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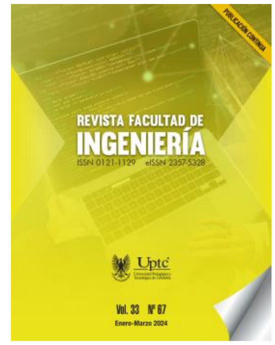

Advancements in Three-Phase Short-Circuit Fault Computation for Power System Generators: A Comprehensive Review

Germán-Antonio Guevara-Velandia[1]
José-Danilo Rairán-Antolines[2]

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Abstract

The Synchronous Machine (SM) representation is crucial for understanding the power system's behavior during transient states, particularly in stability and short circuit studies. The SM is typically modeled using complete models (structure and parameters) that simulate its transient state via a three-phase short-circuit fault. This

[1] M. Sc. Universidad Distrital "Francisco José de Caldas" (Bogotá-Distrito Capital, Colombia). gaguevarav@udistrital.edu.co. ORCID: 0009-0004-7262-010X
[2] Ph. D. Universidad Distrital "Francisco José de Caldas" (Bogotá-Distrito Capital, Colombia). drairan@udistrital.edu.co. ORCID: 0000-0002-1213-7333

paper reviews the current state of the art in the SM representation, focusing on its model structure and parameter determination through test-measurement techniques. Most SM research is centered on these two areas. Research on simulating empirical three-phase short-circuit faults involves two approaches: computing with an empirical short-circuit function and numerical integration using Electromagnetic Transient Programs (EMTP), which show machine behavior through magnitude curves over time. However, current computational limitations prevent analytical descriptions of the SM behavior in transient states. Therefore, the focus of research should be on determining a closed-form solution for the frequency response test, also known as the SSFR, which provides the most information about the SM behavior.

Keywords: current computation; power system generator; short-circuit fault; three-phase fault.

Avances en el cálculo de la falla de corto circuito trifásica para generadores de sistemas de potencia: una revisión

Resumen

La representación de la máquina sincrónica, MS, es de suma importancia cuando se desea conocer el comportamiento del sistema de potencia en estado transitorio, de lo cual se ocupan los estudios de cortocircuito y estabilidad. En el avance de este conocimiento la MS es representada por variados modelos completos (estructura y parámetros) simulando su estado transitorio por condición de falla de cortocircuito trifásico. Esta es la temática que se aborda en este artículo a manera de revisión del estado del arte. La revisión muestra que buena parte de la investigación en la representación de la MS se enfoca en las estructuras de modelo y las técnicas de medición mediante ensayos para obtener datos conducentes a evaluar sus parámetros. La investigación en simulación de las corrientes de falla trifásica se enmarca, de una parte, por el cálculo mediante una función de cortocircuito empírica, y de otra por integración numérica, mediante programas de transitorios electromagnéticos, EMTP, los cuales presentan el comportamiento a través de las curvas de magnitud en el tiempo. Entonces, las limitaciones actuales de cálculo impiden describir analíticamente el comportamiento de la MS en estado transitorio, así se concluye que la investigación debe orientarse a determinar la forma cerrada para el ensayo que ofrece más información de la MS, el de respuesta en frecuencia SSFR.

Palabras clave: cálculo de la corriente; falla de cortocircuito; falla trifásica; generador del sistema de potencia.

Avanços no cálculo de faltas de curto-circuito trifásico para geradores de sistemas de potência: uma revisão

Resumo

A representação da máquina síncrona, MS, é de extrema importância quando se deseja conhecer o comportamento do sistema de potência em estado transitório, que é o que tratam os estudos de curto-circuito e estabilidade. No avanço deste conhecimento, o MS é representado por diversos modelos completos (estrutura e parâmetros) simulando seu estado transitório devido a uma condição de falta de curto-circuito trifásico. Este é o tema abordado neste artigo como uma revisão do estado da arte. A revisão mostra que grande parte da pesquisa na representação de MS concentra-se em estruturas de modelos e técnicas de medição por meio de testes para obter dados que levem à avaliação de seus parâmetros. A investigação em simulação de correntes de falta trifásicas enquadra-se, por um lado, no cálculo utilizando uma função empírica de curto-circuito, e por outro, na integração numérica, recorrendo a programas de transientes electromagnéticos, EMTP, que apresentam o comportamento através da magnitude curvas ao longo do tempo. Portanto, as atuais limitações de cálculo impedem descrever analiticamente o comportamento do MS em estado transitório, concluindo-se assim que a pesquisa deve ter como objetivo determinar a forma fechada para o teste que oferece mais informações sobre o MS, a resposta em frequência do SSFR teste.

Palavras-chave: cálculo atual; falha de curto-circuito; falha trifásica; gerador de sistema de potência.

