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THE DEVELOPMENT OF THE REAL LIFE MODEL OF THE FIVE NODE POWER SYSTEM

STRUKTURA I ANALIZA PRACY PIĘCIOWĘZŁOWEGO SYSTEMU ELEKTROENERGETYCZNEGO

Abstract

This paper presents the process of the development of the real life laboratory model of the five node power system of closed loop structure. The model was built using 'power' scaling and taking into consideration the parameters of the 400 kV lines built in the Polish National Power system. After the three-year development of the model, the parameters of the elements of this model were gained or obtained using classic identification procedures. During this part of the research, some differences between the parameter values given by the manufacturers and those obtained through identification procedures were reported and analyzed. The Matlab/Simulink model of the laboratory setup was then built to emulate the system behavior during dynamic states. The comparison of the currents, voltages and generator speeds proved to be simple tasks since the shape of the short-circuit current waveforms, for example, depends not only on parameter values but also on the time of the fault occurrence with respect to system voltages. Thus, the time responses of the laboratory and Simulink models were compared to evaluate time constants of the post fault processes.

Keywords: close loop power system, short circuits in transmission line, models of HV transmission line, power system dynamics

Streszczenie

W niniejszym artykule opisano proces budowy laboratoryjnego pięciowęzłowego modelu systemu elektroenergetycznego o zamkniętej strukturze. Model wybudowany został z użyciem skalowania „mocowego”, gdzie parametry poszczególnych urządzeń (linii) odpowiadają polskiemu systemowi 400 kV. Po zaprojektowaniu oraz wybudowaniu systemu, co trwało trzy lata, parametry elektryczne i mechaniczne modelu systemu zostały albo uzyskane od producentów elementów, albo zidentyfikowane za pomocą klasycznych procedur. W trakcie tej części badań zaobserwowano znaczące różnice pomiędzy identyfikowanymi parametrami oraz parametrami otrzymanymi od producentów, pomimo zastosowania różnych metod identyfikacyjnych. Następnym krokiem było stworzenie modelu systemu laboratoryjnego w programie Matlab/Simulink w celu emulacji dynamiki rzeczywistego systemu. Porównanie parametrów zwarciovych okazało się trudnym przedsięwzięciem, gdyż odpowiedź systemu zależy nie tylko od wartości jego parametrów, ale także od momentu wystąpienia zakłócenia w stosunku do przebiegu napięcia. Tak więc porównanie dotyczyło głównie czasów zaniku procesów pozakłóceniowych, co pozwoliło na oszacowanie i porównanie stałych czasowych układu laboratoryjnego oraz modelu komputerowego.

Słowa kluczowe: system elektroenergetyczny, zwarcia w linii elektroenergetycznej, modele linii NN, dynamika i stabilność systemu

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1. Introduction

The research work described in this paper includes the development of the multi-node, closed loop structure power system model, the process of the identification of its parameters and comparison of results obtained from simulations with real life system response. The purpose of the model development and construction are for studies of system stability, observability, its dynamic behavior for different conditions of work as well as studies associated with power flow control and cooperation of renewable energy sources with the power system model. The structure of the model resembles the IEEE five node benchmark structure (Fig. 1). However, the parameters of the system elements were calculated on the basis of the Polish National 400 kV network [1, 2]. The model of the system works using a voltage of 400 V and is assumed to be an equivalent of a 400 kV network.

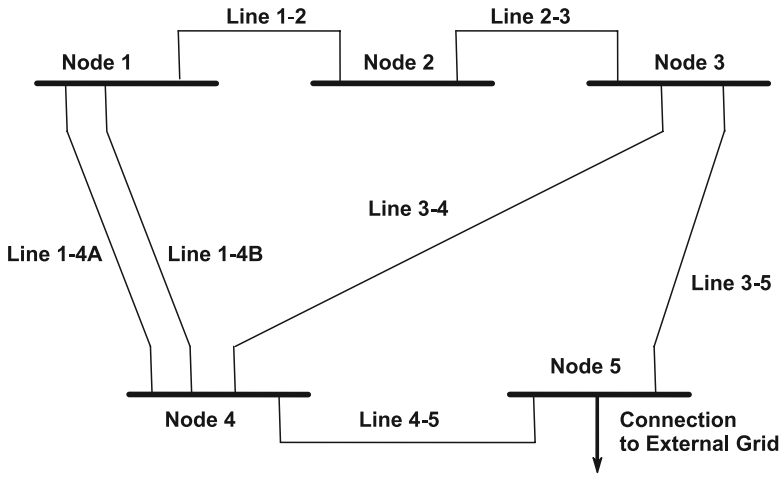


Fig. 1. Structure of the laboratory system model

The voltage ratio is 1:1000, thus calculation of the values of real elements using classic scaling based upon the energy conservation principle, where values of the real life elements

are multiplied by the square of model and real life system voltage ratio $\left(\frac{V_1}{V_2}\right)^2$ is not possible.

The model has to then be built using ratio of powers, i.e. downscaling real life power. The maximum power of all system elements was limited by the capabilities of the lab supply system to a range of 50–60 kVA. The model resembles 1–2 GVA real life system and the following ratios were applied to calculate the model elements [3–5].

Power ratio:

$$\eta_p = 25\,000 \div 1 \text{ (real life system 500 [MVA] = 20 [KVA] model)}$$

Voltage ratio:

$$\eta_U = 1000 \div 1 \text{ (Grid HV 400 [KV] = 400 [V] model)}$$

calculated from voltage and power ratios, current ratio [3, 5]:

$$\eta_I = \frac{\eta_P}{\eta_U} = \frac{25\,000}{1000} = 25$$

The assumed ratios were used to estimate and calculate the values of system parameters. The power of the generators (4 pieces for 4 nodes) was assumed as 20, 16 and 2×10 kVA equivalent to 500, 400 and 2×250 MVA, the line model continuous current rating was assumed to be 30 A (power rating $S = \sqrt{3} \times V_N \cdot I_N \approx 20.8$ kVA).

2. Detailed structure of the laboratory model

The laboratory model was built in the Power System Laboratory at the Faculty of Electrical and Computer Science Engineering. It consists of five nodes – each node in fact resembling the system switchyard. Nodes 1, 3, 4, and 5 (Fig. 2) include generation sets, which consist of a generator propelled by a DC machine driven via a two quadrant converter. The generator sets are connected to the model of the grid using transformers in a similar way to the way in which real life generators are connected to the grid via block transformers [2, 3, 6].

