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Article

Investigation of Short-Circuit Transients in Single-Phase and Three-Phase Synchronous Machines: Time-Domain Modeling and the Influence of Rotor Position

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Abstract

This work examines the transient dynamics of synchronous machines under sudden fault conditions, with emphasis on short-circuit events. The study begins with a single-phase synchronous machine operating in open-circuit mode, where short-circuit current expressions are systematically derived and numerically evaluated using advanced integration algorithms. The transient evolution of stator and field currents is analyzed, highlighting their dependency on rotor position, machine parameters, and electromagnetic interactions. A SIMULINK-based model is implemented to simulate the time-domain responses and visualize the effects of parameter variations. The investigation is then extended to a three-phase synchronous machine with damper windings subjected to line-to-line faults. Generalized voltage equations in the d-q reference frame are formulated, leveraging Park's transformation to enable detailed modeling of transient behavior. Numerical simulations confirm the analytical predictions, revealing the significant influence of rotor angle, leakage inductances, and damper circuits on fault current dynamics. The results provide valuable insights for fault analysis, power system stability assessment, and the design of synchronous machines under transient operating conditions.

Keywords: synchronous machines; transient dynamics; d-q axis modeling; Park's transformation; damper windings; numerical integration; fault analysis; power system stability

1. Introduction

Synchronous machines play a central role in modern electric power systems, acting as the main electromechanical energy converters in large-scale power generation plants and high-performance industrial drives. Their significance is not limited to power generation; they also maintain grid stability by providing synchronized voltage and reactive power support. Because synchronous machines are directly connected to the grid, maintaining operational reliability is critical: sudden disturbances such as load changes, voltage sags, or faults can significantly impact both machine integrity and overall system stability [1].

Among potential disturbances, sudden short-circuit faults are among the most severe. During a short-circuit event, transient currents can surge to several times the rated steady-state current, subsequently decaying over subtransient and transient periods [2,3]. These high currents generate strong electromechanical stresses on both stator and rotor windings, which may lead to insulation damage, overheating, excessive vibration, and

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potentially permanent machine failure. Additionally, these transient currents can propagate through the power system, creating voltage instability, mechanical torque oscillations, and disturbances in interconnected generators and loads [2,4].

The modeling and analysis of these transient events were revolutionized by Park's direct–quadrature (d–q) axis transformation, which converts three-phase machine equations into a rotating reference frame. This reduces the complexity of the equations, eliminates time-varying inductances, and allows the derivation of simplified state-space models for both transient and steady-state conditions [5,6].

Advanced models incorporate damper windings and field dynamics to improve accuracy, capturing both subtransient and transient current decay characteristics. The solution of these nonlinear differential equations often relies on numerical integration techniques such as Runge–Kutta methods [3].

Simulation-based approaches have become indispensable for studying synchronous machine behavior under fault conditions. Platforms such as MATLAB/Simulink allow the development of detailed machine models, including electrical, mechanical, and control subsystems, and enable the simulation of symmetric and asymmetric short-circuit events [5,7].

These tools provide detailed insights into current waveform evolution, electromagnetic torque oscillations, and rotor dynamics under transient conditions. Simulation frameworks also allow for sensitivity analyses and fault mitigation studies in a risk-free environment, reducing development costs and technical risks before practical deployment [2,4,7].

Recent studies confirm the continued importance of accurate transient modeling. Detailed d–q axis models have been validated for both single-phase and three-phase synchronous machines, demonstrating alignment between analytical predictions and time-domain simulation results [1,6].

Current research emphasizes the influence of critical parameters such as transient and subtransient reactances, leakage inductances, rotor angle, and initial operating conditions on the amplitude and decay of transient fault currents [3,4]. Such analyses support machine design, protection strategy development, and power system stability assessment [2,7].

The present study addresses the analysis of both single-phase and three-phase synchronous machines through a structured, stepwise methodological framework. The single-phase representation is employed as an introductory and pedagogical basis, allowing a clear and simplified examination of the fundamental mechanisms governing electromagnetic transients. In contrast, the extension to three-phase machines incorporates additional physical phenomena, including damper winding effects and field system dynamics, thereby enabling a more comprehensive and realistic representation of practical synchronous machine behavior under operating and fault conditions [3,6]. By combining established classical analytical approaches with contemporary numerical simulation techniques, the study develops an integrated perspective that enhances the understanding of fault-induced transient phenomena and their broader implications for machine protection strategies and power system stability assessment.

The contribution of this work lies in the development of a unified analytical and numerical framework for investigating short-circuit transients in synchronous machines. The proposed formulation combines analytical derivation with time-domain simulations performed independently in MATLAB/Simulink and FORTRAN using identical operating conditions. The study focuses on the influence of rotor position and damper windings on transient behavior while providing cross-validation between two independent implementations. The objective is not to introduce a new electromagnetic theory but to provide a consistent computational framework suitable for transient analysis, protection studies, and engineering applications.

2. Mathematical Modeling of Synchronous Machines

When a sudden short-circuit is applied at the terminals of a synchronous machine, the electrical equilibrium of the armature circuit is instantaneously disturbed, leading to the appearance of high-amplitude transient currents. These currents arise due to the rapid redistribution of electromagnetic energy stored in the machine inductances and their interaction with the rotor magnetic field [7,8].

For analytical clarity, the initial investigation can be carried out using an equivalent single-phase representation. Although simplified, this approach preserves the essential electromagnetic coupling mechanisms by incorporating the self-inductances of the stator (armature) and field windings, together with their mutual inductance. The latter is inherently dependent on the angular displacement between the magnetic axes of the stator and rotor, introducing a time-varying coupling effect that significantly influences the transient response [9].

In this section, a mathematical formulation is developed to describe the dynamic behavior of a single-phase synchronous machine subjected to a sudden short-circuit. The derivation starts from the fundamental voltage equations associated with the armature and field circuits, which are expressed in terms of currents and flux linkages. Subsequently, the flux–current relationships are introduced, explicitly accounting for the position-dependent mutual inductance between windings. By combining these relations, a system of coupled differential equations is obtained, capturing the evolution of stator and rotor currents during the transient interval [8,10].

The resulting model provides a rigorous framework for analyzing fault-induced electromagnetic phenomena, including the rapid subtransient response and the subsequent slower decay governed by rotor dynamics. Moreover, it establishes a solid theoretical basis for extending the analysis toward more comprehensive three-phase models formulated in the rotating reference frame, where additional effects such as damper windings and asymmetrical faults can be accurately represented [9,11].

2.1. Fundamental Assumptions

The transient behavior of a synchronous machine subjected to a sudden short-circuit is governed by electromagnetic coupling between the stator (armature) and rotor (field) circuits. For analytical tractability, a single-phase equivalent representation is adopted, which preserves the essential physical interactions while reducing mathematical complexity.

The following assumptions are considered:

- Linear magnetic circuit (no saturation)
- Sinusoidal distribution of magnetomotive forces
- Constant rotor speed during the subtransient interval
- Negligible space harmonics

These assumptions are widely used in transient machine analysis and provide sufficiently accurate results for short-circuit studies [12,13].

The transient behavior of a synchronous machine subjected to a sudden short-circuit is governed by the electromagnetic interaction between the stator (armature) and rotor (field) circuits. For analytical purposes, a single-phase equivalent representation is adopted, which retains the fundamental coupling mechanisms while reducing mathematical complexity.

