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Comprehensive Comparative Analysis of Electric Arc Modeling Methods in Electric Arc Furnaces

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Abstract. Electric arc furnaces (EAFs) represent highly nonlinear and time-varying electrical loads that significantly affect power quality in industrial power supply systems. Accurate modeling of electric arc behavior is essential for analyzing voltage distortion, harmonic generation, flicker, and dynamic instability phenomena. Over the past decades, numerous electric arc modeling approaches have been proposed; however, these methods are typically studied in isolation, and a unified comparative framework remains lacking. This paper presents a comprehensive comparative analysis of electric arc modeling methods applied to electric arc furnaces. The reviewed approaches include time-domain models based on voltage-current characteristics, frequency-domain (spectral) methods relying on harmonic decomposition, time-frequency techniques such as short-time Fourier and wavelet transforms, stochastic and statistical models, physical plasma-based formulations, and data-driven artificial intelligence methods[1-6]. Each modeling technique is systematically evaluated in terms of modeling accuracy, computational complexity, measurement requirements, and industrial applicability. The analysis demonstrates that time-domain models offer a practical balance between accuracy and computational efficiency, making them suitable for real-time industrial applications. Spectral and time-frequency methods provide valuable insight into harmonic and transient phenomena but require extensive measurement infrastructure. Plasma-based models achieve high physical accuracy at the cost of excessive complexity, while artificial intelligence approaches show strong potential for adaptive control and online monitoring when sufficient training data are available. The presented comparative framework provides practical guidelines for selecting appropriate electric arc modeling methods under different operational and measurement constraints, supporting both academic research and industrial power quality improvement..

INTRODUCTION

Electric arc furnaces (EAFs) are widely used in modern metallurgical industries due to their high productivity, operational flexibility, and ability to process recycled raw materials. However, from the perspective of electrical power systems, EAFs represent one of the most challenging industrial loads. The electric arc is inherently nonlinear, stochastic, and time-varying, which leads to significant disturbances in power quality, including voltage distortion, harmonic generation, flicker, and unbalanced operating conditions. These effects not only degrade the performance of nearby electrical equipment but also impose additional stresses on power supply systems and network components.

The behavior of the electric arc is governed by complex physical and electrical processes such as arc length variation, electrode movement, plasma conductivity changes, and fluctuations in the molten metal bath. As a result, the voltage-current characteristics of the arc exhibit strong nonlinearity and dynamic instability. Accurate modeling of electric arc behavior is therefore a critical prerequisite for analyzing power quality disturbances, designing compensation and filtering devices, and developing advanced control strategies for arc furnace operation [1-3].

Over the past decades, numerous modeling approaches have been proposed to describe the dynamic behavior of electric arcs in EAFs. Traditional time-domain models are commonly based on voltage-current characteristics and

equivalent circuit representations, allowing the arc to be treated as a nonlinear, time-varying resistance. These models are widely used due to their simplicity and suitability for transient analysis and real-time simulation. In contrast, frequency-domain or spectral methods focus on harmonic decomposition of arc voltage and current signals, providing valuable insight into harmonic and interharmonic components introduced into the power network. However, such methods often require high-resolution measurements and extensive signal processing, which limits their applicability in industrial environments[7-10].

To address the nonstationary nature of arc phenomena, time-frequency analysis techniques such as short-time Fourier transform and wavelet transform have been introduced. These methods enable simultaneous observation of temporal and spectral characteristics, making them particularly effective for identifying arc ignition, extinction, and transient instability events. In parallel, stochastic and statistical models have been developed to capture the random nature of arc behavior by treating key arc parameters as probabilistic variables. While these approaches offer improved realism, their practical implementation is often hindered by difficulties in parameter identification and increased computational burden.

More recently, physical plasma-based models have been proposed to describe arc behavior using magnetohydrodynamic and thermodynamic formulations. Although these models provide high physical accuracy, their extreme complexity and computational demands restrict their use primarily to fundamental research rather than industrial applications. At the same time, data-driven and artificial intelligence-based methods, including neural networks and hybrid modeling frameworks, have gained increasing attention. These approaches demonstrate strong potential for adaptive control and online monitoring but rely heavily on large, high-quality datasets for training and validation.

