

## Higher order model of synchronous generator

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### ABSTRACT

Synchronous generator conventional model accurately describes only the stator circuit. Concerning the transients for rotor quantities, for example rotor voltage, rotor current, and rotor magneto-motor force, conceivable predetermined with acceptable accuracy if calculations are created on equivalent model properly on consideration of field and damper together with stator circuits. Unfortunately, it was recognized that simulated responses using conventional model with calculated machine parameters often did not match well with actual measured responses, particularly in the quantity's rotor winding. For this intention, the newly method to producing the rotor circuit is to model it as well as the lines that conventionally viewed as the partition of current paths from the physical construction. Besides the physical field and damper circuits, a third circuit for the eddy currents induced in the pole surface could also be added. The all conclusions prove the correctness of synchronous generator model.

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## 1. INTRODUCTION

Transient synchronous generator models extensively applied in many areas take the part of important parts as the beginning point of any power system stability studies. Various generator models have been developed [1]–[4]. For such analysis studies, the models of simple transient states based on the common method, such as the primary swing stability of electromechanical oscillation of the rotor, is useful but not suitable to envisage generator performance concerning control experiments; it creates dissimilar results with the measurements [5]–[8].

The hypothesis that the reciprocated inductances among armature, dampers, and field on direct axis windings are similar is the basis of conventional stability theory of the generator model. Moreover, both copper losses and machine slots are ignored and the latitudinal distribution of the stator fluxes and apertures wave are sinusoidal wave forms. The damper winding that are placed near air-gap present flux linking damper circuits whose value is nearly equal to flux linking armature. This assumption accelerates satisfactory outcomes for many stability studies particularly individuals of network side [9]–[15]. Nevertheless, once it tackles to field current explores, there is a substantial error. Concerning transient condition, the measurements of field current have exposed greater alternating amplitude [16]. Traditional model of two-axis framework designates only the armature circuit appropriately. The additional inductance that indicating the disparity between field-damper and field-armature reciprocated inductances on  $d$  axis has to be involved in the model [17]. This inductance  $X_c$  named Canay inductance, takes significant role to the leakage flux  $\Phi_c$ , shown in Figures 1(a) and 1(b) once Canay inductance is neglected, together base current of field winding and inductance of armature leakage are regarded free parameters. During assessing an identical circuit model, the residual parameters are attained for

the purpose of the model replicates same behaviour from terminal viewpoint. The leakage inductance may possibly not be equal to the value provided by the real system. One method to creating the rotor circuit is to model such effect by a low-order ladder circuit of  $RL$  branches in order to look like the complex frequency-dependent nature of the rotor's surface impedance [18]. Another approach is to model it in conjunction with that traditionally viewed the partition of current paths from the physical structure [19], [20]. In addition to both physical field and damper circuits, a third circuit for the eddy currents induced could also be inserted in the pole surface. These three current paths are in near closeness in the rotor slot.

This study describes the method whereabouts synchronous generator model for stability investigation constructed on the hypothesis that the mutual inductances among armature, dampers, and field on direct axis windings are not the same. Procedure for making the proposed equivalent model and how the advantage of proposed model compare to formerly conventional model are demonstrated. Section 2 tells research method. Section 3 describes result and analysis. While, the conclusion is described in last section.

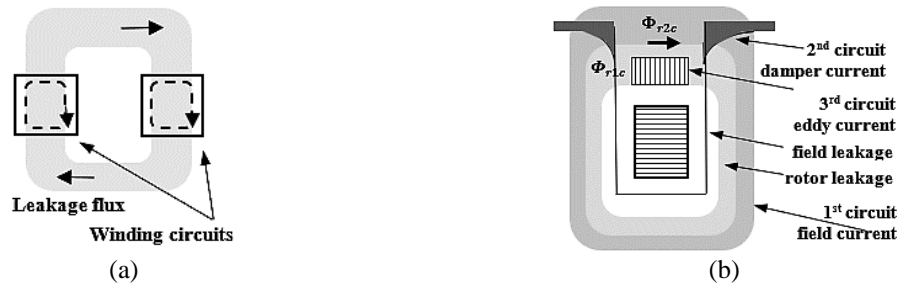


Figure 1. Structure of coupling flux components in a rotor slot (a) in theta direction and (b) in radial direction

## 2. METHOD

In order to compute the machine parameters correspondents to the actual measured responses, the rotor winding quantities, a better arrangement can be attained with enhancements in the structure of the  $d$  axis model. Shielding impacts of the damper currents and eddy currents induced in rotor can influence transient characteristics significantly. The value of this effect depends on the rotor construction.

