IPMC

Assessing the Impact of Supraharmonic Phenomena on Distribution Transformers: Risks and Mitigation Strategies [By Steve Young MIET]

Introduction: The proliferation of renewable energy sources and devices such as photovoltaic (PV) systems, battery energy storage systems (BESS), electric vehicle chargers (EV) and active front-end variable speed drives (AFE) presents specific risks to the electrical grid. This necessitates improved understanding and due considerations from designers, engineers and asset owners/operators. While these technologies offer numerous benefits, they also introduce new challenges, particularly concerning the integrity and longevity of distribution transformers.

One of the critical issues arising from the integration of these technologies into the grid is the phenomenon of supraharmonic voltage and current. Supraharmonics, typically ranging from 2 kHz to 150 kHz, can have detrimental effects on distribution transformers, leading to untimely failure and the generation of excessive dissolved gases. This paper explores the risks associated with supraharmonic phenomena, drawing on recent research to highlight the severity and mechanisms of these impacts.

Understanding Supraharmonic Phenomena: Supraharmonics are high-frequency disturbances that predominantly exist above the traditional harmonic range. They originate from various power electronic devices commonly found in the aforementioned technologies. Traditional harmonic mitigation techniques typically target lower frequencies, leaving higher frequency supraharmonics unaddressed. This gap can lead to their propagation throughout the grid, affecting various equipment.

Impact on Distribution Transformers

Untimely Failure: Supraharmonics induce several stress factors on distribution transformers that can accelerate aging and lead to premature failure. One primary mechanism is the increased dielectric stress on transformer insulation. The high-frequency components can cause arcing and can lead to the development of partial discharges. Under certain conditions, the dielectric field strength can exceed the breakdown strength of the insulation leading to localised discharges. Partial discharges can be created and exacerbated by supraharmonic components.

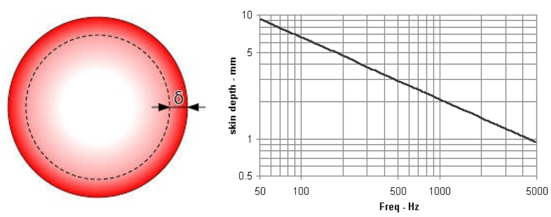

Figure 1: Skin Effect, Skin Depth vs Frequency

Furthermore, increased heating due to supraharmonic currents can give rise to both 'skin' (see Figure 1) and 'proximity effect', manifesting as localised hotspots within the transformer windings. These hotspots can degrade the insulation, further contributing to premature failure. Note, the Skin Depth at 5kHz is <1mm, which can be calculated.

Excessive Dissolved Gases: The presence of these supraharmonic manifestations can lead to the generation of excessive dissolved gases within the transformer insulating fluid. The primary gases of concern are hydrogen, methane, ethylene, and acetylene. These gases are typically produced through thermal and electrical faults within the transformer. Supraharmonics exacerbate these conditions by increasing thermal stress and promoting electrical discharges within the oil, accelerating the deterioration of oil and insulation materials.

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Mitigation Strategies: Addressing the risks posed by supraharmonics requires a multi-faceted approach involving both technology and operational practices. In recent years IPMC has been commissioned to investigate many such applications. Whilst more research in this relatively new field is paramount, we have become increasingly aware of a correlation between heavily loaded transformers, non-compliant levels of supraharmonics and excessive dissolved gases in the insulating oil, especially in embedded generation applications. By design, we have found that typical peak loadings of distribution transformers are in the range of 75% to 111% of the plate rating, with little evidence of due consideration for supraharmonic components. We have also noted a stark difference in the quality of the inverter voltage waveform, when comparing various manufacturer's products.

Filtering Techniques: Installing special high frequency passive filters in conjunction with other mitigation hardware at strategic points within the grid can significantly reduce the presence of supraharmonics. Passive filters, designed to target specific frequency ranges, can attenuate supraharmonics before they propagate further. Wave-clipping filters can also be used to complement passive filters, mitigating higher frequency components above the 9kHz range. In our experience, filters are under-utilised.