I. INTRODUCTION

This paper outlines the process of simulating the SM behavior in transient states. Therefore, a complete model is taken to the three-phase short-circuit condition and solved [1, 2]. If the complete model's solution is unknown in a deterministic way, numerical integration through EMTP is used [3-12]. EMTP (stands for a family of Electromagnetic Transient Programs) simulates machine behavior through magnitude curves of the three-phase short-circuit fault over time. In contrast, the solution yields the "short-circuit function," allowing for a closed-form solution, as demonstrated in [13]. Obtaining the complete model's solution for a SM in transient states is known as computing the three-phase short-circuit currents [14, 15]. An important goal with the presentation of this review is to reduce the time that a researcher or any other reader may need to understand the main problems in the research field. At the same time, this review serves as an inspiration for coming up with new research studies.

In this paper, we divide the computation of the three-phase short-circuit currents into three parts based on the modeling of the SM. Firstly, the conceptual framework of the SM model structures as Ordinary Differential Equations (ODEs) [16, 17]. This framework is the theoretical basis for short-circuit and stability studies in power systems [18, 19]. Starting from the model structure in the phase domain or "*abc* domain" [20, 21] and using the "two-axis theory" [22, 23], we derive the model structure for the machine in the "*dq* domain." Secondly, the tests applied to the generator to obtain machine data [24], including three tests: sudden three-phase short-circuits (SSC) [25-27], load rejection (LR) [28], and Standstill Frequency Response (SSFR) [29-35] are discussed. Thirdly, the simulation of the SM behavior in transient states for the three-phase fault [36, 37, 38] is presented. The simulation stage takes two paths: developing EMTP programs to solve the complete model in the "*abc* domain," with a focus on parameter estimation [4, 10], and inventing new ways to determine machine parameters in the "*dq* domain," including the effect of the saturation curve [39-43].

Discretization in time in EMTP has made it difficult to solve electromagnetic transients in real power systems of significant size within a reasonable time.

Additionally, incomplete information from the SSC test, which only provides direct axis information, combined with the low parametrization and empirical function of short circuit in its model, limits the analytical description of computation results.
The computation of the SM's transient state following a three-phase short-circuit fault aims to improve EMTP models by accounting for saturation effects. However, a more significant advancement would be pursuing a closed-form solution, as progress has already been made in this direction. For instance, a deterministic solution for the machine model's "*dq* domain" under three-phase fault conditions has been reported in [44]. This deterministic computation would contribute to a closed-form solution using information obtained from the SM's SSFR test data.

II. Modeling the Synchronous Machine

According to [2], a complete synchronous-machine model comprises a structure and its parameter values. The structure is defined by its form (lumped-parameter equivalent, transfer functions, or ODE) and its order (the number of equivalent rotor windings), while the parameters are determined from those values that best match the behavior of the model to the measured behavior of the machine, as represented by the data. With the complete SM model, it is possible to simulate any operating condition or specific dynamic state of the machine.

A. Conceptual Framework about Structures of the Machine Model in the Form of an ODE

The two parts of a SM's structure are magnetically interdependent. Thus, the formulation of its behavior requires the definition of a coordinate axis of reference. Among the various possibilities for the reference, only two have certain advantages: a) the stator-fixed axis (referred to as *abc*) in which the main axis aligns with the magnetic axis of phase *a*, and a d axis coincides with the magnetic axis of the rotor rotating at speed ω_s relative to the fixed axis *a*; b) the rotor-located axes (referred to as 0*dq*) in which the main axis aligns with the magnetic axis of the field winding, *d*, but shifted at an angle δ depending on the load so that θ in Figure 1 is $\omega t+\delta+\pi/2$ (refer to [15]). Additionally, Figure 1 shows the windings of the SM and the two reference axis systems.

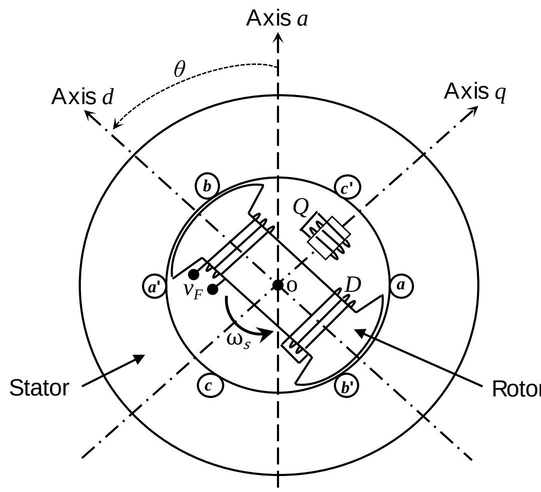

Fig. 1. Representation of the windings in the synchronous machine.