### 2.1. Higher order model of synchronous generator

The traditional synchronous generator model is obtained from the dealings of the joined stator and rotor electric circuit by converting the variables of generator hooked on  $dq$  axes. This converting is used since the state-space equations depiction is more compact and it enables the analytical method proposed in this. The  $d$  axis is counted to be leading the  $q$  axis by 90 degrees and generator agreement is used to described the voltage equations. The traditional generator model is expressed by the corresponding circuits shown in Figure 2 with two damper windings both in  $q$  axis and in  $d$  axis, and counting one field and one damper windings, and also stator windings described through  $q0$  and  $d0$ .

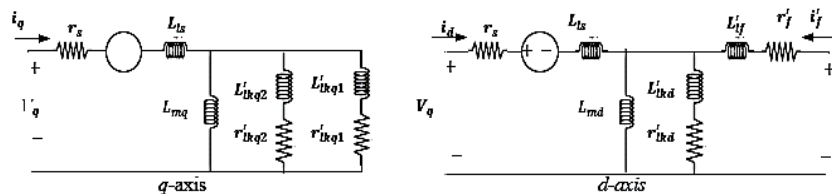


Figure 2. The traditional model of  $q$  axis and  $d$  axis equivalent circuits

Using relation between magnetic and electric circuits described in [21], [22], each of the flux components coupling that the current paths may be transformed to a mutual inductance in an equivalent circuit representative of rotor where the identity of these current paths are preserved. Figure 3 shows an improved  $qd$  circuit model with three  $q$  and three  $d$  rotor circuits. The inductance,  $L'_{r1c}$  and  $L'_{r2c}$ , are the coupling inductances associated with the flux components in the rotor slot, such as  $\phi_{r1c}$  and  $\phi_{r2c}$ . The inductances,  $L'_{l1c}$ ,  $L'_{l2c}$ , and  $L'_{l3c}$ , are from the self-leakages of the field, damper, and eddy current.

Those equation aimed at equivalent circuit through three rotor circuits in Figure 3 [23] can be shown as (1).

$$\begin{aligned}
\psi_q - \psi_{mq} &= x_{ls} i_q \\
\psi_d - \psi_{md} &= x_{ls} i_d \\
\psi_0 &= x_{ls} i_0 \\
\psi'_{kd3} - \psi_{md} &= (x'_{3c} + x'_{r2c}) i'_{kd3} + x'_{r2c} i'_{kd2} + x'_{r2c} i'_f \\
\psi'_{kd2} - \psi_{md} &= x'_{r2c} i'_{kd3} + (x'_{2c} + x'_{r1c} + x'_{r2c}) i'_{kd2} + (x'_{r2c} + x'_{r1c}) i'_f \\
\psi'_f - \psi_{md} &= x'_{r2c} i'_{kd3} + (x'_{r1c} + x'_{r2c}) i'_{kd2} + (x'_{1c} + x'_{r2c} + x'_{r1c}) i'_f \\
\psi'_{kq3} - \psi_{mq} &= x'_{lkq3} i'_{kq3} \\
\psi'_{kq2} - \psi_{mq} &= x'_{lkq2} i'_{kq2} \\
\psi'_{kq1} - \psi_{mq} &= x'_{lkq1} i'_{kq1}
\end{aligned} \tag{1}$$

The flux linkage equations of the three rotor circuits on the  $d$ -axis with mutual coupling can be described as (2).