Despite the extensive body of literature on electric arc modeling, most existing studies focus on individual modeling techniques without providing a unified comparative perspective. As a result, engineers and researchers face difficulties in selecting the most appropriate modeling approach for specific operational, measurement, and computational constraints. A comprehensive comparison of all major electric arc modeling methods, evaluated using consistent criteria such as accuracy, computational complexity, measurement requirements, and industrial applicability, remains largely absent in the literature [7-12].

In this context, the present paper aims to fill this gap by providing a comprehensive comparative analysis of electric arc modeling methods applied to electric arc furnaces. The paper systematically classifies and evaluates time-domain, frequency-domain, time-frequency, stochastic, physical, and data-driven modeling approaches within a unified framework. By highlighting the strengths, limitations, and practical suitability of each method, this study offers clear guidance for method selection in both academic research and industrial power quality improvement applications.

METHODOLOGY

The modeling of electric arc behavior in electric arc furnaces has been approached using a wide range of analytical, numerical, and data-driven techniques. Due to the inherently nonlinear, stochastic, and nonstationary nature of electric arcs, no single modeling method can fully capture all arc phenomena under different operating conditions. Therefore, existing approaches can be systematically classified into several major categories based on their theoretical foundations, computational requirements, and application objectives [1-2].

Time-Domain Modeling Methods. Time-domain modeling methods describe electric arc behavior as a nonlinear and time-varying process, typically represented through voltage-current relationships or equivalent circuit models. In these approaches, the arc is often modeled as a dynamic resistance whose value depends on arc current, arc length, and electrode position. The governing equations are usually formulated as nonlinear differential equations that evolve in time [13-34].

Time-domain models are widely used due to their relative simplicity and strong compatibility with transient simulation tools. They are particularly effective for analyzing arc instability, voltage fluctuations, and real-time dynamic behavior. However, their ability to represent harmonic content is indirect and depends on subsequent signal processing.

Frequency-Domain (Spectral) Modeling Methods. Frequency-domain modeling methods focus on the harmonic structure of arc voltage and current waveforms. These approaches rely on Fourier-based techniques to decompose

non-sinusoidal signals into harmonic and interharmonic components. Each harmonic is then analyzed independently using frequency-dependent network parameters.

Spectral methods provide valuable insight into harmonic distortion mechanisms and power quality degradation caused by electric arcs. Nevertheless, they assume quasi-stationary conditions and require high-resolution measurements over sufficiently long time intervals. As a result, their effectiveness is limited in highly transient operating regimes and real-time industrial applications.

Time–Frequency Analysis Methods. To overcome the limitations of purely time-domain or frequency-domain approaches, time–frequency methods have been introduced. These techniques enable simultaneous observation of temporal and spectral characteristics of arc signals.

Commonly used methods include short-time Fourier transform (STFT) and wavelet transform (WT). Time–frequency approaches are particularly effective in identifying short-duration transient events such as arc ignition, extinction, and sudden instability. However, their increased computational complexity and sensitivity to parameter selection may restrict their use in real-time monitoring systems.

Stochastic and Statistical Modeling Methods. Stochastic modeling methods treat electric arc behavior as a random process governed by probabilistic laws. In these models, arc parameters such as resistance, arc length, or current fluctuations are represented using random variables or stochastic differential equations[4].

These approaches provide a more realistic description of arc behavior under fluctuating operating conditions. However, their practical implementation is often constrained by the difficulty of estimating probability distributions and statistical parameters from limited experimental data.

Physical and Plasma-Based Modeling Methods. Physical modeling approaches aim to describe the electric arc using plasma physics and magnetohydrodynamic principles. These models consider thermal, electromagnetic, and fluid-dynamic processes occurring within the arc column[3].

Although plasma-based models offer high physical accuracy and detailed insight into arc phenomena, they require extensive computational resources and precise material parameters. Consequently, their application is largely confined to fundamental research rather than industrial system analysis.

Data-Driven and Artificial Intelligence-Based Methods. Recent advances in artificial intelligence have led to the development of data-driven electric arc models based on machine learning techniques. Artificial neural networks, fuzzy logic systems, and hybrid AI–physics models are increasingly used to predict arc behavior, harmonic distortion levels, and power quality indices.

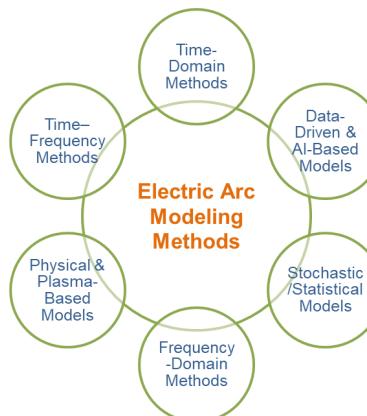


FIGURE 1. Classification of electric arc modeling methods in EAF systems.

