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Arc-Back Phenomenon in Variable Frequency Drives: Analysis and System Design Guidelines for Oil and Gas Applications

Dr. A. Nisar Basha, Ph.D (Power System), C.Eng, P.Eng, MIIT (Arb.)
Chartered Engineer | Professional Engineer | Technical Arbitrator

***Abstract*— Arc-back phenomena in large Variable Frequency Drives (VFDs) constitute a critical reliability and safety challenge in high-power industrial applications. This fault condition arises when rectifier diodes fail under reverse conduction, producing asymmetrical fault currents with significant DC components. Such abnormal currents impose severe thermal and electromechanical stresses on transformers, switchgear, and associated power system infrastructure, often exceeding the mechanical limits of conventional designs. In oil and gas operations, where large VFDs are extensively deployed for compressors, pumps, and drilling systems, arc-back events can lead to catastrophic equipment failure, prolonged downtime, and heightened arc-flash hazards. This research undertakes a systematic analysis of arc-back conditions through advanced power system modeling, transient simulation, and diagnostic methodologies to characterize their impact on system stability, reliability, and safety. Building on this analytical framework, the study further proposes practical mitigation measures—including rectifier monitoring, ultra-fast fault isolation, transformer mechanical reinforcement, and arc-resistant enclosure design—that can be adopted as industrial best practices to enhance resilience of large-scale drive systems**

Keywords— Arc-back, Rectifier Diode Failure, VFD, Transformer, Short Circuit current

I. INTRODUCTION

Medium-voltage (MV) variable frequency drives (VFDs) with input transformers have become a cornerstone in modern motor applications, enabling improved efficiency, controllability, and safety compliance. However, their long-term reliability is challenged by the phenomenon of arc-back, a destructive event that can compromise both the drive and the connected transformer. The issue is particularly critical when considering the mismatch in design life between the major system components. Input transformers are typically engineered for a service life of 30 years, whereas the power electronic devices such as diodes and rectifiers are generally rated for only 15 years. This disparity creates a significant reliability gap, as the probability of at least one arc-back incident occurring during the operational lifetime of the transformer is high.

Arc-back events not only threaten equipment integrity but also pose risks to operational continuity and safety etc. Despite advances in semiconductor technology and protective schemes, the mitigation of arc-back over extended lifecycles remains an unresolved challenge. Current literature often emphasizes short-term reliability and component-level protection, but there is limited focus on holistic strategies that address the full 30-year design horizon of MV VFD installations. This gap underscores the need for research into long-term resilience measures, including advanced protection schemes, predictive maintenance, and design methodologies that harmonize the lifespans of transformers and power electronic components.

The present study aims to investigate the mechanisms of arc-back in large MV VFD systems, quantify its probability over extended operational lifetimes, and propose design and protection strategies that ensure system reliability across the full-service life of the installation. By addressing this challenge, the research contributes to the development of more robust and sustainable MV drive systems for industrial applications.

II. UNDERSTANDING OF ARC BACK PHENOMENON

Arc-back faults in large VFDs generate asymmetrical currents with significant DC components, driving transformer cores into saturation and reducing reactance by ~30–40%. This collapse in impedance produces peak currents ~1.5× higher than three-phase bolted faults, with electromechanical stresses scaling to ~2.7 times. Waveform analysis demonstrates the destructive nature of arc-back events, underscoring the need for advanced diagnostic and mitigation strategies in industrial power systems.

Although transformer reactance X collapses under saturation during arc-back faults, the DC component increases because the asymmetrical conduction path injects a net DC bias into the system. The loss of inductive opposition allows this DC current to surge to very high initial magnitudes, producing peak currents ~1.5 times greater than symmetrical bolted faults

$$i(t) = I_{ac} \cdot \sin(\omega t + \phi) + I_{dc} \cdot e^{-\frac{t}{\tau}}$$

Iac: Symmetrical AC fault current.

Idc: DC offset magnitude (depends on point-on-wave at fault inception).