As illustrated in Figure 1, the stator circuit is characterized by its resistance and self-inductance, while the rotor circuit includes the field resistance and inductance.

The two circuits are coupled through a position-dependent mutual inductance, which varies with the rotor angular position. This coupling plays a key role in determining the transient current response immediately after the fault [14,15].

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These assumptions are widely accepted in modern transient machine modeling and provide sufficiently accurate results for short-circuit analysis in synchronous machines [15,16].

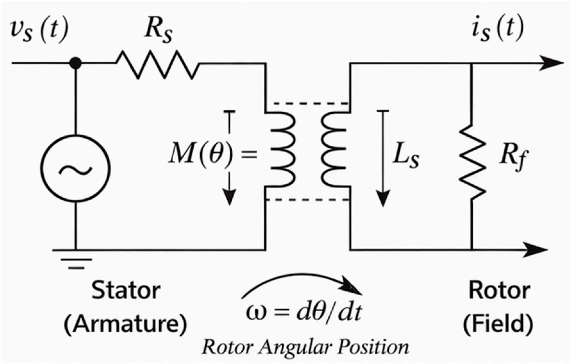

Figure 1. Single-phase equivalent representation of a synchronous machine under short-circuit conditions, showing electromagnetic coupling between stator (armature) and rotor (field) circuits through position-dependent mutual inductance.

2.2. Voltage Equations

Figure 2 illustrates a synchronous machine under a short-circuit condition. The stator and field windings are represented with their corresponding voltages, currents, resistances, and flux linkages. The diagram highlights the short-circuit at the stator terminals, which causes a sudden increase in fault current.

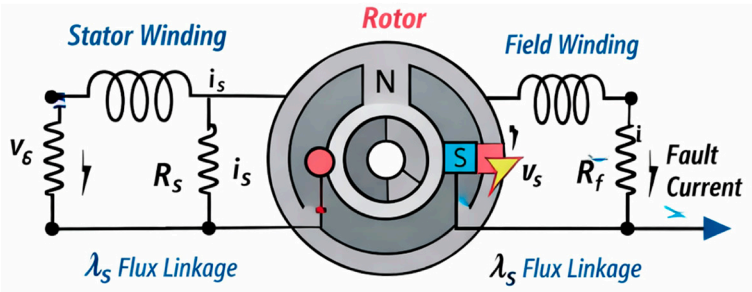

Figure 2. Synchronous Machine under Short-Circuit Condition.

The electrical dynamics of the system are described by the voltage equations of the armature and field windings:

$$v_S(t) = R_s i_s(t) + \frac{d\lambda_s(t)}{dt}$$

$$v_f(t) = R_f i_f(t) + \frac{d\lambda_f(t)}{dt}$$

where

- v_S, v_f are stator and field voltages
- i_s, i_f, if are currents
- R_s, R_f are resistances
- λ_s, λ_f are flux linkages

At the instant of the short-circuit, the stator terminal voltage collapses:

$$v_S(t) = 0, t \geq 0$$

This condition triggers the transient response characterized by high fault currents [13].

As shown in Figure 2, the stator and field windings interact during a short-circuit, and the resulting fault currents can be calculated using the voltage equations presented above.

2.3. Flux Linkage Relationships

The flux linkage relationships in synchronous electrical machines can be rigorously expressed as functions of the stator and rotor currents, as well as the corresponding self- and mutual inductances. These relationships play a fundamental role in describing the electromagnetic behavior of the machine, particularly under transient operating conditions.

The flux linkages associated with the stator and field windings are given by:

$$\lambda_s = L_s i_s + M(\theta) i_f$$

$$\lambda_f = L_f i_f + M(\theta) i_s$$

where L_s and L_f denote the stator and field self-inductances, respectively, while $M(\theta)$ represents the mutual inductance between the stator and rotor circuits. The variable θ corresponds to the electrical rotor position, which introduces a spatial dependency into the magnetic coupling.

From a physical standpoint, the mutual inductance is not constant but varies periodically with the rotor position due to the geometric alignment between stator and rotor magnetic axes.

This position-dependent behavior may be represented in an approximate form through a harmonic formulation, expressed as follows:

$$M(\theta) = M_0 \cos(\theta)$$

where M_0 denotes the maximum mutual inductance between the stator and field winding, assumed constant for the linear magnetic model considered in this study. The variation with rotor position is introduced exclusively through the cosine function.

This formulation captures the fundamental angular dependence of the coupling mechanism, highlighting the variation in mutual inductance as a function of the relative electrical position between the interacting windings.

This approximation captures the fundamental component of the magnetic coupling and reflects the sinusoidal distribution of the air-gap magnetic field. Such a representation is widely adopted in the analytical modeling of synchronous machines, as it provides a balance between accuracy and mathematical tractability.

The dependence of mutual inductance on rotor position is essential for accurately describing electromechanical energy conversion, particularly in dynamic regimes such as fault conditions or transient disturbances. As highlighted in the literature, this spatial variation directly influences torque production and flux interaction mechanisms within the machine [17,18].

Furthermore, the electrical configuration of the synchronous machine under short-circuit conditions is illustrated in Figure 3, which provides a schematic representation of the stator and rotor circuit interactions. As observed in Figure 3, the coupling between windings and the associated inductive elements governs the evolution of currents and flux linkages during fault scenarios, thereby emphasizing the importance of accurate inductance modeling.

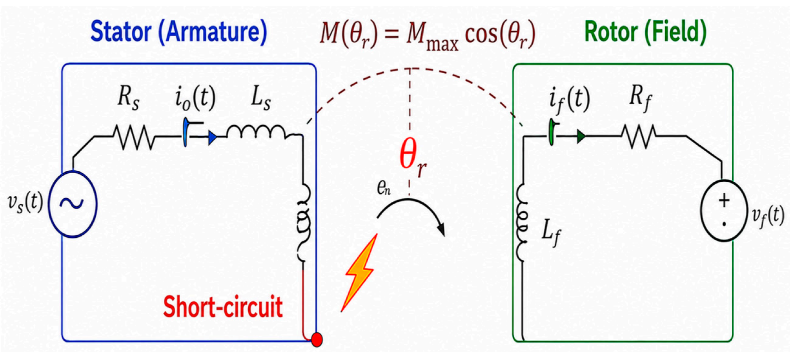

Figure 3. Electrical model of the synchronous machine in short-circuit regime.

2.4. Differential Equation System of the Synchronous Machine

The dynamic operation of a synchronous machine, particularly under abnormal regimes such as short-circuit conditions, can be accurately described by a system of coupled nonlinear differential equations. These equations are obtained by substituting the flux linkage expressions into the fundamental voltage equations of the stator and rotor circuits, thus providing a comprehensive mathematical representation of the electromagnetic interactions within the machine.