1) Model Structure of the Machine in the ABC Domain. The formal theoretical model of the SM assumes v_F and i_F as constants in steady state, while setting i_D and i_Q to zero for the damper windings. Figure 2 displays six windings, each with a resistor (R_i), self-inductance (L_i), and mutual inductances (dots in Figure 2) for characterization. The structure of the model comprises mutually coupled equivalent circuits in either phase-domain or *ABC* domain.

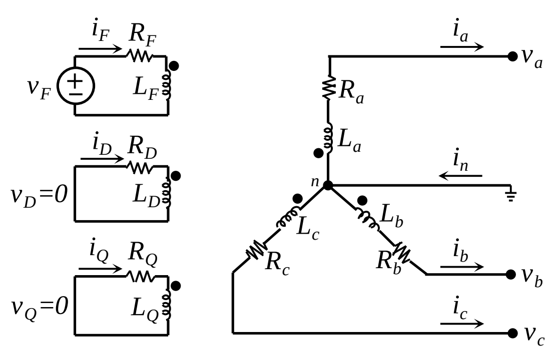

Fig. 2. Mutually coupled circuits of a SM in the *abc* domain.

According to the structure in Figure 2, the following expression represents the voltage general equation.

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$$\begin{pmatrix} v_a \\ v_b \\ v_c \\ -v_F \\ 0 \\ 0 \end{pmatrix} = -\begin{pmatrix} R_a & 0 & 0 & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 & 0 & 0 \\ 0 & 0 & R_a & 0 & 0 & 0 \\ 0 & 0 & 0 & R_F & 0 & 0 \\ 0 & 0 & 0 & 0 & R_D & 0 \\ 0 & 0 & 0 & 0 & 0 & R_Q \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \\ i_F \\ i_D \\ i_Q \end{pmatrix} - \frac{d}{dt} \begin{pmatrix} \psi_a \\ \psi_b \\ \psi_c \\ \psi_F \\ \psi_D \\ \psi_Q \end{pmatrix} \quad (1)$$

The self and mutual inductances of the machine determine the flux linkages between the stator and rotor. Thus, in (1)

$$\begin{pmatrix} \boldsymbol{\psi}_{abc} \\ \boldsymbol{\psi}_{FDQ} \end{pmatrix} = \begin{pmatrix} \mathbf{L}_{ss} & \mathbf{L}_{sr} \\ \mathbf{L}_{rs} & \mathbf{L}_{rr} \end{pmatrix} \begin{pmatrix} \mathbf{I}_{abc} \\ \mathbf{I}_{FDQ} \end{pmatrix} \quad (2)$$

the vectors $\boldsymbol{\psi}_{abc}$ and $\boldsymbol{\psi}_{FDQ}$ consist of the instantaneous values of fluxes in the windings, while $\mathbf{I}_{abc}$ and $\mathbf{I}_{FDQ}$ represent the current's instantaneous values in those windings. The subscripts s and r in the inductances **L** indicate stator and rotor, respectively. The submatrix $\mathbf{L}_{sr}$ contains the mutual inductances between the stator and rotor, and $\mathbf{L}_{sr} = \mathbf{L}_{rs}^{\mathrm{T}}$.

When the reference axes are fixed in the stator, as illustrated in Figure 1, the magnetic circuit of the machine varies depending on the rotor's position. Most inductances rely on the angle θ, representing the angle between the magnetic axis of phase a in the stator and axis d in the rotor. Equations (3), (4), and (5) display $\mathbf{L}_{ss}$, $\mathbf{L}_{sr}$, and $\mathbf{L}_{rr}$ for the salient pole generator.

$$\mathbf{L}_{ss} = \begin{pmatrix} L_s + L_m \cos 2\theta & -M_s + L_m \cos 2(\theta - 120°) & -M_s + L_m \cos 2(\theta + 120°) \\ -M_s + L_m \cos 2(\theta - 120°) & L_s + L_m \cos 2(\theta - 120°) & -M_s + L_m \cos 2\theta \\ -M_s + L_m \cos 2(\theta + 120°) & -M_s + L_m \cos 2\theta & L_s + L_m \cos 2(\theta + 120°) \end{pmatrix} \quad (3)$$

Equation (3) presents L_s as the constant component of L_a, which does not depend on the angle θ, and L_m as the coefficient of L_a's variable component. L_m relies on θ and, therefore, varies with time. The self-inductance for phases *b* and *c* account for a 120º offset between the windings concerning phase *a*. M_s is the constant component of the mutual inductance L_{ba}, independent of θ. By appropriately considering the 120º offset, we can determine L_{ca} and L_{bc}. Moreover, L_{ab} equals L_{ba}, L_{bc} equals L_{cb}, and L_{ac} equals L_{ca}.