$$\begin{bmatrix} x'_{kd3} - \psi_{md} \\ x'_{kd2} - \psi_{md} \\ x'_f - \psi_{md} \end{bmatrix} = \underbrace{\begin{bmatrix} x'_{3c} + x'_{r2c} & x'_{r2c} & x'_{r2c} \\ x'_{r2c} & x'_{2c} + x'_{r1c} + x'_{r2c} & x'_{r2c} + x'_{r1c} \\ x'_{r2c} & x'_{r1c} + x'_{r2c} & x'_{1c} + x'_{r2c} + x'_{r1c} \end{bmatrix}}_{X_r} \begin{bmatrix} i'_{kd3} \\ i'_{kd2} \\ i'_f \end{bmatrix} \tag{2}$$

Determining parameters of generator model to acceptable the frequency response test data, a correct model is decided by first selecting the suitable circuit representation. Consequently, to overlook the leakage couplings of three  $d$  axis rotor circuits is not analogous to dumping the off-diagonal term of full  $X$  matrix in (2), as diagonal values from a parameter suitable could be different between without and with off diagonal elements.

Using the inverse relation  $B = X_r^{-1}$  in [24],  $i'_{kq3}$ ,  $i'_{kq2}$ , and  $i'_f$  can be determined from the values of  $\psi'_{kd3}$ ,  $\psi'_{kd2}$ ,  $\psi'_f$ , and  $\psi_{md}$ .

$$\begin{bmatrix} i'_{kd3} \\ i'_{kd2} \\ i'_f \end{bmatrix} = \underbrace{\begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}}_B \begin{bmatrix} x'_{kd3} - \psi_{md} \\ x'_{kd2} - \psi_{md} \\ x'_f - \psi_{md} \end{bmatrix} \tag{3}$$

The equation for the stator  $qd$  currents and rotor  $q$  axis currents can be attained in the same way, namely:

$$\begin{aligned}
i_q &= \psi_q - \psi_{mq} / x_{ls} \quad i_d = \psi_d - \psi_{md} / x_{ls} \\
i'_{kq3} &= (\psi'_{kq3} - \psi_{mq}) / x'_{lkq3} \quad i'_{kq2} = (\psi'_{kq2} - \psi_{mq}) / x'_{lkq2} \quad i'_{kq1} = (\psi'_{kq1} - \psi_{mq}) / x'_{lkq1}
\end{aligned} \tag{4}$$

the flux linkages,  $\psi_{md}$  and  $\psi_{mq}$ , can be represented in term of the total flux linkages of the winding, that is:

$$\begin{aligned}
\psi_{md} &= x_{md} (i_d + i'_{kd3} + i'_{kd2} + i'_f) = x_{MD} \left( \frac{\psi_d}{x_{ls}} + \sum_{j=1}^3 b_{j1} x'_{kd3} + \sum_{j=1}^3 b_{j2} x'_{kd2} + \sum_{j=1}^3 b_{j3} \psi'_f \right) \\
\psi_{mq} &= x_{mq} (i_q + i'_{kq3} + i'_{kq2} + i'_{kq1}) = x_{MQ} \left( \frac{\psi_q}{x_{ls}} + \frac{\psi'_{kq3}}{x'_{lkq3}} + \frac{\psi'_{kq2}}{x'_{lkq2}} + \frac{\psi'_{kq1}}{x'_{lkq1}} \right)
\end{aligned} \tag{5}$$

where  $\frac{1}{x_{MD}} = \frac{1}{x_{md}} + \sum_i \sum_j b_{ij} + \frac{1}{x_{ls}}$  and  $\frac{1}{x_{MQ}} = \frac{1}{x_{mq}} + \frac{1}{x'_{lkq3}} + \frac{1}{x'_{lkq2}} + \frac{1}{x'_{lkq1}} + \frac{1}{x_{ls}}$ .

