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MODELLING AND ANALYSIS OF A SYNCHRONOUS GENERATOR IN MORE ELECTRIC AIRCRAFT POWER SYSTEM USING SYNOPSYS/SABER SIMULATOR

ABSTRACT *A model for studying synchronous machine (SM) dynamic behaviour in more electric aircraft (MEA) power system is developed and implemented in the Synopys/Saber simulation environment. The modelling language MAST has been used to elaborate the SM model. The elaborated model exhibit a network with the same number of external terminals/ports as the real SM, and represents its behaviour in terms of the electrical (stator and rotor windings) and mechanical (shaft) variables as well. The main advantage of the approach is the ease of describing MEA power system in terms of its topology. Thus, normal and fault operation of any MEA power system can be effectively investigated. The proposed model was applied to study the short-circuit transients of a synchronous generator. The simulation results have proved that the proposed approach can be recommended for analysis of MEA power systems.*

Keywords: *electric machines analysis, electric machines modelling, synchronous generator*

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1. INTRODUCTION

The advancement in power electronics, electric power systems, and electric servosystems is expected to enhance the reliability, fault tolerance, power density and performance of the concept of the more electric aircraft (MEA) for the electrical design system of commercial aircraft, usable by the business and regional aircraft and rotorcraft as well [4, 6, 7, 8].

For the evaluation of aircraft on-board electric power systems and electric servosystems with regard to their weight, behaviour and reliability a novel modelling and simulation tools are being developed. The tools are intended for use in the analysis and conceptual design and of such electrical systems. Diverse methodologies are integrated in the tools, to cover the mentioned aspects at the same time. The tools consist of dedicated model libraries containing object-oriented, physical models of electrical power system components [2].

The model libraries are hierarchically structured to accommodate various models of different complexity, such as interfaces (plugs, databuses, etc.), basic electrical components (wiring, contactors, busbars, etc.), more integrated electrical components (generators, rectifiers, converters, etc.), power users (motor drives, heatings, etc.) and entire system architectures. Thus, the libraries provide an infrastructure for the elaboration or adaptation of simulation models of electrical system architectures.

The fundamental MEA concept, which removes hydraulic, pneumatic and gearbox driven subsystems in favour of electrical driven and servo subsystems, has necessitated the development of high performance starter/generator systems and compact lightweight electric drives and servo subsystems [8].

The importance of synchronous machines (SM) in MEA power systems has been well recognized. They are highly nonlinear, complex electromechanical device, whose dynamic behaviour directly impacts the performance and reliability of the power system network [1, 3, 5]. Apart from providing the ultimate electricity source, they are also used to start the turbine engine. To analyze the dynamic behaviour of the SM, an effective and accurate simulation model is desired. However, it is difficult to develop such a model due to the nonlinear inductances of the SM windings. Further, the model needs to account for dynamics involving electrical and mechanical domains.

One essential requirement for a simulation environment of MEA power systems consisting of many nonlinear components is high computational efficiency. A key technique in achieving this is the use of an advanced network solver such as Synopsys/Saber and the modelling language MAST [9, 10].

The Synopsys/Saber simulation environment – originally developed by Analogy, Inc., now owned by Synopsys [10] – based on a mixed-signal hardware description language called MAST [9]. While using the modelling language MAST you are not only able to develop the various mathematical-based models you need, but are also able to develop mixed-signal and multi-physical (mixed-technology) models. No more restrictive force-fitting of mechanical effects into the electrical domain, but total freedom to use the actual, physical mathematics that describe the desired behaviour – no matter the technology. Moreover, MAST models can be made at any level of abstraction – from simple transfer function descriptions, to detailed physics-based descriptions. And they can be mixed throughout multiple levels of hierarchy.

This paper discusses the background for using the MAST language to model a SM for investigating the multi-physical power behaviour of MEA power systems.

The organization of the paper is the following: in section 2 we present the types of models required for MEA power system. In section 3 a general structure of SM model is described. Section 4 is devoted to the basics of SM model development using MAST language. Finally, as an example of model application, a simulation of short-circuit transients of SM has been described in section 5. And we conclude in section 6.

2. TYPES OF MODELS REQUIRED FOR MEA POWER SYSTEM

Generally, considering the four modelling levels of MEA power system, the four types of models can be characterized, as shown in Fig. 1. At the architectural level the models represents the steady-state power consumptions (no dynamic response). The models are usually used for power budget studding.

At the functional level the models represents the steady-state power consumptions and transient behaviour (inrush current, energy consumption dynamics with regards to input voltage transients, etc.). Such models do not include switching. The band frequency to be modelled is between 0 to 133 Hz for periodic phenomena. The models are usually used for network logic and network stability studying.

