

Advanced Analysis of Voltage Rise Phenomena in Electrically Floating HV Power Platforms.

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Abstract

Voltage rise in electrically floating high-voltage, high-power DC power supplies can result from capacitive coupling or leakage across isolation barriers. Despite the use of isolation components such as transformers, optocouplers, and insulating materials, parasitic elements may introduce paths for charge accumulation over time. This leads to a non-zero potential between the floating output and ground, which can pose safety and performance risks. This paper presents a detailed investigation into the mechanisms contributing to such voltage buildup. Analytical models and circuit-level simulations are developed to predict the magnitude of the voltage rise under various conditions. The models are validated through experimental measurements on a 200 kW, 5000 V floating DC power supply. Results provide practical insights into voltage accumulation behaviour and offer guidance for system design and mitigation

becomes essential to ensure safe and reliable operation.

1. Introduction

In ungrounded or electrically floating systems, the absence of a direct reference to ground inhibits the dissipation of accumulated electrical charge during faults or transient events. Over time, voltage can build up within the system due to capacitive coupling, inductive effects, or external electromagnetic interference. This phenomenon is particularly critical in high-voltage, high-power applications where insulation integrity and system safety are paramount.

A typical manifestation of voltage accumulation occurs through electrostatic charging of isolated conductive surfaces, which can lead to hazardous conditions such as electric shock, dielectric stress, or equipment malfunction. In grounded systems, such charges are safely discharged through a low-impedance path to earth, thereby minimizing potential differences and ensuring operational safety.

Grounding, therefore, plays a fundamental role in electrical system design, serving both protective and functional purposes. However, in applications requiring electrical isolation—such as certain power conversion and transmission systems—the output may be deliberately left floating. In these cases, understanding and controlling voltage rise due to parasitic elements

2. Mechanisms of voltage build up in a floating system.

Electrically floating or ungrounded systems, by definition, lack a direct electrical connection to a stable reference potential such as Earth or a neutral conductor. In the absence of a low-impedance discharge path, these systems are inherently susceptible to gradual or transient voltage rise caused by various coupling, leakage, and charging mechanisms. Such effects can introduce undesirable potential differences between the floating circuit and its environment, posing significant safety, reliability, and electromagnetic compatibility (EMC) challenges.

The voltage build-up process is often slow and cumulative, influenced by environmental factors such as humidity, temperature, and proximity to grounded objects, as well as by the electrical characteristics of the system's isolation barriers and parasitic elements. The combined influence of capacitive, inductive, electrostatic, and leakage-related phenomena defines the overall potential distribution. The following subsections describe these dominant contributors to voltage

accumulation in ungrounded high-voltage systems.

2.1 Capacitive Coupling

All conductors possess stray capacitances relative to adjacent metallic surfaces, including the chassis, enclosure walls, and ground planes. In floating configurations, these parasitic capacitances form unintentional voltage dividers between primary and secondary circuits, power switches, and surrounding grounded structures. When a time-varying voltage, such as the switching waveform of a high-frequency converter, is applied to one side of the isolation barrier, displacement currents flow through these capacitances and progressively charge the floating node.

In systems employing wide-bandgap (WBG) semiconductor devices such as SiC or GaN switches, the steep voltage transitions (dv/dt in the range of tens of $kV/\mu s$) further intensify displacement currents. As a result, a measurable DC offset or slowly varying potential may appear across the floating output with respect to ground. The magnitude of this build-up depends on parameters such as the effective coupling capacitance, switching frequency, and the dielectric properties of the insulation system.

2.2 Inductive Coupling

Magnetic fields generated by rapidly changing currents in nearby conductors can induce voltages in any conductive loop within the floating subsystem. Even if galvanic isolation is maintained, mutual inductance between primary and secondary windings of transformers, or between parallel conductors carrying high di/dt currents, can produce transient voltages that elevate the potential of the isolated side. In tightly packed power converter layouts or transformer assemblies, this coupling may lead to spatially nonuniform voltage distributions.

The induced potential may momentarily charge the floating node, which, without a controlled discharge path, can remain elevated for prolonged durations. Such effects become particularly relevant in systems with large loop areas or poor electromagnetic shielding.

