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ON APPLICATION OF RESISTIVE-CAPACITIVE VOLTAGE DIVIDERS FOR HIGHER HARMONICS MEASUREMENT: A REVIEW OF STUDIES

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Purpose. This article aims to review the application of resistive-capacitive voltage dividers for higher harmonics measurement in medium and high voltage networks. The purpose is to explore their potential as an alternative to traditional magnetic core instrument transformers, addressing the evolving measurement needs of modern power systems.

Methodology. The review delves into the principles, advantages, and challenges associated with resistive-capacitive dividers, offering insights into their suitability for capturing harmonic signals across a wide frequency spectrum. The article examines theoretical foundations, experimental results, and practical considerations to evaluate the capabilities of resistive-capacitive dividers.

Results. It is shown that resistive-capacitive dividers present an alternative solution for accurately measuring voltage signals from direct current offsets to higher frequencies. Their extended frequency range and accuracy make them promising tools for addressing the complexities of power quality in modern energy systems. However, due to the influence of non-identity of resistive and capacitive elements, the measurement error of voltage divider can significantly increase, varying from – 0.64% to + 0.64%, according to the research performed.

Originality. The article provides an original contribution by offering a comprehensive overview of the capabilities and limitations of resistive-capacitive dividers. It highlights their potential impact on power quality analysis in the context of higher harmonics measurement. Therefore, it is necessary to pay attention to this issue.

Practical value. By identifying the advantages and challenges of resistive-capacitive dividers, this review offers practical insights for researchers and practitioners seeking accurate power quality assessment and harmonic analysis. The practical value lies in understanding the potential of resistive-capacitive dividers to enhance measurements in high voltage networks.

Conclusions. The review concludes that resistive-capacitive dividers hold promise as an innovative approach for measuring higher harmonics in the evolving power systems. It emphasizes the importance of addressing the non-identity of resistive and capacitive elements within the divider to improve measurement accuracy and reliability. By bridging the gap left by traditional instrument transformers, resistive-capacitive dividers offer a pathway towards enhanced power quality analysis and optimized network performance. References 18, figures 5.

Key words: resistive-capacitive voltage dividers, higher harmonics measurement, power quality analysis, harmonic distortion, modern power systems, magnetic core instrument transformers.

Problem statement. The landscape of power systems has witnessed a transformative shift in recent years, with an increasing reliance on renewable energy sources and advanced electronic technologies. This transition has prompted a critical need for accurate and reliable measurements of power quality parameters, particularly concerning higher harmonics in medium and high voltage networks. Traditional methods of measurement, including magnetic core instrument transformers, have encountered limitations when confronted with the demands of these modern power systems [1-3].

In response to these challenges, there has been a growing interest in exploring innovative measurement techniques that can effectively capture the intricate dynamics of power quality. Among these alternatives, the utilization of resistive-capacitive voltage dividers has emerged as a promising avenue for higher harmonics measurement [4, 5]. These measurement transducers offer a unique approach to accurately measuring voltage signals across a wide frequency spectrum, extending from direct current (DC) offsets to several megahertz [6].

This article presents a review of the application of resistive-capacitive voltage dividers for higher harmonics measurement in medium and high voltage networks. By delving into the principles, advantages, and challenges associated with resistive-capacitive dividers, this review aims to shed light on their suitability in addressing the evolving measurement needs of modern power systems. Through an examination of theoretical foundations, experimental results, and practical considerations, this article provides insights into the capabilities of resistive-capacitive dividers and their potential contributions to enhanced power quality analysis.

The subsequent sections of this review delve into the distinctive features of resistive-capacitive dividers, their behavior in capturing harmonic signals, the intricacies of their design, and the ways in which they can effectively address the measurement challenges posed by high-frequency components. Additionally, the review explores practical case studies, offering real-world examples that underscore the practicality and reliability of resistive-capacitive dividers in measuring higher harmonics.

