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Towards a Traceable Calibration of Medium Voltage Transformers up to 150 kHz

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Abstract. The increasing integration of power electronics and renewable energy sources in modern electrical grids has introduced new challenges in medium voltage transformer calibration, particularly in the frequency range from 9 kHz to 150 kHz. Accurate and traceable calibration methods are essential to ensure reliable voltage measurement in electrical grids, where power quality and compliance with IEC 61869-1:2024 standards are critical. This study presents advancements in the development of traceable calibration techniques for medium voltage transformers operating within this frequency range. The approach includes the design of generators capable of simulating real world grid disturbances and the establishment of reference measurement systems at National Metrology Institutes. The study further explores generator configurations, such as parallel and series source arrangements, to extend calibration capabilities beyond existing limits. The proposed calibration methodology incorporates precision voltage dividers with high resolution, filtering and amplification techniques, and advanced data acquisition methods to achieve measurement uncertainties below 0.01% for fundamental components and between 0.2 % and 1 % for harmonic components. A key challenge is the ability to measure a fundamental voltage as high as 50 kV while superimposing harmonics with amplitudes as low as 5 V in the 9 kHz to 150 kHz range. These developments aim to enhance power system reliability, improve voltage measurement accuracy, and support the transition to more efficient and resilient electrical grids. The presented results lay the foundation for future calibration services.

1 Introduction

AC electrical power transmission and distribution systems have evolved significantly since the late 19th century to meet growing industrial and societal demands. Over the past two decades, however, substantial transformations have emerged, driven by advances in quantum and digital technologies. These advancements have facilitated the expansion of renewable energy sources, such as photovoltaic panels, wind turbines, fuel cells, and batteries, as well as energy storage solutions [1] [2]. Additionally, the increasing integration of power electronics in both conventional applications (e.g., lighting and power supplies) and emerging technologies (e.g., electric vehicles and decentralized energy production) has introduced significant disturbances within AC and DC networks, particularly in the frequency range up to 150 kHz [3].

Voltage transformers (VTs) play a critical role in power systems by converting voltage between their primary and secondary terminals while ensuring safe electrical isolation. These high precision devices are widely deployed in high (HV) and medium voltage (MV) networks, where accurate voltage measurement is essential for effective energy management. As smart grids continue to evolve, VTs must adapt to new power quality phenomena, making their characterization under realistic operating conditions increasingly necessary [4]. This characterization is crucial for managing their impact on grid performance, improving the reliability of energy systems, and ensuring compliance with updated power quality standards such as IEC 61869-1:2024 [5], which introduces new accuracy requirements for instrument transformers up to at least 150 kHz.

Despite these advancements, metrological challenges persist due to the absence of reference measurement systems, traceable calibration procedures, and validated experimental setups for precise voltage measurements in the 9 kHz–150 kHz range. While significant progress has been made for frequencies up to 9 kHz through the 19NRM05 IT4PQ project [6], further work is required for higher frequencies. To address this gap, a new project 22NRM06 ADMIT [7] has been launched with two primary objectives:

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The development of AC and DC voltage generators designed to simulate grid disturbances focuses on generating fundamental voltage components with amplitudes up to 36 kV for AC and 50 kV for DC. These generators will also superimpose frequency components in the 9 kHz to 150 kHz range, with amplitudes ranging from 5 V to 500 V.

Establishment of reference measurement systems at National Metrology Institutes (NMI) to provide traceability for voltage measuring instruments in the 9 kHz–150 kHz frequency range. This will enable the calibration of VTs with a 0.1% accuracy class. The target uncertainties are 0.01% for the fundamental component and between 0.2 % and 1 %, depending on the voltage level, for the 9 kHz–150 kHz components. For phase measurements, the target uncertainties are 0.01 crad for the fundamental component and between 0.2 crad and 1 crad for the 9 kHz–150 kHz components.