In a cylindrical poles machine, L_m equals zero, meaning L_a, L_b, and L_c are identical to L_s. Therefore, the self-inductances are constant and independent of the rotor's angular position, and the mutual inductances are equivalent to $-M_s$.

$$\mathbf{L}_{sr} = \begin{pmatrix} M_F \cos\theta & M_D \cos\theta & M_Q \operatorname{sen}\theta \\ M_F \cos(\theta - 120°) & M_D \cos(\theta - 120°) & M_Q \operatorname{sen}(\theta - 120°) \\ M_F \cos(\theta + 120°) & M_D \cos(\theta + 120°) & M_Q \operatorname{sen}(\theta + 120°) \end{pmatrix} = \mathbf{L}_{rs}^{T} \quad (4)$$

Equation (4) describes $M_F = N_F N_s \lambda_d$; $M_D = N_D N_s \lambda_d$ y $M_Q = N_Q N_s \lambda_q$, where N_F, N_D, N_Q, and N_s correspond to the number of turns in the field winding, damping winding in the *d*-axis, damping winding in the *q*-axis, and stator winding, respectively. The symbol λ represents the permeance of the medium in which the flux circulates.

$$\mathbf{L}_{rr} = \begin{pmatrix} L_F & M_r & 0 \\ M_r & L_D & 0 \\ 0 & 0 & L_Q \end{pmatrix} \qquad (5)$$

For both types of machines, the magnetic fluxes of the windings in the rotor are independent of the angular position, so all components of L_{rr} are constants. Nonetheless, there is a flux linkage between the field winding *F* and the direct axis damper winding *D* as they share the same axis (Figure 1). Therefore, $L_{FD} = L_{DF} = M_r$. There is no magnetic coupling between any of the windings in the direct axis (*F* and *D*) and the damping winding in the *q* axis. Consequently, $L_{FQ} = L_{QF} = L_{DQ} = L_{QD} = 0$.

Based on (3)-(5) in the general voltage equation (1) and (2), it can be concluded that the terminal voltages of the SM are described by non-linear trigonometric ODEs with time-varying coefficients dependent on the rotor position, where $\theta=\omega t+\delta+\pi/2$. This ODE structure is commonly referred to as the machine model in the time domain, also known as "phase domain" or "*abc* domain".

2) Model Structure of the Machine in the DQ Domain. The variables in the stator (phases *a*, *b*, and *c*) can be transformed into new variables with a reference frame moving with the rotor using the "theory of two axes" [22-23]. This theory allows for the transformation of the equations expressed in the static axis *abc* to the equations in the reference system 0*dq*, which rotates at a constant speed ω_s. If we assume that the rotor speed is constant, and given a balanced system, the transformed equations for the inductances are linear. However, if one of these conditions is not met, the transformed equations become non-linear, and the model must be solved by numerical discretization. Park's work has shown that the variables in the *abc* axes are related to the variables in the *dq* axes through the normalized matrix **P**, given by the following equation.

$$\mathbf{P} = \sqrt{2/3}\begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ cos\,\theta & cos(\theta - 120°) & cos(\theta + 120°) \\ sen\,\theta & sen(\theta - 120°) & sen(\theta + 120°) \end{pmatrix} \quad \therefore \quad \mathbf{P^{-1}} = \mathbf{P}^{\mathrm{T}} \qquad (6)$$

Park's transformation matrix is orthogonal, meaning that its inverse is equal to its transpose, i.e., $\mathbf{P}^{-1} = \mathbf{P}^{T}$. This property ensures that the total power is conserved during the transformation. The angle θ represents a fixed phase shift between the *abc* and *dq* reference frames at the time of transformation at $t = t_x$ at which the transformation is made. This angle is given by $\theta_x = \omega t_x$ and is constant because ω is constant. The Park transformation for the fluxes, tensions and currents of the machine are

$$\boldsymbol{\psi}_{0dq} = \mathbf{P}\boldsymbol{\psi}_{abc};\ \ \mathbf{V}_{0dq} = \mathbf{P}\mathbf{V}_{abc};\quad \mathbf{I}_{0dq} = \mathbf{P}\mathbf{I}_{abc} \tag{7}$$

Given (7) is also deduced that

$$\boldsymbol{\psi}_{abc} = \mathbf{P}^{-1}\boldsymbol{\psi}_{0dq};\qquad \mathbf{V}_{abc} = \mathbf{P}^{-1}\mathbf{V}_{0dq}; \mathbf{I}_{abc} = \mathbf{P}^{-1}\mathbf{I}_{0dq} \tag{8}$$

Equation (2) in the *dq* axes is obtained by substituting (8) for the fluxes $\boldsymbol{\psi}_{abc}$ and currents $\mathbf{I}_{abc}$, while omitting the terms $\boldsymbol{\psi}_{FDQ}$ and $\mathbf{I}_{FDQ}$. By operating $\mathbf{P}$ and $\mathbf{P}^{-1}$, as defined in (6), on the submatrix of inductances from (3) to (5), we can express (2) as shown below, noting that $\mathbf{L}_{rs}\mathbf{P}^{-1} = \mathbf{L}_{rs}\mathbf{P}^{T} = (\mathbf{P}\mathbf{L}_{sr})^{T}$.