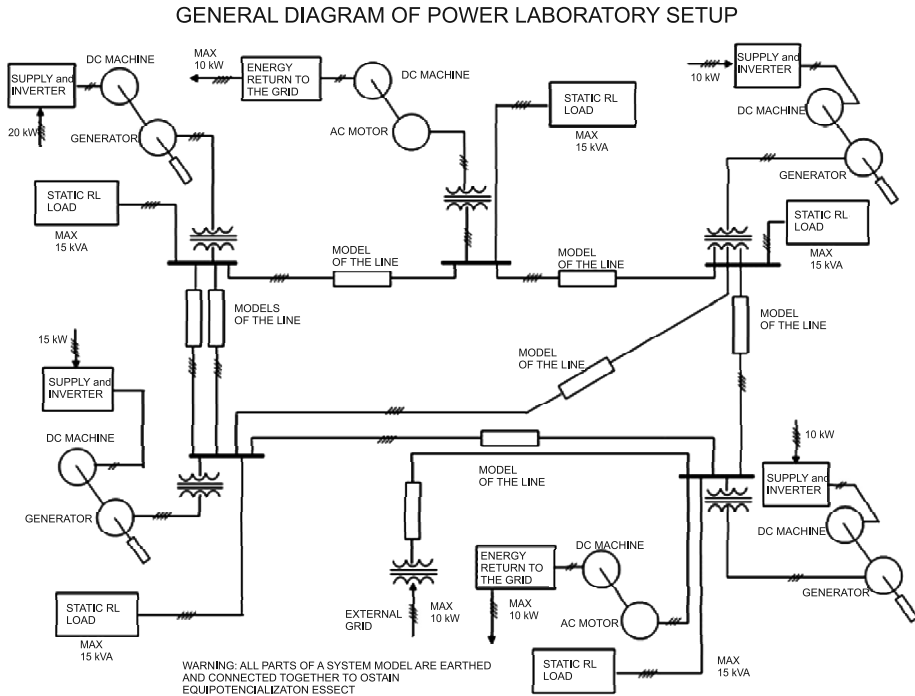


Fig. 2. General diagram of power laboratory setup

One of the nodes (node 5) is connected to the external supply grid via a 10 kVA transformer. Of course, it is impossible to connect a grid to an already working system without synchronization, thus, the blockade disabling the possibility of grid connection in case of voltage presence on switchyard bus was introduced. The generators and line models are connected to the switchyard busses using vacuum based switches, able to connect or disconnect currents up to 1600 A.

All system nodes include loads – passive and/or active ones. Passive loads were built using adjustable resistances and reactances. The active loads consist of the AC machine driven from the system rails via a soft start device. The AC machine propels the DC generator, which returns energy to the grid via a four quadrant converter.

Each node is equipped with sophisticated measurement equipment able to measure currents, active and reactive powers for all lines, generators and loads connected to node's bus for steady state measurements as well as fast response current to current transducers to measure currents during disturbances.

3. The development of elements of the laboratory model

3.1. System generating units

System generating units were built using separately excited DC motors propelling synchronous generator with separate excitation input. The field regulator for each generator was built using a programmable controller with an analog data acquisition module for generator voltage and a custom designed PWM power module for field winding supply. The generator was also equipped with a field current limiter as a protection against generator overcurrent for standalone work [7, 8].

The DC machine control is executed using a dedicated controller able to work in two or four quadrant arrangements. Basic control possibilities include the control of speed or torque of the motor in both directions of the rotation. Also, the slope of the speed and torque ramps can be adjusted, which is very helpful for limiting time of controller response during disturbances. The features of the converter include the possibility to set up different regimes of work – work for constant speed and work for given output torque (given load of the generator working with the system). When generator is working with a certain given torque at 3000 rpm, it delivers to the system a given active power. The generator working with the constant speed control is then used as a swing bus control to balance system loads. Such an approach enables keeping a constant generator speed (constant system frequency) at the required level [9].

3.2. Models of the lines

The power lines in Poland (even 400 kV lines) are too short for wave phenomena to occur. However, if distorted waveforms of currents and voltages are taken into consideration, the classic lumped parameter model (PI type model) may not be sufficient to exhibit the expected line behavior. Thus, chain type models were designed, each consisting of several PI sections. The sections of the lines are identical for every model, and the length of the line is varied by connecting different numbers of sections in series [10, 11].

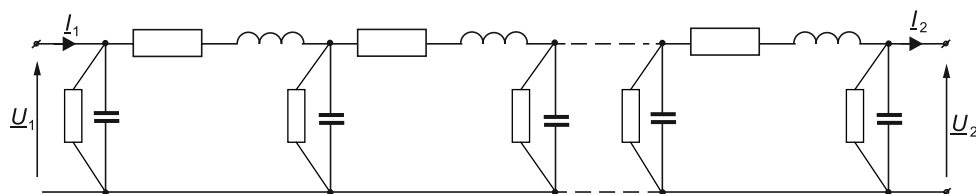


Fig. 3. Scheme of electrical line (transmission line) consisted of n two-port networks [11]

The model of the single power line π -section was built using assumed ratios and taking into consideration parameters of standard 30 km 400 kV as a basic length. The lines were built using 2×3, 2×4, 1×5, 1×6 and 1×8 sections.

3.3. Loads

The passive load includes resistive load banks of 9 kW (for 400 V voltage) divided into 4 steps: 600 W; 1.2 kW; 2.4 kW; 4.8 kW – inductive load 9 kvar controlled via a three phase autotransformer. This setup allows for composing an active load from 0 to 9 kW every 600 W (16 steps of control) and from continuously controlled reactive power. However, the control of the load inductances is not linear, since the inductance connected to the secondary side of the autotransformer is visible from the grid as multiplied by the square of autotransformer adjustable winding ratio [12].

The machine load block (active load) includes 10 kW AC induction motor driven from node bus via transformer, soft-start and propelling DC machine. The DC machine returns energy to the lab supplying grid via the four quadrant converter. The converter is able to vary the power returned to the grid, thus varying the AC machine load [1, 2].

3.4. Measurement arrangements

The system was equipped with state of the art measurement systems. Each input to the node's bus was fitted with current, active and reactive power measurements as well as current to current fast response transducers used to capture current waveform during dynamic processes. Other measured parameters include bus voltages, generator speeds and torque for two chosen generators [2, 3]. The results of the measurements are acquired using computers and D/A cards. Cards are 16 bit, 16 differential input channel devices with maximum sampling up to 1 Mb per channel.