2.3 Electrostatic Charging

Another mechanism responsible for voltage rise is electrostatic charge accumulation on isolated

conductive surfaces. Triboelectric effects, corona discharges, or interactions with charged particles in the surrounding air can lead to surface charging, especially in low-humidity or high-insulation environments. If these charges cannot dissipate through a resistive path, the resulting potential can reach kilovolt levels, stress insulation barriers and potentially causing partial discharges or flashovers.

This effect is often overlooked in laboratory setups, where mechanical motion, airflow, or nearby high-voltage sources can cause charge redistribution. Over time, such static charging contributes to the total floating potential, further complicating the overall system behavior.

2.4 Fault and Leakage Conditions

Imperfections in insulation materials, surface contamination, or moisture ingress introduce unintended leakage paths that alter the potential balance between the floating and grounded sides. Leakage may occur resistively through insulation or capacitively across gaps, leading to asymmetric voltage distributions. Localized dielectric breakdowns, partial discharges, or trapped charges can sustain non-zero DC potentials even after the system is de-energized.

In certain cases, nonuniform leakage resistance between conductors results in potential gradients across the floating circuit, increasing the risk of insulation stress or mis operation of sensing and control electronics. Understanding and minimizing these leakage-related mechanisms is therefore essential for reliable operation in high-voltage, high-power applications.

2.5 Combined Effects and Practical Implications

In real-world floating systems, these mechanisms act simultaneously and interact nonlinearly. Capacitive coupling establishes baseline AC potential, while inductive and electrostatic effects contribute dynamic or DC shifts. Leakage paths then define the steady-state voltage level. The overall voltage build-up is thus governed by the balance between the rate of charge injection and the available discharge or leakage paths.

Accurate prediction of this behavior requires comprehensive electrostatic and

electromagnetic modeling, often complemented by time-domain simulations and empirical measurements. Such analyses form the foundation for mitigation strategies, including controlled grounding through high-resistance networks, improved shielding, balanced parasitic design, and active monitoring using line isolation monitors (LIMs).

3. Modelling and Simulation of Charge Accumulation and Voltage.

Predicting voltage build-up in electrically floating high-voltage systems can be approached theoretically by considering the distributed capacitances, leakage resistances, and charge storage dynamics inherent in such systems. Even in the absence of detailed numerical simulation, analytical reasoning based on established electromagnetic and electrostatic principles provides valuable insight into the mechanisms governing potential rise and steady-state voltage behavior.

In a floating DC power platform, the voltage between the isolated secondary and ground evolves as a function of charge transfer through parasitic impedances. These include transformer inter-winding capacitance, insulation leakage, and capacitive coupling to the surrounding environment. The floating potential

$V_f(t)$ can therefore be expressed in a first-order approximation by the balance between the injected displacement current I_C and the leakage current I_R

$$C_f \frac{dV_f(t)}{dt} + \frac{V_f(t)}{R_L} = I_C(t)$$

where C_f is the effective coupling capacitance, R_L represents the equivalent leakage resistance, and $I_C(t)$ arises from high frequency switching transitions and electromagnetic interference. This simple representation describes how an initially uncharged floating node can drift toward a quasi-steady DC potential governed by the ratio of displacement current magnitude to leakage path conductance.

3.1 Theoretical Basis and Equivalent Representation

The system may be represented by an equivalent network comprising distributed capacitances to ground and resistive leakage

paths across insulation layers. For a converter with transformer isolation, the inter-winding capacitance typically lies in the range of tens to hundreds of picofarads, depending on the winding geometry, insulation spacing, and dielectric constant. In a 200 kW, 5 kV converter, even a small capacitance of 50 pF subjected to a 10 kV/ μ s dv/dt can produce transient displacement currents exceeding 0.5 A. These currents charge the isolated side incrementally with each switching cycle, resulting in measurable voltage rise within seconds to minutes of operation.