Transformer Design Improvements: Improving the design of distribution transformers to better withstand supraharmonic stresses is another viable strategy. This includes using reinforced, higher grade insulation materials that can endure the dielectric stresses. Also to design windings to minimise hotspot formation due to high-frequency currents. Thicker foils between windings, the insulating fluid type, improved cooling, and derated capacity should all be considered. Inherently, the responsibility for identifying these requirements falls to the electrical infrastructure designer, as they should have detailed knowledge of the connected plant and associated duty cycle.

Monitoring and Diagnostics: Implementing monitoring techniques and systems to periodically or continuously assess the health of distribution transformers can pre-empt failures. Dissolved gas analysis (DGA) and partial discharge monitoring (PD) are critical tools for detecting the early signs of supraharmonic-induced stress. By identifying issues early, utilities can perform maintenance or replacements before catastrophic failures occur. Supraharmonic assessments can be undertaken using specialist monitoring equipment and benchmarking the voltage disturbances against IEC 61000-2-2. In addition, the supraharmonic current emissions should be interrogated to determine the skin effect and any impact on the overall Harmonic Loss Factor (*F*HL). Figures 2 and 3 below are examples from a monitored application suffering from dissolved gasses.

Figure 2: 2-9kHz Voltage vs IEC 61000-2-2 Limits

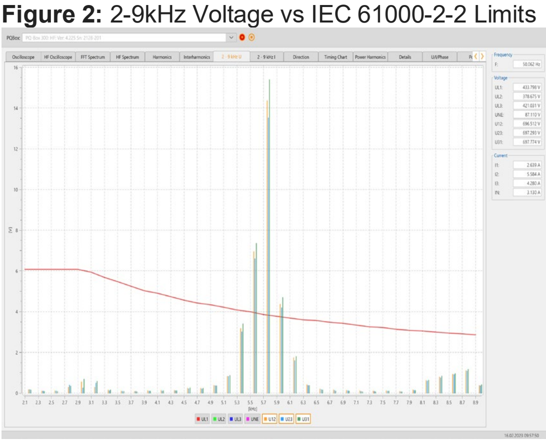
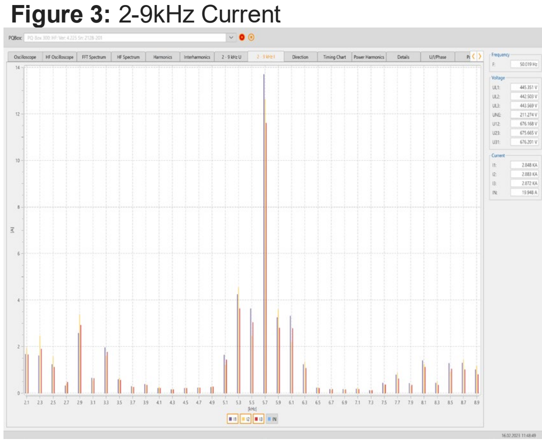


Figure 3: 2-9kHz Current



Note: Excessive supraharmonic voltages give rise to current distortion at the corresponding frequencies.

Other Causes of High Levels of Dissolved Gases: While supraharmonics can significantly contribute to the presence of dissolved gases in transformer oil, there are several other factors that can cause elevated levels of these gases. Whilst these factors fall outside of our area of expertise (IPMC), it would be remiss not to at least acknowledge the existence of environmental, chemical, and/or mechanical influences, as outlined further below.

Environmental Factors: Extreme environmental conditions such as high ambient temperatures, humidity, and contamination can accelerate the aging process of transformer insulation and oil, especially where the transformer has been inadequately specified. High temperatures can increase the rate of chemical reactions within the oil, leading to the production of gases such as hydrogen, methane, and ethylene. Similarly, high humidity can introduce moisture into the transformer oil, which can break down the cellulose insulation, producing carbon dioxide and carbon monoxide.

Figure 4: Dissolved Gasses Manifesting in the Insulating Fluid of a Distribution Transformer

Chemical Factors: Chemical reactions within the transformer oil, often exacerbated by contaminants, can lead to gas formation. Oxidation of the oil, for instance, can occur due to the presence of oxygen, leading to the generation of acids and gases. The degradation of the cellulose insulation due to acid formation can further accelerate gas production. Additionally, improper maintenance or the use of incompatible materials can introduce chemical impurities that catalyse the formation of dissolved gases.