τ = L/R: time constant of DC decay

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In a three-phase bolted fault, the fault current is limited by the system impedance:

$$I_{\text{fault}} = \frac{V}{R + jX}$$

The transformer's reactance X provides inductive opposition, keeping currents symmetrical and balanced.

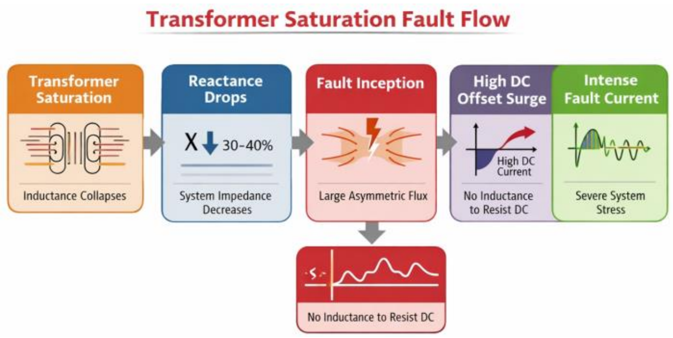
Any DC offset introduced at fault inception decays quickly because the inductance L (linked to X) resists sustained DC flow.

In the event of Arc-Back, when a rectifier diode in a Variable Frequency Drive fails short, the resulting conduction path becomes asymmetrical, introducing a net DC bias into the transformer windings. This DC bias shifts the magnetic operating point of the core, driving it into saturation. Under saturation, the transformer's effective inductance collapses, reducing reactance and thereby lowering system impedance. The loss of inductive opposition permits the DC component of fault current to rise sharply, producing extreme peak currents and severe electromechanical stresses compared to conventional symmetrical faults.

When a transformer enters saturation, its effective inductance L collapses. Since reactance is defined as X=ωL, this collapse results in a sharp reduction in reactance, typically in the range of 30–40%. The consequent drop in reactance lowers the overall system impedance Zs.

X is reduced by 40% → New X=0.6X and R remains unchanged.

At the instant of fault inception, flux asymmetry produces a substantial initial DC offset. The magnitude of this offset is directly proportional to the imbalance in flux linkage. Under normal operating conditions, the transformer's inductance provides opposition to DC current flow. However, once saturation occurs, inductance is effectively unavailable, removing this opposition. As a result, the DC component rises abruptly to a much higher initial value, intensifying the fault current and stressing the system



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III. BEHAVIOUR COMPARISON BETWEEN 3 PHASE BOLTED FAULT CURRENT AND ARC BACK FAULT CONDITION

To gain a deeper understanding of arc-back severity in medium-voltage drive systems, it is essential to conduct a comparative study against the well-established case of a three-phase bolted fault. While a bolted fault represents a symmetrical, high-current short circuit governed primarily by system impedance, an arc-back fault is characterized by asymmetry, transient behavior, and significant DC offset due to transformer saturation. Examining these two fault types side by side highlights the fundamental differences in current magnitude, waveform distortion, protection response, and long-term equipment stress. Such a comparison not only clarifies the unique challenges posed by arc-back events but also provides a framework for developing targeted mitigation strategies that extend beyond conventional fault protection schemes.

Table-1

Aspect	3 Phase Bolted Fault	Arc Back Fault
Nature of Fault	A solid, low-impedance short circuit between all three phases; symmetrical fault.	A transient reverse conduction or flashover from the DC link or converter to the transformer winding; asymmetrical and intermittent.
Fault Path	Metallic (bolted) connection with negligible resistance.	Ionized air or insulation breakdown path; high resistance and unstable.
Current Symmetry	Balanced across all three phases; purely AC component.	Highly asymmetrical; contains large DC offset and transient components.
Magnitude of Current	Extremely high, limited only by system impedance.	Moderate to high, depending on saturation and arc impedance; may cause localized stress.
Transformer Behavior	Core remains unsaturated; inductance limits DC component.	Core saturation occurs; inductance collapses, allowing DC surge.
System Impedance (Zs)	Determined by source and network impedance; stable.	Drops sharply (30–40%) due to inductance collapse.
Protection Response	Conventional overcurrent and differential protection operate effectively.	Protection may mis operate or delay due to DC offset and waveform distortion.
Thermal and Mechanical Stress	Uniform across windings and conductors.	Localized heating and dielectric stress near arc-back point.
Duration	Sustained until protection clears fault.	Typically, transient or intermittent; may recur under certain conditions.
Design Implication	Requires robust short-circuit withstand capability.	Requires arc-back mitigation design (snubbers, surge arresters, isolation schemes etc).