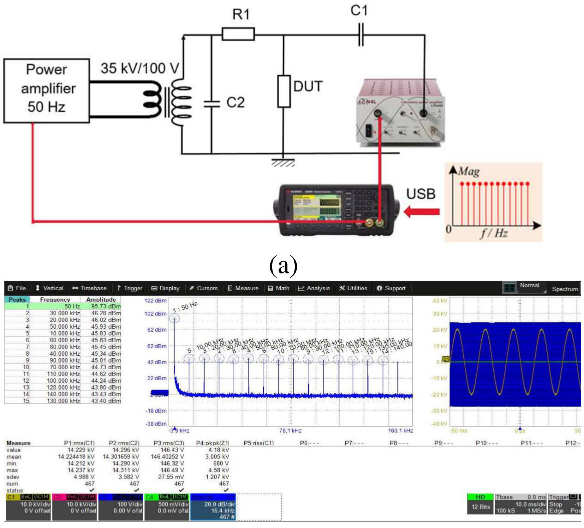
This paper presents the progress made toward achieving these two objectives, detailing the development of HV generators and the establishment of metrological infrastructures for precision voltage measurements in the targeted frequency range.

2 HV generators

To test VTs under real operating conditions, specifically, VTs that could be connected to the MV electrical grid and exposed to harmonics in the 9 kHz to 150 kHz range, it is crucial to develop generation techniques capable of producing disturbances that closely similar to those present on the grid. The facilities that generate voltage with controlled manner up to 150 kHz are very limited. Typically, the best NMI facilities do not go beyond 10 kHz. Similar results are noticeable on the market, where manufacturers of HV amplifiers propose systems that perform less than those at NMIs. Validated and stable generators remain an important tool, which is considered an essential part of the test circuit. Realistic AC and DC voltage with spectral content up to 150 kHz, must be identified for the characterisation of VTs . The project will make a major step by developing novel generation infrastructures allowing NMIs to offer new calibration services.

2.1 AC generator using two sources in parallel

This generator utilizes two grounded parallel generators to combine voltages through appropriate blocking elements and filters, as described in Figure 1. This technique has been commonly used in HV testing to superimpose impulses, such as lightning and switching impulses, onto AC or DC voltages, in accordance with IEC 60060-1 and IEC 60060-2 [8][9]. This technique has been successfully applied in the past for frequencies ranging from 4 kHz to 9 kHz [10], achieving a level of 1 kV in this frequency range, superimposed with 35 kV at 50 Hz. Based on these results, we have decided to further explore this approach to extend the frequency range up to 150 kHz.



(a)

Peaks	Frequency	Amplitude
1	50 Hz	95.73 dBm
2	30.000 kHz	46.28 dBm
3	20.000 kHz	46.02 dBm
4	50.000 kHz	45.93 dBm
5	10.000 kHz	45.83 dBm
6	60.000 kHz	45.83 dBm
7	80.000 kHz	45.45 dBm
8	40.000 kHz	45.34 dBm
9	90.000 kHz	45.01 dBm
10	70.000 kHz	44.73 dBm
11	110.000 kHz	44.62 dBm
12	100.000 kHz	44.24 dBm
13	120.000 kHz	43.80 dBm
14	140.000 kHz	43.43 dBm
15	130.000 kHz	43.40 dBm

Measure	P1:rms(C1)	P2:rms(C2)	P3:rms(C3)	P4:pkpk(Z1)	P5:rise(C1)
value	14.229 kV	14.296 kV	146.43 V	4.18 kV	
mean	14.224418 kV	14.301659 kV	146.40252 V	3.005 kV	
min	14.212 kV	14.290 kV	146.32 V	680 V	
max	14.237 kV	14.311 kV	146.49 V	4.58 kV	
sdev	4.988 V	3.582 V	27.55 mV	1.207 kV	
num	467	467	467	467	
status	✓	✓	✓	✓	

(b)

Fig. 1. The developed generator based on the use of two generators in parallel; a) design principle, b) example of the generation of 14 kV/50 Hz superimposed with multitoned harmonics from 10 kHz to 150 kHz with a step of 10 kHz.

The fundamental 50 Hz signal is generated by an voltage amplifier with a power rating of 6 kVA, capable of delivering voltages up to 120 V with a current of approximately 50 A. The output of this amplifier is stepped up from 100 V to 35 kV using a step up transformer with a power capacity of 5 kVA, which is necessary to supply the required energy to the components of the setup. The harmonic component is provided by an N4L LPA400 amplifier capable of delivering a voltage of 250 V rms with a maximum current of 50 mA. This amplifier can be replaced by a TREK PZD2000A amplifier, which can increase the voltage level to 500 V rms with a current of approximately 150 mA. Both amplifiers are controlled by an arbitrary voltage generator (AVG), which is itself controlled by software that allows for the desired frequency content. This can be a single harmonic or multiple harmonics simultaneously. Issues related to the phase of the signals are managed at the level of this AVG.

