

Overview of Wide-Frequency Measurement Technology for Electrical Parameters in Distribution Substations

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Abstract: The rapid development of modern transmission and distribution systems requires transformers with wide bandwidth and high accuracy to meet the measurement needs of new characteristics in distribution substations, including wide dynamic ranges in the time-frequency domain and multi-parameter measurements. This paper outlines the measurement principles and structural design of new wide-frequency voltage and current measurement technologies. Based on the current status and measurement demands of distribution substations, an analysis of the economic, safety, and reliability aspects of these technologies is conducted. The results of the analysis indicate that capacitive voltage transformers and current transformers based on Rogowski coils are the current suitable solutions for wide-frequency measurement in distribution substations. Finally, the paper provides a forward-looking perspective on the development prospects of wide-frequency electrical parameter sensing technologies in distribution substations.

Keywords: Distribution Substations, Electrical Parameters, Wide-Frequency Measurement, Voltage Transformer, Current Transformer.

1. Introduction

With the rapid development of renewable energy in distribution substations and the widespread application of nonlinear loads, unbalanced loads, and impact loads in power systems[1], traditional power systems face new challenges. In recent years, under the background of developing a new type of power system incorporating sources, grids, loads, and storage, distributed renewable energy, load diversity, and real-time variability have become prominent trends in the power industry[2]. These trends not only alter the traditional structure of power systems[3] but also introduce new features in the power grid, such as wide dynamic ranges in the time-frequency domain and multi-parameter characteristics[4]. This results in an increase in power quality issues, including voltage fluctuations and flickers, power harmonics and waveform distortions, voltage interruptions, three-phase voltage imbalances, and deviations in power supply voltage[1,5,6], which pose significant challenges for high-accuracy metering and precise voltage and current sensing for power users[7]. Traditional transformers are insufficiently responsive to the high-frequency components and transient impact signals resulting from the random variations in renewable energy generation and diverse load types, making it difficult to capture accurate data, which poses considerable risks to the stability and safety of power systems.

Voltage and current are two critical power quality parameters in power systems[8,9]. Transformers, as essential measurement devices in power systems, convert high voltage and high current into low voltage and low current[7] and are widely used in various stages of power system line protection and monitoring to ensure the safe and stable operation of the power grid. Currently, transformer sensing principles and components are becoming increasingly diverse, and exploring and applying new transformer technologies to enhance the accuracy and reliability of power quality detection has become an important research direction. In one study[10], temperature dependency was identified as a primary cause of ratio error in reflective Sagnac-type fiber optic current transformers, and measures were taken to suppress temperature factors within the device structure. However, solutions for outdoor adverse temperature conditions still require further investigation. Another study[11] proposed a broadband, fully integrated Hall-effect-based current sensor, which, by reducing capacitive input in electronic readout, pushes the acquisition bandwidth of the entire measurement system to the upper limit of the Hall probe's bandwidth. However, achieving a larger bandwidth would require the development of different offset reduction techniques or acceptance of a greater residual offset. In a separate study[12], optimizing the optical path system design of voltage fiber optic transformers was found to suppress polarization error sources, although measurement accuracy for optical voltage transformers could still not be fully guaranteed.

This paper discusses the theoretical principles and structural design of representative wide-frequency measurement technologies for electrical parameters at the current stage. Based on the present development and measurement demands of distributed energy and diverse loads in distribution substations, this paper analyzes the economic, safety, and reliability aspects of these technologies. Finally, it offers insights into the future development of wide-frequency measurement technology for electrical parameters in distribution substations.

2. Wide-Frequency Voltage Measurement Technology

Traditional voltage transformers typically operate at power frequencies (50/60Hz). However, with the rapid development of distributed renewable energy generation and the increasing diversity of loads on the user side, high-frequency signals and harmonic components in the power grid have significantly increased. To comprehensively assess power quality parameters related to voltage, wide-frequency voltage measurement technology utilizes specially designed voltage transformers and high-precision data acquisition systems to accurately measure voltage signals over a wide frequency range (typically from power frequency up to several kilohertz or even higher).

2.1. Quasi-Reciprocal Reflective Optical Voltage Transformer

The quasi-reciprocal reflective optical voltage transformer is a voltage measurement device based on optical principles, which uses the reflective properties of light and optical components to measure voltage. Its structure is shown in Figure 1:

