Optimization Strategies for Enhancing Performance and Reliability of MV Switchgear

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Abstract - *Medium-voltage (MV) switchgear is an essential component of today's electrical power distribution networks; however, the increasing loads, reduced dimensions, and environmental constraints have made it harder to guarantee its reliability, safety, and thermo-electrical efficiency. Thanks to the recent progress in Multiphysics simulations (electromagnetic, thermal, fluid, and mechanical analysis), significant improvements in the design process have been achieved. The current paper provides a thorough survey of state-of-the-art studies related to Multiphysics analysis and optimization of medium-voltage switchgear devices. Such aspects as electro-thermal interaction, heat generation calculation, insulation characteristics (SF6 alternatives), condition monitoring, reliability evaluation, and digitalization trends are discussed. The case study describes how using CFD inputs along with machine learning algorithms can help reveal key factors influencing the temperature distribution such as material properties, busbar arrangement, and air flows. Other advancementsindigitalization of switchgears, environmentally sustainable insulation gases, thermal optimization methods, and reliability assessment of MV and GIS switches are presented. This review reveals promising research directions in combining Multiphysics modeling, explainable machine learning, and experimental validation.*

Key Words: **Medium-voltage switchgear, Multiphysics simulation, Electro-thermal analysis, SF_6 alternatives, Condition monitoring, Busbar geometry.**

1. INTRODUCTION

Medium Voltage (MV) switchgear is a crucial part of the electrical power system infrastructure that deals with the switching, protection, and control of electrical networks. The demand for compact substations with a higher current rating and better reliability has created a substantial amount of thermal, electrical, and mechanical stress on the modern switchgear system. Of these, the rise in the temperature of the current-carrying parts along with contacts is well identified today as one of the principal causes of aging of the insulation materials [1]. Conventional methods of designing switchgear basically depend on intuitive calculations using equations, tolerance specifications according to standards, and simplified analytical calculations. While these approaches guarantee acceptable performance, they are, in general, insufficient for the correct calculations of localized heating effects or the internal complexities of electromagnetic losses, heat flow, or air flow movements within the switchgear compartment, for instance, for the detection of inefficient thermal spots or the emergence of hotspots, as pointed out in [2]. In order to overcome the mentioned challenges, the analysis method of Multiphysics field coupling has proven to be useful for the assessment and optimization of switchgears. The Multiphysics simulation is capable of simulating the electrical, thermal, and fluid dynamic phenomena, and hence it helps the simulation to estimate the temperature distribution and loss issues for the switchgears [3], [5]. The simulation has been effectively carried out on high voltage as well as medium-voltage switchgears [6]. Apart from simulation studies, reliability and stability analyses have gained significance due to the growing complexities in power systems. Probabilistic and reliability analyses have been used to assess operational risks, modes of failure, and system stability which are related to switchgear layouts [7], [8]. These references are special since they stress the significance of sophisticated monitoring and prediction methods for safe and uninterruptible operation.

Recently, there have also been approaches concentrating on the study of switchgear operating under abnormal or faulty conditions, where thermal stress becomes increasingly serious. Numerical simulations and experimental results have proved that temperature increase due to a faulty condition can accelerate the degradation of contacts and insulation failure unless it is handled properly [9]. Therefore, condition monitoring methods relying on temperature increase factors/indicators and thermal signs have also emerged to identify the early deterioration of connections of switchgears [10], [11]. Although considerable advancements have been made in Multiphysics simulation using CFD, most of the existing conventional data-driven models, which could be applied for thermal prediction, were not interpretable from a physical standpoint. To resolve this, new research has emerged utilizing interpretable machine learning frameworks, which integrated Multiphysics simulation using CFD with AI, allowing for accurate and interpretable prediction of temperature rise [1]. As far as the problems mentioned, this review paper gives an overall description of the modern developments in the simulation, thermal analysis, and insulation studies, as well as the reliability assessment of the MV switch gear. As a case study, this paper chooses the use of the interpretable machine learning-assisted Multiphysics CFD model introduced in [1] and synthesizes research trends, challenges, and future directions for the development of switchgear systems that are reliable, thermally efficient, and intelligent.