To ensure proper operation and protect each generator, two filters are included. A HV capacitor, C1, rated at 50 kV, is placed on the amplifier side. Together with the output impedance of the amplifier, it forms a high pass filter with a cut-off frequency in the range of several tens of kHz, ensuring that the 50 Hz component is sufficiently attenuated. Additionally, a resistor R1 and a capacitor C2 also rated at 50 kV, are used to protect the transformer from HF components. These elements form a low pass filter with a cut-off frequency in the range of tens of hertz, ensuring that HF components are significantly attenuated on the transformer side.

In Figure 1b, an example of the generation of 14 kV/50 Hz superimposed with multitoned harmonics from 10 kHz to 150 kHz with a step of 10 kHz. The FFT window lists frequency components with their respective amplitudes. The differences in harmonic levels are due to the frequency response of the HF amplifier, which is perfectly correctable. This generator operates correctly with voltage stability at 50 Hz better than 0.01% and better than 0.1% for harmonics up to 150 kHz.

2.2 AC generator using two sources in series

A variation of the generator discussed in the previous chapter consists of using both sources in series, Figure 2. A Step-Up Transformer (SUT) is fed by a Low-Frequency Amplifier (LFA) to generate the fundamental 50 Hz component at MV level. A High-Frequency Amplifier (HFA) is connected in series with the secondary winding of the transformer to generate harmonic components up to 150 kHz. The combination of LFA/SUT and HFA allows for the synthesis of a HV signal containing both the fundamental frequency (50 Hz) and HF harmonics. Two reference devices are used for measurement, one for fundamental tone (Low Frequency Reference Device, LFRD) and one for the HF tones (High Frequency Reference Device, HFRD).

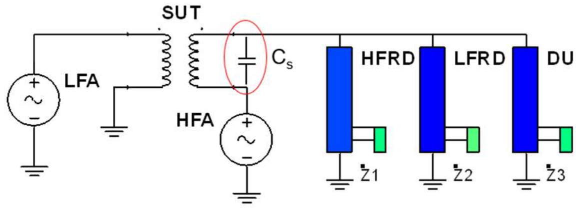


Fig. 2. The developed system based on the use of generators in series and its associated measuring systems

The arrangement of the generators is a critical consideration. If the HFA is positioned after the SUT at the HV point, it must be properly insulated to withstand the maximum voltage of the SUT. Achieving insulation for the HFA up to 35 kV requires powering all instrumentation with batteries, which presents significant challenges due to the intrinsic characteristics of the HFA. For this reason, we prefer the configuration shown in Figure 2, where the HFA is positioned before the SUT (low-voltage point), utilizing its natural insulation. In this setup, the HF current delivered by the HFA flows through the secondary winding of the SUT, which can lead to two potential issues. First, if the current flowing through the secondary winding exceeds its maximum allowable limit (typically a few tens of milliamperes at 35 kV), it may cause damage to the winding. Secondly, a significant amount of the generated high-frequency components willdrop in the secondary winding of the SUT. To mitigate this last effect, a capacitor Cs (typically in the nF range) is parallel-connected to the secondary windings of the SUT. However, this solution may significantly increase the power required for the LFA. The use of this capacitor, if correctly dimensioned, makes the portion of the HF current still flowing through the SUT negligible. Similarly, it is crucial to verify that the 50 Hz current flowing through the HFA via the ground return remains within its allowable limit.

2.3 AC generator using a step up transformer

This method consists of using a single voltage transformer to deliver both the 50 Hz frequency and harmonic frequencies up to 150 kHz, as shown in Figure 3. It is used to produce distorted voltages at MV using the simple circuit in figure compensating for the frequency behaviour of the generation setup components.