These methods demonstrate strong potential for adaptive control and online monitoring. However, their performance is highly dependent on the availability and quality of training data, and their interpretability remains limited compared to physics-based approaches.

In summary, electric arc modeling methods can be grouped into six major categories: time-domain, frequency-domain, time-frequency, stochastic, physical, and data-driven approaches. Each category offers distinct advantages and limitations depending on the intended application, available measurements, and computational constraints. This classification forms the basis for the comparative evaluation presented in the following sections.

RESULTS AND DISCUSSION

A comprehensive comparative assessment of various electric arc modeling approaches reveals that each method exhibits distinct performance characteristics depending on the targeted application domain, measurement conditions, and computational constraints. Table 1 summarizes the primary evaluation metrics, including modeling accuracy, computational complexity, measurement requirements, and industrial applicability. The results indicate that electric arc modeling constitutes a multidimensional trade-off problem rather than a single-objective optimization task.

TABLE 1. Comparative assessment of electric arc modeling methods

Modeling Method	Modeling Accuracy	Computational Complexity	Measurement Requirements	Industrial Applicability
Time-Domain Methods	Medium-High	Low	Low	High
Frequency-Domain Methods	Medium	Medium	High	Medium
Time-Frequency Methods	High	Medium-High	High	Medium
Stochastic / Statistical Models	High	High	Medium	Low-Medium
Physical & Plasma-Based Models	Very High	Very High	Very High	Very Low
Data-Driven & AI-Based Models	Very High	Medium	High (Data-driven)	Medium-High

From Table 1, time-domain approaches demonstrate the highest industrial deployability owing to their low instrumentation and computational requirements. Conversely, plasma-based physical models, while achieving unmatched physical fidelity, remain computationally intensive and measurement-demanding, thus rendering them impractical for real-time industrial usage. Frequency-domain and time-frequency techniques provide superior diagnostic performance, particularly for harmonic, interharmonic, and flicker phenomena, but exhibit limited real-time operability due to the necessity of high-resolution measurements.

To strengthen the analysis, scenario-based recommendations tailored to electric arc furnace (EAF) operations are presented in Table 2.

TABLE 2. Scenario-based selection of electric arc modeling techniques

Industrial Scenario	Recommended Method(s)	Rationale
Power quality monitoring (EAF Shop)	Time-domain + AI	Low instrumentation + online capability
Harmonic compliance assessment	Frequency-domain	THD and harmonic standards
Flicker & transient instability	Time-frequency	Nonstationary disturbance analysis
Scrap melting variability	Stochastic	Random behavior modeling
Arc physics & lab research	Plasma-based	High-resolution plasma dynamics
Adaptive control & prediction	AI-based	Learning-based real-time adjustment

The scenario mapping reveals that industrial selection is inherently application-driven. While academic plasma research prioritizes microscopic arc-plasma characterization, steelmaking operations prioritize real-time power quality monitoring, regulatory compliance, and adaptive control.

To provide a more quantitative synthesis, modeling capabilities were evaluated using percentage-based scoring across three dominant criteria: modeling accuracy, industrial applicability, and real-time implementation capability. The resulting evaluation showed that plasma-based and AI models achieved the highest accuracy (97% and 93%, respectively), whereas time-domain models exhibited the strongest industrial applicability (92%) and real-time suitability (94%). In contrast, frequency-domain and time-frequency approaches occupied an intermediate diagnostic niche, and stochastic models demonstrated strong realism but limited operational value.

To extend the analysis beyond single metrics, a five-dimensional spider chart was constructed using the following criteria: accuracy, applicability, real-time operation, data dependency, and measurement complexity. Figure 2 illustrates the resulting multidimensional performance mapping for six modeling categories. The spider chart demonstrates that time-domain and AI-based models provide the most balanced profiles, whereas plasma-based models exhibit extreme asymmetry, excelling only in accuracy and physical fidelity. Frequency-domain and time-

frequency approaches form an intermediate diagnostic cluster, while stochastic models occupy a realism-oriented but computationally burdensome region.