3.5. Short circuit Module

A special module was built to simulate the system response to a short circuit. The module can provide any type of short circuit (any configuration) and the duration of this short circuit can be adjusted from 50 to 2000 ms, by 1 ms [11, 13]. Additional features of the module include triggering signal to the cards (4 cards with 64 channels), which can be connected to measure the required quantities in different nodes.

4. Identification of system parameters for modelling purposes

The model based on the described concept was built in power lab and the properties of the model were tested. These properties include static power flow distribution as well as system response to the disturbances such as short circuits for a chosen system states in several locations, line disconnection, generator shut down or rapid change in generator load and/or generators excitation currents.

The static condition of work and dynamic response of the system were investigated during real life model tests. Additionally, the Matlab/Simulink model was built to emulate a real life laboratory system and to test the possibility of real life dynamic behavior prediction.

The adequacy of the model is strongly dependent on parameter values and the complexity of used single element models. The values of the parameters had to be approximated from the real life lab model. Some of parameters required to perform the simulation can be obtained from the manufacturers of the system components (generators, transformers) or found using advanced parameter identification techniques.

4.1. Parameters of the lines

The parameters of single pi-section of the line corresponding to the 30 km of real 400 kV line (R_L , X_L –longitude resistance and reactance; G_L , B_L – parallel conductance and susceptance of line) were measured using technical methods. The measurements were performed several times, using different measuring devices and then the average value was calculated for each element. The measurements of the mutual inductance between phases were done for a series connections of two phases of 8 segments line. After the first measurement, the connection of phases was reversed and then the mutual inductance M was calculated in following way [10, 11, 14]:

$$M = \frac{L1_{zg} - L1_{re}}{4} \quad (1)$$

where:

$L1_{zg}$ – average inductance of one section for initial connection,

$L1_{re}$ – average inductance of one section for reverse connection.

The parameters derived from the model were multiplied by assumed ratios for the system model and compared to the real life 400 kV line [11].

The Matlab model used during dynamic states requires not only values of the elements for positive and negative sequences, but also the values of the elements for the '0' sequence [15]. These values of parameters for the zero sequence, used in the simulation, were estimated on the basis of the parameter estimation for the real line and transformation to the model scale.

Phase L1		Phase L2		Phase L3	
Resistance					
$R_8 =$	0.3186 Ω	$R_8 =$	0.3189 Ω	$R_8 =$	0.3178 Ω
$R_1 =$	0.0398 Ω	$R_1 =$	0.0399 Ω	$R_1 =$	0.0397 Ω
Inductance					
$Z_8 =$	1.863491	$Z_8 =$	1.880975	$Z_8 =$	1.885867
$Z_1 =$	0.232936	$Z_1 =$	0.235122	$Z_1 =$	0.235733
$X_1 =$	0.229629	$X_1 =$	0.231846	$X_1 =$	0.232466
$L_{11} =$	0.000731	$L_{12} =$	0.000738	$L_{13} =$	0.000740
Phase L1-L3 consistently coupled		Phase L1-L2 consistently coupled		Phase L2-L3 consistently coupled	
$Z_{16p} =$	3.758951407	$Z_{16c} =$	3.817120623	$Z_{16c} =$	3.82364404
$X_{16p} =$	3.758135813	$X_{16c} =$	3.81631746	$X_{16c} =$	3.822842248
$L_{16p} =$	0.01196249	$L_{16c} =$	0.012147687	$L_{16c} =$	0.012168456
Phase L1-L3 oppositely coupled		Phase L1-L2 oppositely coupled		Phase L2-L3 oppositely coupled	
$Z_{16p} =$	3.758951407	$Z_{16p} =$	3.736507937	$Z_{16p} =$	3.778454633
$X_{16p} =$	3.758135813	$X_{16p} =$	3.735687443	$X_{16p} =$	3.77764325
$L_{16p} =$	0.01196249	$L_{16p} =$	0.011891035	$L_{16p} =$	0.012024584
$M_{1-3} =$	5.86369E-06	$M_{1-2} =$	8.0204E-06	$M_{1-2} =$	4.49602E-06

4.2. Parameters of the transformer model

The transformer model used for simulation is the simplest linear model with standard elements. The parameter estimation was performed using basic measurements for short circuit and no load at the secondary side of the transformer $U_{Z\%}$, ΔP_{Cu} , I_0 and ΔP_{Fe} for the stated conditions [12] (Fig. 4).

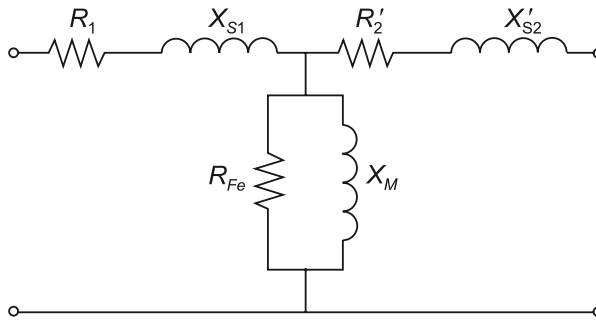


Fig. 4. Basic diagram of the transformer equivalent circuit [12]

Additionally, the resistances of the primary and secondary side were measured using Wheatstone bridge and using DC source, volt and amp meters as for small transformers, winding resistances can be comparable to the leakage reactances [16].

Tap Transformer 10 kVA					
Resistance R_1, R_2' and reactance X_{S1}, X_{S2}'					
Tap 440 V		Tap 400 V		Tap 360 V	
$R_1 =$	0.173 Ω	$R_1 =$	0.173 Ω	$R_1 =$	0.173 Ω
$R_2' =$	0.127 Ω	$R_2' =$	0.115 Ω	$R_2' =$	0.102 Ω
$X_{S1} =$	0.156 Ω	$X_{S1} =$	0.158 Ω	$X_{S1} =$	0.174 Ω
$X_{S2} =$	0.156 Ω	$X_{S2} =$	0.158 Ω	$X_{S2} =$	0.174 Ω
$Z =$	0.432 Ω	$Z =$	0.428 Ω	$Z =$	0.444 Ω
Vertical impedance (no load condition)					
$Z_p =$	259.0991 Ω	$R_{Fe} =$	580.501 Ω	$X_M =$	295.560 Ω
Transformer 10 kVA			Transformer 20 kVA		
Resistance R_1, R_2' and reactance X_{S1}, X_{S2}'					
$R_1 =$	0.155 Ω			$R_1 =$	0.050 Ω
$R_2' =$	0.113 Ω			$R_2' =$	0.034 Ω
$X_{S1} =$	0.150 Ω			$X_{S1} =$	0.063 Ω
$X_{S2} =$	0.150 Ω			$X_{S2} =$	0.063 Ω
$Z =$	0.403 Ω			$Z =$	0.152 Ω
Vertical Impedance (no load condition)					
$Z_p =$	249.3506 Ω			$Z_p =$	115.935 Ω
$R_{Fe} =$	572.1854 Ω			$R_{Fe} =$	592.5047 Ω
$X_M =$	277.041 Ω			$X_M =$	118.220 Ω

