ARCHIVES OF ELECTRICAL ENGINEERING VOL. 68(4), pp. 749–769 (2019)

DOI 0.24425/aee.2019.130681

Modeling of transient states in the start-up path during voltage and start-up power application

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(Received: 11.02.2019, revised: 08.05.2019)

Abstract: During a blackout, after the post-disaster collapse of an electric power system (EPS), units of thermal power plants should switch-over to the house load operation mode (PPW). However, regarding the dynamics of a post-disaster blackout process, many units can be in forced outage Therefore, restart of these units from the start-up sources with a self-start capability is necessary. The *Transmission Network Code* in force imposes periodic tests and system tests for such sources. Any system test must be preceded and followed by simulation investigations in which the possibilities: (1) to bring voltage to the started-up power plant by a starting path and (2) to activate the highest-power auxiliaries (PW) of the unit being started-up are evaluated. In the paper, chosen results of simulative investigations of the transient phenomena in the starting path from the hydroelectric power plant of Włocławek (HPP Włocławek) to the thermal power plant of Pątnów (TPP Pątnów), related to the system test conducted in September 2017 have been presented.

Key words: blackout, electric power system, restoration power

1. Introduction

If electric power system (EPS) defence attempts fail, the restoration of the system is necessary, and the network operators including a transmission system operator (TSO), distribution system operator (DSO) along with the energy producers are responsible for it. They have to implement system restitution plans prepared and checked before [1]. Bringing voltage and start-up power to the thermal units in forced outage is one of the vital steps in the system restoration. To power the thermal power plant's block, the source with a self-start capability (such as hydro-generator in hydropower plants) and a separated electric power grid section (so called starting path) are required.

Starting path's development process is related to the electric power devices operating conditions which are far from the normal ones. Therefore, the verification of correctness of the starting path's operation is necessary and accomplished by the cyclic system tests arranged by the TSO according to the Transmission Network Code [2]. Computer simulation is a very helpful solution for the starting path's operation evaluation while bringing voltage and start-up power to a started unit. Due to the suitable computer programs and detailed data on the power system components, the true physical phenomena accompanying the test of bringing voltage and start-up power to the thermal power unit can be mapped with high accuracy. Thus, the would-be emergency conditions that can occur during starting path development can be analyzed before implementing the system test procedure. Also, the scenarios posing a threat to the power machine and devices can be simulated using a computer model with no risk of damage to the expensive devices.

The PSCAD v.4.2.1 program (referred to as PSCAD) developed by Manitoba HVDC Research Centre [3] is a program that enables such a type of simulative analysis of steady state conditions as well as electromagnetic and electro-mechanical conditions. In the paper, chosen results of simulative investigations carried out when preparing the system test of bringing voltage and start-up power from the hydroelectric power plant of Włocławek (HPP Włocławek) to Unit 2 in the thermal power plant of Pątnów (TPP Pątnów) as well as the verification of the elaborated model referring to the results from the true system test have been presented [4–7].

2. Model of starting path from HPP Włocławek to TPP Pątnów

A true scheme of starting path from HPP Włocławek to TPP Pątnów has been presented in [4]. No permission was given to present it in this publication. The list of the modeled starting path components is given in Table 1. In Figs. 1, 2 and 3, some sections of the starting path model developed using PSCAD [7] is shown.

2.1. Models of HZ1, HZ2, HZ5 and HZ6 hydro-electric sets

Hydro-electric sets HZ1 and HZ2 as well as HZ5 and HZ6 are grouped in two duo-blocks 1 and 3. A model of each hydro-electric set consists of: synchronous generators, rotating mass models, static exciters, water turbines and turbine speed governors. The hydro-electric sets are identical. Configuration panels of particular models have been completed referring to the data obtained from HPP Włocławek.

The basic element of the HZ1 hydro-electric set is a synchronous generator (S) and its chosen parameters are shown in Table 2. To map the mechanical phenomena accompanying the rotation of the great masses, a rotating mass model (Multimass (SyncM/c)) has been coupled to the generator model. Each of the modeled generators is equipped with static exciting systems mapped by the model compatible to the standard IEEE ExST1A. It is adequate to the true ones installed in HPP Włocławek.