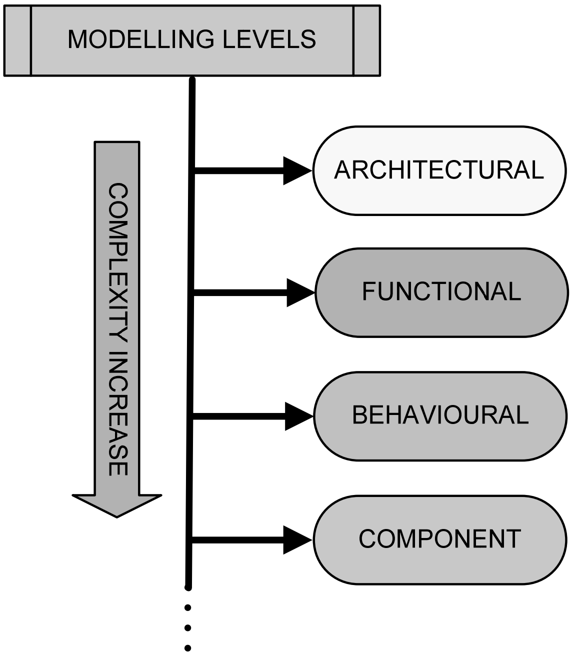


Fig. 1. Schematic of MEA power system modelling levels

At the behavioural level the models are detailed functional models. They represents the actual dynamic waveforms, i.e., same representativeness as the functional models ones, and full representativeness of the waveforms (switching, HF rejection, etc.). Nevertheless, the phenomena above 250 kHz shall not be included. The models are usually used for network power quality studding.

At the component level the models include a representative model of each single component of the MEA system or sub-system. The models are usually used for verification of local operation, and deep analysis of each component behaviour.

Other general requirements for the equipment model are following.

The model must have links to external environment, i.e., input and output power interfaces/ports representative of the real equipment in terms of electrical and/or mechanical behaviour (steady state and transient response).

The model shall be easily integrated in a global network test bench at aircraft level and shall not induce any specific parameters request which could be not compatible with other equipment models.

The equipments models shall be fully representative of the electrical and/or mechanical behaviour with regard to the electrical network and/or mechanical characteristics, while building the global models of aircraft electrical networks.

The behaviour of AC 3-phase models shall be representative in case of phase loss scenarios/faults.

In the following section a behavioural model of a SM will be considered.

3. GENERAL STRUCTURE OF SM MODEL

A SM, according to its degree of freedom, can be represented as a multi-port electromechanical converter (transducer) with pair of terminals (ports), which are the winding and shaft terminals (ports), as shown in Fig. 2. The machine dynamic is described by two power parameters at each pair of terminals (ports). It is assumed that fundamental port quantities (variables) of the SM model are: voltages ($\mathbf{v}_s$ – stator, $\mathbf{v}_r$ – rotor in terms of vector), currents ($\mathbf{i}_s$ – stator, $\mathbf{i}_r$ – rotor in terms of vector), rotor angular velocity (ω_{rm}), and external (load) torque (T_m).

The internal structure of the model, shown in Fig. 2, depends upon the assumed models of the energy transformation, energy conversion, energy accumulation and energy dissipation processes in SM. The transformer couplings represent the process of electromagnetic energy transformation, and the electromechanical couplings represent the process of electromechanical energy conversion, respectively.

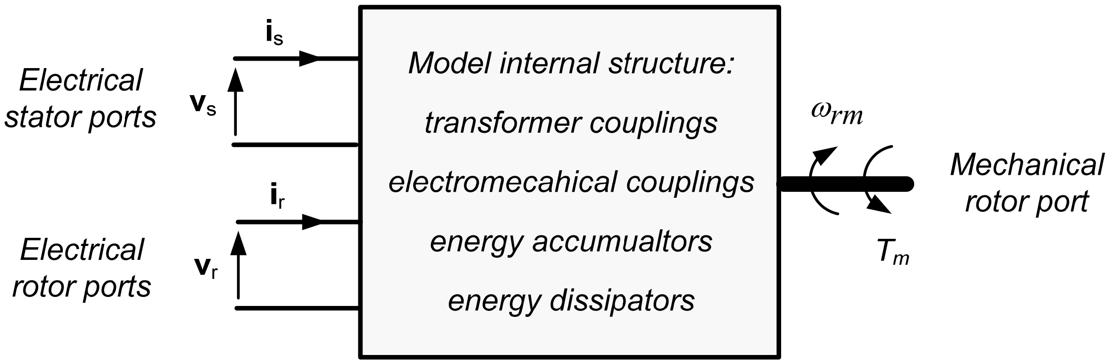


Fig. 2. General structure of synchronous machine model – direction of positive power flows assumed for the motor operation

For developing the SM model in terms of its ports/terminals variables, i.e., especially for MEA power system analysis and design, the general equations of motion of SM are recalled, and next a combined Park's transformation of variables is performed.

Circuit theory is utilized to establish the general voltage and torque equations, expressed in terms of machine variables, for a SM shown in Fig. 2. The voltage, and torque equations in machine variables may be expressed as [5]

$$\mathbf{v}_s = \mathbf{R}_s \mathbf{i}_s + p\,\boldsymbol{\lambda}_s^r \tag{1}$$

$$\mathbf{v}_r = \mathbf{R}_r \mathbf{i}_r + p\,\boldsymbol{\lambda}_r^r \tag{2}$$

$$T_e = J\left(\frac{2}{P}\right)p\omega_r + B_m\left(\frac{2}{P}\right)\omega_r + T_e \tag{3}$$

where, the electromagnetic torque

$$T_e = (\frac{P}{2})\frac{\partial W_c(\mathbf{i}_s,\mathbf{i}_r,\theta_r)}{\partial \theta_r} \tag{4}$$