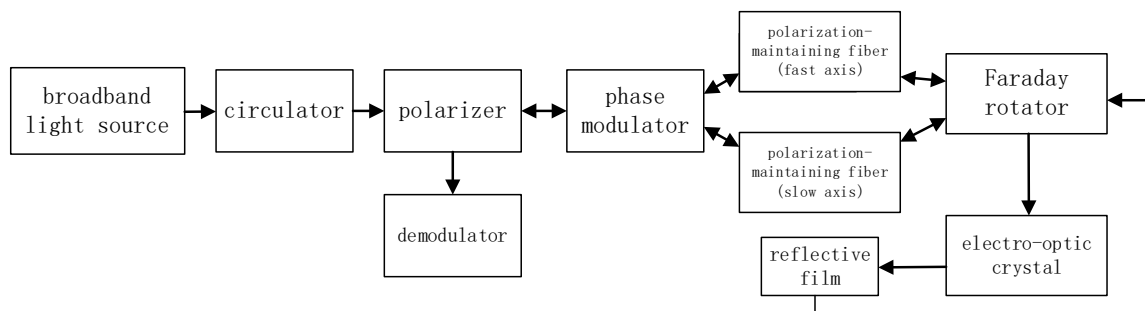


Figure 1: Structure of the Quasi-Reciprocal Reflective Optical Voltage Transformer

The optical path structure of the quasi-reciprocal reflective optical voltage transformer includes a light source, circulator, polarizer, phase modulator, polarization-maintaining delay fiber, Faraday collimator, electro-optic crystal, and reflective film. First, the light emitted from a broadband light source passes through the circulator and reaches the polarizer, where it is converted into linearly polarized light. The polarized light is then divided by the polarizer and phase modulator into two orthogonal modes. After modulation by the phase modulator, these two modes are transmitted along the fast and slow axes of the polarization-maintaining delay fiber. At the sensor head, the light is collimated through a collimating lens and then enters the Faraday rotator, where its polarization plane is rotated by a specific angle to vertically enter the electro-optic crystal and reflect off the reflective film on its surface, doubling the phase shift in the electro-optic crystal. When passing through the Faraday rotator again, the light undergoes another rotation and mode exchange. Finally, at the phase modulator, the light interferes with the polarizer. As these two interfering beams have each traveled along the two orthogonal axes of the polarization-maintaining fiber during transmission, the light returned to the detector carries only the phase modulation information from the sensor head. The optical signal is reflected back to the fiber and transmitted to the detection device, where a demodulator detects changes in phase or polarization state to calculate the measured voltage.

The light emitted from the broadband light source is polarized by a polarization device and then transmitted via optical fiber to the measurement point. At the measurement point, the light signal passes through an electro-optic crystal, whose refractive index changes with the applied voltage, thereby altering the phase or polarization state of the light passing through the crystal. The relationship between the refractive index of the electro-optic crystal and the applied electric field is shown in Equation (1):

$$n(E) = n_0 + \Delta n = n_0 + \frac{1}{2}r_{ijk}E_j \quad (1)$$

Where $n(E)$ is the refractive index under the applied electric field E ; n_0 is the intrinsic refractive index of the crystal without an electric field; r_{ijk} is the electro-optic coefficient tensor of the crystal, describing the relationship between the electric field and the refractive index of the crystal; E_j is the electric field component applied to the crystal; and Δn represents the change in refractive index.

The light passing through the electro-optic crystal undergoes a phase shift that is proportional to the applied voltage. The phase shift is given by the following formula:

$$\Delta\varphi = \frac{2\pi L}{\lambda}\Delta n = \frac{2\pi L}{\lambda} \cdot \frac{1}{2}r_{ijk}E_j \quad (2)$$

Where $\Delta\varphi$ is the phase change of light after passing through the electro-optic crystal, L is the propagation path length of light in the electro-optic crystal, and λ is the wavelength of the light.

The relationship between the electric field component E_j on the crystal and the measured voltage V can be described using the definition of electric field intensity. The electric field E_j is generated by the voltage V and the effective thickness d of the crystal, expressed as:

$$E_j = \frac{V}{d} \quad (3)$$

By detecting the interference intensity, the measured voltage V can be derived using the inverse formula for interference intensity:

$$V = \frac{d}{\pi L} \cdot \frac{\lambda}{r_{ijk}} \cdot \Delta\varphi \quad (4)$$

2.2. AC-Modulated Dual Optical Path Balanced Voltage Transformer

The AC-modulated dual optical path balanced voltage transformer is an optical voltage measurement device that utilizes a dual optical path structure and AC modulation technology to achieve voltage measurement. Its structure is shown in Figure 2:

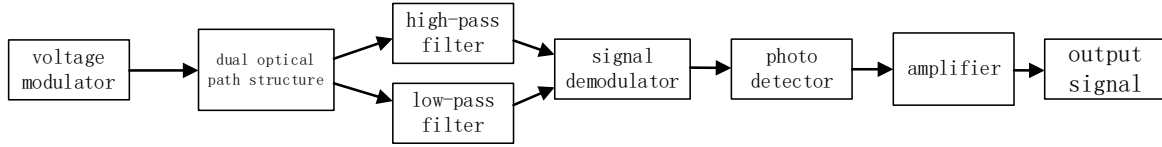


Figure 2: Structure of the AC-Modulated Dual Optical Path Balanced Voltage Transformer

The structure of the AC-modulated dual optical path balanced voltage transformer includes a voltage modulator, dual optical path structure, high-pass and low-pass filters, photo detectors, and a signal demodulator. First, the input voltage signal is converted into an optical signal. The AC modulation technique modulates this optical signal so that the two beams in the dual optical path structure follow different paths during transmission. By applying the AC modulation method, high-pass and low-pass filters are used twice to identify the balance coefficient. This modulation of the optical signal's frequency or amplitude achieves balance, and the photo detector then converts the optical signal back into an electrical signal. Finally, phase detection, amplitude detection, and other demodulation processes are applied to the received electrical signal to ensure accurate measurement of the input voltage signal.