By traversing the technical intricacies of resistive-capacitive voltage dividers, this review aims to contribute to the broader understanding of their utility and potential impact on power quality assessment. The exploration of their benefits, accuracy, linearity, and adaptability provides a foundational understanding that can guide researchers and practitioners in harnessing the advantages of resistive-capacitive dividers to meet the demands of the modern power systems. Ultimately, the comprehensive insights provided in this review illuminate the path toward effective utilization of resistive-capacitive dividers in the measurement of higher harmonics in medium and high voltage networks.

Material and results. The necessity of higher harmonics measurement in high voltage networks stems from the evolving landscape of power generation and consumption. As modern power systems incorporate a higher proportion of renewable energy sources, electronic devices, and complex loads, the harmonic content within the network has become increasingly significant. Higher harmonics, which are multiples of the fundamental frequency, can arise from nonlinear loads, such as variable frequency drives and electronic converters, as well as from intermittent renewable sources like wind and solar. These harmonics have the potential to cause a multitude of issues, including increased losses, reduced efficiency, overheating of equipment, and interference with sensitive electronic devices. To ensure the reliability, stability, and efficiency of high voltage networks, it is imperative to accurately measure and analyze the presence and magnitude of higher harmonics. By understanding the harmonic profile of the network, operators and engineers can implement targeted mitigation strategies, optimize system design, and ensure compliance with power quality standards. Therefore, higher harmonics measurement stands as a crucial diagnostic tool in safeguarding the integrity and performance of high voltage networks in the face of changing energy paradigms and complex load dynamics.

Traditional magnetic core instrument transformers have long been the cornerstone of voltage and current measurement in power systems. However, their application for higher harmonics measurement presents certain challenges. These transformers are designed primarily for accurate measurements within the fundamental frequency range and may exhibit limited frequency response beyond that range. The presence of a magnetic core introduces non-linearities that can distort the accurate representation of higher harmonic signals. Additionally, the inherent design characteristics of these transformers, optimized for standard power frequency operation, might not be conducive to effectively capturing the rapidly changing and often non-sinusoidal waveforms associated with higher harmonics. Despite these limitations, traditional magnetic core instrument transformers can provide a basic indication of the presence of higher harmonics within a network. They remain valuable tools for assessing power quality at fundamental frequencies and offering insights into broad trends in harmonic distortion [7]. However, for in-depth and precise higher harmonics analysis, alternative measurement techniques such as resistive-capacitive voltage dividers have gained attention due to their capability to accurately measure a wider frequency spectrum, thus bridging the gap left by the limitations of traditional instrument transformers.

Voltage dividers, spanning various types including resistive, capacitive, and mixed resistive-capacitive configurations, are increasingly regarded as expected alternatives to traditional magnetic core instrument transformers for the accurate measurement of higher harmonics in high voltage networks. As power systems evolve to incorporate renewable energy sources and sophisticated electronic devices, the need for precise harmonic analysis becomes paramount. Traditional magnetic core instrument transformers may exhibit limitations in capturing higher harmonic components due to their inherent design characteristics. In contrast, voltage dividers offer advantages such as extended frequency response, enabling them to accurately measure voltage signals across a wider frequency spectrum, from DC offsets to higher frequencies. Resistive-capacitive voltage dividers, in their basic form, do not inherently provide galvanic insulation between the input and output sides [8]. Like traditional resistive and capacitive voltage dividers, the resistive and capacitive components in an RC voltage divider are directly connected between the input and output terminals. While resistive-capacitive voltage dividers lack inherent galvanic insulation, their exceptional accuracy and ability to accommodate diverse frequency ranges position them as viable options for effectively assessing power quality, diagnosing harmonic distortion, and optimizing the performance of high voltage networks in the presence of non-linear loads and dynamic energy patterns.

In the following sections, authors will delve into a review of recent advancements and achievements in the realm of voltage dividers. This exploration will encompass the innovative research, technological developments, and practical applications that have propelled these devices as promising tools for higher harmonics measurement in high voltage networks.

Currently, research is ongoing on various designs of voltage dividers, including purely resistive ones. For example, the paper [9] presents a resistive voltage divider designed for high voltage networks, catering to accurate measurements of higher harmonics and voltage distortions at 400 kV. It also aids in assessing and correcting frequency characteristics in traditional measurement transformers.