The measurements were done for three types of transformers with windings arranged star/delta used in lab system model: 10 kVA 400/400 V, 20 kVA 400/400 V and transformer with taps 10 kVA 400/360-400-440 V used for grid connection.

The most difficult cases in this research were the mechanical parameters identification procedures for generator – DC motor units, which were used to model the generator-turbine setup. The shaft of the generator is connected to the DC machine shaft using coupling, thus the mechanical data such as friction and moments of inertia have to be estimated for the whole unit.

Unit mechanical losses for nominal speed were estimated by measurement of the difference of DC machine input power and calculated machine electrical losses. Of course, this approach required measurements of the resistances of the DC machine and its currents for nominal speed and no load (generator was disconnected from the bus). Then, the moment of inertia for every generating unit was calculated in the following way, using the speed deceleration curve and known mechanical losses [17]:

$$J = \left(\frac{30}{\pi} \right)^2 \frac{P_{\text{mech}} \cdot \Delta t}{n_n \cdot \Delta n} = \frac{P_{\text{mech}} \cdot \Delta t}{\omega_n \cdot \Delta \omega} [\text{kg} \cdot \text{m}^2] \quad (2)$$

where:

P_{mech} – mechanical losses close to nominal speed,
 ω_n – nominal speed [18].

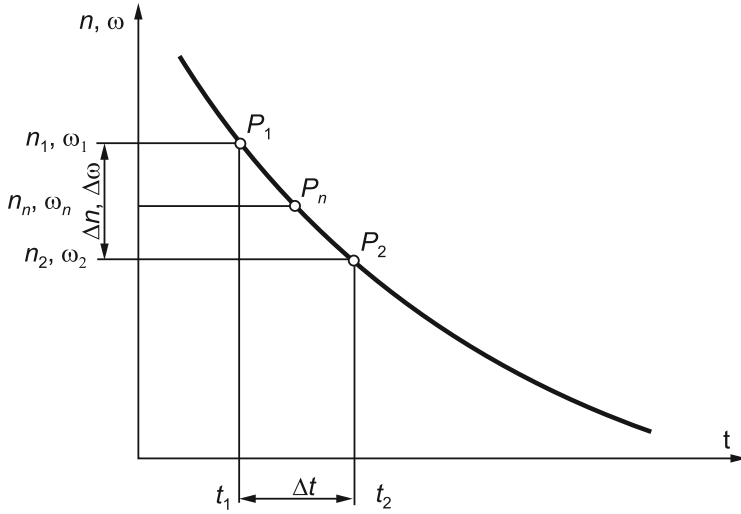


Fig. 5. Example of speed versus time curve [17]

Knowledge of the nominal speed losses also allows the calculation of the friction coefficient which is necessary to form the rotor movement equation in the Matlab model.

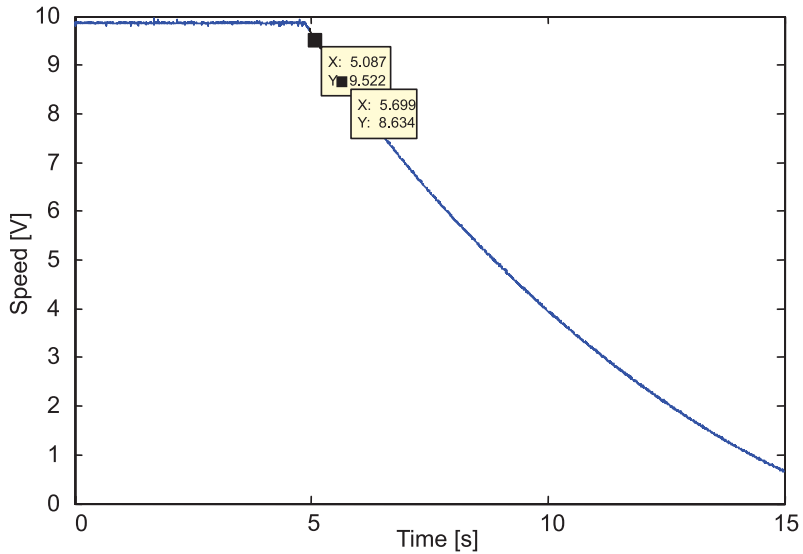


Fig. 6. Received speed versus time curve for 20 kVA generating unit

4.3. Identification of the generator electrical parameters

The resistances of the stator and field were measured using an ohmmeter and Thomson bridge, while synchronous reactances X_d and X_q of the generator were measured using a limited slip method [16, 18]. Figure 7 shows the obtained waveforms and dependencies 3 and 4 explain the calculation concept.

$$X_d = \frac{U_{s \max}}{\sqrt{3}I_{s \min}} \quad (3)$$

$$X_q = \frac{U_{s \min}}{\sqrt{3}I_{s \max}} \quad (4)$$

The calculations of the generator subtransient reactances X_d'' , X_q'' .