$$\begin{pmatrix}\psi_0\\ \psi_d\\ \psi_q\\ \psi_F\\ \psi_D\\ \psi_Q\end{pmatrix} = \begin{pmatrix} L_0 & 0 & 0 & 0 & 0 & 0\\ 0 & L_d & 0 & kM_F & kM_D & 0\\ 0 & 0 & L_q & 0 & 0 & kM_Q\\ 0 & kM_F & 0 & L_F & M_r & 0\\ 0 & kM_D & 0 & M_r & L_D & 0\\ 0 & 0 & kM_Q & 0 & 0 & L_Q \end{pmatrix}\begin{pmatrix} i_0\\ i_d\\ i_q\\ i_F\\ i_D\\ i_Q\end{pmatrix} \tag{9}$$

where $L_0 = L_s - 2M_s$; $L_d = L_s + M_s + 1.5L_m$; $L_q = L_s + M_s - 1.5L_m$ y $k = \sqrt{1.5}$. From this equalities $L_s = ⅓(L_0 + L_d + L_q)$ and $L_m = ⅓(L_d - L_q)$. Equation (10) comes from the substitution of (8) and the flux matrix in (9) in (1).

$$\begin{pmatrix} v_0\\ v_d\\ v_q\\ -v_F\\ 0\\ 0\end{pmatrix} = -\begin{pmatrix} R_a & 0 & 0 & 0 & 0 & 0\\ 0 & R_a & \omega L_q & 0 & 0 & k\omega M_Q\\ 0 & -\omega L_d & R_a & -k\omega M_F & -k\omega M_D & 0\\ 0 & 0 & 0 & R_F & 0 & 0\\ 0 & 0 & 0 & 0 & R_D & 0\\ 0 & 0 & 0 & 0 & 0 & R_Q \end{pmatrix}\begin{pmatrix} i_0\\ i_d\\ i_q\\ i_F\\ i_D\\ i_Q\end{pmatrix}$$
$$-\begin{pmatrix} L_0 & 0 & 0 & 0 & 0 & 0\\ 0 & L_d & 0 & kM_F & kM_D & 0\\ 0 & 0 & L_q & 0 & 0 & kM_Q\\ 0 & kM_F & 0 & L_F & M_r & 0\\ 0 & kM_D & 0 & M_r & L_D & 0\\ 0 & 0 & kM_Q & 0 & 0 & L_Q \end{pmatrix}\frac{d}{dt}\begin{pmatrix} i_0\\ i_d\\ i_q\\ i_F\\ i_D\\ i_Q\end{pmatrix} \tag{10}$$

If the reference axes are fixed in the rotor, the voltage equation for the SM expressed in (1) and (2) takes the form of a linear ODE with constant coefficients given by (10). This is because the inductance matrix elements, which correspond to the flux linkages in (9), are independent of time. The model structure of the SM as an ODE

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in (10) defines its model in *dq* domain, which is represented in the form of mutually coupled equivalent circuits, as shown in Figure 3. Equation (10) can be expressed in a compact form as follows.

$$\mathbf{V} = -\mathbf{RI} - \mathbf{L}\frac{d}{dt}\mathbf{I} \tag{11}$$

B. Applied Tests for the SM to Obtain the Value of its Parameters

Three-phase short circuits, also known as symmetric failures, account for approximately 5% of electrical failures. These failures generate the highest current intensity, making it crucial for power systems to be protected against them. Therefore, short-circuit studies prioritize the analysis of this type of failure.

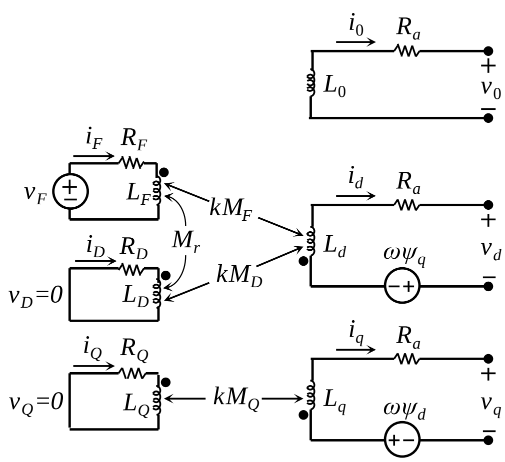

Fig. 3. Mutually coupled circuits of the SM in the *dq* domain [15].

Transient-stability studies require observation of the power angle of the SM since it is related to torque. Therefore, it becomes important to compute torque in three scenarios: 1) during the design stage of the SM and power system, 2) during a failure to ensure the current does not exceed operational limits, and 3) for a few seconds after the failure has been cleared. To compute torque, the current and magnetic flux in the SM must be simulated using models. The parameters of these models are determined using the Frequency Response test.