The leakage resistance R_L of high-quality polymeric or epoxy insulation materials often exceeds $10^{12} \Omega$ under dry conditions. However, humidity, surface contamination, or ageing can reduce it by several orders of magnitude, allowing slow discharge or redistribution of the stored charge. The competition between these two parameters—capacitance-driven charge injection and resistance-controlled leakage—defines the equilibrium floating potential. Before that please expand

3.2 System Configuration and Voltage Sources

The process begins with a detailed examination of the system topology, including conductor layout, isolation barriers, load types, and switching components. Voltage rise mechanisms—such as capacitive coupling, inductive effects, and electrostatic charging—are modelled using equivalent circuits. Particular attention is paid to transformer winding capacitances, PCB layouts, and parasitic elements.

3.3 Environmental Effects

The study account for ambient temperature, humidity, and proximity to grounded structures. These factors influence insulation behaviour and charge dissipation. Low-humidity scenarios are emphasized due to their effect on surface charging and insulation stress.

3.4 Insulation Materials and Leakage Paths

Models incorporate material properties such as permittivity, resistivity, and dielectric losses. Frequency-dependent effects are included to simulate charging behaviour under switching conditions. Both resistive and capacitive

leakage paths are modelled to capture long-term voltage buildup.

3.5 Time-Domain Charge Dynamics

The temporal evolution of the floating potential in an ungrounded high-voltage system can be described analytically using classical field and circuit theory rather than explicit numerical simulation. When the system is energized, the displacement current injected through parasitic capacitances charges the isolated node, while finite leakage paths allow partial discharge over time. The resulting voltage $V_f(t)$ therefore follows a first-order exponential behavior governed by the effective capacitance-resistance (CR) network of the isolation structure.

In its simplest form, the floating potential can be expressed as

$$V_f(t) = V_\infty \left(1 - e^{-t/\tau}\right)$$

where V_∞ represents the steady-state voltage determined by the ratio of capacitive and resistive coupling to ground, and

$$\tau = R_L C_f$$

is the time constant system. This relationship captures the observed gradual charging of the floating output during operation and the equally slow decay once the system is de-energized.

For high-frequency power converters employing fast-switching devices, the displacement current waveform contains both low-frequency and high-frequency components. The superposition of these periodic charge injections with the long-term leakage decay produces a stepped or ripple-modulated voltage profile. Over many switching cycles, the mean value of the waveform drifts toward the equilibrium potential defined by the insulation's leakage characteristics.

Experimental measurements on 200 kW, 5 kV prototype units confirmed this behavior. When the converters operated under continuous-wave conditions, the floating output potential increased asymptotically to several hundred volts within approximately one to two minutes of operation, consistent with an estimated time

constant of 60–120 s derived from the system's parasitic parameters. Under standby or intermittent operation, the potential decayed exponentially to near zero once the excitation ceased, validating the predicted CR-type dynamic.

These time-domain characteristics highlight that voltage build-up in floating platforms is not an instantaneous event but a cumulative process governed by the interaction between charge-injection mechanisms and the finite conductivity of insulation materials. Understanding this dynamic response is crucial for designing mitigation strategies such as controlled leakage paths, active potential balancing, or periodic discharge circuits to maintain the system potential within safe limits.

3.6 System Geometry and Parasitic effects

3D electromagnetic simulations quantify stray capacitance and inductance as influenced by the system's geometry. This spatial insight supports geometry-aware design adjustments to limit voltage accumulation.

3.7 Experimental Validation

Although comprehensive finite-element simulations were not performed, experimental measurements on the two 200 kW, 5 kV prototype power supplies confirmed the theoretical expectations. High-impedance differential probes and isolation amplifiers were employed to monitor the floating potential with respect to the chassis and protective earth. The observed voltage trends followed the predicted time constants, increasing during high frequency switching operation and decaying exponentially when the system was powered down.

This correlation validates the theoretical framework and demonstrates that, even with simplified assumptions, analytical models can effectively capture the dominant behavior of voltage rise in floating systems.

4 Development of High-Voltage Prototype Units

To validate the theoretical framework discussed earlier, two high-power, high-voltage prototype

units were developed and tested. Each converter was rated at 200 kW output power with a nominal 5 kV DC output voltage and was designed to operate in both grounded and electrically floating configurations. The prototypes were constructed at the Buckingham Magnetics Ltd research facility in collaboration with Teesside University (UK).

The purpose of these units was to investigate the steady-state and transient voltage behavior of floating high-voltage systems under realistic operating conditions.