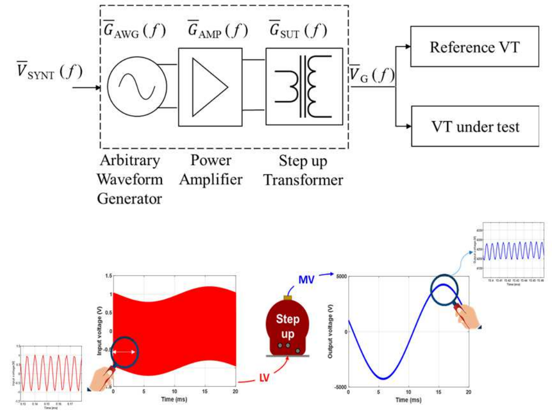


Fig. 3. Producing distorted voltages at MV using the simple circuit in figure compensating for the frequency behaviour of the generation setup components.

The arbitrary waveform generator produces a signal that includes the fundamental 50 Hz frequency along with its harmonics. It can be observed that the fundamental frequency has approximately the same amplitude as the harmonics. This signal is then amplified using a power amplifier to energize the step-up transformer, which boosts the voltage to meet the required test conditions while considering the frequency response of the transformer, which plays a crucial role in achieving the desired voltage levels accurately. Assuming that the transformer ratio at high frequencies is significantly lower than at the fundamental frequency, the fundamental component will be amplified more than the harmonics. As a result, the output of the transformer will deliver a high amplitude at fundamental frequency with harmonics at relatively lower levels. The compensating for the frequency behaviour of the generation setup components is performed. The amplified signal is then applied to the voltage transformer under test. A reference VT is used to compare the output and evaluate the performance of the transformer under test. Two key phenomena are considered in this setup. First, the frequency response of the transformer is sensitive to the load. To mitigate this effect, the frequency behaviour of the transformer must be characterized for each measurement campaign under the same conditions as its actual use. This characterization can be performed at low voltage using a frequency sweep method by using the same set up as that used in HV (figure 3). Second, the current flowing through the step-up transformer can increase significantly due to HF components, even if their amplitudes are limited. The rms current must be monitored to ensure it does not exceed its allowable limit due to the internal impedance of the transformer.

2.4 DC generator using two sources in series

The test system consists of two sources connected in series for DC generation, as illustrated in Figure 4. It comprises four key components: a HV direct current (HVDC) source, an arbitrary waveform generator (AWG) with a power amplifier, a HF voltage transformer (HFVT), and the DUT including the HV divider for measurement.

The HVDC source provides a stable 50 kV dc voltage with an adequate filtering mechanism to minimize harmonic distortion, ensuring that the primary voltage remains free from unwanted HF components that could interfere with the experiment. The arbitrary waveform generator, coupled with a power amplifier, generates the input signal containing harmonic frequencies up to 150 kHz. The power amplifier ensures that the signal meets the required test conditions, with a power requirement of approximately 1 kVA at 500V, a frequency range of 9 – 150 kHz, and an output voltage exceeding 50 V, allowing sufficient excitation of the HFVT.

The HFVT is a step-up HF transformer, designed to increase the applied voltage while maintaining a stable frequency response. Its key specifications include compliance with the same power and frequency as the power amplifier, a turn ratio of 10 to ensure effective voltage transformation up to 500 V, and insulation between primary and secondary windings up to 10 kV dc, preventing electrical breakdown under HV operation.

The DUT and the measurement system are used to measure the HV by comparison. The DUT is simulated using a capacitance of approximately 3.5 nF, ensuring that the system operates effectively for large capacitance values. The ground potential is set on the HVDC source side, with a sufficient blocking capacitor connected in parallel to the HVDC source to prevent HF currents from passing through. In this configuration, both the DUT and the reference measurement system can operate in a floating mode. Additionally, the voltage drop caused by the impedance of the secondary winding of the HF voltage transformer (HFVT) must be taken into account for accurate measurement.

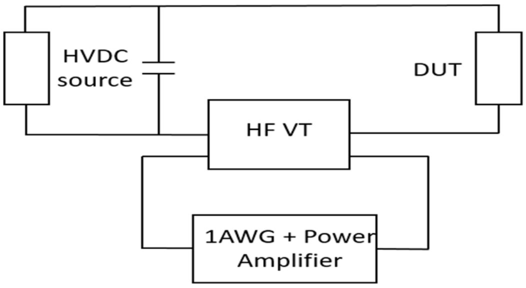


Fig. 4. The developed generator based on the use of two generators in parallel

The test results confirm the system's ability to superimpose a DC voltage with harmonic components across a frequency range of 9 kHz to 150 kHz, validating its suitability for HF applications. Additionally, the system successfully generates 500 V within the frequency range of ~75 kHz to 150 kHz, even under high-capacitance conditions, with the potential for higher voltage generation when capacitance is reduced. Furthermore, the system is capable of producing 1000 V within the 9 kHz to 75 kHz range, demonstrating its efficiency in voltage amplification at lower frequencies. These results highlight the system's effectiveness in handling both low- and HF voltage generation, with its performance influenced by capacitance and frequency-dependent characteristics.