the electrical angular rotor displacement

$$\theta_r = \int_0^t \omega_r(\xi)d\xi + \theta_r(0) \tag{5}$$

$$\theta_r = (P/2)\theta_{rm} \tag{6}$$

the electrical angular velocity of the rotor

$$\omega_r = (P/2)\omega_{rm} \tag{7}$$

In the above equations the used symbols denote: $\mathbf{R}_s$ – stator winding resistance matrix, $\mathbf{R}_r$ – rotor windings resistance matrix, λ_s – stator flux linkage in terms of vector, λ_r – rotor flux linkage in terms of vector, W_c – coenergy stored in the magnetic coupling field, J – rotor inertia, P – number of poles, ω_{rm} – mechanical angular velocity of the rotor, θ_{rm} – mechanical angular rotor displacement, B_m – frictional constant, T_m – rotational (load) torque, t – time, ξ – dummy variable, p – differential operator d/dt. The subscript s denotes variables and parameters associated with the stator circuits, the subscript r denotes variables and parameters associated with the rotor circuits.

Equations (1) – (5) cannot efficiently be represented by an behavioural model for MEA power systems analysis because the flux linkages are functions of the angular rotor displacement. To eliminate the rotor position dependent stator and rotor flux linkages, the machine variables have to be transformed to a common rotor *qd*0 reference frame (Park's transformation). After performing the transformation, the equations (1) – (3) become [5]

$$\mathbf{v}^{r}_{qd0s} = \mathbf{R}_s\mathbf{i}^{r}_{qd0s} + \omega_r\boldsymbol{\lambda}^{r}_{dqs} + p\boldsymbol{\lambda}^{r}_{qd0s} \tag{8}$$

$$\mathbf{v}'^{r}_{qdr} = \mathbf{R}'_r\mathbf{i}^{r}_{qdr} + p\boldsymbol{\lambda}'^{r}_{qdr} \tag{9}$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda^r_{ds} i^r_{qs} - \lambda^r_{qs} i^r_{ds}) \tag{10}$$

where, the stator flux linkage matrix

$$(\boldsymbol{\lambda}^r_{dqs})^T = [\lambda^r_{ds} \quad -\lambda^r_{qs} \quad 0] \tag{11}$$

The above equations (3) and (8) – (10) have to be linked with the network equations of MEA power system. The linking equations interfacing the power system network variables $asbscs$ to the SM model variables $qd0$, may be expressed as [5]

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos\theta_{r2} & \sin\theta_{r2} & 1 \\ \cos\theta_{r1} & \sin\theta_{r1} & 1 \end{bmatrix} \begin{bmatrix} v^r_{qs} \\ v^r_{ds} \\ v_{0s} \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} i^r_{qs} \\ i^r_{ds} \\ i_{0s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos\theta_{r2} & \cos\theta_{r1} \\ \sin\theta_r & \sin\theta_{r2} & \sin\theta_{r1} \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \tag{13}$$

where

$$\theta_{r1} = \theta_r + 2\pi/3 \qquad \theta_{r2} = \theta_r - 2\pi/3$$

If a magnetically linear system of SM is assumed then the flux linkage equations in the $qd0$ reference frame in expanded form become

$$\lambda^r_{qs} = L_{ls} i^r_{qs} + L_{mq}(i^r_{qs} + i'^r_{kq}) \tag{14}$$

$$\lambda^r_{ds} = L_{ls} i^r_{ds} + L_{md}(i^r_{ds} + i'^r_{kd} + i'^r_{fd}) \tag{15}$$

$$\lambda_{0s} = L_{ls} i_{0s} \tag{16}$$

$$\lambda'^r_{kq} = L'_{lkq} i'^r_{kq} + L_{mq}(i^r_{qs} + i'^r_{kq}) \tag{17}$$

$$\lambda'^r_{kd} = L'_{lkd} i'^r_{kd} + L_{md}(i^r_{ds} + i'^r_{kd} + i'^r_{fd}) \tag{18}$$

$$\lambda'^{r}_{fd} = L'_{lfd} i'^{r}_{fd} + L_{md}\left(i^{r}_{ds} + i'^{r}_{kd} + i'^{r}_{fd}\right) \tag{19}$$

where the symbols used in the above equations denote:

v^{r}_{qs}, v^{r}_{ds}, v_{0s}, v'^{r}_{fd} – stator and field winding voltages,

i^{r}_{qs}, i^{r}_{ds}, i_{0s} – stator currents,

i'^{r}_{kq}, i'^{r}_{kd}, i'_{fd} – damper and field windings currents,

r_{s}, r'_{kq}, r'_{kd}, r'_{fd} – stator, damper and field windings resistances,

L_{ls}, L'_{lkq}, L'_{lkd}, L'_{lfd} – stator, damper and field windings leakage inductances,

L_{mq}, L_{md} – magnetizing inductances in q and d axis respectively.

The raised index *r* denotes variables referred to $qd0$ frame fixed in the rotor, *prim* denotes values of variables and parameters referred to the stator circuits.

In the following section a behavioural model of a synchronous machine is developed using MAST language.