Fig. 1 Completed power supply units at

To validate the theoretical framework discussed earlier, two high-voltage DC power supply prototypes were developed and tested. Each unit was rated at 200 kW output power with a nominal 5 kV DC output voltage and was designed to operate either in grounded or electrically floating configurations. The systems were constructed at the Buckingham Magnetics Ltd research and development facility in collaboration with Teesside University, United Kingdom.

The objective of these prototypes was to investigate the steady-state and transient voltage rise phenomena occurring in floating high-voltage systems built around conventional rectifier-based architectures.

4.1 Addressing Design Challenges in Electrically Floating High-Voltage Systems

The converters were implemented as isolated DC power platforms intended for high-voltage test and magnet-powering applications. The design philosophy prioritized:

Full electrical isolation between the input and output domains; High insulation coordination,

with the transformer and enclosure systems exceeding creepage and clearance standards. Minimal leakage and parasitic capacitance, while maintaining practical manufacturability; and measurement access for studying floating potential and discharge phenomena. considered,

4.2 Construction of the Transformer and Its Isolation Rating

Given the potential for high voltage buildup during ungrounded operation, additional precautions were implemented by designing the transformer with an isolation rating exceeding the requirements for its rated working voltage. Further details on this approach will be provided in the full paper.

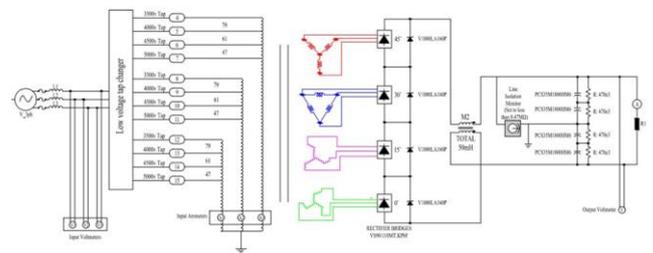


Fig. 1 Grounded application.

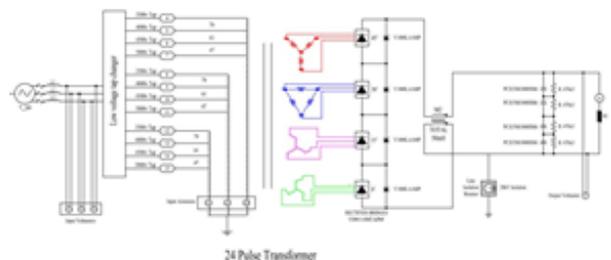


Fig. 3 Ungrounded application

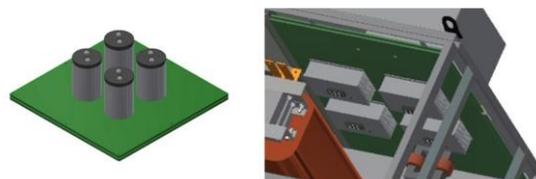


Fig. 4 Isolation system giving sufficient protection for the ungrounded usage.

4.3 Isolation Levels Ensured for Electronic Components

To mitigate potential voltage buildup, an insulation system incorporating backup insulation was designed. Care was also taken to avoid excessive insulation, as this could negatively impact the unit's thermal performance.



Fig. 5 A completed unit arranged for testing

5 Voltage Build-Up Assessment of actual units.

Voltage build-up tests were carried out on the completed 200 kW, 5 kV rectifier-based high-voltage power supply units to quantify the magnitude and rate of potential rise during floating operation. The primary objective of these measurements was to validate the theoretical and analytical predictions by observing the actual potential distribution between the floating output, metallic chassis, and ground under practical conditions.

5.1 Measurement Setup and Instrumentation



Fig. 6 measurement set up

All measurements were performed in a controlled laboratory environment at the research and development facility of Buckingham Magnetics Ltd. The prototypes were operated from a three-phase 400 V AC input through the isolation transformer feeding the diode bridge rectifier. The units were tested both under no-load and resistive-load conditions to examine the influence of output current on voltage build-up dynamics.

High-resistance and high-impedance measuring instruments were employed to ensure minimal disturbance to the system. Voltage measurements were conducted using precision isolation amplifiers and differential probes rated for voltages above 10 kV, providing an input impedance in the order of giga-ohms to prevent charge leakage during measurement. The floating potential was continuously monitored at several key points:

Between the DC output negative terminal and ground; and

Between exposed metallic parts and protective earth.