3 Measuring systems

3.1 Specific challenges

The most commonly used method for measuring HVs exceeding 1000 V is the use of a high voltage divider. The HV is first divided using a HV divider, then transmitted via a coaxial cable to a digitizer capable of accurately measuring the transmitted voltage. The voltage divider, along with its digitizer, are essential components in ensuring the desired measurement uncertainty.

Regarding voltage dividers, two types are commonly used for measuring high DC or AC voltages at 50 Hz, superimposed with harmonics in the 9 kHz to 150 kHz frequency range. These are the RC mixed divider and the universal divider. The latter is similar to the RC divider but includes a small resistor in series with the capacitance, allowing fine-tuning of the frequency response at higher frequencies. Both dividers are highly effective for ensuring accurate HV measurements. Commercially available voltage dividers can achieve bandwidths extending up to several tens of MHz. Over the past three decades, NMIs have developed various dividers capable of measuring very HVs, with relatively wide bandwidths. However, these dividers are typically designed for DC, AC, or impulse voltage measurements and have never been specifically designed for applications where the fundamental frequency is superimposed with low amplitude of harmonics. The main challenge lies in measuring a 50 kVp (DC or AC/50 Hz) voltage superimposed with harmonics that can reach amplitudes as low as 5 V, corresponding to a dynamic range of 80 dB. Measuring such signal presents significant technical challenges due to the extreme dynamic range requirement. To achieve an accurate measurement of the 5 V harmonic up to 150 kHz with an uncertainty of 1%, a system sensitivity of at least 120 dB is required, which exceeds the capabilities of most conventional measurement systems. One of the primary challenges is the linearity and accuracy of voltage dividers, as even minor nonlinearity can introduce distortion or phase shifts in the measurement of HF harmonics. Furthermore, most analogue-to-digital converters (ADCs) have limited resolution when required to capture HF components up to 150 kHz. Typically, ADCs offer a dynamic range of around 100 dB, restricting their ability to accurately capture both the fundamental HV component and the low level harmonics simultaneously. Additionally, the ADC must meet several key requirements, including high bandwidth to minimize phase shift; High sampling frequency to correctly acquire the HF components and High dynamic range of at least 120 dB, which is extremely difficult to achieve with current technology. To overcome these technical constraints two solutions are proposed, the first one is to use a filtering and amplifying techniques. The second is to use a HV system with a very high sensitivity with a dynamic range of at least 120 dB.

3.2 HV system with enhanced supraharmonics sensitivity

A modular HV divider is designed to measure up to 60 kV DC, 42 kV AC_{rms}, and withstand 150 kV lightning impulse voltages. A schematic of the system is presented in Figure 5 and builds on the experience of an earlier design [11]. For future use in substations the divider to withstand 1.95 times the nominal phase voltage and if needed the HV modules can be stacked.

The voltage divider has two outputs, one for DC and AC fundamental components, and the other for harmonics measurement. The harmonics measurement branch incorporates a precision voltage divider, filtering, and amplification before data acquisition. Filtering is necessary to attenuate the fundamental component, while the amplifier enhances the signal for precise measurement using the data acquisition system.

The voltage divider, with a nominal scale factor (SF) of 15000, reduces the HV to measurable levels, lower than 2.0 V, 1.4 V, and 5.6 V for DC, AC, and impulse signals, respectively. It consists of HV/LV branches (720 MΩ/46 kΩ) and a capacitive branch for AC measurements from 0.5 Hz to 2.9 MHz (560 pF/6.9 µF) in series with damping resistors (120 Ω/0.01 Ω) which gives a bandwidth of 13 MHz (Figure 5).