Assuming a short-circuit condition at the stator terminals (i.e., zero stator voltage), the voltage equations can be expressed as follows:

$$0 = R_s i_s + \frac{d}{dt}\left(L_s i_s + M(\theta) i_f\right)$$

$$v_f = R_f i_f + \frac{d}{dt}\left[L_f i_f + M(\theta) i_s\right]$$

where R_s and R_f denote the stator and field winding resistances respectively, and v_f denotes the excitation (field) voltage. By expanding the time derivatives, the equations can be rewritten in a more explicit differential form:

$$0 = R_s i_s + L_s \frac{di_s}{dt} + M(\theta)\frac{di_f}{dt} + \frac{dM(\theta)}{dt} i_f \quad (1)$$

$$v_f = R_f i_f + L_f \frac{di_f}{dt} + M(\theta)\frac{di_s}{dt} + \frac{dM(\theta)}{dt} i_s$$

A critical aspect of this formulation is the presence of the derivative of the mutual inductance term, $\frac{dM(\theta)}{dt}$, which reflects the time-varying nature of the magnetic coupling between stator and rotor windings. Considering the commonly accepted approximation of the mutual inductance: $M(\theta) = M_0 cos(\theta)$ its time derivative can be expressed as:

$$\frac{dM(\theta)}{dt} = \frac{dM}{d\theta}\frac{d\theta}{dt} = -M_o \omega \sin(\theta)$$

$$\omega = \frac{d\theta}{dt}$$

where ω is the electrical angular velocity of the rotor. Since the rotor is assumed to rotate at constant synchronous speed, the time derivative of the mutual inductance follows directly from the chain rule. Consequently, only the rotor position introduces time dependence into the mutual inductance, whereas M_o remains constant throughout the analysis. This formulation clearly demonstrates that the system becomes nonlinear and time-varying due to the trigonometric dependence on rotor position and speed. Such characteristics significantly increase the complexity of the analysis and typically require numerical solution techniques or transformations into alternative reference frames, such as the Park (d–q) transformation [19,20].

The physical interpretation of the above mathematical model is further supported by the electrical equivalent representation of the synchronous machine under fault conditions. As illustrated in Figure 4, the interaction between stator and rotor circuits, including resistive and inductive elements, governs the transient current behavior and flux evolution during short-circuit events [21].

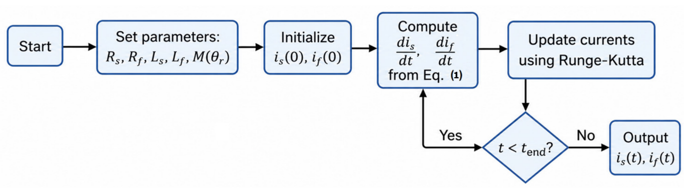

Figure 4. Electrical equivalent circuit of a synchronous machine under short-circuit conditions.

2.5. Extension to Three-Phase Machine in the d–q Reference Frame

For a more comprehensive and analytically tractable representation of synchronous machine dynamics, the three-phase system is commonly transformed into a rotating reference frame using Park's transformation. This approach allows the time-varying inductances present in the phase domain to be converted into constant parameters in the d–q frame, thereby significantly simplifying the mathematical analysis of the machine, especially under transient and fault conditions [22].

In the rotating d–q reference frame, the stator voltage equations can be expressed as:

$$v_d = R_s i_s + L_d \frac{di_d}{dt} - \omega_r L_q i_q + v_{fd}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + v_{fq}$$

where v_d and v_q are the direct-axis and quadrature-axis stator voltages, i_d and i_q are the corresponding current components, and L_d, L_q represent the d-axis and q-axis inductances. The term ω_r denotes the rotor electrical angular velocity, while v_{fd} and v_{fq} account for the contributions of the field excitation projected onto the d–q axes.

A key advantage of this transformation lies in the decoupling of the stator variables into orthogonal components aligned with the rotor magnetic field. This enables a clearer interpretation of electromagnetic torque production and flux linkages, as well as improved numerical stability in simulation models. Moreover, the d–q model forms the foundation for advanced control strategies such as vector control and direct torque control in electrical drives [23].

To further enhance the accuracy of the model, damper windings (also known as amortisseur windings) are included. These windings are represented by additional circuits in both the d-axis and q-axis, each characterized by their own resistances and inductances. The inclusion of damper windings is essential for capturing subtransient effects, damping oscillations, and accurately modeling the machine's response during disturbances such as short circuits or sudden load changes [24].

The complete structure of the synchronous machine model in the rotating reference frame, including stator, field, and damper windings, is illustrated in Figure 5, entitled:

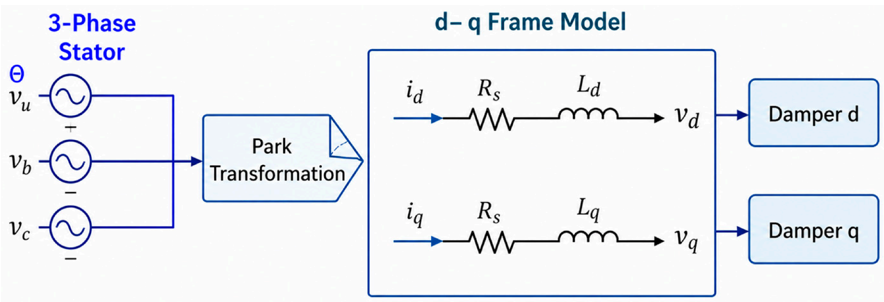

Figure 5. Three-phase synchronous machine model in the d–q rotating reference frame with damper windings.

As shown in Figure 5, the equivalent model consists of multiple coupled circuits corresponding to the d-axis and q-axis components. The stator windings are represented in the rotating frame, while the rotor circuits include both the field winding (aligned with the d-axis) and the damper windings distributed along both axes. This representation provides a highly effective framework for analyzing transient stability, electromagnetic interactions, and control performance in synchronous machines.

2.6. Example Simulation Results

To validate the previously developed mathematical model and to illustrate the dynamic behavior of the synchronous machine under fault conditions, time-domain simulations are typically performed. These simulations provide valuable insight into the transient evolution of electrical quantities, particularly the stator and field currents, following a disturbance such as a short circuit. The results of such a simulation are presented in Figure 6, entitled:

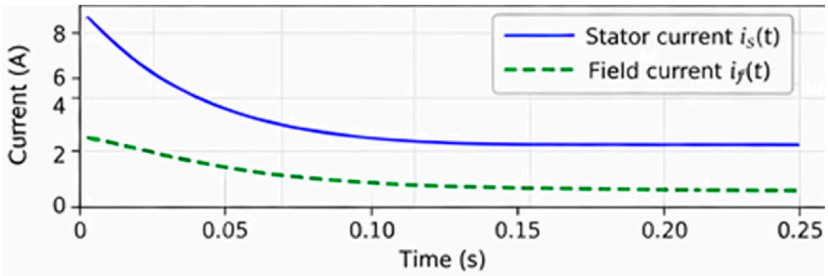

Figure 6. Typical transient response of stator and field currents following a short-circuit event.

As illustrated in Figure 6, the stator current exhibits a rapid increase immediately after the occurrence of the short circuit, reaching a high initial peak value. This behavior is primarily associated with the subtransient reactance of the machine, which governs the initial current magnitude. Subsequently, the current decays in a non-uniform manner, transitioning through subtransient and transient regimes before eventually approaching a steady-state value. This multi-stage decay process is well documented in the literature and reflects the influence of different machine time constants associated with stator, field, and damper windings [25].

In parallel, the field current response demonstrates a slower dynamic evolution due to the higher inductance and time constant of the rotor circuit. Following the disturbance, the field current may exhibit oscillatory behavior or gradual variation depending on the excitation system and machine parameters. The interaction between stator and rotor circuits, as described by the mutual inductance and its position dependency, plays a crucial role in shaping this response [26].

Furthermore, the presence of damper windings significantly contributes to the damping of oscillations observed in both stator and rotor currents. These windings absorb transient energy and help stabilize the system more rapidly, thereby improving the overall dynamic performance of the machine during fault conditions [27].