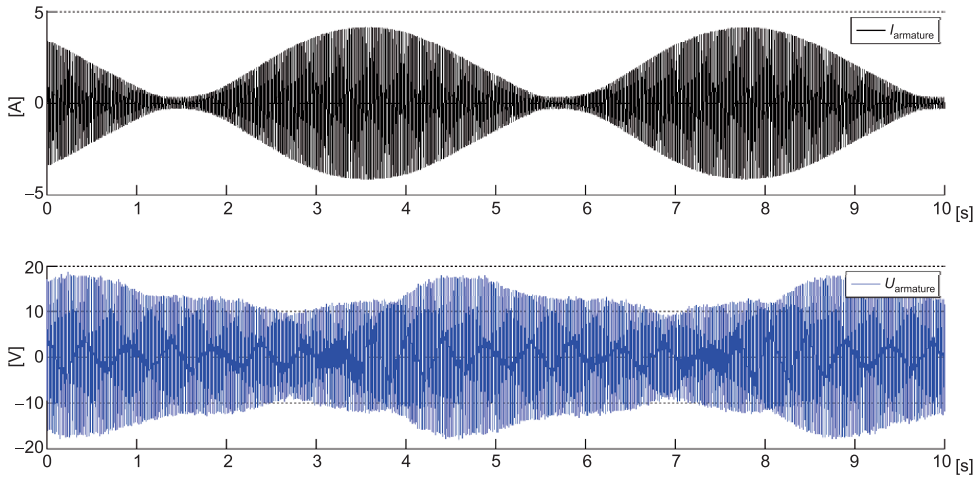


Fig. 7. Current and voltage waveforms used for limited slip method

The determinations of the generators X_d'' , X_q'' parameters were done for stand still conditions. Two stator windings were supplied via a single phase autotransformer and voltmeter was connected to the field winding. The maximum induced voltage indicates that the rotor is positioned along d axle and the minimum indicates q axle rotor position. For known d and q rotor positions, the measurement setup from Fig. 8 was used to measure input (stator) voltage and current as well as winding losses for short circuited field winding [16].

$$X_d'' = \sqrt{Z_d''^2 - R_d''^2} \quad (5)$$

$$Z_d'' = \frac{U}{2I} \quad (6)$$

$$R_d'' = \frac{P}{2I^2} \quad (7)$$

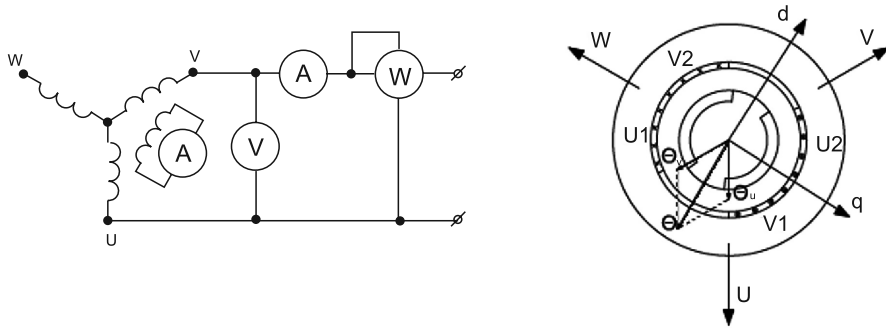


Fig. 8. Wiring diagram used to determine the X_d'' , X_q'' reactance [16]

The measured parameters were compared to the data obtained from the manufacturers of the generators and DC machines. This comparison showed some differences.

Parameter name		Gen. 10 kVA	Gen. 20 kVA	Gen. 16.8 kVA
Nominal apparent power	S_n (VA)	10000	22000	16000
Nominal voltage	V_n (V)	400	400	400
frequency	f_n (Hz)	50	50	50
Nominal field current	i_{fn} (A)	4.3	6.9	7.85
Stator				
Stator winding resistance	R_s (ohm)	0.71 (0.87)	0.37(0.36)	0.55(0.54)
Field				
Field winding resistance	R_f (Ohm)	23.72 (21.19)	13.50 (12.00)	11.90(9.79)
Field reactance	L_f (H)	Not calculated	Not calculated	Not calculated
Cage				
Rotor cage equivalent resistance	$R_{kd'}$ (Ohm)	1.6	1.16	1.3
Mechanical parameters				
Moment of inertia for generator only	J (kg.m ²)	0.023	0.065	0.058
Moment of inertia for whole genset setup	J (kg.m ²)	0.066	0.085	0.075
Inertia constant for whole genset	H	0.20	0.34	0.26
Number of pole pairs	—	1	1	1
Reactances and time constants of the generators in SI units				
Reactance	X_d	41.6	32.3 (27.1)	38.2
Reactance	X_d'	2.9	2.1	2.6
Reactance	X_d''	2.67 (0.9)	1.53 (0.9)	1.68 (1.0)

Reactance	X_a	23.4	4.6 (11.8)	16.6
Reactance	X_a''	1.33	0.8	0.86
Time constant	T_{do}' (ms)	525	600	600
Time constant	T_d' (ms)	36	47	41
Time constant	T_{do}'' (ms)	5.8	6	6
Reactances and time constants of the generators in pu				
Reactance	X_d	2.60	3.73	3.82
Reactance	X_d'	0.18	0.29	0.26
Reactance	X_d''	0.055	0.12	0.10
Reactance	X_q	1.46	1.62	1.66
Time constant	T_{do}' (ms)	525	600	600
Time constant	T_{do}'' (ms)	5.8	6	6
Time constant	T_d' (ms)	36	47	41

In the above table, bold values are given by the machine manufacturer and others are calculated or estimated from the measurements.

In real life models of the system, the dynamic response is not only affected by the parameters of system elements but also by the time constants of used regulators. These regulators in the system include, for example, PID regulators of the DC motor drives which are responsible for the mechanical response of the DC motor propelling generator. The regulators enable work of the DC motor (equivalent of the turbine) in two basic control modes – for constant speed and for constant torque. The first mode of work corresponds to the ‘swing mode’ generator, where speed is controlled and generator active power changes to match system requirements. The constant torque mode is used to control generator active power, regardless of its speed. This type of work is popular in the power system, when power station works on the active power demand given from power authorities, however, during standalone work, the generator will change its speed as the load changes [19–21]. As mentioned above, the DC motor control also has adjustable limits to the controlled quantities, but not only are the values of the controlled quantities are adjustable, but also the speed of changes of these quantities.

The field regulator for each generator was built using a programmable controller with an analog data acquisition module for generator voltage and custom design PWM power module for field winding supply. Of course, the controller uses a programmable PID procedure [7, 8].

The settings of the PID controllers have a great influence on system dynamics and stability. Experiments showed that at certain excitation and speed regulator settings, even a single generator working on resistive load can, during steady state work, fall into oscillations. This happened due to the fact that time constants of the regulators were almost equal or one was a multiple of the second. Thus, the knowledge of regulator settings is crucial for the prediction of the system dynamics.