2. LITERATURE REVIEW

In order to comprehend the coupled mechanical, electrical, and thermal behaviours of switchgear, Multiphysics simulations have become essential. Matin et al. (2025) emphasized the importance of multi-physics modelling in operational reliability by developing an interpretable machine learning model in conjunction with CFD analysis to forecast temperature rise in medium-voltage switchgear [1]. Similar to this, Du et al. (2025) investigated Multiphysics coupling and structure optimization in flux-switching permanent magnet linear motors, which has implications for switchgear design in situations where electromagnetic-thermal coupling is important [2]. The significance of integrating various physical domains for performance enhancement was highlighted by Hou et al. (2024) and Zhang et al. (2024), who demonstrated simulation-based multi-physical field analysis to optimize thermal management in high-voltage switchgear [5,6]. The viability of computational design in predicting localized heating and stress points was confirmed by Huang et al. (2023) and Zheng et al. (2023), who also used COMSOL and other multi-physics simulation tools to study small switchgear thermal behaviour [13,15]. All of these studies show that multi-physics simulation is crucial for switchgear system design optimization and reliability evaluation.

One important factor influencing insulation deterioration and operational life in switchgear components is temperature rise. Significant hotspots in busbars and connections were found when Yang et al. (2024) examined temperature rise characteristics under fault conditions [9]. In order to provide a predictive maintenance framework, Kejani et al. (2024) suggested monitoring methods for medium-voltage switchgear connections based on temperature rise indices [10,11]. Experimental research on electrical disruption by Vega et al. (2024) demonstrated the importance of precise thermal modelling in averting failures [12]. Other studies, like Seker et al. (2023) and Wu et al. (2022), validated simulation models for real-world applications by benchmarking numerical simulations with experimental data for medium-voltage switchgear, demonstrating a strong correlation [14,24]. Switchgear research continues to prioritize insulation performance. In order to help design high-voltage applications with optimal insulation, Bharanidharan et al. (2025) used FEM to simulate the dielectric behaviour of SF6 and N2 [3]. With a focus on multi-physics coupling in environmental conditions, Xiaohan et al. (2021) investigated the relationship betweeinsulation performance and humidity [27]. Gao (2022) examined environmentally friendly gas mixtures, emphasizing problems with material compatibility in MV switchgear [25]. Reliability analysis and monitoring of switching apparatuses play an essential role in ensuring operational safety. A study conducted by Pranjic and Virtic in 2024 explored operational reliability through Monte Carlo simulation for different types of substations [7]. The application of switchgear and protection for ensuring power system stability was emphasized by Shukla and Zadokar in 2024 [8]. A study conducted by Kastelan et al. in 2022 discussed digitalization in switchgear, including progress in condition monitoring and predictive maintenance techniques [20]. Massaoudi et al. in 2020, and Miljanovic et al. in 2022, 2023, proposed partial discharge localization through UHF and HFCT methods, underscoring the need for signal processing and machine learning integration for assessment [23, 30]. Mechanical and structural design of switchgear is equally important for reliability concerns, especially under fault currents and environmental stresses. Shah et al. (2022) conducted the structural and modal analysis of composite material-based GIS structures for seismic applications [21]. Weiwei et al. (2023) investigated environmental design modifications, which could ensure robustness in different climatic conditions [19].

3. RESEARCH GAPS AND FUTURE DIRECTIONS

- Lack of fully united electro-thermal-structural-fluid coupled models.
- Limited accuracy to predict hotspots in the vicinity of contacts and joints
- Insufficient long-term experimental validation under high-current conditions
- Inadequate datasets to train AI-based monitoring algorithms
- Limited understanding of long-term performance of SF_6-free insulation systems
- Incomplete coupling of arc dynamics and pressure increase, as well as the associated mechanical degradation of the enclosure.

Addressing these gaps enables the development of reliable, compact, and environmentally sustainable next-generation switchgear.

4. METHODOLOGY

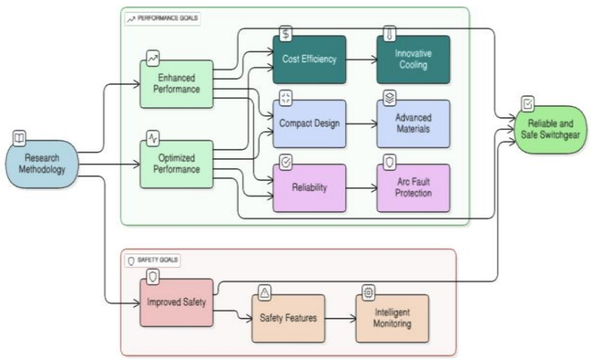

Fig - 1 Flow chart of Methodology

5. CASE STUDY REVIEW

Machine Learning–Assisted Thermal Prediction in MV Switchgear

Reliable temperature rise prediction is a basic need in the design of medium voltage (MV) switchgears because temperature overstress has a direct impact on the reliability of the equipment. Although traditional solutions involving experimental temperature rise tests as well as CFD simulations can efficiently provide accurate solutions, these processes involve high computational costs that make it difficult to apply in the design stage to search for optimal solutions. To overcome these problems, researchers proposed an innovative machine learning-based thermal prediction solution combined with CFD analysis by Matin et al. [1].