Tests are conducted to obtain measurements from the SM to determine its parameters. Over the years, a wide range of methods have been used to characterize the SM, which can be classified into three groups: steady-state tests, transient tests, and frequency response tests. The following is a reference to the last two categories. ***1) Sudden Three-Phase Short-Circuit Test, SSC.*** To characterize the behavior of a SM in transient state, the SSC test is performed. The SM, initially in a steady-state and open-circuit condition, is suddenly switched to an operational condition by applying a short circuit to the armature terminals, as detailed in section 11.4 of [24]. The structure of the model used for the SSC test is called the "constant voltage behind reactance" model. The equivalent network of this model is based on the constant field flux linkage theorem, which is derived from (10), as shown in Chapter 6 of [15]. The theorem's deductions involve approximations that lead to the representation of the SM in its stationary, sub-transient, and transient states using phasor diagrams and equivalent circuits to obtain the constant voltage behind impedance. In this model, when the SSC test occurs at *t*=0, the effective value of the maximum current is computed based on the envelope, with the *dc* component subtracted, as shown in Figure 4.

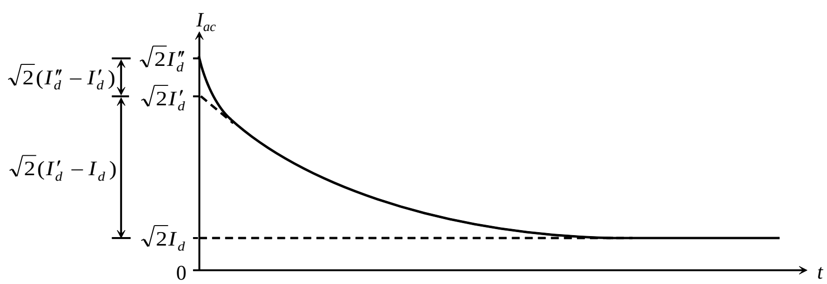

Fig. 4. Envelope of the armature current I_{ac} for the SSC fault [15].

The symmetric component I_{ac} in Figure 4, as described in (12), can be obtained from the model of constant voltage behind impedance with three simplifications: 1) neglecting the saliency and resistances of the armature windings, 2) approximating $I_a \approx I_d$, and 3) assuming a single voltage $E = E_q > E_q' > E_q''$ which leads to the assumption of constant field voltage.

$$I(t) = \frac{E}{X_d} + \left(\frac{E}{X_d'} - \frac{E}{X_d}\right) e^{\left(-\frac{t}{\tau_d'}\right)} + \left(\frac{E}{X_d''} - \frac{E}{X_d'}\right) e^{\left(-\frac{t}{\tau_d''}\right)} \quad (12)$$

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Section 11 of [24] presents (12), which describes the structure of the model of constant voltage behind reactance shown in Figure 5.

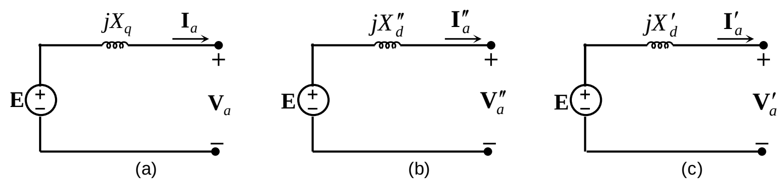

Fig. 5. Model of constant voltage behind reactance of the SM. (a) Steady state, (b) Sub transient state, and (c) Transient state.

In [24], the SSC test procedure explains how to determine the characteristic quantities X'_d, X''_d, τ'_d and τ''_d. However, these values are only obtained for the direct axis, according to (12) and its model structure shown in Figure 5. Although the values for the quadrature axis can be computed, they cannot be directly measured using these tests. Section 11.5 of [24] describes methods for obtaining parameter values from the SSC test, which involve graphical techniques such as polynomial or spline interpolation. The advances in SM theory introduced many constants [45], and the initial approximation of the parameters were subsequently eliminated [46-47].

2) Load Rejection Test. To determine the transient state of the SM, load rejection tests require sudden changes in the stator and field windings, which interrupt the armature currents of the machine under the conditions of $i_d = 0$ and $i_q = 0$. These conditions can be achieved by sub- or over-exciting the machine at a percentage of the nominal charge. Regardless, precise measurement of the rotor's angular position is necessary.

Two types of tests exist: stator-decrement tests and rotor-decrement tests [24]. The methodology for obtaining the SM parameters from these tests varies, as demonstrated in [38, 48]. However, some experts believe that the stator-decrement test is more acceptable than the rotor-decrement test [2].