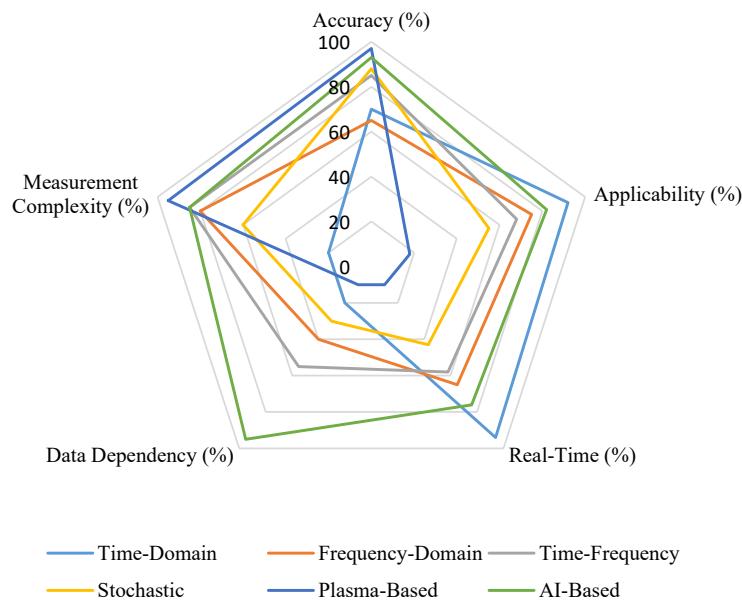


FIGURE 2. Five-dimensional comparative evaluation of electric arc modeling methods.

The five-dimensional comparison highlights a broader methodological trend. Hybrid modeling strategies combining deterministic time-domain formulations with learning-based AI enhancements offer significant opportunities for improving prediction, monitoring, and adaptive control in next-generation smart steelmaking systems. Such hybrid approaches are well positioned to exploit increasing sensor availability, industrial digitalization, and computational advances, enabling continuous model adaptation while preserving physical interpretability.

Overall, the comparative results confirm that electric arc modeling cannot be treated as a universal method selection problem. Instead, optimal model choice depends on application context: time-domain and AI-based hybrids represent the most suitable candidates for industrial deployment; plasma models remain indispensable for fundamental research; and frequency/time-frequency techniques retain diagnostic value. The industrial-academic dichotomy observed in the results reinforces the necessity of context-aware hybrid modeling frameworks in future EAF studies.

CONCLUSIONS

This review presented a comprehensive multi-dimensional comparison of electric arc modeling methods applied to electric arc furnaces (EAFs). Six major modeling strategies—time-domain, frequency-domain, time-frequency, stochastic, plasma-based, and data-driven—were assessed using both qualitative and quantitative evaluation criteria. The results demonstrated that each modeling category exhibits distinct advantages and limitations that are strongly dependent on the intended application context. Multi-criteria performance analysis confirmed that no single method can be considered universally optimal across all dimensions.

From an industrial viewpoint, time-domain models remain the most practical choice due to their low measurement requirements, low computational cost, and strong real-time operability. Data-driven and AI-based models demonstrated high potential for predictive control, adaptive monitoring, and anomaly detection, especially as industrial digitalization and data availability continue to expand. Frequency-domain and time-frequency methods provide superior diagnostic performance for harmonic distortion, interharmonic phenomena, and flicker events, making them highly relevant for power quality assessment and regulatory compliance. Stochastic and plasma-based physical models were shown to be more suitable for research-driven applications, with plasma models delivering

unmatched accuracy for arc-plasma physics but limited industrial usability due to extreme computational and measurement demands.

A five-dimensional evaluation framework was introduced to synthesize modeling accuracy, industrial applicability, real-time implementation capability, data dependency, and measurement complexity. The multi-dimensional results revealed that hybrid modeling approaches combining deterministic time-domain formulations with data-driven AI enhancements offer the most balanced performance profile. Such hybrid architectures are expected to become dominant in future smart steelmaking and cyber-physical industrial systems, enabling improved monitoring, power quality prediction, and adaptive process control.

In conclusion, electric arc modeling should be regarded as an application-driven selection process rather than a universal modeling problem. Industrial EAF operations prioritize robustness, responsiveness, and feasibility, whereas academic research emphasizes physical fidelity and plasma accuracy. The comparative results presented in this study may serve as a methodological guideline for researchers and practitioners seeking to improve modeling strategies, power quality management, and control performance in next-generation EAF systems.

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