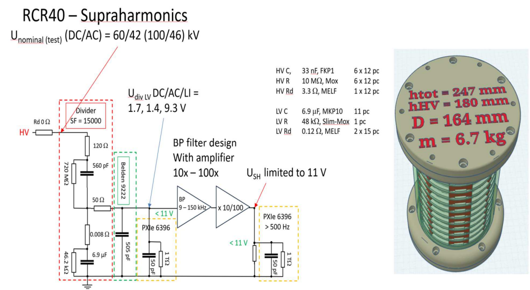


Fig. 5: Schematic and physical layout of the measurement system

For the divider, the components of both the LVand HV arms use the same type, value and batch of components to minimize the effects of voltage, frequency, and temperature variations. The raw output signal from the HV divider (DC – 13 MHz) is in parallel amplified in an active a band-pass filter (9–150 kHz) with selectable amplification factors of e.g., 10x - 100x to increase the sensitivity for supraharmonics signals. The raw and amplified signals are sampled simultaneously using a PXIe NI 6396 data acquisition board (8 differential simultaneously sampled channels, 18-bit resolution, ≤ 15 MS/s, 1 MHz bandwidth). The two channels per divider, one for DC to 150 kHz, and one for the filtered and amplified 9–150 kHz signal, gives an optimal dynamic range of about 120 dB. The measurement uncertainty is estimated to limit this to about 100 dB.

The physical construction of the divider is compact (165 mm diameter, 250 mm high, weighs 6.7 kg) and optimized for HF response and low signal distortion. The system ensures accurate HV measurements across a broad frequency range (DC–150 kHz), making it suitable for harmonic analysis and HV testing while addressing key challenges such as low noise, electromagnetic interference (EMI) immunity, and stable frequency response.

3.3 HV system with high sensitivity

The high sensitivity wideband system is based on a wideband divider [12] with 150 kV maximum peak input voltage. The divider can be used with or without an attenuator, and the total nominal scale factors are 200000 and 2000, respectively. The bandwidth extends from DC to 10 MHz. Voltages up to 500 V can be measured using the attenuator only. The divider and the schematic diagram showing the system component values is shown in Figure 6. All capacitors in the divider and in the attenuator are NP0 type surface mount components connected in series. Low TC type parallel resistors have been used. The wideband signal is then digitized using Applicos WFD20 data acquisition board [13] with 20-bit resolution, 2 MS/s maximum sampling rate, 2 MHz maximum bandwidth (-3 dB), and 108 dB spurious free dynamic range. The digitizer system has two simultaneously sampling channels. This allows calibration of both magnitude and phase errors of the measuring system connected in parallel with the reference divider. A waveform generator provides the sampling clock to the two digitizer boards. Sampling clock can either be tied with the source frequency or driven by software phase lock to ensure coherent sampling.

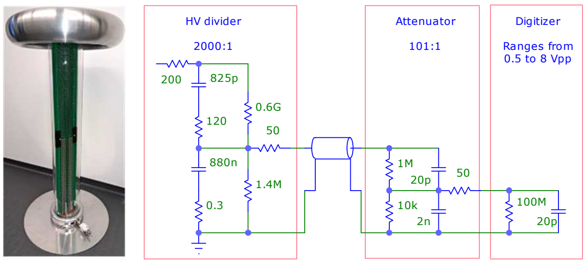


Fig. 6. The high sensitivity wideband measurement system. The high voltage divider on the left, and system schematic diagram on the right.

4 Conclusion

The traceable calibration of medium voltage transformers in the frequency range up to 150 kHz represents a crucial advancement in electrical metrology for modern power grids. This study demonstrated innovative approaches by developing both AC and DC generators capable of simulating realistic grid disturbances, effectively combining the fundamental voltage component with low-amplitude harmonics. By implementing reference measurement systems and high-sensitivity voltage dividers, the work achieved remarkably low measurement uncertainties (0.01% for the fundamental frequency and between 0.2% and 1% for harmonic components), even at voltage levels up to 50 kV. These advancements pave the way for enhanced characterization and calibration of transformers, thereby ensuring improved reliability in electrical systems and compliance with new standards such as IEC 61869-1:2024. Ultimately, the foundation laid by these developments supports the evolution toward smarter, more efficient, and resilient power grids that can better accommodate the growing integration of renewable energy sources and power electronic devices.

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