5. The development of Matlab Simulink model of laboratory setup

The static condition of work and dynamic response of the system were investigated during real life model tests. Due to the fact that short circuits and changes of the real life system structure cause stress to model elements and the system work setup for a required steady state is long and difficult process, the Matlab Simulink model was built to emulate real life laboratory system. The structure of the digital model was built using standard Simulink blocks, such as generator, turbine, transformers, π -section line models and RL loads. The parameters obtained from the identification procedure from laboratory setup were then used in the developed digital model (Fig. 9). First, outcomes of the simulation where the values of system parameters and the settings and limits of the regulators were applied to the standard Simulink models of generators, lines, turbines (equivalent of DC motor) and transformers were not satisfactory. This means that stable work of the system couldn't be reached in a reasonable time. Thus, the excitation regulators and the regulators of the turbine were modified, but still results were not satisfactory due to the interaction of the modified regulators with additional elements of control present in used steam turbine models. Only when the steam turbine model (STG) was replaced by a hydro turbine, the simulations showed convergence to a steady state work within the expected time [6, 15].

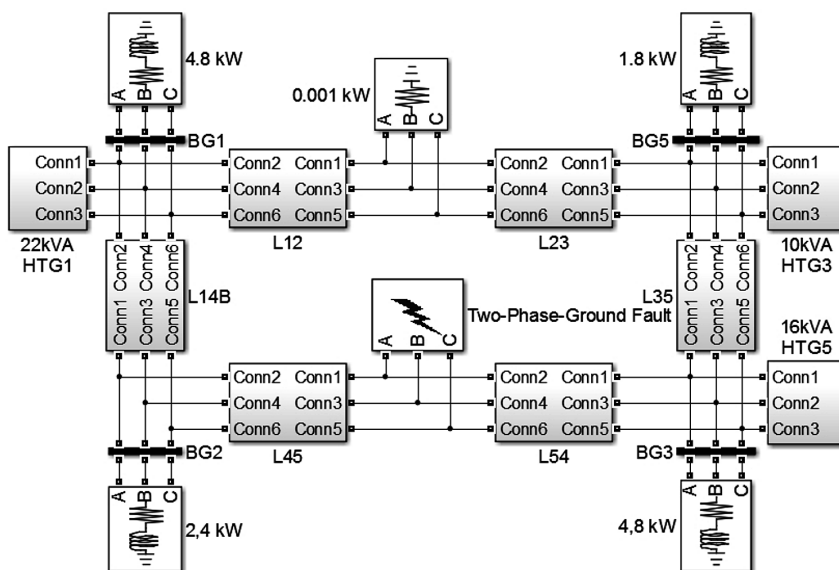


Fig. 9. The power system model created in Matlab/Simulink [15]

6. The range of tests and their results

At first, the laboratory setup was built in power lab and the properties of the model were tested. These properties include static power flow distribution as well as system response to the disturbances applied for chosen system states in several locations such as short

circuits, line disconnection, generator shut down or rapid change in generator load and/or its excitation [2, 4].

During the simulation of the Matlab model, it was noticed that the adequacy of the simulation results is strongly dependent on the parameter values and the complexity of used single element models. The values of the parameters had to be approximated from the real life lab model. Some of parameters required to perform the simulation were obtained from the manufacturers of the system elements (generators, transformers) or found using advanced parameter identification techniques. The initial assumption that the simulations of the dynamics of the multi-node system can be done using nonlinear complex models had to be verified, since the model was not stable or showed very narrow stability limits. Thus, the structure of the model was built using elements with linear characteristics. Actually, two models were finally built – one to perform the simulation for the solver operating in continuous mode to allow analysis of the system waveforms in the time domain and the second in phasor mode to allow tracking of the system state trends and shortening real times of the simulation.

6.1. The comparison of the results obtained from the real system and simulation

The results section shows the comparison of the measurements taken from the laboratory model and results obtained from the simulations for both steady state and the dynamic response of the system. Three generation nodes were used due to the failure of the coupling in one of the generator-DC motor sets.

Several simulations were performed to compare the lab setup and digital model performance at chosen steady state regimes of work. In real life and in simulation, two generators were working as PV generators, i.e. constant active power and constant voltage at the output and a third one was working as a swing bus with constant speed control [1, 2, 22].

The results of one of the comparisons are shown in the figures below:

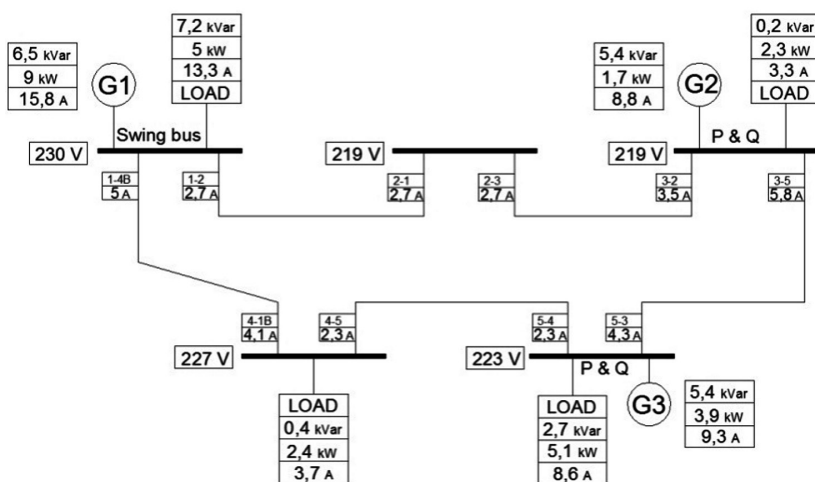


Fig. 10. Example of power flow in the laboratory model for steady state work

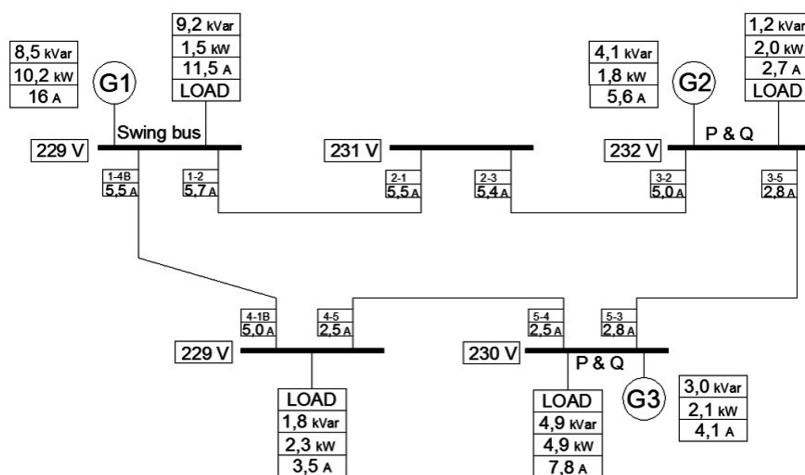


Fig. 11. Example of power flow simulation for steady state work

The research showed that it is very difficult to obtain similar conditions of work in the system and the simulation circuit even for the same loads and the same regime of work. This statement especially concerns the reactive power distribution. The system is built as an equivalent of the 400 kV version and includes relatively long lines, this introduces large capacitances, since the whole system consists of 25 π -sections of line models building