Work [10] introduces a computational tool devised for the simulation and design of resistive voltage dividers. By employing a finite-element approach for precise calculation of divider stray capacitances, followed by a circuit solver technique founded on modified node potentials, the tool delivers frequency responses. The computational tool was successfully validated on an actual resistive voltage divider, yielding promising results in computational accuracy, with minor disparities found within a frequency range up to 10 kHz.

Voltage dividers for high-voltage direct current (HVDC) systems are traditionally based on a resistive design too [11, 12], whereas mixed resistive-capacitive concept typically applied in high-voltage alternating (HVAC) systems [13].

There are new publications devoted to research and development of resistive-capacitive voltage dividers. For example, article [14] addresses the crucial role of on-site transient voltage measurement in power system fault analysis and equipment insulation optimization. The limitations of conventional voltage transformers in capturing transient voltages are acknowledged. The paper presents a novel wideband parallel resistive–capacitive voltage divider, tailored for online monitoring of transient voltages in a 220 kV power grid. The divider's design, including high-voltage and low-voltage arm structures, is detailed. The study delves into the electric field distribution within the high-voltage arm and explores factors influencing the upper frequency limit. Through testing, the divider's performance is verified, with deviations in scale factors under various voltage waveforms and temperatures within 3%.

Recent works [15, 16] show that the non-identity of resistive and capacitive elements within the high-voltage arm of a voltage divider can influence both the amplitude-frequency and phase-frequency characteristics of the voltage divider. When the resistive and capacitive elements are not identical, it can introduce variations in the impedance and phase relationships within the divider circuit. These variations, in turn, affect the voltage division ratio at different frequencies, leading to changes in both the amplitude and phase response of the voltage divider as a function of frequency. Therefore, the non-identity of these elements can result in deviations from the ideal behavior of the voltage divider, affecting its overall performance and accuracy in measuring voltages at different frequencies.

In this article, an additional study was made of the influence of the non-identity of resistors and capacitors that make up the high-voltage arm on the frequency characteristics of a voltage divider. For this purpose, a circuit simulation of a resistive-capacitive voltage divider was performed, taking into account the spread of the parameters of its elements. The main circuit of the study is shown below in Fig. 1 (due to the large size, the equivalent circuit is shown partially). The voltage divider described in [6] was used for simulation. The Micro-Cap 12.2.0.2 circuit simulation software [17] designed for electronic circuit analysis and design was used for simulation.

To simulate 1.5 megaohms ±0.1% resistors' values varying within specified margins the following values were set "RESISTANCE=1.4985meg+3k*RNDC". In the same way, to simulate 1500 picofarads ±5% capacitors' values changing within specified margins the following values were set "CAPACITANCE=1425p+150p*RNDC". Here "RNDC" is the built-in function, that returns a new random value between 0 and 1 at the start of each new Monte Carlo analysis or stepping run [17].