IV. CASE STUDY ON ARC BACK CONDITION

A case study was carried out using PSCAD simulation software to evaluate the arc-back phenomenon in a 36-pulse Variable Frequency Drive (VFD) system and to assess the mechanical forces acting on the transformer under such conditions.

The modelling configuration for this study comprised two 4.3 MVA four-winding transformers, collectively supplying an 8 MW VFD system.

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Arc-back Analysis PSCAD Model used for Case Study

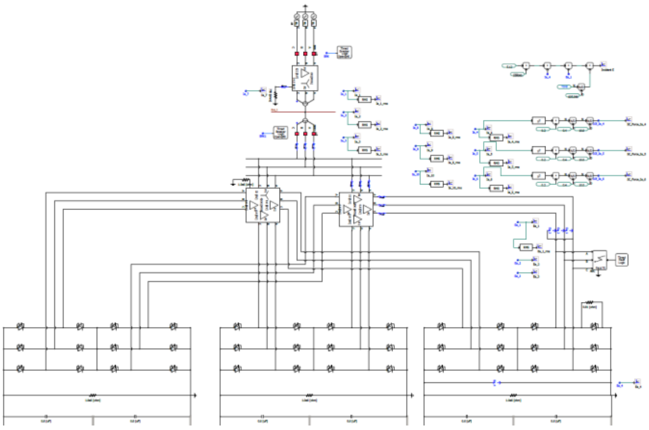

Figure-2

Results of the study concludes as below;