The flux linkages of stator and rotor circuit are attained by integrating their individual voltage equations:

$$\begin{aligned}
\psi_q &= \omega_b \int \{v_q - (\omega_r / \omega_b) \psi_d + (r_s / x_{ls}) (\psi_{mq} - \psi_q)\} dt \\
\psi_d &= \omega_b \int \{v_d - (\omega_r / \omega_b) \psi_q + (r_s / x_{ls}) (\psi_{md} - \psi_d)\} dt \\
\psi_0 &= \omega_b \int \{v_0 - (\omega_r / \omega_b) \psi_0\} dt \\
\psi'_{kq3} &= (\omega_b r'_{lkq3} / x'_{lkq3}) \int (\psi_{mq} - \psi'_{kq3}) dt \\
\psi'_{kq2} &= (\omega_b r'_{lkq2} / x'_{lkq2}) \int (\psi_{mq} - \psi'_{kq2}) dt \\
\psi'_{kq1} &= (\omega_b r'_{lkq1} / x'_{lkq1}) \int (\psi_{mq} - \psi'_{kq1}) dt \\
\psi'_{kd3} &= -\omega_b r'_{kd3} \int \{b_{11} \psi'_{kd3} + b_{12} \psi'_{kd2} + b_{13} \psi'_f + (b_{11} + b_{12} + b_{13}) \psi_{md}\} dt
\end{aligned}$$

$$\begin{aligned}\psi'_{kd2} &= -\omega_b r'_{kd2} \int \{b_{21}\psi'_{kd2} + b_{22}\psi'_{kd2} + b_{23}\psi'_f + (b_{21} + b_{22} + b_{23})\psi_{md}\} dt \\ \psi'_f &= (\omega_b r'_f / \psi_{md}) \int \{E_f - x_{md}(b_{31}\psi'_{kd3} + b_{31}\psi'_{kd2} + b_{33}\psi'_f - (b_{31} + b_{32} + b_{33})\psi_{md})\} dt\end{aligned}\quad (6)$$

where  $E_f = x_{md}v'_f/r'_f$ . The rotor speed,  $\omega_r(t)$ , is shaped from expression of slip speed:

$$\omega_r(t) - \omega_e = (P/2J) \int_0^t (T_{em} + T_{mech} - T_{damp}) dt \quad (7)$$

where the value of  $T_{em}$  is negative and it is computed from:

$$T_{em} = (3/2)(P/2\omega_b)(\psi_d i_q - \psi_q i_d) \quad (8)$$

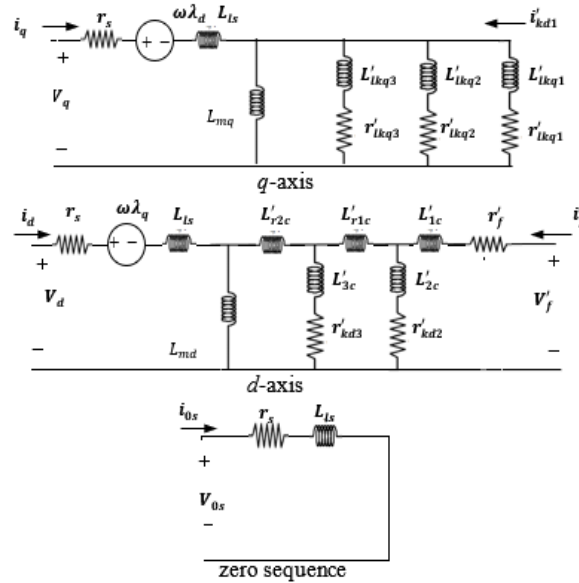


Figure 3. A proposed model with leakage coupling between  $d$ -axis circuits [23]

## 2.2. Synchronous generator simulation in MATLAB/Simulink

A higher order of synchronous generator model is designed exposed in Figure 4, by means of Simulink components [25]. As shown, the conversion of input stator  $abc$  voltages to the rotor  $qd$  reference frame are made within the  $abc$  to  $qd0$  block. The block  $qd$  gen comprises simulation of generator suitable in rotor's reference frame. The stator  $abc$  voltages, excitation voltage, and applied mechanical torque on the rotor are the input of the reference frame. While, the outputs exist terminals of voltage magnitude, current, active power and reactive power, and also load angle, slip, and accelerating torque.