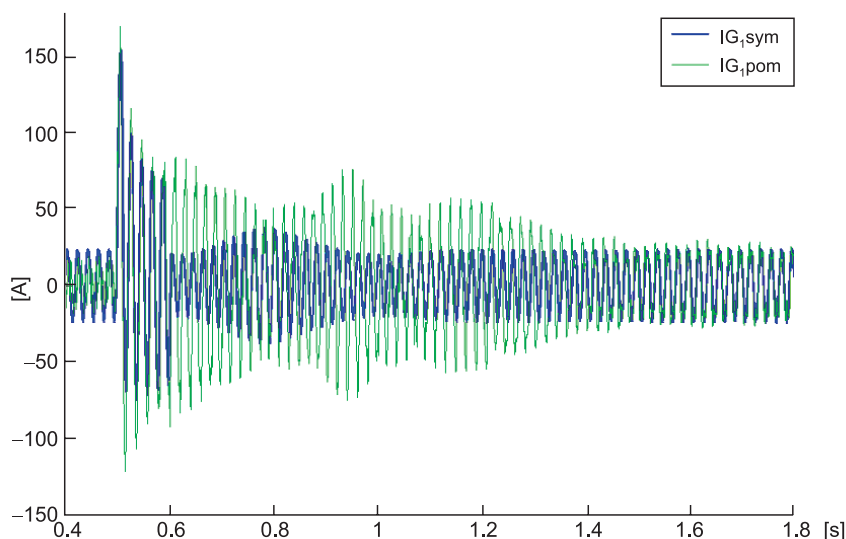


Fig. 12. The currents of generator 1 acquired from real life system (IG_{1,pom}) and obtained from the simulation (IG_{1,sym}) for 0.1 s short circuit and for shorted phase L2–L3 with ground between second and third section of line 4–5

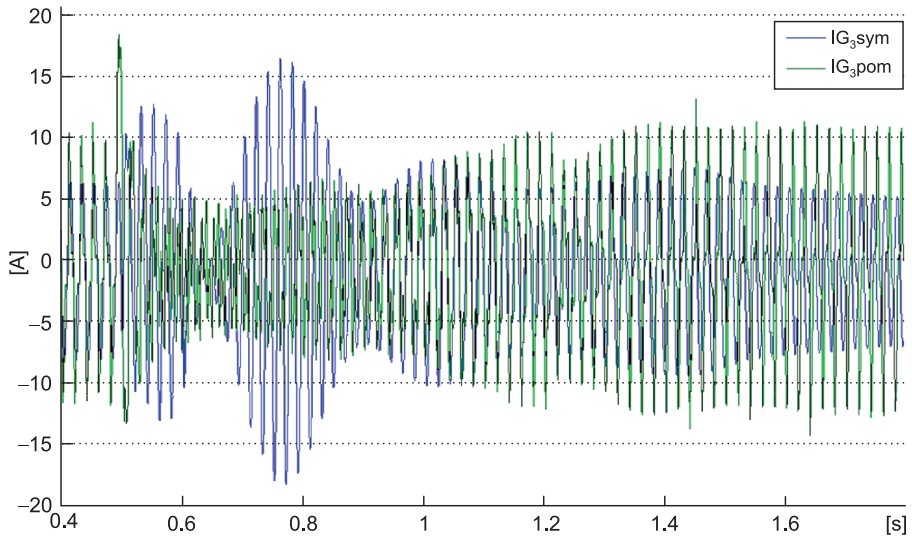


Fig. 13. The currents of generator 3 acquired from real life system ($IG_{3,pom}$) and obtained from the simulation ($IG_{3,sym}$) for 0.1 s short circuit and for 'healthy' phase ($L1$) for two phase ($L2-L3$) with ground shortcircuit between second and third section of line 4-5

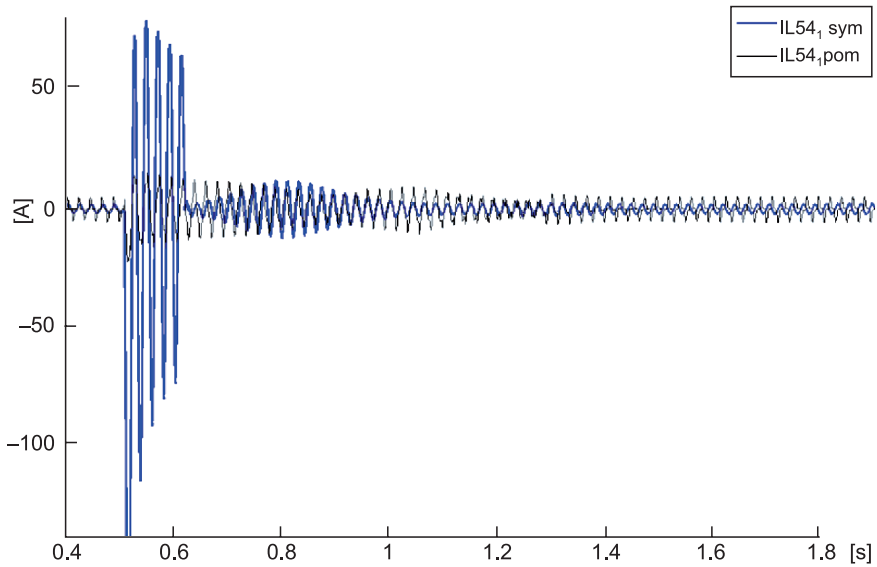


Fig. 14. The currents of line 5-4 acquired from real life system ($IL_{54,pom}$) and obtained from the simulation ($IL_{54,sym}$) for 0.1 s short circuit and for shorted phase $L2-L3$ with ground between second and third section of line 4-5