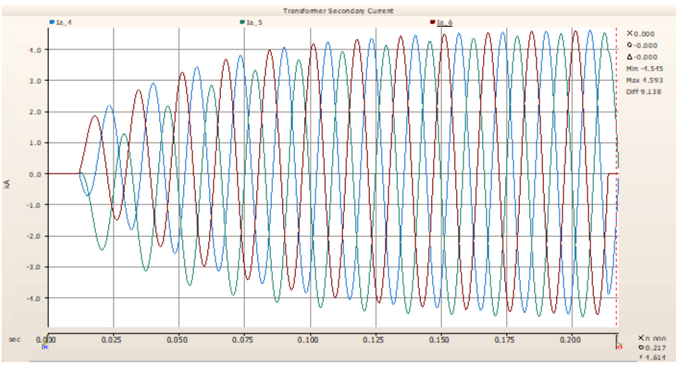

Figure -3 : Transformer Secondary Current under 3 Phase Fault

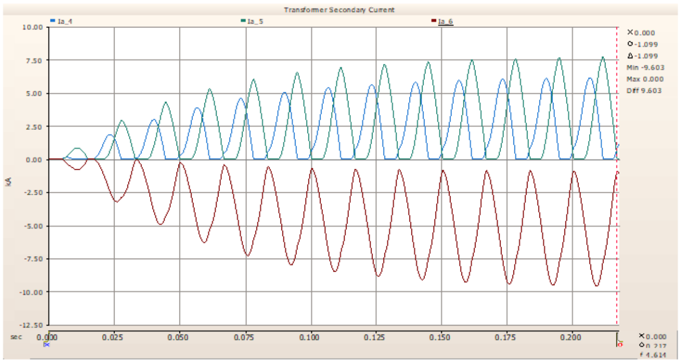

Figure -4 : Transformer Secondary Current under Arc Back

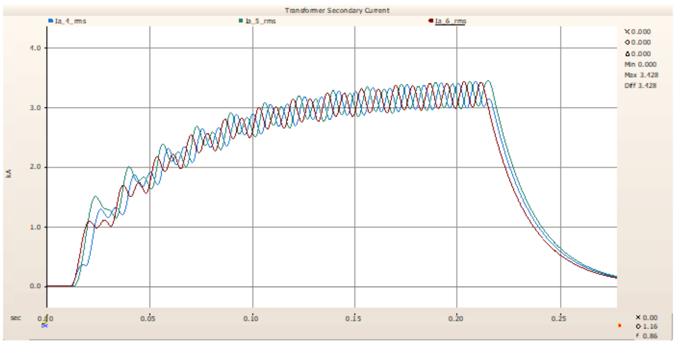

Figure -5 : Transformer Secondary Current under 3 Phase Fault (RMS)

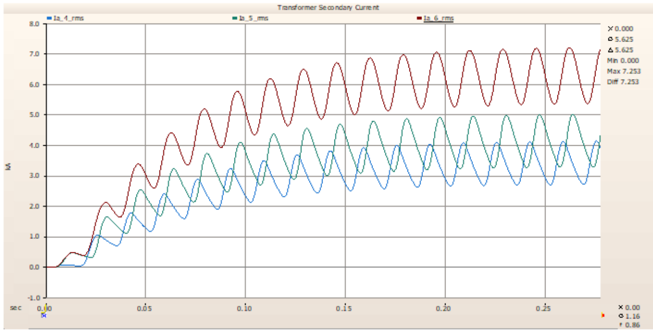

Figure -6 : Transformer Secondary Current under Arc Back (RMS)

Fault current in the event of Arc back in secondary side of the transformer is Approximately 1.6 - 2 times more than that of the three Phase Fault Current.

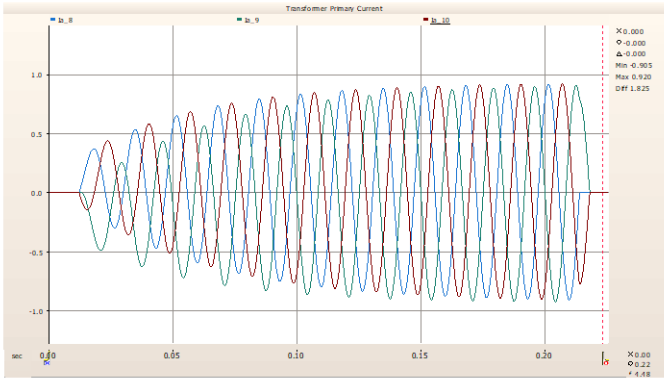

Figure -7 : Transformer Primary Current under 3 Phase Fault (RMS)

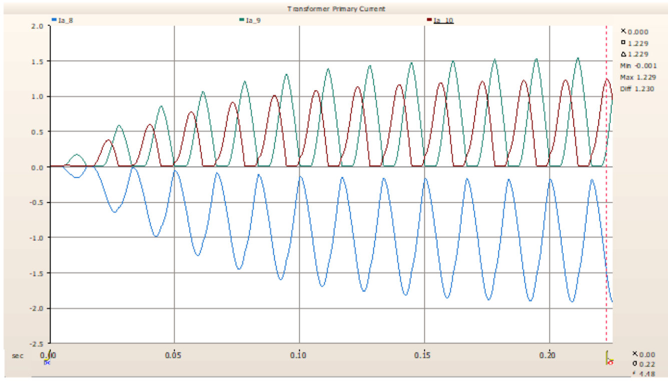

Figure -8 : Transformer Primary Current under Arc Back

Fault current in the event of Arc back in primary side of the transformer is Approximately 2 times more than than that of the three Phase Fault Current.