Figures 5 and 6 describe  $q$  axis and  $d$  axis circuit parts within the  $qd$  gen block that contains three rotor circuits in every axis. The block of  $q$  axis circuit comprises three damper windings. The  $d$  axis circuit encloses one field armature winding and two damper windings. The synchronous generator parameters are shown in Table 1.

Table 1. High order generator parameters [26]

Machine type-1						Machine type-2					
Characteristic Constant		$q$ axis part		$d$ axis part		Characteristic Constant		$q$ axis part		$d$ axis part	
Frated	60	xmd	1.70	xmq	1.61	Frated	60	xmd	1.70	xmq	1.61
Poles	2	xpr2c	0.06523	xplkq3	0.1225	Poles	2	xpr2c	0.06650	xplkq3	0.1225
Vrated	26e3	xpr1c	0.01925	xplkq2	0.3248	Vrated	26e3	xpr1c	0.0	xplkq2	0.3248
Srated	722e6	xp1c	0.1055	xplkq1	0.6802	Srated	722e6	xp1c	0.12094	xplkq1	0.6802
rs	0.004	xp2c	0.03076	rpkq3	0.2237	rs	0.004	xp2c	0.06563	rpkq3	0.2237
xls	0.19	xp3c	-0.009134	rpkq2	0.03537	xls	0.19	xp3c	0.00988	rpkq2	0.03537
xpd	0.346	rpkd3	0.02467	rpkq1	0.005698	xpd	0.346	rpkd3	0.02334	rpkq1	0.005698
xpq	0.642	rpkd2	0.01297			xpq	0.642	rpkd2	0.01848		
H	3	lpkd1	0.00112			H	3	lpkd1	0.00109		

