of alarms from the system, but rather that the alarms have not been confirmed, addressed and audited. After the on-site inspection, the operating staff will post the manual judgment, repair measures, retest results and defect photos on the platform, and then the system will analyse changes in temperature, images and the duration before and after treatment [4]. If a certain kind of equipment frequently produces false alarms, either raise or lower the recognition threshold, add more training samples, etc.; if a specific type of defect occurs many times at a low level and then increases to a high level, the warning rule is too strict, and the grading standard should be adjusted. The above data feedback will help to improve the accuracy of the model and optimise the inspection plan; therefore, intelligent inspection will be continuous enhanced and improve from single recognition.

4. Application optimization and safeguard path of intelligent substation inspection

4.1. Differentiated optimization for typical scenarios

Substations are not all of the same kind. Due to various differences in the voltage level, equipment arrangement and working environment, they all require infrared measurement and image recognition. Light intensity, rain, fog, equipment distance, background interference, bird nests and foreign objects are all typical problems of outdoor open-type substations. Therefore, the inspection system needs to improve image denoising and target positioning, and infrared region calibration should be carried out; fixed recognition frames are to be set for high-risk areas, such as disconnector contacts, bus joints and cable terminals, etc. There are many devices in the indoor GIS room and the relay protection room, and the light conditions here are relatively stable; therefore, a system that can detect meters, pressure plates, indicator lights and local temperatures is more suitable for this place, and the focus has shifted from general patrols to specific verifications.

Table 1. Key adaptation points of intelligent inspection in typical substation scenarios.

Scenario	Key Objects	Main Recognition Content	Optimization Focus	Expected Effect
Outdoor main transformer area	Bushings, radiators, conservator, terminal boxes	Temperature rise, oil level, leakage, appearance damage	Strengthen infrared point calibration and shielding recognition	Improve continuous sensing of main equipment
110 kV bay area	Disconnectors, circuit breakers, transformers, arresters	Contact temperature, mechanism position, porcelain contamination, foreign objects	Combine phase difference with historical trends	Reduce contact heating and misoperation risks
10 kV switchgear room	Switch cabinets, cable terminals, protection plates	Cabinet temperature, indicator lights, meter readings, plate status	Improvement of Visible-light Recognition and Infrared Thermal Analysis.	Improve refined indoor inspection quality
Special operating periods	Heavy-load and historically defective equipment	Sudden rise in temperature, recurrence of defects, abnormal fluctuation	Increase the frequency of inspections and link work-order review.	Enhance peak-load and extreme-weather support

As shown in the case of intelligent inspection and renovation of an 110kV substation, there are two main transformers, four 110kV bays and thirty-six 10kV switch cabinets in the station. In the old way, manual inspection was carried out twice a day, and infrared measurement was done with a handheld device. After the renovation, fifty-eight fixed infrared temperature points have been set up at the high- and low-voltage transformer bushings, bus bridges, cable terminals, indoor switch cabinets, etc., and inspection robots are used to recognise meters, indicator lights, pressure plates and equipment appearance. One month after start-up, it was discovered that the A-phase temperature at the 10 kV cable end was about 12°C higher than that of phase B and phase C. On-site inspection revealed that the terminal crimping was loose, so it was rectified, and now the temperature difference is less than 3°C. Based on the difference in temperature and the status of the image, it can be detected early on that there is an abnormal situation before a clear fault occurs.

4.2. Continuous improvement path for data governance and algorithm iteration

The accuracy of infrared measurement and image recognition is closely related to the quality of data and the quantity of samples. If the names of the equipment are not consistent, the inspection points will be unstable and the image angles will frequently change; even strong algorithms cannot make reliable judgments [5]. Therefore, in the optimisation of intelligent inspection, data governance should be given the same weight as equipment deployment. The equipment ledger, point code, image format, temperature unit, defect type, warning level and work order status should all be in line with the same standard; historical data needs to be stored by equipment, part, time and operating condition to create a queryable, comparable and traceable database.

Algorithm iteration should be driven by changes in the model and other information from the field. If there is a high false-alarm rate, the reasons may be weak reflection, background noise in infrared imaging, incorrect angle of view, shielding by equipment, etc., so adjust the recognition area and threshold parameters accordingly. For defects that are not included in the scope of the alarm, similar samples should be added; that is to say, early-stage abnormal images and slightly increased temperature-rise data can be used to help the model learn how to detect the initial features of the defect. The end of a switch cabinet cable is a typical case, and if the system only learns obvious heating samples, it will not consider the initial temperature difference of 5-10 ℃. Some small differences have been corrected manually in the sample library, and now the system will be more sensitive to alterations in hidden risks. With an increase in the number of samples, intelligent inspection will be able to predict the probability of defects rather than identify defects; thus, it will be more suitable for condition-based maintenance.

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