The input voltage signal $V_{in}(t)$ is converted by the voltage modulator into variations in optical intensity $I(t)$, typically represented using a modulation index m :

$$I(t) = I_0[1 + m \cdot \sin(2\pi f_m t) \cdot V_{in}(t)] \quad (5)$$

Where I_0 is the DC component of the optical signal, m is the modulation depth, and f_m is the frequency of the modulation signal.

During transmission in the dual optical path system, the optical signal is superimposed with internal noise $N(t)$, resulting in a mixed signal $S(t)$ expressed as:

$$S(t) = I(t) + N(t) \quad (6)$$

Using AC modulation, the signal is elevated to a higher frequency band, and then low-pass $H_{LP}(f)$ and high-pass filters $H_{HP}(f)$ are applied to find the balance coefficient K :

$$K = \frac{S_{LP}}{S_{HP}} \quad (7)$$

Where S_{LP} and S_{HP} represent the low-frequency and high-frequency components, respectively.

The obtained balance coefficient is then used in the demodulation process to recover the original voltage signal $V_{out}(t)$:

$$V_{out}(t) = K \cdot S_{LP}(t) \quad (8)$$

Finally, the output voltage signal V_{output} is amplified by a factor A through an amplifier:

$$V_{output} = A \cdot V_{out}(t) \quad (9)$$

2.3. Capacitive Voltage Transformer

A capacitive voltage transformer (CVT) is a voltage measurement device used in high-voltage power systems, utilizing the principle of capacitive voltage division for voltage measurement. Its structure is shown in Figure 3:

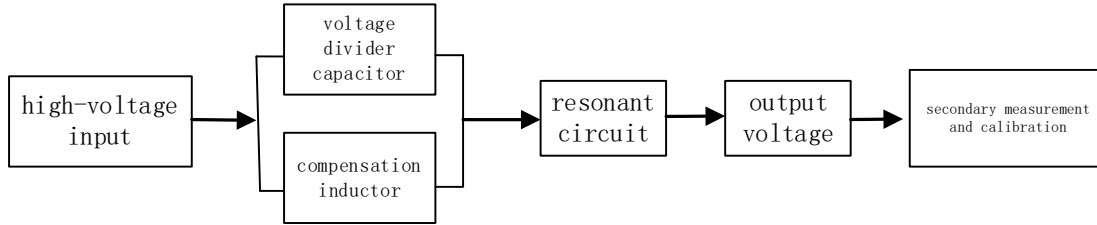


Figure 3: Structure of the Capacitive Voltage Transformer

The structure of a capacitive voltage transformer includes a high-voltage capacitor, a low-voltage capacitor, primary and secondary windings, a compensation device, a measuring instrument, and a protection device. First, the high-voltage capacitor and low-voltage capacitor are connected in series to form a capacitive divider. When a high voltage is applied across the capacitive divider, the two capacitors divide the voltage proportionally according to their capacitances, resulting in a low voltage across the low-voltage capacitor. The primary and secondary windings are then combined to form an intermediate transformer, with the primary side connected to the low-voltage end of the capacitive divider. Through the principle of electromagnetic induction, the low voltage is transformed and isolated to output a more stable and moderate voltage. Typically, a compensation inductor is connected in parallel with the primary side of the intermediate transformer to further improve measurement accuracy and long-term stability. The low-voltage measurement is then sent to the secondary measurement system, which consists of measuring instruments and protection devices. The measuring instrument ensures accurate measurement and calibration of the voltage signal, ensuring that the final voltage measurement matches the actual high voltage.

The voltage across a capacitor is inversely proportional to its capacitance, allowing for capacitive voltage division. Given the input voltage V_H and capacitances C_1 and C_2 , the output low voltage V_L can be expressed as:

$$V_L = V_H \cdot \frac{C_1}{C_1 + C_2} \quad (10)$$

Where C_1 is the capacitance on the high-voltage side, and C_2 is the capacitance on the low-voltage side.

To improve measurement accuracy and frequency response, the capacitive voltage transformer is usually combined with a compensation inductor L to form a resonant circuit. Under resonance conditions, the circuit impedance is minimized, and the output voltage amplitude is maximized. The compensation inductor L can be expressed as:

$$L = \frac{1}{4\pi^2 C f_0^2} \quad (11)$$

To ensure measurement accuracy, in resonance conditions, the stable output measurement voltage also requires calibration, which can be expressed as

$$V_{cal} = K \cdot V_L \quad (12)$$

Where K is the calibration coefficient, and V_{cal} is the calibrated measured voltage.