The transient responses depicted in Figure 6 confirm the theoretical predictions derived from the nonlinear differential equation system and the d–q model. Such results are essential for validating simulation models and for assessing the stability and protection performance of synchronous machines operating within power systems.

2.7. State-Space Representation

For advanced analysis, simulation, and control design, the dynamic model of the synchronous machine can be reformulated using a state-space representation. This approach provides a compact and systematic description of the system dynamics, allowing efficient numerical implementation and facilitating the application of modern control techniques. The state vector is defined as:

$$x(t) = \begin{bmatrix} i_s(t) \\ i_f(t) \end{bmatrix}$$

where $i_s(t)$ and $i_f(t)$ denote the stator and field currents, respectively. Based on this definition, the nonlinear differential equations derived earlier can be rewritten in the general state-space form:

$$\dot{x} = A(\theta)x + Bu$$

where A(θ) denotes the state matrix, whose coefficients depend on the rotor position through the mutual inductance M(θ), B is the input matrix, $x = \begin{bmatrix} i_s \ i_f \end{bmatrix}^T$, and $u = \begin{bmatrix} v_s \ \ v_f \end{bmatrix}^T$.

In this formulation, the matrix $A(\theta)$ contains coefficients that depend explicitly on the rotor electrical position (θ), reflecting the position-dependent nature of the mutual inductance and its time derivative. The input matrix B defines how the excitation voltage v_f influences the system dynamics.

A key characteristic of this representation is that the system matrix is time-varying because it depends explicitly on the rotor electrical position through the mutual inductance M(θ). Under the assumptions adopted in this study, namely a linear magnetic circuit and constant synchronous rotor speed, the electrical subsystem is more appropriately described as a linear time-varying (LTV) system rather than a nonlinear system. Consequently, the model cannot be treated as linear time-invariant (LTI), and numerical integration is required to evaluate its transient response.

This formulation is particularly advantageous for implementing simulation algorithms and studying transient phenomena such as short-circuit responses, stability limits, and dynamic interactions between electrical variables [28,29].

To better illustrate the structure of the state-space model and the interaction between system components, a conceptual block representation is provided in Figure 7, entitled:

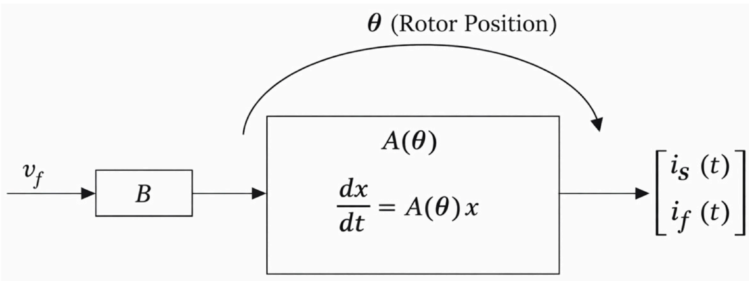

Figure 7. State-space block diagram representation of the synchronous machine model.

As shown in Figure 7, the system can be interpreted as a dynamic block where the input v_f is processed through the input matrix B, while the internal dynamics are governed by the state matrix $A(\theta)$. The output corresponds to the state vector $x(t)$, which evolves over time according to the differential equation. This representation highlights the coupling between stator and rotor currents and emphasizes the influence of rotor position on system behavior. Furthermore, it provides a clear framework for implementing numerical solvers and control algorithms. The state-space formulation is particularly suitable for numerical integration using high-accuracy methods such as the Runge–Kutta algorithms, which are widely employed for solving linear time-varying differential equations in electrical machine simulations [28].

These methods ensure stable and precise computation of system trajectories, even in the presence of strong nonlinearities and time-varying parameters.

Moreover, this modeling approach enables straightforward extensions of the system by including additional state variables, such as damper winding currents or mechanical dynamics (e.g., rotor speed and position). Such extensions are essential for developing comprehensive models used in power system stability analysis and real-time control applications [30,31].

2.8. Physical Interpretation of the State-Space Model

The derived state-space representation of the synchronous machine provides not only a compact mathematical formulation but also a clear framework for understanding the underlying physical phenomena that govern machine behavior under transient conditions. The model captures several key aspects of machine dynamics, which are essential for both analysis and design of protection and control strategies:

- Rapid current rise immediately after fault initiation:
  Following the onset of a short-circuit or other transient event, the stator currents increase sharply, reaching a peak dictated by the machine's subtransient reactance. This initial surge reflects the immediate electromagnetic response of the stator windings and the interaction with the rotor circuit [32,33].
- Energy exchange between stator and rotor circuits:
  The mutual inductance $M(\theta)$ facilitates energy transfer between the stator and rotor circuits. This interaction governs the redistribution of electromagnetic energy during transients and is crucial for accurately predicting the time evolution of both stator and rotor currents [34,35].
- Oscillatory behavior due to electromechanical coupling:
  The coupling between electrical and mechanical subsystems, mediated by the rotor position and angular velocity, produces oscillatory responses in both current and flux. These oscillations are indicative of the machine's natural modes of electromechanical interaction and are strongly influenced by the presence of damper windings [36,37].
- Dependence on rotor angular position:
  The time-varying mutual inductance introduces a modulation of the electromagnetic interactions according to the rotor's instantaneous angular position θ. This position dependence directly affects the peak amplitude and shape of the transient currents, contributing to the variation observed in fault responses [38,39].

These effects are effectively visualized in the state-space block diagram (Figure 7), which illustrates how the rotor position influences the system matrix $A(\theta)$ and, consequently, the evolution of the state vector $x(t) = \left[i_s,\ i_f\right]^T$.

The state-space representation of the synchronous machine can be written in compact form as:

$$\dot{x} = A(\theta)x + Bu$$

where $(x \in R^n)$ denotes the state vector of the system, and typically includes electrical variables such as stator and rotor currents in the (d)- and (q)- axes, flux linkages, and, depending on the model complexity, mechanical variables such as rotor angular speed. The input vector (u) represents the external excitation applied to the system, most commonly the field voltage or other control signals associated with the excitation subsystem.

The matrix A(θ) is the state matrix and depends explicitly on the rotor electrical position through the mutual inductance M(θ). Under the assumptions adopted in this study, this dependence makes the electrical subsystem linear time-varying (LTV). The matrix therefore captures the variation in the electromagnetic coupling with rotor position while preserving linearity with respect to the state variables.

The input matrix (B) characterizes how the excitation voltage influences the state variables of the system. It defines the coupling path between the excitation system and the internal electromagnetic dynamics of the machine, thereby governing the system's response to changes in field voltage or other control inputs.

Overall, the state-space formulation provides a compact and systematic framework for describing the coupled electrical and mechanical dynamics of the synchronous machine. The explicit dependence of $A(\theta)$ on rotor position allows the model to directly capture the impact of rotor angle variations on system behavior, which is essential for accurate transient analysis, stability studies, and numerical simulation of synchronous machine performance.

The feedback loop from rotor position in Figure 7 clearly demonstrates how the dynamics of the system are inherently coupled to mechanical motion, leading to modulation phenomena in transient currents.

In summary, the state-space formulation not only facilitates numerical computation but also provides a transparent physical interpretation of transient processes in synchronous machines. The interplay between rapid current rise, energy exchange, electromechanical oscillations, and rotor-position modulation highlights the complexity of machine response during faults and underscores the importance of accurate modeling for simulation, control, and protection studies [28,40].