3) Standstill Frequency-Response Tests, SSFR. The SSFR tests, which were introduced in the previous century, are valuable for determining characteristic quantities and the SM parameters using models of higher complexity than the voltage behind reactance. These tests are an alternative to the short-circuit test [49-

51], because, unlike the model in (12), they allow identification of the field windings. Moreover, in comparison to the SSC test, they do not require electromagnetic efforts in the SM.

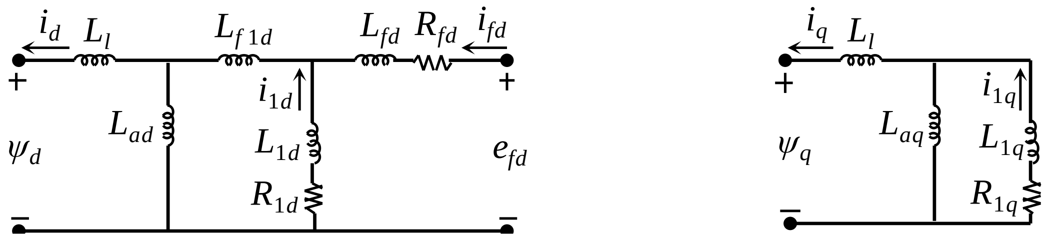

Fig. 6. Equivalent circuits referred to the stator for the 2.1 model of the SM [21].

The lumped-parameter equivalent circuit characterizes the SM's model structure in this test. It comprises a two-port network for the *d*-axis, which corresponds to the equivalent armature and field windings, and a single-port network for the *q*-axis due to the absence of rotor winding in that axis. The model structure's order is determined by the number of rotor windings in each circuit [17]. Figure 6 displays the structure of the 2.1 model, which has 2 rotor windings in the *d*-axis and 1 in the *q*-axis, among the six model structures listed in Table 1 [2]. The concept of two-port networks is expressed analytically as follows:

$$\begin{pmatrix} \psi_a(s) \\ i_f(s) \end{pmatrix} = \begin{pmatrix} L(s) & G(s) \\ sG(s) & \frac{G(s)}{L_{af0}(s)} \end{pmatrix} \begin{pmatrix} i_a(s) \\ e_f(s) \end{pmatrix} \qquad (13)$$

The transfer functions of the two-port network equation are referred to as "operational" parameters. For the direct axis, the transfer functions are as follows:

$$L_d(s) \equiv -\frac{\psi_d}{i_d}\bigg|_{e'_{fd}=0} ;\ G(s) \equiv \frac{\psi_d}{e'_{fd}}\bigg|_{i_d=0} ;\ sG(s) \equiv \frac{i'_{fd}}{i_d}\bigg|_{e'_{fd}=0}\ \ y\ \ L_{af0}(s) \equiv -\frac{e'_{fd}}{s \cdot i_d}\bigg|_{i'_{fd}=0} \qquad (14)$$

The transfer function for the quadrature axis is

$$L_q(s) \equiv -\frac{\psi_q}{i_q}\bigg|_{e'_{fq}=0} \qquad (15)$$

Although obtaining measurements for the test while the machine is online is possible [2], the usual approach for this test involves isolating the generator and bringing it to a standstill while applying steady-state sinusoidal voltages and currents to the armature and/or field winding terminals. The resulting data, corresponding to transfer

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functions (14) and (15), is saved as relations between the magnitudes and phases of voltages and currents. Specific procedures for the SSFR test are presented in [24]. The SSFR test is important for the SM because it allows the study of the machine using data for q and d axis. Making the test online implies that the generator does not get out of operation, but the required instrumentation should be more robust.

The Bode diagrams obtained from the SSFR test are used to estimate the parameters of the SM model through an optimization process to adjust the curves. Determining the parameters in terms of reactance and time constants allows for the evaluation of the model parameters in (12). Conversely, determining the parameters in terms of resistors and inductances indirectly provides the numerical values of the elements in the matrix for the model in (10).

III. Simulation of the Synchronous Machine in the Transient State

The full model of the SM can be utilized to simulate various operating conditions and dynamic states. Three-phase short-circuit failure is commonly used to simulate the transient response of the machine. On the other hand, the magnitude of the currents for the three-phase short-circuit failure can be computed using the machine with no load since the magnitude of the fault currents remains the same whether the generator is loaded or not.

To simulate the behavior of the generator in the transient state due to a three-phase short-circuit, the whole model must be adjusted to these conditions and solved. If the model has an ODE structure, solving it leads to the "short-circuit function." If this function can be determined, the closed-form solution is known. If not, numerical integration using Electromagnetic Transient Programs (EMTP) is used, resulting in curves showing the short-circuit current magnitude versus time. Alternatively, discrete-time simulation using block diagrams in software such as Simulink can also be used. The solution of the SM model in the transient state is also called the computation of the three-phase short-circuit current.