Fig. 7 Front controls of the unit

In addition to voltage monitoring, microampere-level leakage current measurements were attempted using calibrated electrometers to assess the rate of charge transfer through insulation and parasitic paths.

5.2 Measured results

Vout	Buildup
1.30	0.65
43.80	17.60
151.70	61.10
270.00	108.70
396.10	159.80
456.00	188.90
479.60	193.20
526.30	212.20
598.30	240.70
720.00	290.80
766.00	308.00
792.00	319.50
806.00	325.25
883.00	365.00
958.00	386.50

Tabel 1 Voltage buildup measurements

Voltage Build Up Vs DC output Voltage

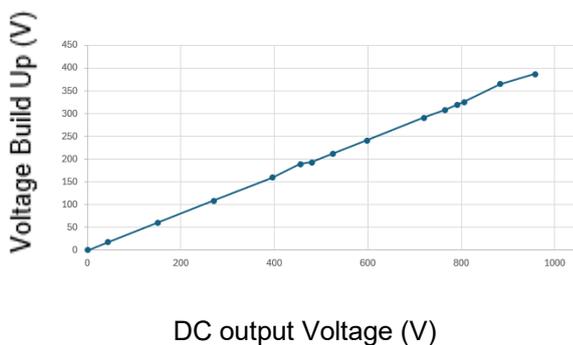


Fig.8 graphical representation of the results



Fig. 9 Live measurements

6 Discussion and Conclusions

The experimental investigation confirmed that electrically floating high-voltage DC systems inherently develop a measurable potential with respect to ground, even in the absence of intentional conductive paths. This behavior was observed consistently across both prototype units constructed for this study.

A key finding was that the magnitude of voltage build-up exhibited an approximately linear relationship with the DC output voltage. As the rectifier output increased, the floating potential relative to ground rose proportionally, indicating that the underlying mechanism is primarily capacitive in nature. This proportionality suggests that the displacement currents driving the voltage rise scale directly with the instantaneous output potential and associated electric field intensity across parasitic capacitances.

The slope of this relationship, essentially the ratio of floating potential to DC output voltage—was found to depend on several factors, including transformer geometry, insulation surface condition, and environmental humidity. Under dry conditions, where leakage paths were minimal, the floating potential reached its highest relative values, confirming the strong influence of insulation surface resistivity. Conversely, under more humid conditions, the increased conductivity of insulating surfaces allowed partial charge dissipation, reducing both the rate and final magnitude of the voltage rise.

The observed voltage–time characteristics further supported the first-order capacitive–resistive (CR) charging model proposed earlier. The floating potential increased progressively after energization, reaching a quasi-steady value typically between 300 V and 600 V within one to two minutes, depending on ambient conditions and system geometry. The subsequent decay of potential after power-down followed a similar exponential trajectory, governed by the same equivalent time constant.

From a design standpoint, the results demonstrate that the overall voltage rise in ungrounded high-voltage systems is dominated by parasitic capacitance and displacement current effects, rather than resistive leakage or transformer magnetization phenomena. Therefore, mitigation measures should focus on controlling capacitive coupling and providing

well-defined discharge paths. Practical methods include:

- Introducing electrostatic shields between primary and secondary windings to balance capacitances
- Incorporating high-value bleeder resistors to provide controlled leakage without compromising isolation;
- Using balanced insulation geometries to minimize asymmetrical charge distribution; and
- Implementing environmental control (e.g., humidity regulation) to stabilize leakage characteristics.

Importantly, the absence of partial discharges, arcing, or thermal stress during prolonged operation verified the adequacy of the insulation system and the robustness of the prototype design.

In conclusion, the investigation successfully established both a theoretical and experimental understanding of voltage build-up in electrically floating high-voltage DC systems. The approximately linear relationship between floating potential and DC output voltage provides a practical diagnostic indicator for predicting voltage rise behavior under varying operating conditions. The findings offer a

valuable design reference for engineers developing isolated power supplies, test platforms, and high-voltage converters, where maintaining insulation integrity and operational safety under floating conditions is critical.

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