3. Discussions and Practical Relevance

3.1. Proposed Model: Analysis of Synchronous Machines Under Fault Conditions

The proposed model presents an advanced approach for analyzing the behavior of synchronous machines under fault conditions, based on the simultaneous integration of electromagnetic and electromechanical phenomena within a unified mathematical framework. Unlike classical models, this method employs the d–q transformation, high-order numerical integration, and the explicit inclusion of damper winding effects, providing an accurate representation of complex transient regimes [41].

The overall structure of the proposed model is illustrated in Figure 8.

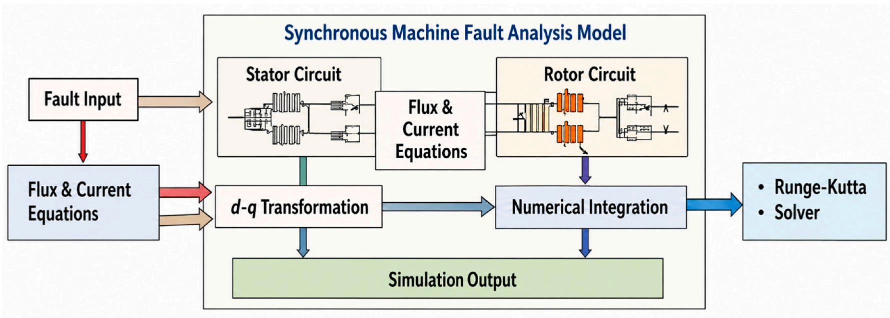

Figure 8. Proposed model for synchronous machine fault analysis integrating stator–rotor dynamics, d–q transformation, and numerical integration.

The figure clearly depicts the processing flow of the model, starting from the Fault Input, which introduces an initial perturbation into the system. This disturbance is then propagated to the Flux and Current Equations block, where the fundamental relationships among voltages, currents, and magnetic fluxes are described.

The Stator Circuit and Rotor Circuit blocks model the electromagnetic behavior of the two main subsystems. Their interaction is critical, as faults lead to rapid redistribution of magnetic energy, resulting in high-amplitude currents and transient oscillations [42].

The d–q transformation plays a central role in this model. By converting the three-phase system into a rotating reference frame, it eliminates the time dependency of the inductances and simplifies mathematical analysis.

This transformation allows the separation of direct and quadrature components, facilitating interpretation of the physical phenomena.

Numerical integration, performed using Runge–Kutta methods, enables the solution of the linear time-varying differential equation system. This is required because the system coefficients depend continuously on the rotor position through the mutual inductance [43].

The final outputs are generated in the Simulation Output block and include:

- Stator currents

- Excitation currents
- Electromagnetic torque
- Rotor angle

From a practical perspective, this model allows for:

- Correct sizing of protective devices
- Transient stability analysis
- Optimization of damper winding parameters

Compared with simplified analytical formulations, the proposed implementation provides a unified representation of stator, field, and damper circuit dynamics within the same simulation framework while remaining suitable for transient fault analysis.

Therefore, the proposed model serves as a critical tool for modern power system analysis, particularly in the context of increasing network complexity and the integration of renewable energy sources [44].

3.2. Classical Model: Phase-Domain Approach

The classical phase-domain model represents one of the most commonly used methods for fault analysis in power systems, largely due to its simplicity and ease of implementation. This approach models electrical quantities directly in the phase coordinates (a, b, c), without relying on complex mathematical transformations.

The general structure of the phase-domain model is shown in Figure 9.

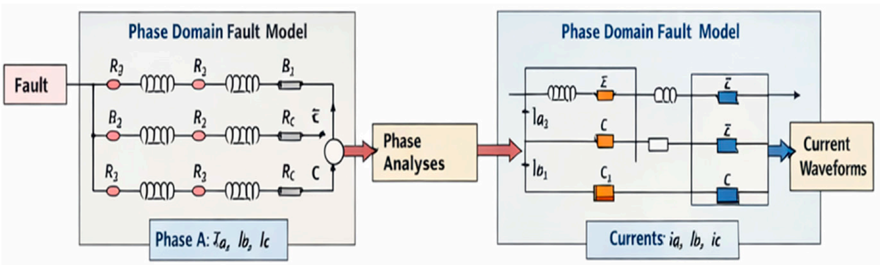

Figure 9. Classical phase-domain fault model illustrating three-phase current behavior under fault conditions.

The figure illustrates the two primary stages of the analysis. First, the circuit is modeled in the phase domain, where each phase is represented by an equivalent circuit consisting of resistances and inductances. This allows the fault to be introduced directly as a short-circuit connection, enabling a straightforward depiction of the system's response. After the fault is applied, the resulting currents in the three phases (i_a, i_b, i_c) are calculated and analyzed. These currents reflect the imbalances and high amplitudes caused by the fault and are influenced by subtransient reactance, rotor position, and the type of fault.

While the phase-domain approach provides an intuitive and quick method for evaluating fault currents, it has notable limitations. The inductances depend on rotor position, making analytical solutions challenging, and the model does not allow a clear separation of the subtransient, transient, and steady-state components of the current. Consequently, its use in advanced studies, such as detailed stability analysis or optimization of machine parameters, is limited [45].

Despite these limitations, the classical model remains valuable for preliminary calculations, rapid protection studies, and simple validation tasks. Compared with the proposed d–q-based model, it offers lower accuracy but benefits from reduced computational complexity and shorter calculation times. However, in modern power system analysis, phase-domain models are increasingly replaced by numerical simulations and transformation-based methods that can capture electromechanical interactions more accurately [46].

3.3. Simplified Model: Reduced-Order Approach

The reduced-order model represents a simplified approach, typically used when rapid analysis is required without delving into the detailed dynamics of transient phenomena. Unlike the proposed d–q model or the classical phase-domain model, this approach assumes constant inductances and neglects rotor dynamics and damper winding effects, providing only an approximate representation of system behavior.

A comparative overview of the main models used in synchronous machine fault analysis is presented in Table 1.

Table 1. Comparison of synchronous machine fault analysis models.

	Criterion	Proposed Model	Classical Model	Reduced Order Model
Accuracy	High	High	Medium	Low
Computational Speed	Fast	Slow	Slow	Very Fast
Complexity	Complex	Complex	Moderate	Simple
Applicability	Single- and Three-Phase Transient Analysis		Three-Phase, Steady-State Analysis	Basic Fault Study

The table highlights the differences among the proposed, classical, and simplified models in terms of key criteria such as accuracy, computational speed, complexity, and applicability. In terms of accuracy, the proposed model offers the highest fidelity, capturing all relevant electromechanical interactions. The simplified model, in contrast, provides reduced accuracy because it ignores dynamic rotor behavior and the influence of damper windings [47].

Regarding computational speed, the reduced-order model excels. Its simplicity allows for very fast calculations, making it particularly suitable for real-time applications and embedded system simulations. While the proposed model delivers far greater precision, it requires solving a complex system of nonlinear differential equations, resulting in longer computation times. The classical phase-domain model occupies an intermediate position, offering moderate accuracy and computational effort.

From the perspective of complexity, the reduced-order model is straightforward to implement, as it relies on fixed parameters and avoids the integration of electromechanical interactions. The classical model requires handling rotor-dependent inductances, while the proposed d–q approach necessitates advanced numerical integration and the management of interdependent electromagnetic and mechanical variables.