4. SM MODEL DEVELOPMENT USING MAST LANGUAGE

The library of the Synopsys/Saber simulator contains a SM model in terms of $qd0$ variables. However, the insight into the core part of the model, i.e., the equation formulation, is protected for the user. Because of that is not possible to verify the library SM model and make any modifications. Thus, for a specific studies of a MEA power system you need to build-up your own model.

A behavioural model in MAST is considered to be a model whose behaviour is described using the features of the language itself – not by simply connecting pre-existing models together. A behavioural model may also include existing models, but not to the exclusion of having language-based functionality directly incorporated into the model description. The basic unit of system description in MAST is the template. Templates are synonymous to models. Templates may contain netlists, formulae, algorithms, or any combination of these.

The model was implemented with language MAST and tested with the Synopsys/Saber simulator. The MAST file contains the following items, here presented with examples:

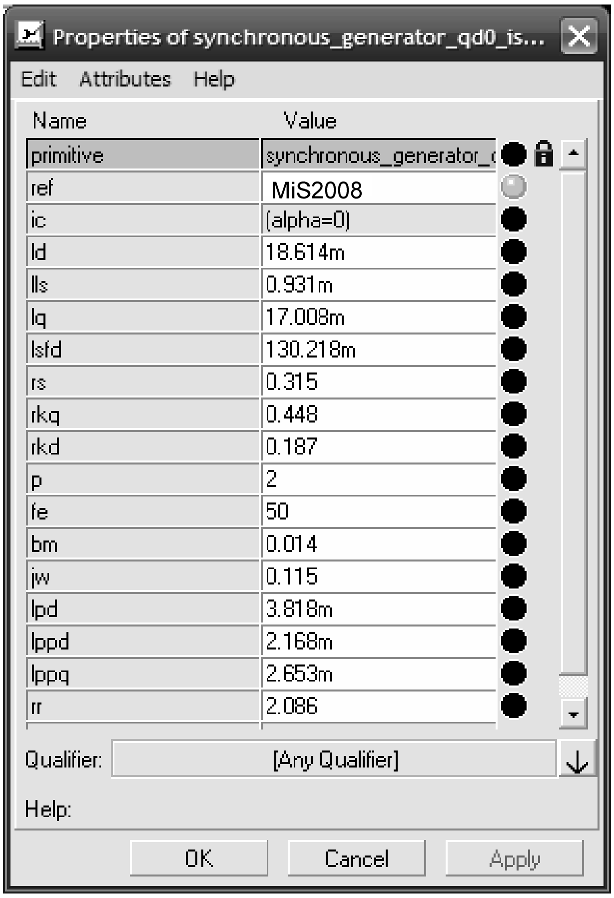
```
#------------------------------------------------------------------------
#The name of the template, the name of the connection points, and the name of the arguments
#------------------------------------------------------------------------
template synchronous_generator_qd0_issue1 v230_a v230_b v230_c vna vnb vnc v24_fp v24_fm rotor =
        Lls, Rs,
#------------------------------------------------------------------------
# Header
#------------------------------------------------------------------------
# Connection pins declaration
#------------------------------------------------------------------------
      electrical    v230_a
      electrical    vna, vnb, vnc
      electrical    v24_fp
      electrical    v24_fm
      rotational_vel rotor
#------------------------------------------------------------------------
# Parameters declaration
#------------------------------------------------------------------------
number Lls=1.026m
struc {         #initial condition
} ic=()
#------------------------------------------------------------------------
# Beginning of the template
#------------------------------------------------------------------------
{
<consts.sin                  # constants used in mathematical calculations
   number ang                 #[rad] phase shift
   val l Lmd, Lmq            #[H] Stator d,q axis magnetizing inductance
   #----------------------- # Connections
    branch ias=i(v230_a->vna),     vas=v(v230_a,vna),     # stator - phase as
     struc{number bp,inc;}sp_alpha[*]     # sample points definition for alpha
#------------------------------------------------------------------------
# Parameters section
#------------------------------------------------------------------------
   parameters{
     ang=2*math_pi/3                      # phase shift
   }
#------------------------------------------------------------------------
# Values section
#------------------------------------------------------------------------
   values{
```

```
   wm = w_radps(rotor)         # mechanical angular velocity of the rotor
# -----Flux linkages for level 0
   phiqs = Lls*iqs + Lmq*(iqs+ikq)
   phikq = Llkq*ikq + Lmq*(iqs + ikq)
   phifd = Llfd*ifd + Lmd*(ids + ifd + ikd)
   Te = 3/2*p*((phids*iqs)-(phiqs*ids))
  }
#-------------------------------------------------------------------------
# control section
#-------------------------------------------------------------------------
  control_section{
      newton_step(alpha,ns_alpha)
      initial_condition(alpha,deg_to_rad*(ic->alpha))
  }
#-------------------------------------------------------------------------
# Equations section
#-------------------------------------------------------------------------
  equations{
      # voltages qd0 -> abc
      vas=vqs*cos(p*alpha)+vds*sin(p*alpha)+v0s
      # currents abc -> qd0
      iqs=2/3*(ias*cos(p*alpha)+ibs*cos(p*alpha-ang)+ics*cos(p*alpha+ang))
      # voltage equations
      iqs: vqs = Rs*iqs + we*phids + d_by_dt(phiqs)  #
      ikq:   0 = Rkq*ikq + d_by_dt(phikq)          #
      ifd: vfd = Rfd*ifd + d_by_dt(phifd)          #
      # mechanical equation
      tq_Nm(rotor) += Te - visc - mom
      mom= d_by_dt(Jw*wm)
      alpha: wm=d_by_dt(alpha)
  }
}
#-------------------------------------------------------------------------
# End of the template
#-------------------------------------------------------------------------
```

In the following section the elaborated behavioural model of a SM is used to simulate the dynamic performance during faults (short-circuit) at the machine terminals.