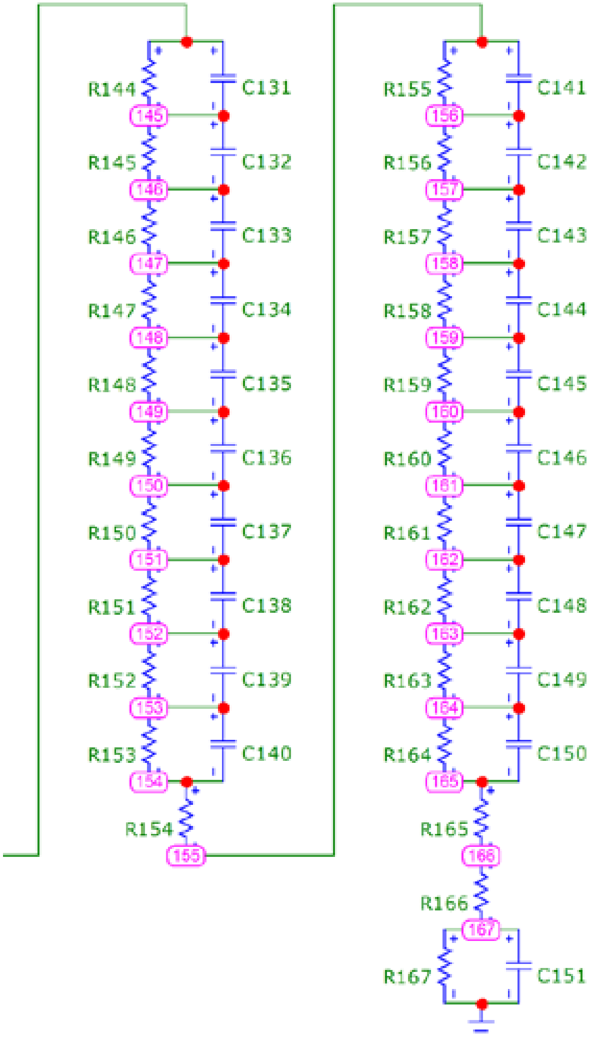

Fig. 1. Simulated resistive-capacitive voltage divider (model fragment, showing the connection of high-voltage and low-voltage arm of the divider in the node 166)

Frequency characteristics of simulated resistive capacitive voltage divider are shown in Fig. 2, demonstrating the amplitude-frequency characteristic and Fig. 3, displaying the phase-frequency characteristic variations.

The nominal division ratio of the simulated voltage divider is 10000:1. In the idealized case, when all resistors and capacitors of the high-voltage arm are considered the same, the ratio of the signal amplitude at the output of the voltage divider to the voltage amplitude at the input would differ by 10000 times, which corresponds to a –80 dB change in level. But in fact, due to the circumstance that the resistive and capacitance elements are not identical, the actual division factor can vary from 9936.88:1 to 10064.68:1, which corresponds to –79.945 dB to –80.056 dB change in level according to Fig. 2. These figures mean that ignoring the effect of non-identity of resistive and capacitive elements, the measurement error of the simulated voltage divider can reach ±0.64%. The above obtained graphs cover 100 variations of a voltage divider circuit in which the values of 150 resistors and 150 capacitors of high-voltage arm are varied.

The graphs in Fig. 4 demonstrate the operation of the simulated voltage divider when exposed to the distorted sinusoidal voltage waveform (30 higher harmonics in total).

The virtual higher-order harmonic generation was performed according to procedure given in [18]. Here and after input high-voltage waveform is shown in red, and output low-voltage signal is in blue. The Fig. 5 separately shows how the signal difference looks like, corresponding to the obtained measurement error of ±0.64%.

In summary, the utilization of broadband resistive-capacitive voltage dividers holds the potential to effectively measure harmonics across a wide frequency range. However, it is important to acknowledge that the accuracy of such measurements can be notably influenced by the non-identity of the resistive and capacitive components comprising the divider. As we reflect on the strides made in harnessing the capabilities of these dividers, it becomes evident that addressing and mitigating these non-idealities will be a key consideration for refining the precision and reliability of harmonic measurement techniques in medium and high voltage networks.

Conclusions. In light of the evolving landscape of power systems characterized by the integration of renewable energy sources and advanced electronic technologies, the demand for accurate power quality measurements has become paramount. Specifically, the assessment of higher harmonics in medium and high voltage networks has gained significance, as these harmonics can arise from nonlinear loads and intermittent renewable sources, potentially causing operational challenges and equipment degradation. Traditional magnetic core instrument transformers, while valuable for fundamental frequency measurements, face limitations in accurately capturing higher harmonics due to their design characteristics and frequency response constraints.