The applicability of each model further emphasizes its practical role. The proposed model is suitable for detailed transient analyses, complex fault studies, and parameter optimization tasks, providing comprehensive insight into system behavior. The classical phase-domain model remains useful for preliminary evaluations and simple protection studies, whereas the reduced-order model is primarily applied to rapid estimates, real-time simulations, and simplified control algorithms.

Technically, the reduced-order model simplifies the system by treating inductances as constants, neglecting dynamic effects, and approximating overall machine behavior. While this expedites computation, it introduces significant limitations: peak currents may be underestimated, oscillatory behavior cannot be captured, and little information on transient stability is available. Nonetheless, its key advantage is computational speed, which makes it highly effective for scenarios where execution time is critical, such as embedded control systems or online monitoring platforms.

In summary, a combined analysis of the three models reveals a clear trade-off between accuracy, complexity, and speed. The proposed model stands out as the most comprehensive and reliable, particularly for modern power system studies involving stability assessment, protection design, and machine optimization. The classical phase-domain model occupies a middle ground, offering reasonable accuracy and moderate computational requirements. Finally, the reduced-order model, while the fastest, sacrifices precision and is best suited for preliminary evaluations or applications demanding minimal computational overhead.

4. Simulation and Results

The developed model was implemented in MATLAB R2024b/SIMULINK to accurately replicate the dynamic behavior of both single-phase and three-phase synchronous machines. The model incorporates stator and rotor resistances, leakage and mutual inductances, as well as excitation and damper windings, ensuring a detailed representation of machine dynamics.

To improve reproducibility and facilitate interpretation of the obtained transient responses, the representative machine parameters and numerical simulation settings adopted throughout the study are summarized in Table 2. The selected values correspond to a medium-sized laboratory synchronous machine frequently employed in transient-performance investigations and are representative of typical operating conditions reported in the literature.

The parameter set presented in Table 2 was employed consistently throughout all simulation scenarios. Prior to fault initiation, the machine operated under rated steady-state conditions with constant excitation voltage and synchronous rotor speed.

For the single-phase inductance matrix, the selected parameters satisfy the positive-definiteness condition $L_s\ L_f - M^2(\theta) > 0$ which guarantees a physically meaningful inductance matrix and ensures numerical stability throughout the simulations.

The selected parameter values ensure realistic transient-current amplitudes and damping characteristics while maintaining numerical stability during fault simulations. Identical parameters and initialization conditions were used in both MATLAB/Simulink and FORTRAN implementations in order to ensure a meaningful validation procedure.

The simulations were conducted under nominal operating conditions and at constant synchronous speed. Prior to the initiation of any fault scenario, the machine was assumed to have reached a steady-state operating regime with rated excitation applied. Short-circuit events were subsequently introduced only after the steady-state operating point had been fully established, ensuring consistent initial conditions across all simulation cases.

The fault studies presented in this work are limited to line-to-line short-circuit conditions. Single-line-to-ground faults were intentionally excluded because the adopted two-axis synchronous-machine formulation does not include zero-sequence components, neutral grounding, or grounding-path representation.

The governing system of differential equations was solved using adaptive Runge–Kutta numerical integration schemes implemented within the MATLAB/Simulink environment. For validation purposes, an identical mathematical formulation, along with the same operating assumptions and initialization procedures, was implemented independently in FORTRAN. This parallel implementation ensured a consistent and reliable comparative framework for assessing numerical accuracy and model fidelity.

In both simulation environments, the monitored variables included stator currents, field currents, electromagnetic torque, rotor angular position, and damping-related dynamic behavior during fault transients. The comparison between the two implementations revealed a maximum deviation of less than 3% in the transient current response under identical operating conditions, thereby confirming a high degree of agreement between the numerical solutions and validating the robustness of the proposed modeling approach.

Table 2. Synchronous generator parameters.

Parameter	Symbol	Value
Rated apparent power	Sn	10 kVA
Rated line voltage	Vn	400 V
Rated frequency	fn	50 Hz
Number of poles	p	4
Rated speed	nr	1500 rpm
Stator resistance	Rs	0.42 Ω
Field winding resistance	Rf	3.8 Ω
Stator leakage inductance	Lls	6.5 mH
Field winding inductance	Lf	0.82 H
Mutual inductance amplitude	M_0	0.38 H
Direct-axis synchronous inductance	Ld	0.92 H
Quadrature-axis synchronous inductance	Lq	0.87 H
Damper winding resistance	Rd	0.18 Ω
Damper winding inductance	Ldamp	0.11 H
Excitation voltage	Vf	110 V
Rotor inertia	J	0.12 kg·m^2
Friction coefficient	B	0.002 N·m·s/rad
Fault application time	tf	0.10 s
Simulation duration	tsim	1.0 s
Numerical solver	–	ode45 (Runge–Kutta)
Relative tolerance	–	10^{-6}
Maximum integration step	–	10 µs
Stator self-inductance	Ls	0.92 H

Fault conditions consisting of line-to-line short circuits were introduced to investigate the transient response of the synchronous machine under asymmetric fault conditions. The simulations capture the evolution of stator and rotor currents, electromagnetic torque, and rotor angle during the fault transient.

To validate the accuracy of the MATLAB/SIMULINK implementation, results were compared with a reference FORTRAN model. The observed deviations were minimal, remaining below 3%, confirming both the correctness of the modeling approach and the reliability of the numerical integration methods employed.

The simulations presented in this work were intentionally performed using a single representative parameter set in order to investigate the physical behavior of the proposed model under identical operating conditions. Consequently, the objective of this study is model validation rather than a comprehensive parametric sensitivity analysis. Investigation of leakage-inductance variations, alternative numerical solvers, and extended benchmark comparisons constitutes a valuable direction for future work.

This simulation framework provides a robust platform for evaluating machine responses under various fault conditions and forms a solid basis for further studies in protection design, transient stability analysis, and parameter optimization.

4.1. Transient Regimes of the Stator Current

Following the occurrence of a short-circuit, the stator current exhibits three distinct transient regimes that reflect the physical dynamics of energy flow and dissipation in the machine. In the subtransient regime (0–10 ms), the current reaches a high peak due to the influence of the machine's subtransient reactance X_d'' and the sudden release of magnetic energy stored in leakage fluxes. As the fault progresses, the machine enters the transient regime (approximately 0.1–0.3 s), during which the current decays exponentially as energy is dissipated in resistive and rotor paths, producing damped oscillations. Finally, the steady-state regime develops, where only the sinusoidal component at the system frequency (50 Hz) remains.

Mathematically, the stator current $i_s(t)$ can be decomposed into a periodic (AC) component and an aperiodic component that represents the DC offset, the latter being dependent on the initial angle and moment of fault initiation. The DC offset arises because the stored magnetic energy cannot change instantaneously, leading to characteristic current overshoots and subsequent damping behavior during transient processes [48].

Figure 10—Stator Current Transient Response Following a Short-Circuit illustrates this typical evolution of the stator current, with clear demarcations of subtransient, transient, and steady-state intervals.

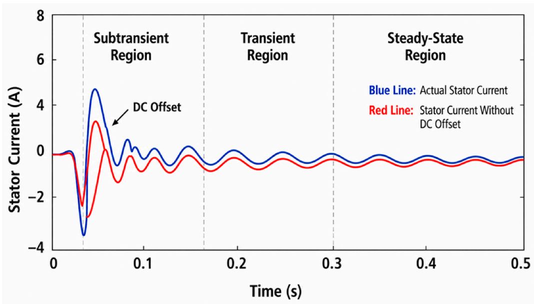

Figure 10. Stator current response during a short-circuit: subtransient spike, transient decay, and steady-state sinusoid.