A. Solution Using EMTP Programs

Initially, the EMTP focused on proposing models that accurately reproduced transient behavior during short-circuits with improved computational efficiency, as described in [5-6], such as EMTP-RV, ATP, MicroTran, EMTDC, and NETOMAC. A comparative study of simulation techniques, such as [7] and specifically [8], reexamined the three modeling techniques for SMs using EMTP: *dq* model, phase-domain model, and voltage-behind-reactance model. It concluded that the voltage-behind-reactance model is the most precise. Currently, the development of EMTP focuses on the use of finite element algorithms [9-12], which achieve better approximations in computing the SM [3-4].

Large generators with salient poles can be accurately tested using the SSFR method [29]. The precision of the obtained parameters is verified by comparing them with two values: 1) factory values during machine design and 2) values obtained using the traditional SSC test with no load. Additionally, [29] reports comparing the measured short-circuit current waveform with the curves obtained from simulation using the SSFR machine model in an EMT software.

B. Closed-Form Solution

The SSC test is currently the preferred method of testing SMs due to three main reasons: 1) commercially, it is a classical test used for acceptance, performance testing, and parameter determination for dynamic analysis, and is performed by the factory as part of the technical information [24]. 2) The test provides sufficient information for the model with lower parametrization (X'_d, X''_d, τ'_d and τ''_d) as given by (12). 3) It provides accurate results for the behavior of the first electromagnetic oscillation. In [24], presents the short circuit function (built empirically) for the computation of the three-phase short-circuit failure of the synchronous generator with no load, which is expressed as:

$$i_a(t) = \sqrt{2}E\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)e^{\left(-\frac{t}{\tau'_d}\right)} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)e^{\left(-\frac{t}{\tau''_d}\right)}\right]sin(\omega t + \lambda)$$
$$-\sqrt{2}E\left[\left(\frac{1}{X''_d} + \frac{1}{X''_q}\right)e^{\left(-\frac{t}{\tau_a}\right)}\right]sin\lambda \qquad (16)$$

$$-\sqrt{2}E\left[\left(\frac{1}{X_d''}-\frac{1}{X_q''}\right)e^{\left(-\frac{t}{\tau_a}\right)}\right]sin(2\omega t+\lambda)$$

The computed results are only as accurate as the estimated parameter values in the equation. It is worth noting that this equation is based on simplifications and approximations, and the value for the quadrature axis is not obtained from test measurements but is instead determined by fitting the equation.

The deterministic solution of the structure model in the *dq* domain given by (10) is known. Thomas A. Lipo applied the modal theory technique, which uses eigenvalues and eigenvectors, to solve the transient condition of the SM under a three-phase failure [44]. In contrast, Gibson H. M. Sianipar presented a solution procedure in [13] that differs from the model in (10) by using the eigenvalues of the state-space system [52]. Although Sianipar's approach presents an equation of the current for the system in *dq* in terms of sums, there is no evidence of an explicit example.

IV. CONCLUSIONS

Current computing limitations prevent us from formally and completely describing the behavior of the SM in the transient state. To solve the model structure of the SM in the time domain or “phase domain” described by (1) and (2), numerical integration using EMTP is necessary due to the non-linear differential equations, which have trigonometric terms and time-variant coefficients based on the rotor position. Unfortunately, there is no known deterministic solution for these equations. The analytical description of the SM is based on an empirical equation with low parameterization, and its estimated values are obtained solely from the SSC test for direct axis components, see (12) and (16). Therefore, the analytical description of the SM in the transient state is restricted to observing the time-variant three-phase short-circuit curves and utilizing the empirical short-circuit function. The model structure of the empirical short-circuit function is a constant voltage behind reactance, which highlights the simplicity of simulating an SM.

The research should focus on determining the closed form for the SSFR test to provide more information about the SM. As shown in this paper, this test is a viable alternative to the three-phase short-circuit test for large generators. The SSFR test enables the identification of the field windings, the equivalent winding for the armature in the *q* axis, and the inclusion of a variable number of damped windings in the model structure of equivalent circuits of lumped parameters for each axis. Therefore, the SSFR test is the method that provides the most information for determining the characteristic quantities and parameters of the SM, surpassing the voltage behind reactance model in complexity. If the information from the SSFR test were used in the structure of the model given by (10), which represents all the windings of the machine by their resistance and inductance parameters and currents in the *d* and *q* axes, the analytical expression of the short-circuit function given by the closed-form solution to the structure in (10) would describe all the simultaneous and interrelated transients in the stator and rotor of the SM.

AUTHORS' CONTRIBUTION

Germán-Antonio Guevara-Velandia: conceptualization; investigation; methodology; writing-review and editing.

José-Danilo Rairán-Antolines: conceptualization; investigation; methodology; writing-original draft.

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