5. SIMULATION OF SHORT-CIRCUIT TRANSIENTS OF SM

To test our SM model a dynamic performance during 3-phase and 2-phase faults (short-circuit) at the machine terminals is simulated. The parameters of the simulated 3-phase synchronous generator, shown in the window “symbol properties” of the Synopsys/Saber simulator, are shown below.



Name	Value
primitive	synchronous_generator_
ref	MiS2008
ic	(alpha=0)
ld	18.614m
lls	0.931m
lq	17.008m
lsfd	130.218m
rs	0.315
rkq	0.448
rkd	0.187
p	2
fe	50
bm	0.014
jw	0.115
lpd	3.818m
lppd	2.168m
lppq	2.653m
rr	2.086

Qualifier: [Any Qualifier]

Help:

The schematic diagram of the simulated system is illustrated in Fig. 3. Chosen simulation results are shown in the Fig. 4 through 6. In each case the machine is connected to a *RL* load of a negligible value of resistance and inductance, i.e., before the fault a no-load state of the machine can be assumed. In case of the 3-phase fault the field current is set-up to induce a rated value of the voltage at the machine terminals. In turn, in case of the 2-phase fault the field current is reduced to set-up the voltage at the machine terminals equal to 40% of its rated value. For both cases a constant angular velocity of the rotor is assumed. The model parameters are assumed constant. The total simulation time is about 1.5 seconds, and the initial integration step is 1e-5 s.

From the carried out simulations it can be noticed that results from the SM behavioural model match closely to the results of analytical model [1], i.e., the validity of the proposed model has been verified. Therefore, the proposed approach can be recommended for analysis of MEA power systems.

6. CONCLUSIONS

A model for studying SM dynamic behaviour in MEA power system was developed and implemented in the Synopys/Saber simulation environment. The modelling language MAST has been used to elaborate the synchronous machine model. The elaborated model exhibit a network with the same number of external terminals/ports as the real synchronous machine, and represents its behaviour in terms of the electrical (stator and rotor windings) and mechanical (shaft) variables as well. The main advantage of the approach is the ease of describing MEA power system in terms of its topology. Thus, normal and fault operation of any MEA power system can be effectively investigated. The proposed model was applied to study the short-circuit transients of a synchronous generator. The simulation results have proved that the proposed approach can be recommended for analysis of MEA power systems.

