Abstract

Power distribution cables are essential components of power distribution systems, responsible for delivering electric energy to support social production and daily life, and playing a foundational role in economic development and societal operation. However, during manufacturing, installation, and operation, cables are often subject to various forms of damage, such as mechanical stress, corrosion, and water ingress, which may lead to defects. These defects can cause failures that seriously threaten power supply security and the stable operation of the power system. Therefore, the development of efficient and reliable methods for defect detection and localization in power cables is of great practical significance. Time Domain Reflectometry (TDR) is widely used for detecting and localizing cable defects. By injecting a pulse signal into the cable and analyzing the reflected signal, TDR enables the detection and localization of defects. However, due to limited understanding of defect-related signal propagation characteristics, the lack of advanced signal processing techniques, and performance limitations of detection equipment, traditional TDR methods struggle to accurately detect, localize, and evaluate defects under conditions such as signal distortion and multiple reflections. These limitations restrict the practical effectiveness of TDR and pose challenges to cable operation and maintenance. To address these issues, this dissertation focuses on several key challenges in cable defect detection and proposes comprehensive research solutions covering modeling, defect localization, severity assessment, and system implementation.

To address the limitation that current cable defect reflection signal modeling mainly focuses on single-defect modeling, a general multiple-defect cable reflection signal modeling and simulation method was proposed, which achieved accurate modeling and simulation of reflection signals in multiple-defect and multiple-joint cables. Based on the frequency-dependent distributed parameter model of the cable body, a transmission line model was established to accurately represent the propagation characteristics. Furthermore, for different types of defects, equivalent circuit models and S-parameter models were established using equivalent circuit methods and finite element methods, respectively. By combining these models, the reflection coefficient spectrum of multiple-defect cables was constructed, from which the time-domain reflection signals were obtained. The modeling results demonstrated a quantitative relationship between defect type, severity, and propagation characteristics, providing an important basis for defect type discrimination and severity assessment. This research provides a theoretical foundation for subsequent analysis of defect reflection signals under complex conditions.

To address the problem of interference in defect detection and localization caused by multiple reflections under multi-defect conditions, a pulse reconstruction-based method for multi-defect detection and localization was developed. This method effectively suppressed the interference of multiple reflections and achieved accurate detection and localization of defects in multi-defect environments. First, the TDR-based estimation method for the cable's characteristic impedance and propagation constants was improved to enable precise evaluation of cable parameters. Then, using the estimated cable parameters, a defect detection and localization algorithm based on time-varying matched filtering was proposed, which effectively suppresses the influence of cable attenuation, dispersion, and environmental noise on localization accuracy. Finally, by combining the evaluation results with the reflection coefficient spectrum, a pulse-reconstruction-based framework for multi-defect detection and localization was developed to accurately identify and locate multiple defect reflections. Simulation and experimental results demonstrated that, compared to existing methods, the proposed approach could accurately determine the number of multiple defects and exhibited superior localization accuracy and robustness.

To address the problem that defect severity cannot be accurately and quantitatively evaluated in TDR measurements, an evaluation method based on double-frequency Time-Frequency Domain Reflectometry (TFDR) was proposed. The method quantitatively evaluates defect severity by estimating the characteristic impedance and physical size of defects. First, a chirp signal was employed as the excitation source to enhance the sensitivity of the measurement to variations in defect severity. Then, the influence of defect parameters—such as characteristic impedance and physical size—on the reflected signal and localization results was analyzed. Based on this, a double-frequency dual-injection measurement strategy was designed to enable independent estimation of characteristic impedance and physical size, thereby enabling quantitative evaluation of defect severity. Simulation and experimental results demonstrated that the proposed double-frequency TFDR method is accurate and robust, enabling accurate estimation of the characteristic impedance of defects and the physical size of short defects with lengths ranging from about ten centimeters to several meters.

To address the problem of weak reflected signals and limited detection distance in multiple-defect cable TDR measurements, a TDR system with high-voltage (HV) pulse injection and fast range switching was developed. By combining HV pulse injection with fast range switching multi-ratio signal measurement, the system significantly enhanced the strength of the reflected signal and the signal-to-noise ratio (SNR), and extended the detectable range in multiple-defect cables. Specifically, an HV pulse generator based on a series-stacked MOSFET architecture was designed, capable of generating HV pulses with adjustable amplitudes from 0 to 4.93 kV and pulse width from 200 ns to 1 μs, to meet the testing requirements of different cables. In addition, a fast range switching voltage divider with 4 different ratios was developed, which can rapidly change the division ratio during signal acquisition, thereby expanding the dynamic range of the TDR system. Based on these modules, a complete TDR system for multiple-defect cable detection and localization was constructed. Experimental results demonstrated that the system significantly enhanced the TDR capability for detecting weak and distant defects, exhibiting high practicality and strong engineering applicability.