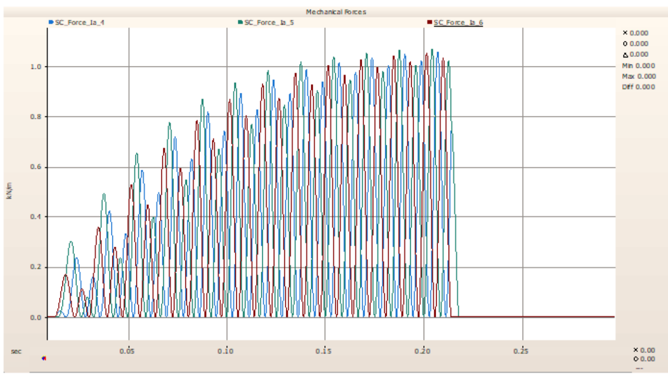

Figure -9 : Mechanical forces on the Transformer in 3 Phase Fault

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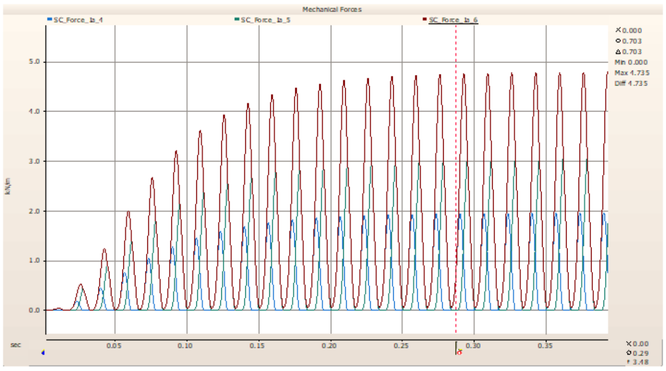

Figure -10 : Mechanical forces on the Transformer in Arc Back

Mechanical forces in the event of Arc back in transformer is Approximately 4-5 times more than than that of the three Phase Fault.

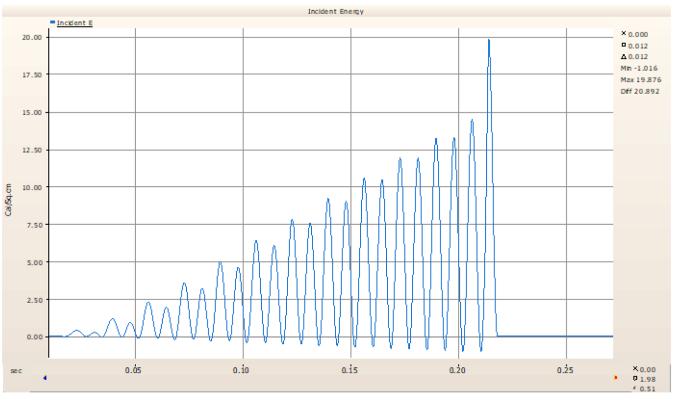

Figure -11 : Incident Energy in the system during 3 Phase Fault

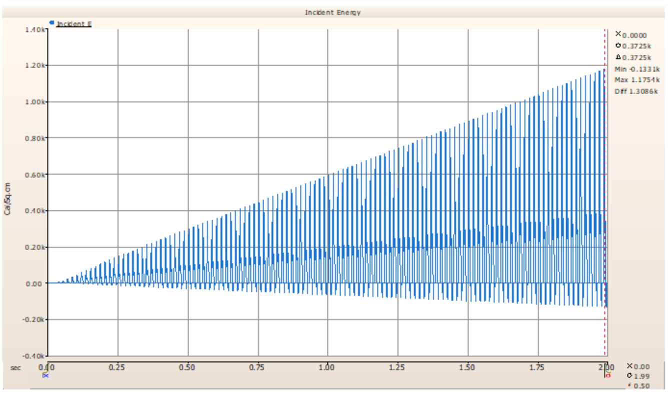

Figure -12 : Incident Energy in the system during Arc Back

Incident Energy in the event of Arc back in transformer is Approximately 50-60 times more than than that of the three Phase Fault.