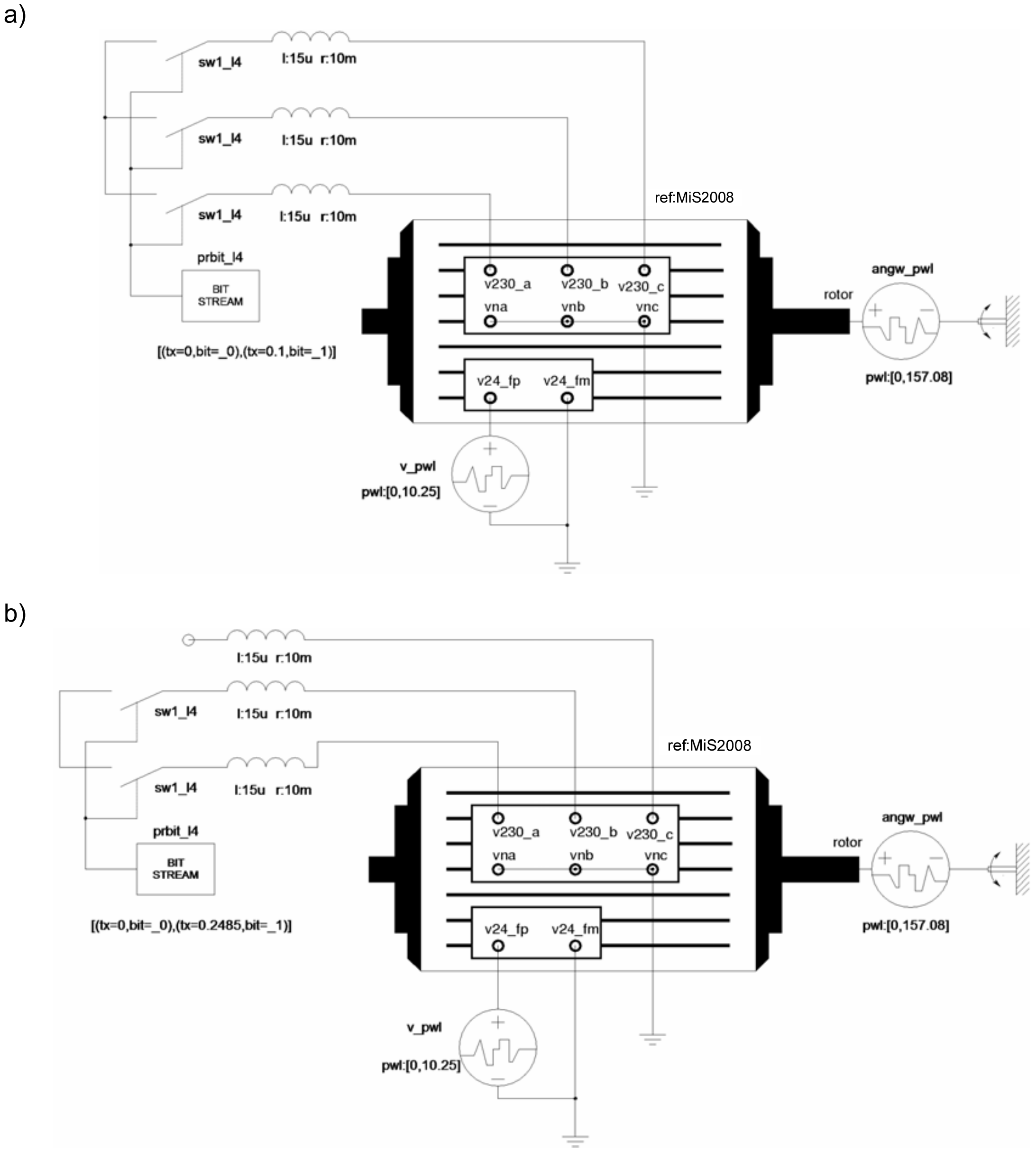
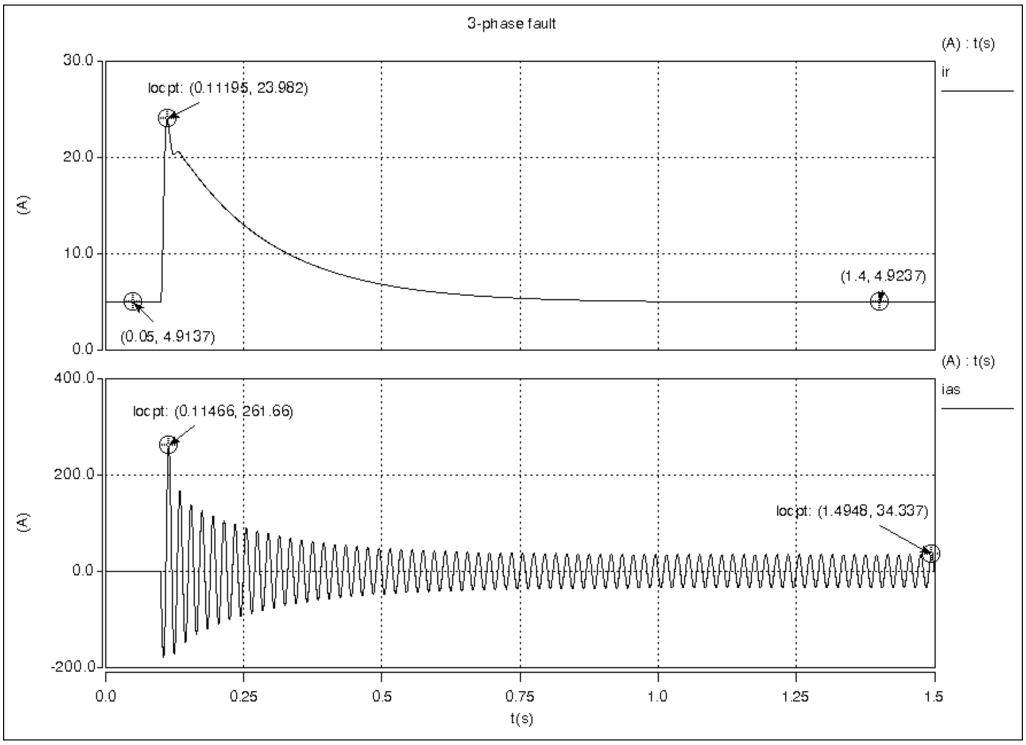


Fig. 3. Example of power system for synchronous generator transients short-circuit simulation using Synopsys/Saber: a) 3-phase fault b) 2-phase fault

a)



b)