2.4. Resistive-Capacitive Electronic Voltage Transformer

The resistive-capacitive (RC) electronic voltage transformer is a high-precision voltage measurement device that uses the impedance characteristics of resistive and capacitive components to measure and convert voltage. Its structure is shown in Figure 4:

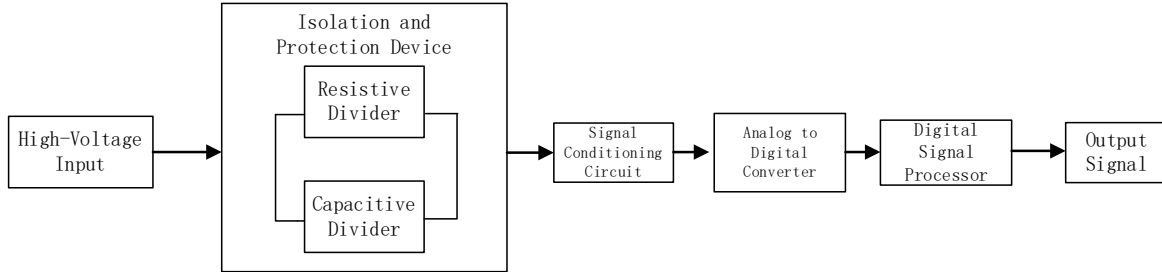


Figure 4: Structure of the Resistive-Capacitive Electronic Voltage Transformer

The RC electronic voltage transformer consists of a resistive divider, capacitive divider, isolation protection device, signal conditioning circuit, analog-to-digital converter (ADC), and digital signal processor (DSP). First, a resistive divider composed of multiple resistors initially reduces the high voltage being measured. Then, a capacitive divider formed by multiple capacitors further reduces the high-voltage signal in conjunction with the resistive divider. An isolation protection device is installed to protect subsequent circuits from high-voltage interference, ensuring the safety and stability of the measurement. The divided voltage signal is then processed by filters and amplifiers in the signal conditioning circuit, converted to a digital signal through the ADC, and processed by the DSP to extract the effective voltage information. Finally, the processed low-voltage signal is output for measurement and monitoring.

Based on the high-voltage signal being measured, appropriate resistor and capacitor values are selected to construct the RC divider circuit. High-stability, low-temperature-drift resistors and capacitors are typically used to achieve high-precision measurements. By utilizing the different impedance characteristics of resistors and capacitors for AC voltage, the RC divider provides a precise division of the input voltage signal. The voltage drop across the resistor represents a proportionally scaled output voltage signal, which is then converted from an analog to a digital signal and transmitted via optical fiber to a data processing platform for actual voltage monitoring and analysis.

In the RC divider circuit, after the high input voltage V_{in} is divided by the resistor R and capacitor C , the output voltage V_{out} can be expressed as:

$$V_{out} = V_{in} \cdot \frac{Z_R}{Z_R + Z_C} \quad (13)$$

Where Z_R is the impedance of the resistor $Z_R=R$, and Z_C is the impedance of the capacitor, $Z_C=\frac{1}{j\omega C}$, with $\omega=2\pi f$ representing the angular frequency.

During the signal conditioning process, the divided signal needs to be filtered and amplified, and the processed analog signal V_{signal} can be represented as:

$$V_{signal} = A \cdot V_{out} \quad (14)$$

where A is the amplification factor.

After passing through the ADC, the analog signal is converted to a digital signal $V_{digital}$:

$$V_{digital} = ADC(V_{signal}) \quad (15)$$

where "ADC" denotes the analog-to-digital conversion process.

3. Wide-Frequency Current Measurement Technology

Traditional current transformers are primarily designed for current measurement at power frequencies (50/60Hz) and tend to exhibit errors in the presence of high-frequency signals and harmonics. Wide-frequency current measurement technology has emerged in response to this challenge. By designing specialized current transformers, this technology can accurately measure current signals across a wide frequency range, to meet the modern power system's need for high-precision current measurement.