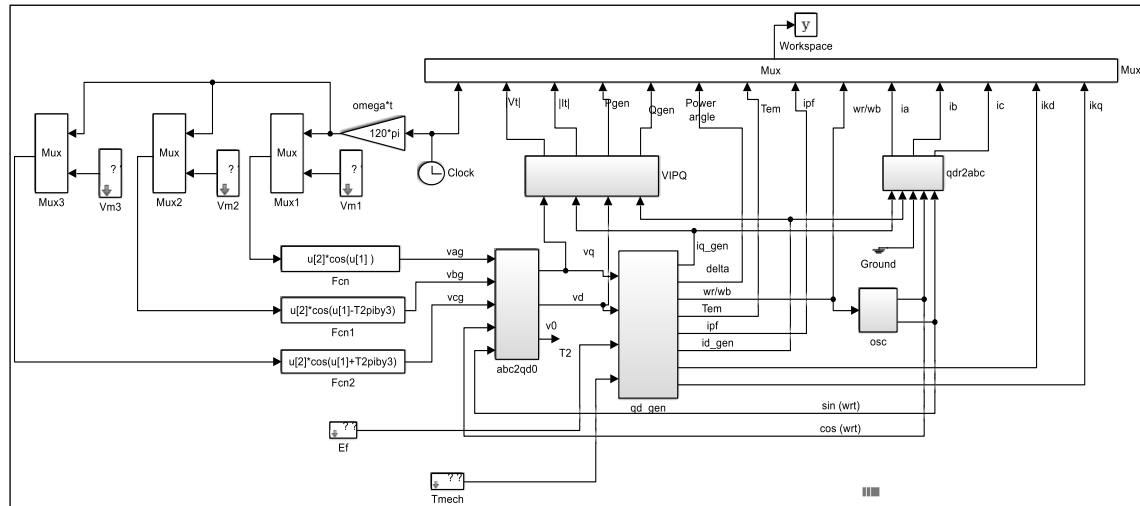
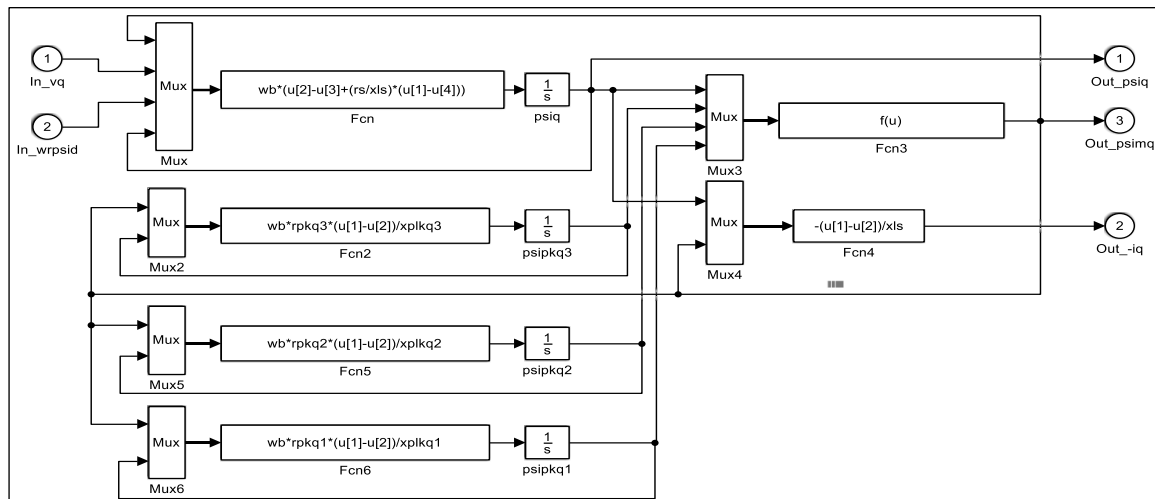
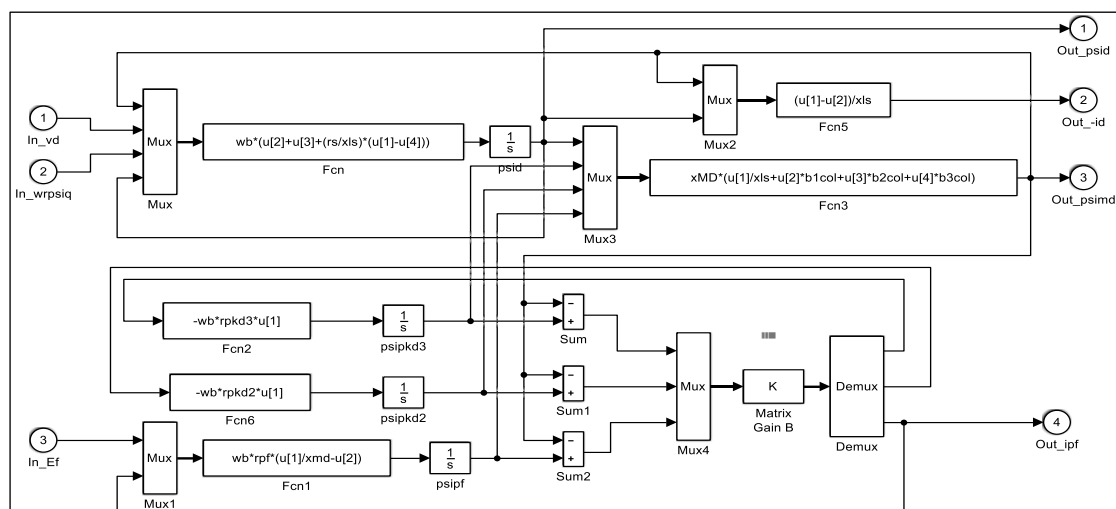


Figure 4. Simulink diagram of high order synchronous generator model

Figure 5. The inside part of  $q$  axis blockFigure 6. The inside part of  $d$  axis block

### 3. RESULTS AND DISCUSSION

With the resolve of exploring shielding effects of the damper winding currents and the eddy currents produced in rotor can impact transient characteristic of the rotor, numeral simulations were conducted for various different operating conditions, for example step change in mechanical torque and step change in input voltages. The high order model of synchronous generator is used and the values of field, torque and input voltage perturbations about operating point of field current are subject to change in p.u. Figures 7(a)-7(c) show curves of field current for the period of short circuit simulation is at field, torque and input voltage perturbations using machine parameters in Table 1. Field current under a three-phase sudden short-circuit is described by (9) [27].