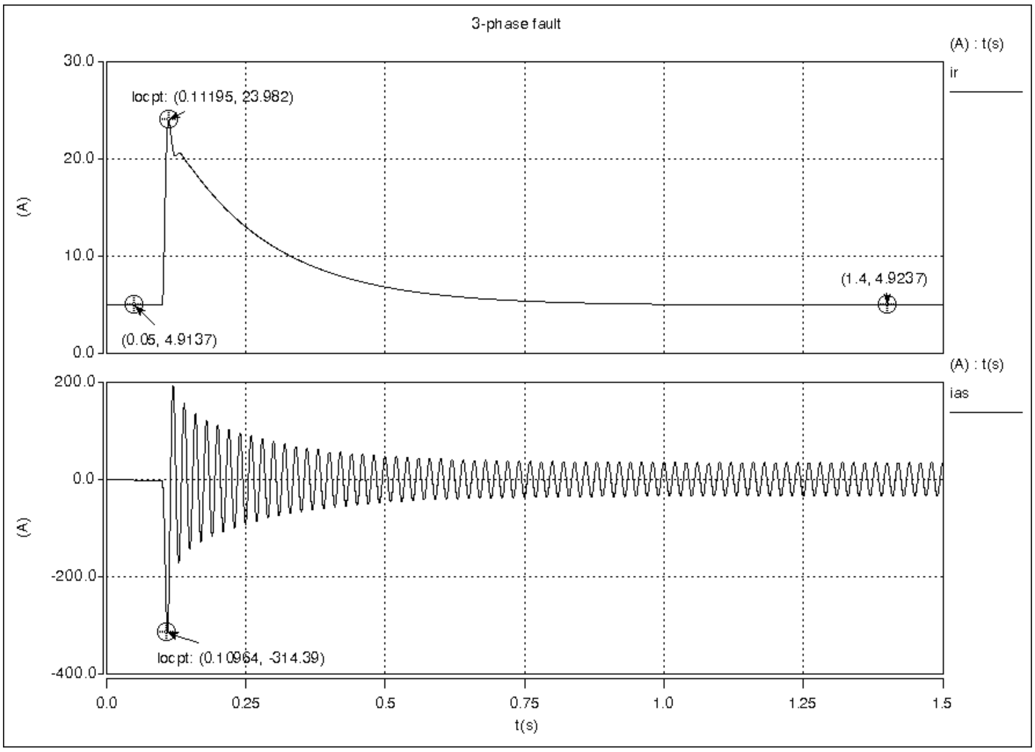


Fig. 4. Simulation results of 3-phase short-circuit (*ir* – field windings current, *ias* – stator phase current): a) stator voltage value at the time of fault $v_{as} = V_{max}$, b) stator voltage value at the time of fault $v_{as} = 0$

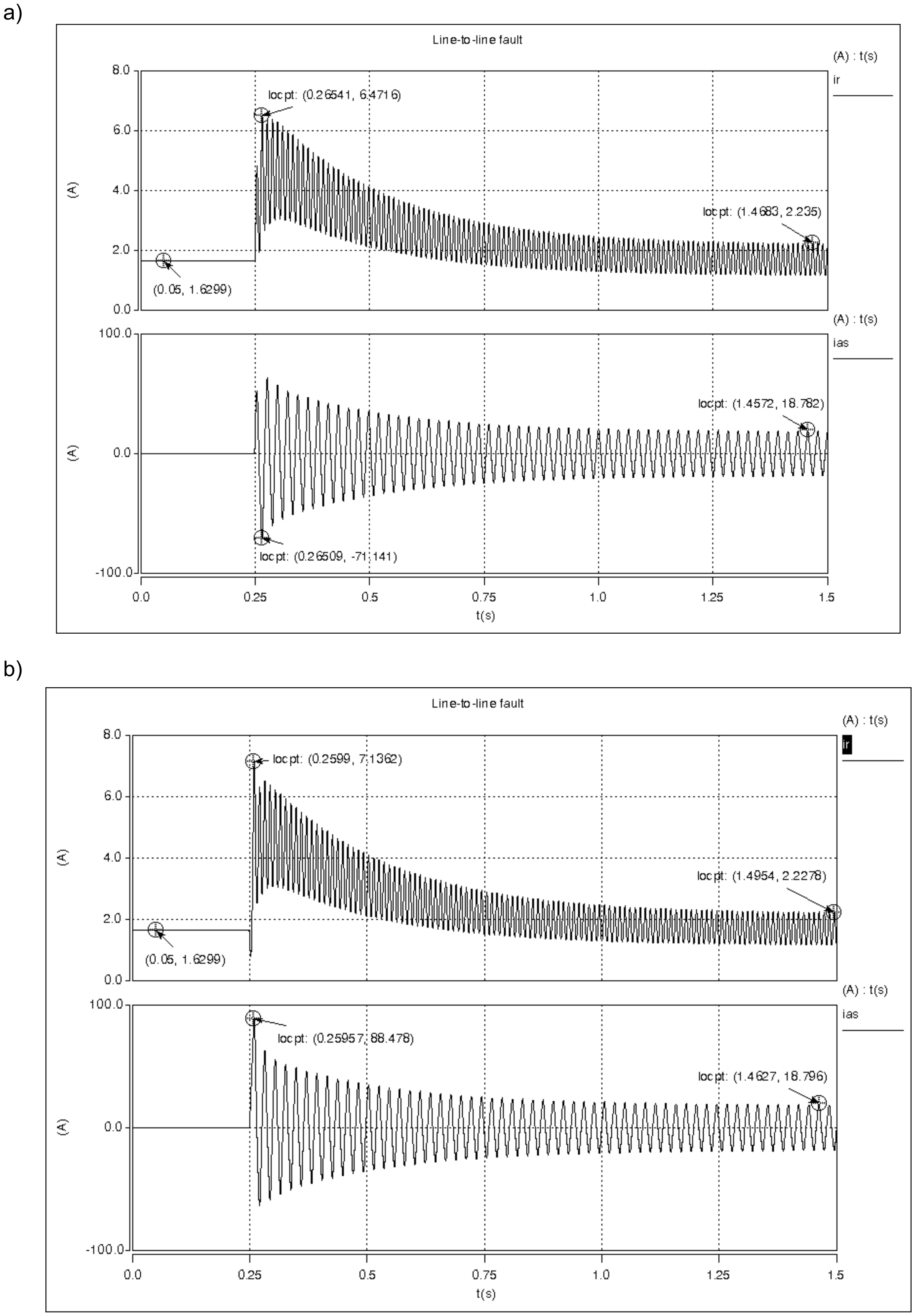


Fig. 5. Simulation results of 2-phase short-circuit (*ir* - field windings current, *ias* – stator phase current): a) stator voltage value at the time of fault $v_{as} = V_{max}$, b) stator voltage value at the time of fault $v_{as} = 0$