3.1. Phase-Modulated All-Fiber Optical Current Transformer

The phase-modulated all-fiber optical current transformer is a current measurement device based on optical principles, using all-fiber technology and optical sensing principles to measure current. Its structure is shown in Figure 5:

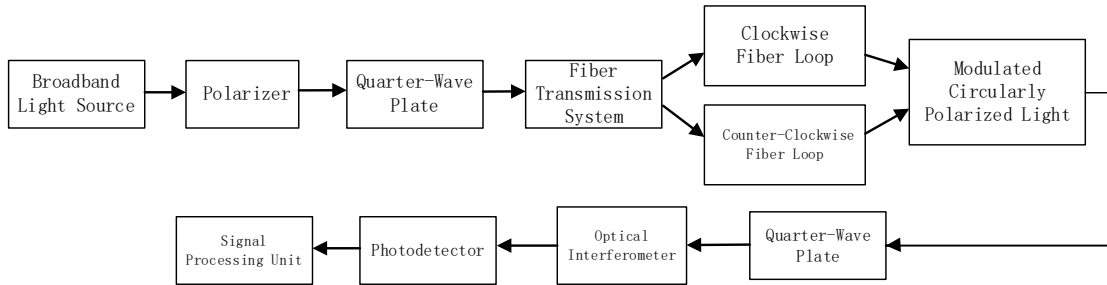


Figure 5: Structure of the Phase-Modulated All-Fiber Optical Current Transformer

The structure of the phase-modulated all-fiber optical current transformer includes a fiber transmission system, phase modulator, fiber coil, optical interferometer, photodetector, and signal processing unit. First, a light source signal is transmitted through the fiber transmission system to the conductor carrying the measured current. The fiber coil is wound around the conductor, allowing the light signal in this area to experience the magneto-optic effect due to the magnetic field created by the current. The phase modulator alters the phase, encoding the light signal with phase information. The optical interferometer detects phase changes through interference, and the photodetector converts the optical signal into an electrical signal. Finally, the signal processing unit amplifies, filters, performs analog-to-digital conversion, and processes the digital signal to demodulate and calculate the measured current.

The light emitted from the source is first polarized and then split into two identical linearly polarized beams. A quarter-wave plate converts the linearly polarized light into circularly polarized light, with each circularly polarized beam passing clockwise and counterclockwise through the sensing fiber loop. Due to the magneto-optic effect in the fiber, the magnetic field generated by the current induces a phase change $\Delta\phi$ in the light signal as it propagates through the fiber. The phase change $\Delta\phi$ due to the magnetic field generated by the current can be expressed as:

$$\Delta\phi = \frac{2\pi}{\lambda} \cdot \Delta n \cdot L \quad (16)$$

Where λ is the wavelength of the light, Δn is the refractive index change due to the magneto-optic effect, and L is the effective length of the fiber.

The modulated circularly polarized light is converted back into linearly polarized light by another quarter-wave plate, and the two polarized beams converge at the same point, creating interference. The intensity I of the interference light can be expressed as:

$$I = I_0(1 + \cos(\Delta\phi)) \quad (17)$$

Where I_0 is the maximum intensity of the interference light. By capturing, processing, and demodulating the interference light intensity information, the phase information can be obtained. The measured current value is then derived based on the relationship between the magnetic field generated by the current and the phase change[9].

3.2. Quantum Current Transformer Based on Nitrogen-Vacancy Centers

The nitrogen-vacancy (NV) center-based quantum current transformer is a precision quantum measurement device that utilizes the NV centers in diamond, a quantum system, to measure magnetic fields and thereby measure current via spatial magnetic measurements or the zero-flux principle[7]. Its structure is shown in Figure 6:

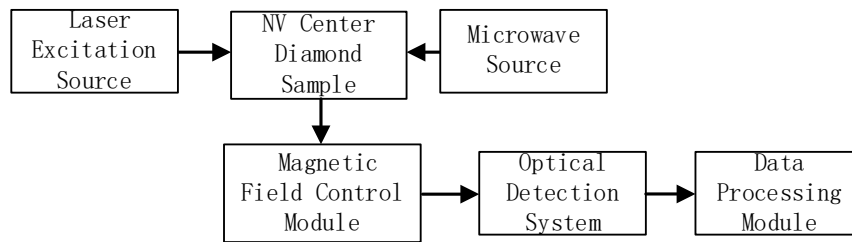


Figure 6: Structure of the Nitrogen-Vacancy Center-Based Quantum Current Transformer

The NV center-based quantum current transformer includes an NV center diamond sample, a laser excitation source, a microwave source, a magnetic field control module, an optical detection system, and a data processing module. The NV center diamond sample serves as the core sensor for detecting the magnetic field in the environment. First, the laser excitation source activates the NV centers by exciting electrons to an excited state. The microwave source provides microwave signals to control the spin state of electrons in the NV centers, while the optical detection system captures the fluorescence signals emitted by the NV centers. Finally, the data processing module collects, analyzes, and computes magnetic field data from these signals, achieving high-precision current measurement.

When an external magnetic field is applied, the magnetic field vector along the NV axis creates two resonance absorption dips. The relationship between the fluorescence intensity I of the NV center and the magnetic field strength B can be expressed as:

$$I(B) = I_0 \cdot e^{-kB} \quad (18)$$

Where I_0 is the initial fluorescence intensity, and k is the attenuation constant related to the magnetic field strength.