$$i_f = i_{fo} + i_{fo} \left( \frac{x_d - x'_d}{x'_d} \right) \left\{ e^{-t/T'_d} - \left( 1 - \frac{T_{kd}}{T''_d} \right) e^{-t/T'_d} - \frac{T_{kd}}{T''_d} e^{-t/T_a} \cos 2\pi f t \right\} \quad (9)$$

Where  $i_{fo}$  is field current before abrupt short circuit; while  $T_{kd}$  denotes time constant of  $d$  axis damper circuit, and others are general reactance and time constants expressed by the two-axis theory. The magnitude of the field current will vary with the existence of perturbations. The emergence of torsional disturbances causes the value of the field current to decrease. Conversely, a disturbance in the input voltage will increase the field current. but after the disturbance subsides the field current value returns to its previous value.

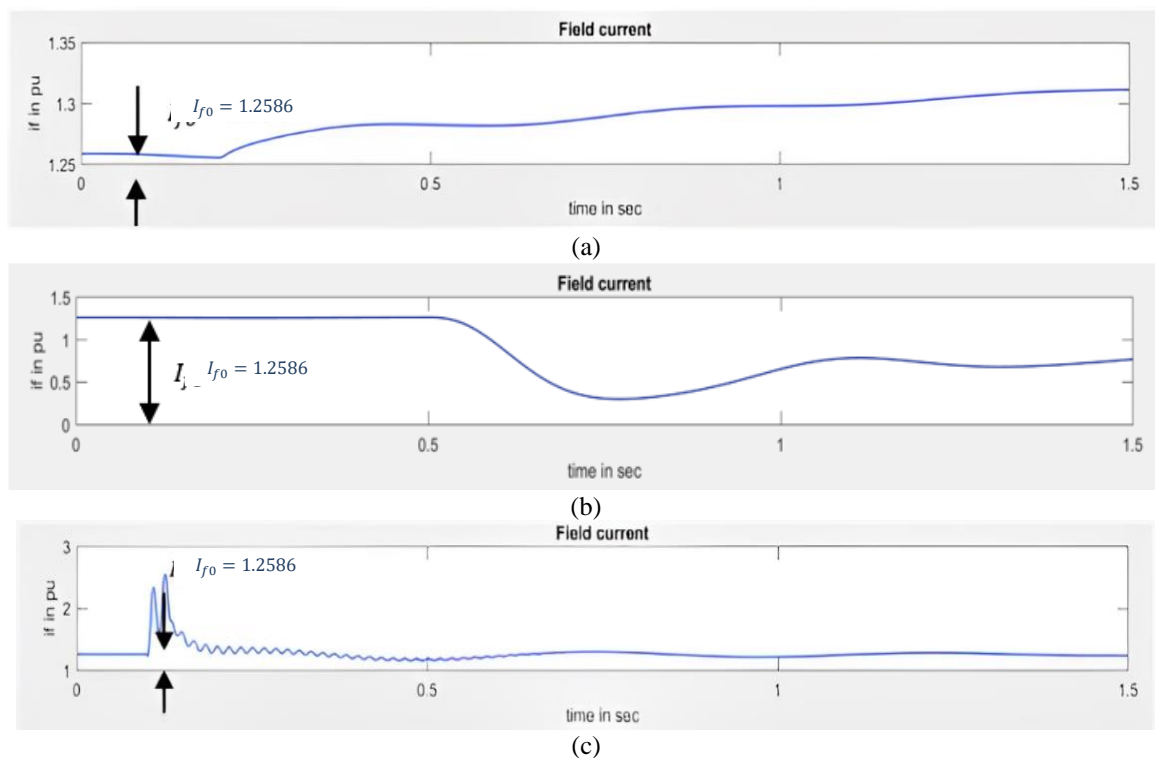


Figure 7. Field current curve under three phase short circuit on: (a) field perturbation, (b) torque perturbation, and (c) input voltage perturbation

Figure 8(a) shows curve of stator input voltage. The form of the signal is a step function with a magnitude of 1 p.u.; in the period between 0.1-2.7 seconds has a magnitude of 0 p.u which is considered as a disturbance. Figures 8(b) and 8(c) show curves of field current during short circuit simulation under different two of machine parameters. The use of a larger reactance value in  $x_{r1c}$  and  $x_{r2c}$  results in oscillations that occur in the event of a disturbance.