For the study cited in this article, an air-insulated MV switchgear system simulation was conducted to analyse the corresponding coupled electric-thermal-fluid phenomenon under rated conditions. Sources of heat generation were identified as Joule losses in conductors and contact resistances at busbar connections. The simulation model accounted for conduction in solid parts, natural convection in the enclosure, and radiation from the enclosure to simulate the system's thermal behaviour under steady conditions. The simulation results are verified with temperature rise tests under conditions prescribed in international standards [1].

The generated data set was then utilized to train an interpretable ML model with the capability of estimating maximum temperature rise at critical spots in switchgear. Unlike traditional ML models that function as a "black box," the developed method was more concerned with opacity and successfully measured the effect of input parameters on thermal characteristics. Analysis of importance to the features revealed that the main parameters causing hot spots were the magnitude of the current, resistance, and conductor geometry, aligning with thermal switchgear design principles identified by existing research [1].

The mission-ready model demonstrated prediction capabilities comparable to full CFD simulations in terms of accuracy, yet with less computational cost. This made it possible to quickly test various design configurations without having to rely on repeated full-scale ⅜simulations. It was shown that interpretable machine learning can contribute to CFD-based Multiphysics simulations to allow for fast thermal analysis with maintained physical understanding of the heat generation and dissipation mechanisms [1].

The broader outlook of this case study is that it addresses a scalable framework for simulation-driven switchgear design. There is a strong potential for the integration of CFD-based multi-physics modelling with explainable machine learning in early-stage design optimization, reliability assessment, and future digital switchgear applications using real-time monitoring and predictive maintenance strategies [1].

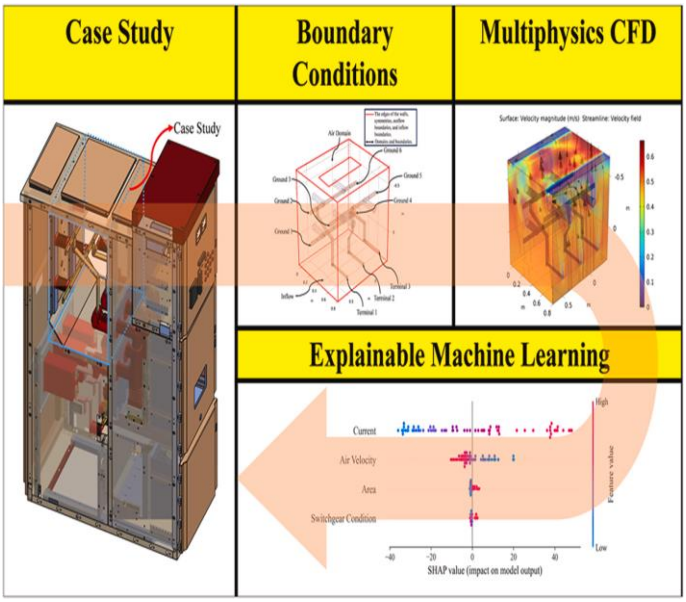

Fig - 2 Graphical Review [1]

6. CONCLUSIONS

In this review paper, recent advancements in thermal and multi-physics analyses for medium voltage-switchgear, especially temperature rise effects acting as factors controlling reliability and operational life, have been discussed.
Temperature increase is always found to be an important performance-limiting factor in the existing literature for the degradation of insulations, contact wear, and overall safety of the system.
A case study analysis reveals the integration of Multiphysics CFD simulations and machine learning models is capable of enabling an accurate temperature forecast while remaining physically transparent.
Compared to traditional empirical approaches and black box AI models, interpretative machine learning methods improve explainability, which makes it easier to understand the prominent thermal variables and processes.
Reviews of literature have found that combined electro-thermal-fluid modelling will help to improve the accuracy of thermal analysis and facilitate the rational design-optimization of the various components within a switch gear relay.
Advances in the area of insulation materials, conductor layout, and enclosures have been found to decrease the temperature rise and enhance the operational reliability.
The adoption of digital monitoring systems and data analytics in diagnostic provides ease of real-time assessment and predictive maintenance techniques.

Research is anticipated to be focused on physics-informed explainable data-driven techniques in the coming future to efficiently develop safe and sustainable next-generation medium voltage switchgear systems.

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