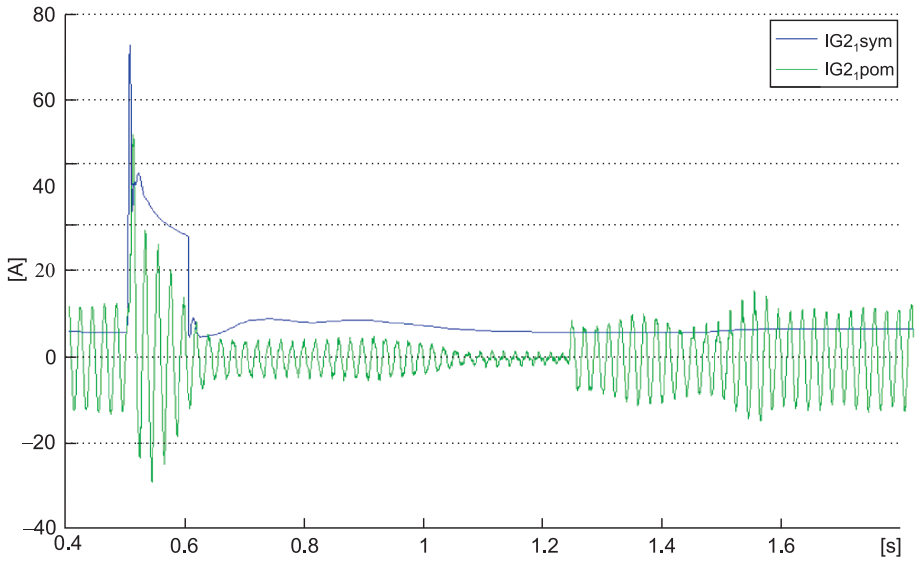


Fig. 15. The currents of generator 2 acquired from real life system ($IG2_{pom}$) and obtained from the phasor simulation ($IG2_{sym}$) for 0.1 s short circuit and for shorted phase $L2-L3$ with ground between second and third section of line 4-5

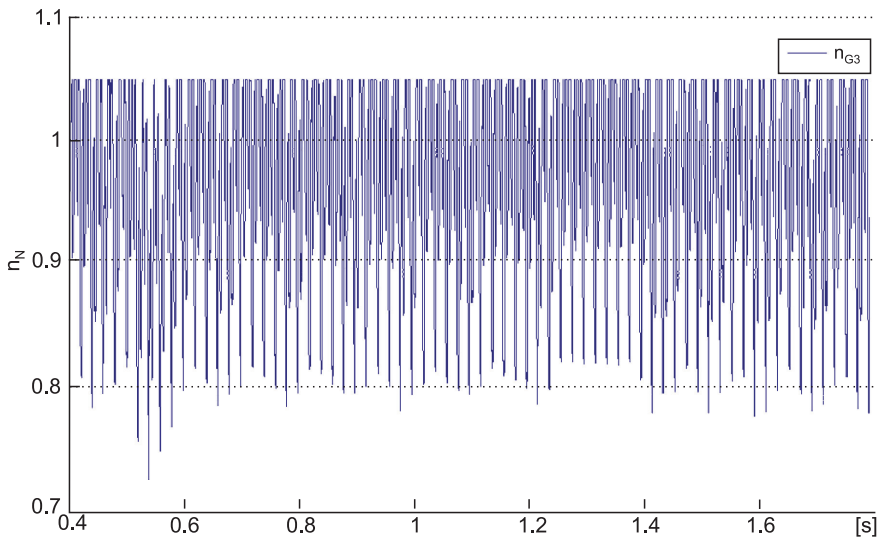


Fig. 16. The normalized speed of generator 3 acquired from real life system (n_{G3}) for 0.1 s short circuit and for shorted phase $L2-L3$ with ground between second and third section of line 4-5

a close loop structure and an 8π section line at the diagonal. When the system is working using whole branches, the reactive power of line capacitors is about 7.3 kvar and for small resistive loads, it causes generator work as reactive compensators consuming reactive power.

The following figures show the currents in system elements during disturbances and dynamic response of the system and Simulink model to these disturbances. The measurement setup allows the acquisition of current waveforms from all system elements, thus, every experiment creates over 20 data sets. Usually, not all data are measured, but only the selected data – this prevents buffer overflows in data acquisition cards. The basic considered disturbance is a short circuit applied in the real system using a short circuit module [13].

The analysis of the above figure shows similar dynamic response (time of oscillation dumping) and similar amplitude during the first stage of the short circuit. This waveform was chosen since the time instant of short circuit in the real system and simulation was picked to assure the same position of disturbance with respect to the system and model voltages. This strategy assures that the value of the non periodic component for the real system and the simulation model is practically the same.

At first view, the currents in Fig. 14 are totally different, however, for the simulation the current exhibits a large non-periodic component while due to a specific position of the beginning of the disturbance, the measured current is almost free of this component. However, the oscillation dumping is almost the same, indicating similar dynamic properties of the lab setup and the Simulink model.

7. Conclusions

The described research work shows the process of the development of a five node power system model at Cracow University of Technology. The system was designed to assess the factors which have the influence on system stability, to build a base for FACTS devices application and to research system stability and controllability. The control of the electrical power system is associated with the overall activities called ‘smart grid’ which are the main activities promoted by the EU. The developed system will also be used as the base for researching the influence of renewable energy sources on the power system and for evaluation of different types of their connections to the grid.

Due to the fact that system is tested using a short circuit module, it does not include protection devices and the operation of the system requires basic knowledge about system behavior. This knowledge was gained during the experiments performed over the system during the two years of research work. The parameters of the system were obtained from the manufacturers of the system elements or were measured and calculated.

The identification of system elements was necessary not only to build the Matlab Simulink model but also to evaluate the system’s dynamics. Of course, the lab model dynamics differs from real life system dynamics since the downscaling was used only to scale electrical quantities – powers, voltages and currents, but was not applied to generators moment of inertia.

The Simulink model was built using standard blocks available in the library, thus the identification and estimation of the system parameters had to include all values necessary for

simulation. The simulation models were built for two solvers – for continuous and for phasor solver. The main problem during simulation of the complicated multi-node, multi generator close loop system includes the determination of the initial condition and establishment of the generator modes of work.

The results of the simulation showed similar dynamics of the digital model to the dynamics of the real life laboratory setup i.e. similar times of oscillation dumping, however, the values of the short circuit currents had different amplitudes.

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