To address these challenges, resistive-capacitive voltage dividers have emerged as a promising alternative for higher harmonics measurement. This review has shed light on the principles, advantages, and challenges associated with resistive-capacitive dividers, showcasing their ability to measure

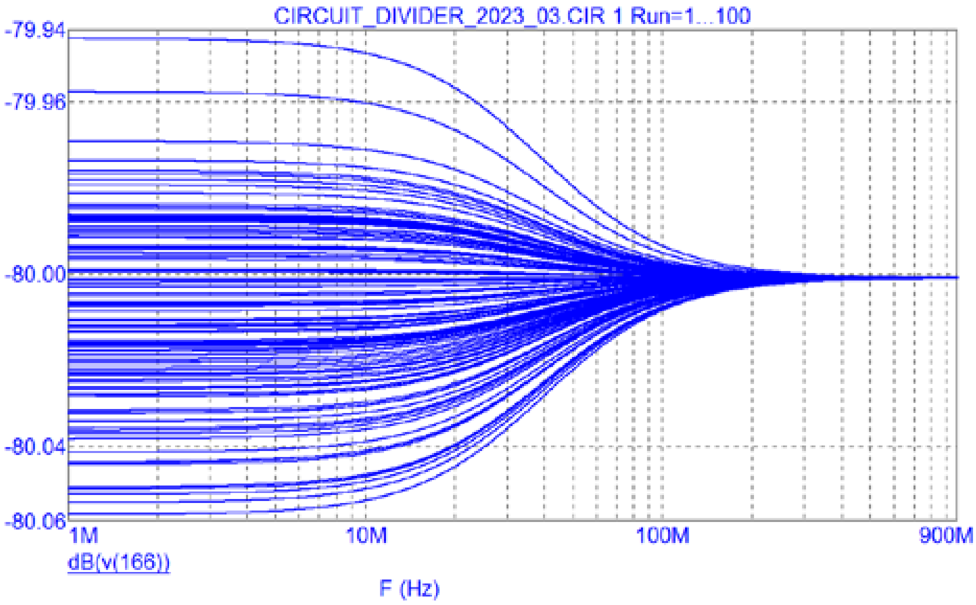

Fig. 2. Variations of amplitude-frequency characteristic due to non-identity of resistive and capacitive elements

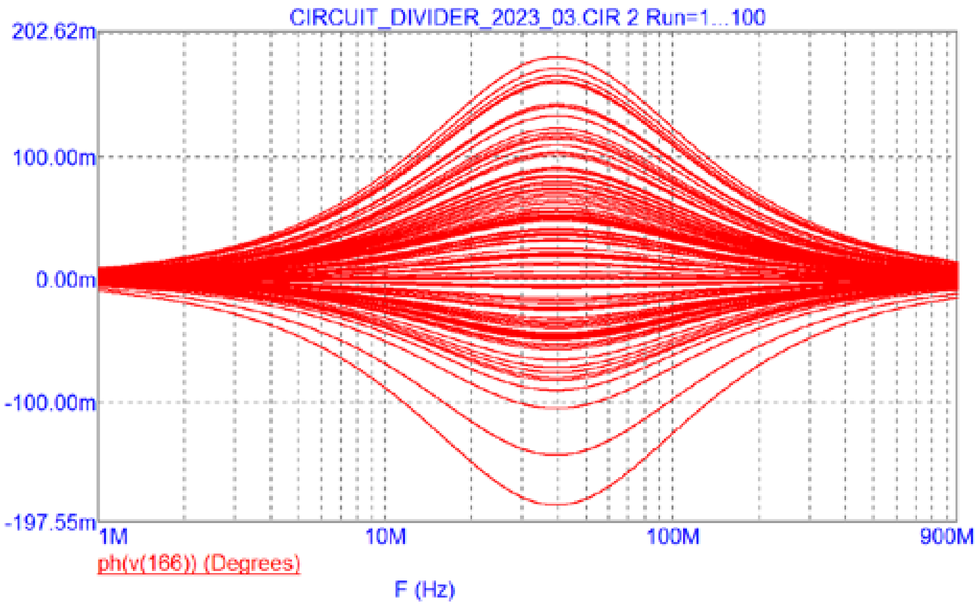

Fig. 3. Variations of phase-frequency characteristic also caused by non-identity of resistive and capacitive elements

voltage signals across a broad frequency range, from DC offsets to higher frequencies. Through the exploration of theoretical foundations, experimental results, and practical considerations, it has become evident that resistive-capacitive dividers offer a versatile solution to the evolving measurement needs of modern power systems.