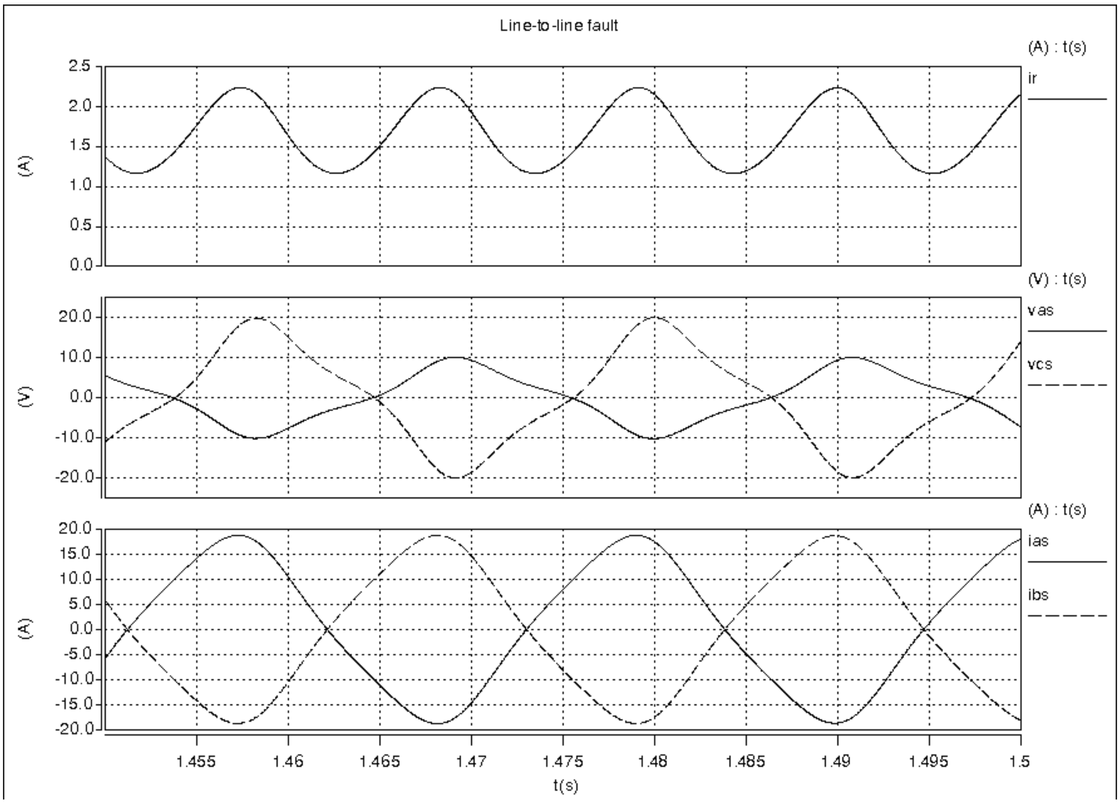


Fig. 6. Simulation results of 2-phase short-circuit (ir - field windings current, vas, vcs – stator phase voltages ias – stator phase current,): stator voltage value at the time of fault $v_{as} = V_{max}$

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MODELOWANIE I ANALIZA GENERATORA SYNCHRONICZNEGO W SYSTEMIE ELEKTROENERGETYCZNYM NOWOCZESNEGO SAMOLOTU. ZASTOSOWANIE SYMULATORA SYNOPSYS/SABER

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STRESZCZENIE *W artykule przedstawiono model do badania stanów dynamicznych generatora synchronicznego (GS) w systemie elektroenergetycznym nowoczesnego samolotu (ang. more electric aircraft). Opracowany model GS implementowano do symulatora Synopsys/Saber. Wykorzystano język modelowania MAST tego symulatora do zapisu równań modelu GS. Opracowany model reprezentuje sieć o tej samej liczbie zacisków/bram zewnętrznych co rzeczywisty GS i jednocześnie opisuje zachowanie GS w funkcji wielkości elektrycznych (uzwojeń stajana i wirnika) oraz mechanicznych (wału). Zasadniczą zaletą takiego podejścia jest łatwy sposób opisania systemu elektroenergetycznym nowoczesnego samolotu w oparciu o jego topologię. Stąd badania pracy systemu w stanach normalnych i awaryjnych są bardziej efektywne. Opracowany model zastosowano do badania procesu zwarcia udarowego GS. Przedstawione wyniki symulacji wskazują, że proponowane podejście do modelowania można rekomendować od analizy systemu elektroenergetycznego nowoczesnego samolotu.*