CONCLUSION

The case study demonstrates that the impact of arc-back on VFD transformers is significantly high, primarily due to the severe mechanical forces acting on transformer windings. Such stresses can lead to catastrophic failures, including core deformation and winding damage, if not properly mitigated.
To ensure reliability and safety, these systems must be designed with primary and secondary protection principles.

Primary Protection:

VFD transformers shall be designed in accordance with:

- IEEE 551: Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems
- IEC 61378-1: Converter transformers – Part 1: Transformers for industrial applications
- IEC 61378-3: Converter transformers – Part 3: Application guide
- IEEE C57.110: Transformer Capability with Harmonics (Non-Sinusoidal) Loads
- IEEE C57.18.10: Standard Practices and Requirements for Semiconductor Power Rectifier Transformers
- IEEE Std 1566: Standard for Performance of Adjustable-Speed AC Drives Rated 375 kW and Larger
- IEC 61800: Standard series covering variable speed drives (VSDs / VFDs)

Furthermore, transformers must be capable of withstanding the maximum arc-back current as calculated per IEEE 551 (Section 8.7). Mechanical reinforcement of transformer windings and structural components is mandatory, based on detailed Arc Back Analysis conducted using PSCAD or equivalent simulation tools to derive peak fault current and mechanical forces.

Secondary Protection:

Rectifier Monitoring System (RMS): Early detection of diode failure, automatic tripping, and blocking of restart attempts during plant operation.

Fast Isolation: For Current Source Inverters (CSI) and Load Commutated Inverters (LCI), *fast isolation* is mandatory to mitigate severe fault conditions. While fuses are generally recommended, any space constraints within substation or any Offshore constains must be carefully reviewed. In such cases, ultra-fast earthing switches may be employed as a backup measure to reduce arc-flash incident energy.

Many OEMs advocate the use of differential protection schemes to ensure rapid isolation of transformer faults. However, protection actions exceeding 10–15 ms are typically ineffective. Practical limitations such as CT errors,saturation due to high arc-back current, relay inaccuracies, and inherent delays etc. often compromise the effectiveness of differential protection, potentially resulting in severe transformer damage. Therefore, without the implementation of the aforementioned primary protection measures, reliance on differential protection alone is insufficient. If differential protection must be adopted due to substation space constraints, then:

- The CT error margin and relay accuracy must be thoroughly analyzed.
- The overall trip time must be evaluated in detail.
- The transformer must be mechanically reinforced and designed to withstand at least the equivalent mechanical forces corresponding to the practical trip time, rather than the absolute highest mechanical

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forces. This approach accounts for the practical limitations in transformer manufacturing and the constraints of physical accommodation within the available substation space mainly in offshore projects.

Thyristor Valve Protection: Incorporation of metal oxide surge arrestors across individual thyristor arms in Voltage Source Inverters (VSI). Although arc-back is practically eliminated in VSI, surge arrestors are recommended to mitigate overvoltage and switching stress.

Arc-Resistant Enclosures: Drives should be installed within arc-resistant enclosures to safeguard both personnel and equipment. When conducting an arc-flash analysis for such systems, special attention is required because most modern software tools calculate incident energy based on fault current, rather than arc-back current. Since IEEE 1584 does not explicitly account for arc-back current, the responsibility falls on the power system engineer to apply sound engineering judgment in order to derive solutions that maintain safety without compromise.

It is anticipated that future international standards will address these limitations in greater detail, providing more comprehensive guidance for systems where arc-back phenomena are significant.

Although real-world system resistances and impedances may reduce fault stresses compared to the idealized conditions assumed in the IEEE 551 model, the residual risk remains significant. Consequently, the adoption of combinational mitigation strategies integrating both primary and secondary protection schemes is strongly recommended. Such an approach, supported by sound engineering judgment, is essential to ensure the reliable and safe operation of medium-voltage Variable Frequency Drive (MV VFD) systems.

REFERENCE

- IEEE 551: Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems
- IEEE C57.18.10: Standard Practices and Requirements
  for Semiconductor Power Rectifier Transformers
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