As shown in Figure 10, the total current waveform comprises a high-amplitude subtransient peak, followed by damped transient oscillations and a final steady sinusoidal component. Understanding these regimes is essential for the accurate design of protection relays and for assessing transient stability margins in synchronous machines under fault conditions [49].

4.2. Single-Phase Machine

For the single-phase synchronous machine, the transient response is strongly influenced by the rotor position at the instant of fault occurrence. According to the adopted mutual-inductance model $M(\theta) = M_0\cos(\theta)$, the magnitude of the mutual inductance reaches its maximum at $\theta = 0$ and $\theta = \pi$, corresponding to the strongest electromagnetic coupling between the stator and rotor windings. Conversely, the mutual inductance becomes zero at $\theta = \pi/2$ and $\theta = 3\pi/2$, where the direct magnetic coupling vanishes.

In this configuration, the stator current rises significantly to maintain continuity of the magnetic flux, in accordance with Lenz's law.

Conversely, when the rotor position corresponds to $\theta = \pi/2$ or $3\pi/2$, the mutual inductance is zero. Under these conditions, the initial electromagnetic coupling between the stator and field winding is minimized, leading to lower fault-current amplitudes under otherwise identical operating conditions.

This behavior can be explained by the variation in mutual inductance with rotor position and the principle of flux linkage conservation.

The obtained results clearly demonstrate that the peak short-circuit current is strongly dependent on the initial rotor position at the instant of fault inception.

The largest transient current amplitudes are obtained when the fault is initiated at rotor positions corresponding to the maximum magnitude of the mutual inductance ($\theta = 0 \; or \; \pi$). Under these conditions, the stator and field circuits share the strongest magnetic coupling prior to fault inception. Owing to the continuity of magnetic flux linkages, the electrical state variables cannot change instantaneously at the fault instant. Consequently, the redistribution of the stored magnetic energy produces the highest transient current peaks. This mechanism should be distinguished from the maximum rate of change in mutual inductance, which is proportional to $\frac{dM}{dt} = -M_o \omega \sin(\theta)$. The latter governs the variation in the mutual inductance during rotor motion but is not the quantity determining the initial current peak at the instant of fault application.

Conversely, lower peak current values are observed when the relative angular displacement between the rotor and stator results in reduced magnetic coupling. This behavior is directly associated with the rotor-position-dependent variation in mutual inductance, which determines the initial distribution of magnetic energy stored within the machine prior to fault occurrence.

At the instant of short-circuit initiation, the conservation of flux linkages imposes continuity constraints on the electromagnetic state variables, leading to transient current responses that depend strongly on the instantaneous rotor angle. Consequently, the fault-current waveform is governed not only by the electrical parameters of the machine, such as winding resistances and inductances, but also by the electromechanical configuration existing at the moment of fault application.

These findings confirm that rotor position represents a critical factor in the accurate prediction of short-circuit transients and should therefore be explicitly considered in dynamic fault analyses, protection-system studies, and transient stability assessments involving synchronous machines.

Physically, the distribution of magnetic flux between the rotor and stator depends on their relative positions, which affects the instantaneous inductance and the stored electromagnetic energy [50].

Therefore, the transient-current magnitude immediately after fault inception is primarily determined by the initial magnetic-energy distribution imposed by the rotor position and the continuity of the flux linkages, whereas the time derivative of the mutual inductance influences the subsequent transient evolution after the fault has been established.

As shown in Figure 11, the stator current exhibits higher peaks when the rotor is initially positioned at $\theta_0 = \pi/2$ and $3\pi/2$, while the response is significantly lower for rotor positions of 0 and π, reflecting the effect of mutual inductance and flux linkage on the transient behavior.

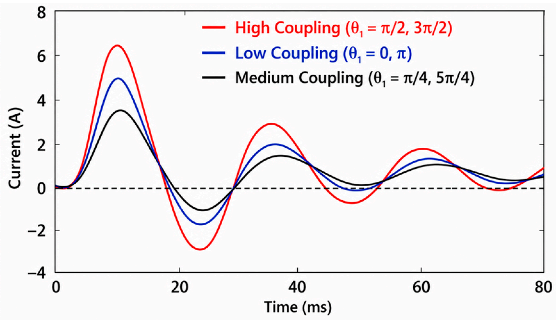

Figure 11. Effect of Rotor Position on Transient Stator Current in a Single-Phase Machine.

4.3. Three-Phase Machine and the Effect of Damper Windings

The present simulations include the complete synchronous-machine model incorporating the damper windings. The observed transient behavior is therefore representative of the complete machine configuration used throughout this study. Since simulations without damper windings were not included in the present work, the influence of the damper circuits is discussed qualitatively on the basis of the electromagnetic model rather than through a dedicated comparative analysis. A systematic comparison between configurations with enabled and disabled damper windings under identical operating conditions is considered an important extension of the present work and will be addressed in future research.

The main characteristics of the simulated line-to-line short-circuit response are:

- Very high initial current, potentially 8–10 times the rated value
- Presence of a DC offset in the stator current
- Rapidly damped oscillations
- Stabilization within ~0.08–0.2 s

The rotor's initial position ($\theta_0 = 0, \pi/2, \pi, 3\pi/2$) also affects the transient behavior: the polarity of the DC offset changes depending on the rotor angle, and the initial current amplitude varies slightly [51].

As shown in Figure 12, the stator current exhibits a high initial peak followed by rapidly damped oscillations, with a DC offset whose polarity depends on the initial rotor position. All simulations presented in this paper were performed using the same machine parameters and complete winding configuration. Consequently, the results should be interpreted as the transient response of the complete synchronous-machine model rather than as a parametric comparison between different damper-winding configurations.

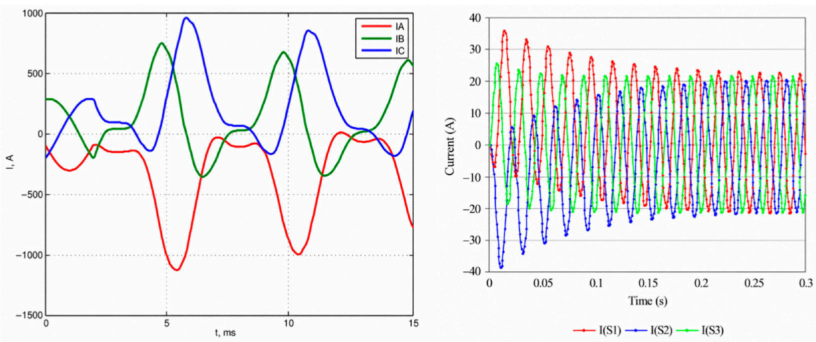

Figure 12. Stator Current Response during a Line-to-Line Short-Circuit with Damper Windings.

4.4. Physical and Energetic Interpretation

At the moment of a short-circuit, the magnetic energy stored in the machine cannot vanish instantaneously. This energy is converted into large electric currents, limited only by the machine's reactance. The interaction between the main flux and the leakage fluxes determines the precise shape of the stator current waveform [52].

The total stator current can be interpreted as the sum of two components:

- Forced component: sinusoidal current corresponding to the steady-state regime
- Free component: damped oscillations resulting from transient energy stored in the magnetic fields

Damper windings play a critical role in energy management:

- They induce currents opposing flux variations
- They dissipate transient energy
- They reduce oscillation amplitude
- They increase overall system stability

According to the adopted synchronous-machine model and established electromagnetic theory, damper windings contribute to the dissipation of transient energy and to the attenuation of oscillatory components. However, the present work does not include a dedicated numerical comparison between machine configurations with enabled and disabled damper windings.