Mechanical Factors: Mechanical stresses such as vibrations, shocks, and indeed overloads can cause physical damage to the transformer components. These stresses can lead to partial discharges and arcing, which generate gases such as acetylene and ethylene. Mechanical issues like poor connections and loose fittings can exacerbate these conditions by creating localised hotspots.

Case Study and Research Insights: The University of Queensland published a paper called ‘’Supraharmonics Transfer Characteristics of Transformer’’. The study involved extensive field measurements and laboratory experiments to quantify the effects of supraharmonics on transformer performance. The researchers found that transformers that were exposed to supraharmonics exhibited significantly higher levels of dissolved gases and showed signs of accelerated aging compared to those operating under traditional harmonic conditions. The study also highlighted the effectiveness of advanced filtering techniques and the importance of improved transformer designs in mitigating these impacts.

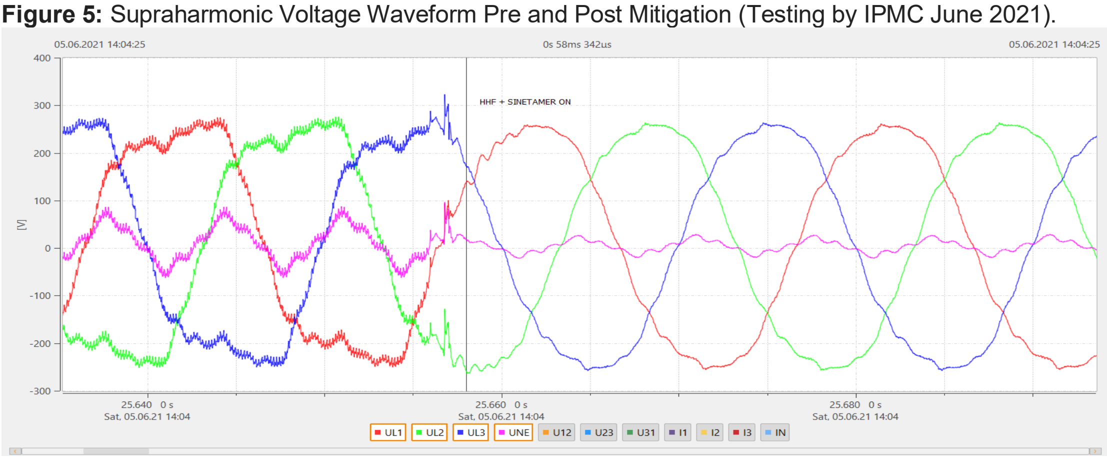
Another similar paper called ‘’Effects of Power System Harmonics on Distribution Transformer Insulation Performance’’ produced by Waterloo University of Canada provides further useful information pertaining to this phenomenon.

In Addition: Other studies, such as those by CIGRÉ (International Council on Large Electric Systems), have highlighted the role of environmental, chemical, and mechanical factors in the production of dissolved gases within transformers. These studies emphasise the need for comprehensive monitoring and maintenance strategies to address the various causes of gas formation and ensure the reliable operation of transformers.

Conclusion: The integration of PV, BESS, EV and AFE drives into the electrical grid presents unique challenges, particularly concerning the phenomenon of supraharmonics. These high-frequency disturbances can cause significant stress on distribution transformers, leading to untimely failures and the generation of excessive dissolved gases.

It is also important to acknowledge the detrimental and in some cases deleterious impact that supraharmonics can have on cabling, switchgear, controls, overload protection and even data acquisition, due to common-mode noise.

Figure 5: Supraharmonic Voltage Waveform Pre and Post Mitigation (Testing by IPMC June 2021).



Addressing these risks requires due consideration at design stage, including hardware selection, advanced filtering, improved transformer designs, and proactive monitoring. Due to the high switching frequency of the system inverters, existing harmonic standards such as ENA G5/5 may be considered as academic. The assessing Engineer must adopt more sophisticated instrumentation and modelling techniques in conjunction with appropriate benchmarking, such as IEC 61000-2-2.

Additionally, other factors such as environmental conditions, chemical reactions, and mechanical stresses can also contribute to the presence of dissolved gases, necessitating a holistic approach to transformer maintenance and monitoring. As the application of renewable energy systems, EV chargers and AFE drives continue to proliferate, understanding and mitigating the impacts of supraharmonics and other contributing factors will be crucial to ensuring the reliability and longevity of the electrical grid and associated hardware.