While resistive-capacitive dividers hold promise for higher harmonics measurement, their accuracy can be influenced by the non-identity of resistive and capacitive elements within the divider. This non-identity introduces variations in impedance and phase relationships, impacting the amplitude and phase response of the divider at different frequencies. The importance of addressing these non-idealities cannot be overstated, as it forms a critical aspect of enhancing the precision and reliability of harmonic measurements.

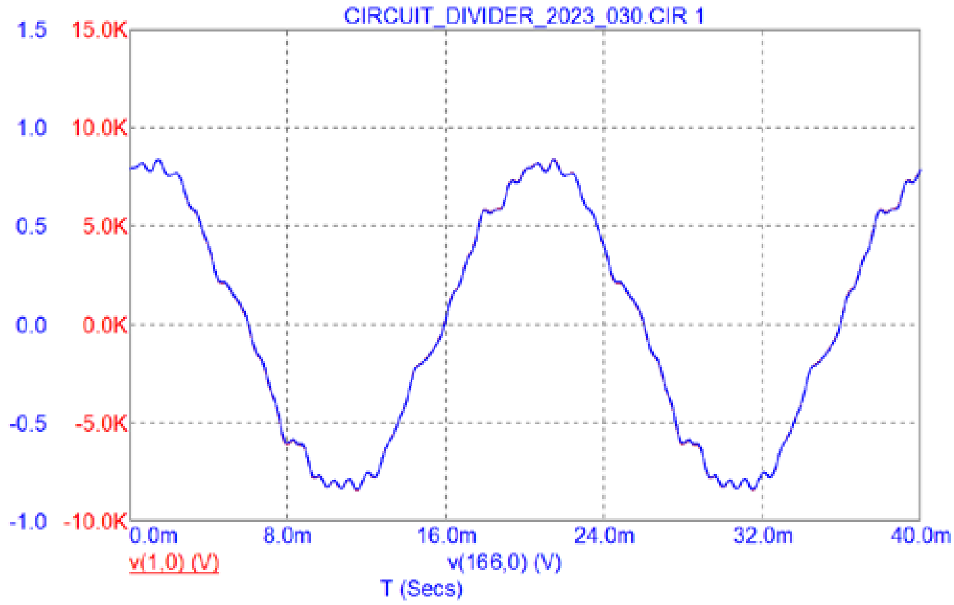

Fig. 4. An example of simulated voltage divider input and output voltage

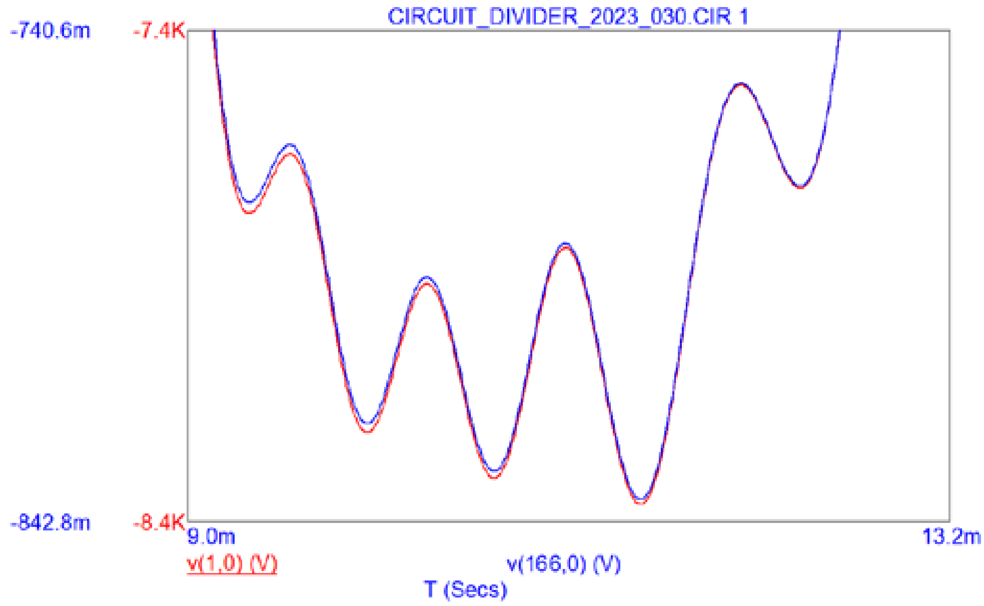

Fig. 5. An example of the difference between the output signal and the input voltage of a broadband resistive-capacitive voltage divider on an enlarged scale