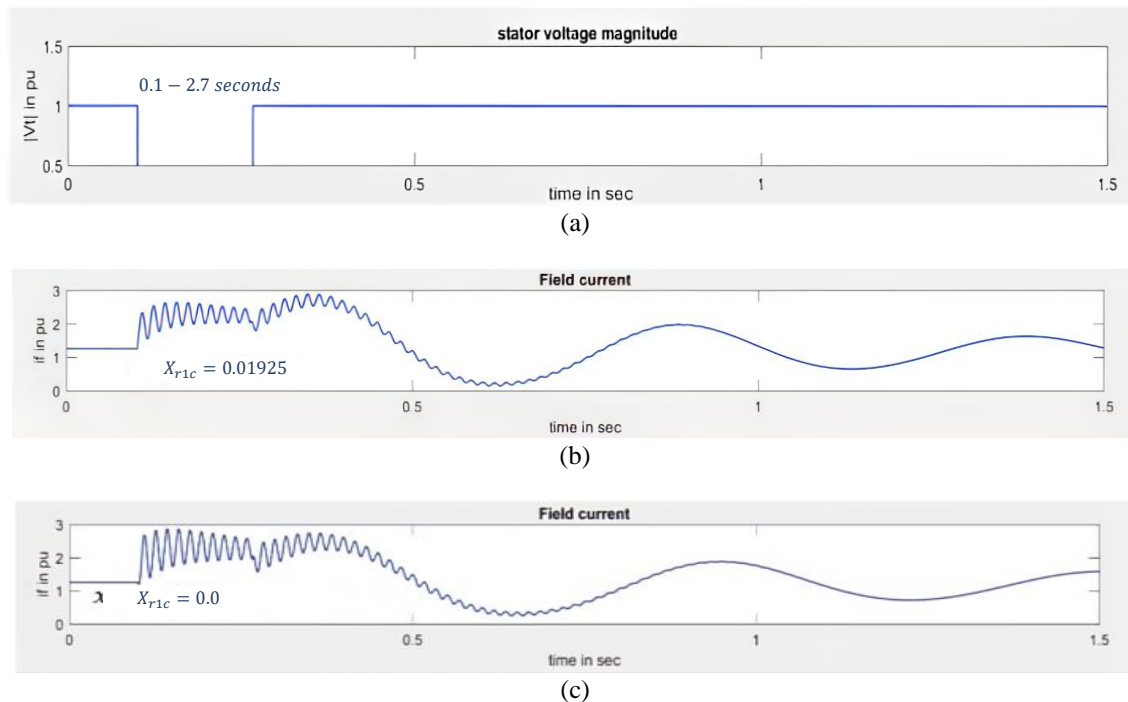


Figure 8. Short circuit simulation of a proposed model with leakage coupling between  $d$ -axis circuits (a) stator input voltage, (b) short circuit response from  $2 \times 3$  model with non-zero  $x_{r1c}$  and  $x_{r2c}$  with machine type-1, and (c) short circuit response from  $2 \times 3$  model with non-zero  $x_{r1c}$  and  $x_{r2c}$  with machine type-2

#### 4. CONCLUSION

The authors examined synchronous generator dynamics, for example field current characteristics at transients, three-phase sudden short-circuit in specific. The following goals are described: i) To observe the field current effect based on the quantity in the three-phase abrupt short-circuit experiment, a model of synchronous generator concerning field mutual leakage reactance, namely Canay reactance, that relates to magnetic flux connecting merely on the rotor area should desire be applied; ii) The simulation results display that the field current in the short circuit assessment will be dissimilar due to occurrence of different types of perturbations; and iii) Considering dynamic stability, the resulting trends are noticed in field current fluctuating frequency for application of high excitation: a. designed for  $x_{rc} > 0$ , negative damping trend rises; b. designed for  $x_{rc} \leq 0$ , negative damping trend recovers.

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