Figure 13 illustrates the AC sinusoidal component and the decaying free (damped) component, with labeled axes for current (A) and time (ms or s).

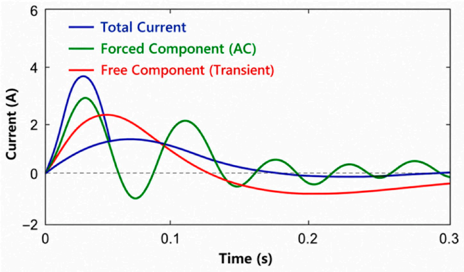

Figure 13. Decomposition of Stator Current into Forced and Free Components during a Short-Circuit.

4.5. Technical Conclusion

The analysis clearly shows that the short-circuit current is highly dependent on the rotor angle. Three-phase machines exhibit greater stability due to the presence of internal damping, and simulation results obtained in MATLAB/SIMULINK closely match those from the FORTRAN model. These findings are crucial for designing reliable protection systems and for accurately evaluating electromechanical stresses under fault conditions. In practical terms, the transient response is critically influenced by rotor position, and three-phase machines maintain higher stability thanks to their inherent damping. The consistency between MATLAB/SIMULINK and FORTRAN results provides confidence in the modeling approach, supporting tasks such as protective device design, equipment sizing, and stability analysis under fault conditions.

4.6. Model Limitations and Future Experimental Validation

Despite the comprehensive analytical and numerical framework developed in this study, several limitations should be acknowledged. The present investigation is primarily based on mathematical modeling and numerical simulation of synchronous-machine short-circuit transients, without direct experimental validation. Although the adopted models are derived from well-established electromagnetic principles and their numerical implementation has been verified through cross-comparison between MATLAB/Simulink and FORTRAN environments, the absence of laboratory measurements limits the ability to fully assess the influence of practical operating conditions and non-ideal machine characteristics.

Consequently, the results presented herein should be interpreted as the outcome of a validated numerical investigation rather than a complete experimental characterization of synchronous-machine transient behavior. Certain physical phenomena, including magnetic saturation, manufacturing tolerances, temperature-dependent parameter variations, mechanical losses, and measurement uncertainties, have not been explicitly considered within the scope of the current study. These factors may affect the transient response of real machines and could lead to deviations between simulated and experimentally observed behavior.

Another limitation arises from the use of lumped-parameter machine models, which provide an efficient representation of the dominant electromechanical dynamics but may not fully capture localized electromagnetic effects, complex flux distributions, or spatial harmonics occurring within the machine structure. While such simplifications are appropriate for transient stability studies, protection analysis, and fault-current evaluation, they may not accurately represent all electromagnetic interactions occurring during severe fault conditions.

Future research will therefore focus on the experimental validation of the proposed methodology using a dedicated laboratory-scale synchronous-machine test platform. Controlled short-circuit experiments will be performed to verify the predicted transient current waveforms, electromagnetic torque oscillations, rotor-angle dynamics, and damping characteristics. In addition, finite-element simulations using ANSYS Maxwell will be conducted to complement the analytical model and provide a higher-fidelity representation of machine behavior. Such analyses will enable the investigation of magnetic saturation effects, detailed flux-density distributions, localized electromagnetic phenomena, and practical measurement constraints that cannot be fully addressed through lumped-parameter modeling alone.

The combined use of experimental measurements and finite-element benchmarking is expected to further enhance the accuracy and applicability of the proposed framework, providing a more complete understanding of synchronous-machine transient phenomena and supporting the development of improved protection, monitoring, and stability assessment methodologies for modern power systems.

5. Conclusions

Synchronous machines remain fundamental components of modern power systems, serving not only as primary electromechanical energy converters but also as key elements for voltage regulation and grid stability. Their direct coupling to the network makes them highly sensitive to disturbances, particularly short-circuit faults, which induce severe transient regimes characterized by high-magnitude currents, strong electromagnetic forces, and significant electromechanical interactions.

This study demonstrates that accurate analysis of fault-induced transients requires rigorous mathematical modeling capable of capturing the coupled dynamics of stator and rotor circuits. The initial single-phase formulation provides valuable physical insight into flux redistribution and electromagnetic coupling mechanisms. However, the extension to three-phase systems using the d–q transformation is essential for achieving analytical tractability and numerical efficiency. By transforming the system into a rotating reference frame, time-varying inductances are eliminated, enabling a clearer interpretation of machine dynamics and facilitating state-space representation.

A key outcome of the analysis is the inherently nonlinear and time-varying nature of the system. The position-dependent mutual inductance introduces a strong dependency of the transient response on the rotor angle, making the fault current amplitude and waveform highly sensitive to the initial operating conditions. This behavior is consistently validated through both analytical derivations and simulation results.

The transient stator current evolution is shown to consist of three distinct regimes: subtransient, transient, and steady-state. The subtransient interval is dominated by high initial current peaks governed by subtransient reactance and the rapid release of stored magnetic energy. This is followed by a transient decay phase characterized by damped oscillations due to energy dissipation in resistive and rotor circuits. Finally, the system reaches a steady-state regime where only the fundamental frequency component persists. The presence of a DC offset component further highlights the continuity constraint of magnetic flux linkages at the instant of fault initiation.

The complete machine model adopted in this study includes damper windings, allowing the simulation of subtransient current behavior under fault conditions. The obtained results are consistent with the expected damping action of damper circuits reported in the literature. However, because the present investigation was performed using a single machine configuration, no direct quantitative comparison between simulations with enabled and disabled damper windings is presented. Such a comparative assessment represents an important topic for future work. The proposed analytical framework provides a consistent representation of synchronous-machine transient behavior and has been validated through independent MATLAB/Simulink and FORTRAN implementations. The results demonstrate the capability of the model to reproduce the influence of rotor position and damper windings under identical operating conditions. Although the present study is not intended as a comprehensive parametric sensitivity investigation, it establishes a validated basis for future analyses involving parameter variation and benchmark comparisons.

The classical phase-domain model offers moderate accuracy with simpler implementation but lacks the ability to clearly separate transient components. The reduced-order model, while computationally efficient, neglects critical dynamic effects and is therefore limited to approximate or real-time applications.

Simulation results obtained using MATLAB/Simulink show strong agreement with reference FORTRAN implementations, with deviations below 3%, confirming the validity and robustness of the proposed modeling framework. Time-domain simulations were performed using the MATLAB ODE45 Runge–Kutta solver with the numerical settings described in Section 3. These settings provided stable numerical integration of the proposed linear time-varying model throughout the investigated transient events.

From a practical perspective, the findings of this study have direct implications for power system engineering. Accurate prediction of transient currents and electromechanical stresses is crucial for the proper sizing of protection devices, insulation coordination, and mechanical design. Furthermore, the sensitivity of the transient response to rotor position and system parameters highlights the need for detailed modeling in stability assessment and fault analysis.

In conclusion, the integration of analytical modeling and numerical simulation provides a comprehensive framework for understanding synchronous machine behavior under fault conditions. The proposed approach offers high accuracy and physical insight, making it a valuable tool for advanced power system analysis, control design, and protection strategy development, particularly in the context of increasingly complex and dynamic electrical networks.

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