According to Ampère's law, the relationship between the current $I_{current}$ and the resulting magnetic field strength B can be expressed as:

$$I_{current} = \frac{2\pi r B}{\mu_0} \quad (19)$$

Where μ_0 is the vacuum permeability, and r is the distance from the current source. By detecting the attenuation amplitude of the fluorescence intensity and analyzing the position and broadening of the magnetic resonance spectrum, the strength of the external magnetic field acting on the electron spin can be determined. Subsequently, the measured current can be calculated from the magnetic field data[4].

3.3. Redundant Hall Electronic Current Transformer

The redundant Hall electronic current transformer is a current measurement device used in high-voltage power systems, utilizing the Hall effect and a redundant design structure to achieve current measurement. Its structure is shown in Figure 7:

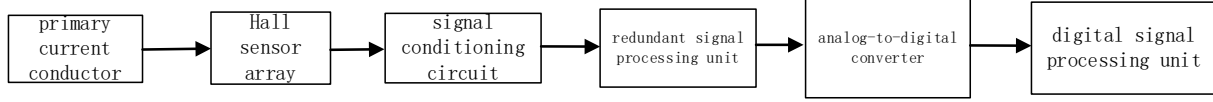


Figure 7: Structure of the Redundant Hall Electronic Current Transformer

The structure of the redundant Hall electronic current transformer includes a primary current conductor, an array of Hall sensors, a signal conditioning circuit, a redundant signal processing unit, an analog-to-digital converter (ADC), and a digital signal processing unit (DSP). First, the magnetic field generated in the primary current conductor is detected by the Hall sensors. The Hall sensor array contains multiple Hall sensors that detect the magnetic field generated by the primary current conductor, with each sensor producing a voltage signal proportional to the magnetic field strength. These signals are processed by the redundant signal processing unit for amplification, filtering, and offset adjustment. The DSP unit processes the multiple signals from different Hall sensors, performing data fusion and redundancy checks. The ADC then converts the analog signals into digital signals, which the DSP further processes to achieve precise current measurement.

When current flows through a conductive material placed in a magnetic field perpendicular to the current direction, an electric field is generated within the material, perpendicular to both the current and magnetic field directions. This electric field can be used to measure the magnetic field strength and thereby indirectly measure the current. In a Hall electronic current transformer, multiple Hall sensors are used within a system to measure the same current, achieving multi-sensor redundancy. Each sensor operates independently, producing individual measurement results. By applying data fusion algorithms, such as weighted averaging or Kalman filtering, the system combines the measurements from multiple sensors to obtain a more accurate and reliable measurement value. The system can monitor the status of the sensors in real-time. If a sensor anomaly or failure is detected, it can automatically isolate that sensor and continue measuring with data from the remaining sensors, ensuring continuity and reliability of the system[13].

The voltage generated by the Hall effect, V_H , can be expressed as:

$$V_H = \frac{B \cdot I}{n \cdot q \cdot d} \quad (20)$$

Where B is the magnetic field strength perpendicular to the current direction, I is the current through the conductor, n is the carrier concentration, q is the charge of the carriers, and d is the thickness of the material.

Using the relationship between Hall voltage and current, the expression for current I can be derived as:

$$I = \frac{V_H \cdot n \cdot q \cdot d}{B} \quad (21)$$

Assuming there are N Hall sensors with current measurements $I_1, \dots, I_N$, the weighted average for the redundant system can be represented as:

$$I_{avg} = \frac{\sum_{i=1}^N w_i \cdot I_i}{\sum_{i=1}^N w_i} \quad (22)$$

Where w_i is the weight of each sensor, and I_{avg} is the output measured current value.

3.4. Rogowski Coil-Based Current Transformer

The Rogowski coil-based current transformer is a high-precision current measurement device that utilizes the structure of the Rogowski coil and current induction technology to measure current. Its structure is shown in Figure 8:

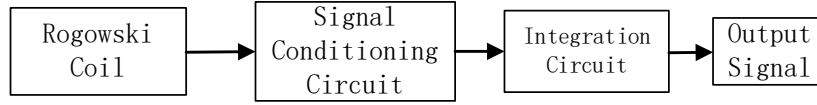


Figure 8: Structure of the Rogowski Coil-Based Current Transformer

The structure of the Rogowski coil-based current transformer includes a Rogowski coil, a signal conditioning circuit, and an integration circuit. When the measured current flows through a conductor, it generates a changing magnetic field. The Rogowski coil surrounds the conductor and detects changes in the current, producing an induced electromotive force (EMF) proportional to the rate of change of the current. The signal conditioning circuit performs preliminary amplification and filtering on the induced EMF output by the Rogowski coil, and then the integration circuit integrates the induced EMF signal to obtain the actual current measurement signal.

The Rogowski coil is typically composed of a uniformly wound coil on a non-magnetic material, forming a closed loop structure. When the measured current flows through the conductor, it creates a changing magnetic field around it. When the magnetic flux through the loop path of the Rogowski coil changes, an EMF is induced in the coil. Since the EMF is the derivative of the current, the integration circuit is required to convert the induced EMF into a current signal, with the output of the integration circuit being proportional to the measured current.