In this pursuit, recent advancements have been made, as demonstrated by studies that have explored various designs and configurations of voltage dividers. Efforts to simulate and analyze the effects of non-identical elements within resistive-capacitive dividers have offered valuable insights into the intricacies of their behavior. However, ongoing research and development are necessary to fully understand and address the impact of non-identity on measurement accuracy, paving the way for improved harmonic analysis in high voltage networks.

As power systems continue to evolve, the comprehensive understanding of resistive-capacitive dividers and their potential applications can provide researchers and practitioners with valuable tools to enhance power quality assessment, diagnosis of harmonic distortion, and optimization of network performance. By addressing challenges and advancing the state of the art in harmonic measurement techniques, the integration of resistive-capacitive dividers holds the promise of fostering resilient and efficient power systems capable of meeting the demands of modern energy landscapes.

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ПРО ЗАСТОСУВАННЯ РЕЗИСТИВНО-ЄМНІСНИХ ДІЛЬНИКІВ НАПРУГИ ДЛЯ ВИМІРЮВАННЯ ВИЩИХ ГАРМОНІК: ОГЛЯД ДОСЛІДЖЕНЬ

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Стаття спрямована на огляд застосування резистивно-ємнісних дільників напруги для вимірювання вищих гармонік у мережах середньої та високої напруги. Мета полягає у дослідженні їхнього потенціалу як альтернативи традиційним вимірювальним трансформаторам із магнітним сердечником, що відповідає потребам сучасних вимірювальних систем, що постійно змінюються. В огляді розглядаються принципи, переваги та проблеми, пов'язані з резистивно-ємнісними дільниками, та пропонується розуміння їх придатності для уловлювання гармонійних сигналів у широкому діапазоні частот. Розглянуто теоретичні засади, експериментальні результати та практичні міркування щодо оцінки можливостей резистивно-ємнісних дільників. Показано, що резистивно-ємнісні дільники є альтернативним рішенням для точного вимірювання сигналів напруги – від напруги постійного струму до напруги високих частот. Їх розширений частотний діапазон і точність роблять їх перспективними інструментами для вирішення складних питань якості електроенергії в сучасних енергосистемах. Однак через вплив неідентичності резистивних і ємнісних елементів похибка вимірювання дільника напруги може значно збільшуватися, коливаючись від –0,64% до +0,64%, згідно з проведеними дослідженнями. Тому цьому питанню необхідно приділяти увагу. Визначаючи переваги та проблеми резистивно-ємнісних дільників, цей огляд пропонує практичну інформацію для дослідників і практиків, яким потрібні точна оцінка якості електроенергії та гармонічний аналіз. Практична цінність полягає у розумінні потенціалу резистивно-ємнісних дільників для поліпшення вимірювань у мережах високої напруги. Зроблено висновок, що резистивно-ємнісні дільники є перспективними як інноваційний підхід для вимірювання вищих гармонік у енергосистемах, що розвиваються. Це підкреслює важливість усунення неідентичності резистивних і ємнісних елементів у дільнику для підвищення точності вимірювань і надійності. Заповнюючи прогалину, залишену традиційними вимірювальними трансформаторами, резистивно-ємнісні дільники пропонують шлях до вдосконаленого аналізу якості електроенергії та оптимізації роботи мережі.

Ключові слова: резистивно-ємнісні дільники напруги, вимірювання вищих гармонік, аналіз якості електроенергії, гармонічні спотворення, сучасні енергосистеми, вимірювальні трансформатори з магнітним осердям.

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