The induced EMF E in the Rogowski coil can be expressed using Faraday's law of electromagnetic induction as:

$$E = -\frac{d\Phi}{dt} \quad (23)$$

Where E is the induced EMF, and Φ is the magnetic flux passing through the coil.

The magnetic flux Φ can be expressed as:

$$\Phi = B \cdot A \cdot \cos(\theta) \quad (24)$$

Where B is the magnetic field strength, A is the effective area of the coil, and θ is the angle between the magnetic field direction and the normal to the coil.

The magnetic field B generated by the current I in the conductor is typically proportional to the current, meaning that changes in current cause changes in magnetic field strength. The relationship between the magnetic field strength and current can be expressed as:

$$B = k \cdot I \quad (25)$$

Where k is a constant related to the geometry and material properties of the Rogowski coil.

The magnetic flux Φ can be further expressed as:

$$\Phi = B \cdot A \cdot \cos(\theta) = k \cdot I \cdot A \cdot \cos(\theta) \quad (26)$$

Taking the time derivative of the magnetic flux Φ gives:

$$\frac{d\Phi}{dt} = k \cdot A \cdot \cos(\theta) \cdot \frac{dI}{dt}$$

Thus, the induced EMF E can be represented by the following relationship:

$$E = k \cdot A \cdot \cos(\theta) \cdot \frac{dI}{dt} \quad (27)$$

To obtain the measured current

$$I = \frac{I}{k \cdot A \cdot \cos(\theta)} \int E dt \quad (28)$$

4. Application Selection Analysis for Distribution Substations

With the development of modern power grids, especially the widespread integration of distributed energy and various new types of loads, the power quality in distribution substations faces increasingly complex challenges and changes[14]. New types of disturbances, such as harmonic distortion and wide-frequency oscillations, have emerged[1,7,9], resulting in power quality characteristics that span a wide frequency range. This section analyzes the application selection based on the measurement principles and structural diagrams of the above wide-frequency measurement technologies, considering the practical situation of distribution substations. The analysis addresses three aspects: economic efficiency, safety, and reliability, aiming to balance cost, performance, and risk to meet the application requirements of distribution substations.

4.1. Economic Efficiency

Economic efficiency primarily refers to the cost involved in applying wide-frequency transformers in distribution substations. This includes equipment procurement, installation and maintenance costs, and potential energy-saving or efficiency gains during operation.

The quasi-reciprocal reflective optical voltage transformer, due to its use of optical technology, has relatively high manufacturing costs. While the prices of optical components may gradually decrease, the initial investment for its application in distribution substations is substantial, and installation and maintenance require specialized skills and equipment, making its economic efficiency generally low. The AC-modulated dual optical path balanced voltage transformer provides relatively stable measurements, but its complex structure, high-cost modulation system, and optical components make it economically less feasible, especially in distribution substations. This system also requires high-precision modulation devices and frequent calibration, adding to the operational and maintenance costs. The capacitive voltage transformer, widely used in power systems, has relatively low manufacturing costs, is easy to install, and requires less frequent maintenance, making it highly economical. For distribution substations, this device offers a favorable cost-performance ratio and is an economical choice. The RC electronic voltage transformer also has low manufacturing costs, as electronic components are readily available and installation and maintenance are relatively simple, thus providing high economic efficiency.

The phase-modulated all-fiber optical current transformer involves high manufacturing and installation costs, with fiber optic components and high-precision modulation devices contributing to significant initial investment. In distribution substations, especially in budget-constrained scenarios, its economic efficiency is low. The nitrogen-vacancy center-based quantum current transformer is an emerging technology with high R&D and manufacturing costs. Since it is not yet widely commercialized, its economic efficiency is very poor. In standard application scenarios such as distribution substations, the high initial equipment and maintenance costs make it a less economical choice. The Hall electronic current transformer with redundancy mechanism has relatively low costs and is a mature technology suitable for wide application. Although adding redundancy slightly increases the cost, its overall economic efficiency remains favorable in distribution substations. The Rogowski coil, being a coreless current transformer, has low manufacturing costs and is easy to install, making it a highly economical option for application in distribution substations.

4.2. Safety

In terms of safety, the primary focus is on whether wide-frequency transformers in distribution substations can ensure the safe operation of the distribution system and related equipment amidst various power fluctuations and load changes.

The quasi-reciprocal reflective optical voltage transformer offers strong electromagnetic isolation, effectively avoiding conventional electromagnetic interference, and performs well in complex power systems. Its optical transmission component does not produce arcs, short circuits, or other electrical safety issues, providing a high level of safety. The AC-modulated dual optical path balanced voltage transformer also uses optical paths, providing effective electrical isolation that prevents high voltage from directly impacting other parts of the system. Consequently, it has high safety, and its AC modulation system effectively manages voltage fluctuations, making it adaptable to complex load environments. The capacitive voltage transformer achieves voltage measurement through capacitive voltage division. Although its isolation performance is not as strong as that of optical transformers, it still offers reliable safety. Its design and safety have been widely validated over years of application, presenting a low risk. The RC electronic voltage transformer, on the other hand, employs electronic measurement technology, which provides limited isolation and is somewhat lacking in interference resistance. Its relative lack of safety makes it vulnerable in the face of complex distribution substation loads, where insufficient electrical isolation and resistance to electromagnetic interference could pose safety risks.

The phase-modulated all-fiber optical current transformer has excellent electromagnetic isolation, is entirely unaffected by external electromagnetic interference, and thus has high safety. Furthermore, its operation is based on fiber transmission without involving high-voltage electrical parts, eliminating risks such as electrical short circuits and breakdowns, making it suitable for applications with high safety requirements. The nitrogen-vacancy center-based quantum current transformer offers ultra-high sensitivity and interference resistance; since it measures using quantum effects, it is entirely unaffected by external electromagnetic interference, providing an extremely high level of safety. The Hall electronic current transformer with redundancy mechanism operates based on electromagnetic fields, with relatively limited interference resistance, particularly in complex electromagnetic environments. Although the transformer's redundancy design enables it to continue operating even if some components fail, its overall safety is still lower than that of optical or quantum transformers. The Rogowski coil-based current transformer, with no electrical contact, offers high safety as it effectively avoids risks such as electrical short circuits, making it suitable for the safety demands of distribution substations. Additionally, since it operates based on electromagnetic induction, it has strong interference resistance and can operate stably in complex electromagnetic environments, ensuring system safety.

4.3. Reliability

Reliability refers to the stability and performance retention of wide-frequency transformers during long-term operation. With the integration of distributed power sources and diverse loads, the working environment of distribution substations has become more complex and variable. Key aspects of reliability analysis include whether the transformer can maintain accurate measurement capabilities over prolonged periods, exhibit low failure rates, and have a long lifespan.

The quasi-reciprocal reflective optical voltage transformer may face reduced reliability in outdoor substation environments due to potential impacts on optical components, such as fiber bending or damage, especially in harsh environments. This transformer's sensitivity to maintenance costs over time is also a concern. The AC-modulated dual optical path balanced voltage transformer improves reliability through its dual-path design, which minimizes measurement issues caused by single-path

failures. However, the sensitivity of optical systems to harsh environments presents challenges for long-term reliability. The capacitive voltage transformer offers high reliability, with a long service life and stable performance, especially in outdoor environments. Its relatively simple structure results in a low failure rate, making it suitable for long-term use. Conversely, the RC electronic voltage transformer has limited reliability over long-term operation. Its stability and measurement accuracy may be affected, particularly in variable external environments.

The phase-modulated all-fiber optical current transformer's reliability in long-term use is somewhat limited, as fiber components may be susceptible to damage in harsh environments, such as bending or breakage due to external forces. Additionally, its complex modulation system requires periodic calibration and maintenance, which may reduce its reliability in prolonged use within distribution substations. The nitrogen-vacancy center-based quantum current transformer, while offering extremely high measurement accuracy, has not yet been widely validated for reliability in large-scale applications. The complexity of quantum devices may render them sensitive to external environmental factors, raising concerns about their long-term operational stability. The Hall electronic current transformer with a redundancy mechanism significantly enhances reliability due to its redundancy design. In the event of a single component failure, the system can automatically switch to a backup path, ensuring uninterrupted measurement. Given the maturity of electronic components, this transformer exhibits good long-term stability, making it suitable for complex environments in distribution substations. The Rogowski coil-based current transformer is highly reliable, particularly well-suited for measuring current variations over a wide frequency range. It consistently provides stable and accurate measurements, with a simple structure that leads to a low failure rate. Its robust adaptability allows it to operate for extended periods in outdoor or harsh environments, making it particularly suitable for the demands of distribution substations.

5. Conclusion

Based on the current development of distributed energy and diverse load requirements in distribution substations, this paper discusses the theoretical principles and structural design of four representative wide-frequency voltage transformers and four wide-frequency current transformers. Additionally, an analysis of the economic efficiency, safety, and reliability of these technologies was conducted. The analysis results indicate that the capacitive voltage transformer and the Rogowski coil-based current transformer are the most suitable wide-frequency measurement solutions for application in distribution substations at this stage. In the future, the use of wide-frequency transformer sensing data at both the source and load ends in distribution substations will drive more precise power monitoring and control. Among these, optical transformers, with their capability to capture transient signals in real time, offer potential for further improving wide-frequency measurement accuracy, enhancing the monitoring of harmonics and other electrical parameters. Consequently, how to enhance the economic efficiency and stability of optical transformers while simultaneously improving the precision and efficiency of signal processing will be an important research direction for future wide-frequency measurement technology.

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