Water turbines have been mapped using a Hydro Tur1 model which is the model with an inelastic water column and has no compensatory chamber. The turbine model has been completed with the speed governor model Hydro Gov2. It is a PID controller.

Table 1. List of components of the modeled starting path

No.	Localization	Elements/Designation		Basic parameters
1	HPP Włocławek (WLC)	Hydrogenerator	HZ1	31.8 MW; 10.5 kV
2		Hydrogenerator	HZ2	31.8 MW; 10.5 kV
3		Hydrogenerator	HZ5	31.8 MW; 10.5 kV
4		Hydrogenerator	HZ6	31.8 MW; 10.5 kV
5		Unit transformer	T1	72 MVA; 121 ± (2 · 2.5%)/10.5 kV
6		Unit transformer	T3	72 MVA; 121 ± (2 · 2.5%)/10.5 kV
7	WLC–WLW	Line	L1a	110 kV; 2.5 km
8	WLC–WLW	Line	L1c	110 kV; 2.5 km
9	WLW–WLA	Line	L2	110 kV; 18 km
10	WLA–AT2	Autotransformer	AT2	160 MVA; 230 ± (101%)/120 kV
11	WLA–PAT	Line	L3	220 kV; 75.3 km
12	TPP Pątnów (PAT) – unit no 2	Unit transformer	TB2	240 MVA; 250/15.75 kV
13		3-windings auxiliary transformer	TZ2	20/10/10 MVA; transformer
14		Flue gas desulfurisation system transformer	TZ20	31.5 MVA; 15.75 ± (8 · 1.25%)/6.3
15		Cooling water pump	PWCh-2	1 MW; 6 kV
16		Feed water pump	PWZ-2A	3.15 MW; 6kV
17		Undergate air fan	WP-2A	0.5 MW; 6 kV
18		Exhaust fan	WC-2A	0.7 MW; 6 kV
19		Flue gas fan	WS	5.25 MW; 6 kV
20		Circulating pump	PC1	1.45 MW; 6 kV
21		Circulating pump	PC2	1.45 MW; 6 kV

Table 2. List of basic parameters of generator G1 in HPP Włocławek

Parameter	Value	Parameter	Value
Name	HG1	L-N voltage U_T [kV]	6.062
Type	hydrogenerator	Current I [kA]	1.75
Frequency f [Hz]	50	Power factor $\cos\varphi$ [–]	0.85
Apparent power S [MVA]	31.8	Rotation speed n [obr/min]	57.7
Active power P [MW]	26.7	Type of exciter	ExST1A

Equation describing the mechanical dynamics of the generator is:

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{J} \cdot (T - T_{\mathrm{MECH}} - D \cdot \omega), \tag{1}$$

where: ω is the rotational speed [rad/s], t is the time [s], J is the moment of inertia [kg·m^2], T is the electrical torque [Nm], T_{MECH} is the mechanical torque [Nm], D is the mechanical damping [Nm·s].

The electrical torque is calculated based on the following equation:

$$T = \Psi_q \cdot i_{D1} - \Psi_d \cdot i_{Q1}\,, \tag{2}$$

where: Ψ_q, Ψ_d represent the magnetic flux [Wb], d is the Direct-Axis (d-axis) winding, q is a Quadrature-Axis (q-axis) windings, i_{D1}, i_{Q1} represent the current of the direct component [A].

2.2. List of models of unit transformers T1 and T3 in HPP Włocławek

Unit transformers T1 and T3 in HPP Włocławek have been modeled referring to the classic transformer model applied in power system computer-aided design (PSCAD). The configuration data of the models have been completed basied on the data obtained from HPP Włocławek (Table 3). Equation (3) describes the voltage-current relationship for the two, coupled coils in the classic transformer model:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{bmatrix} \cdot \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \tag{3}$$

where: V_1, V_2 represent the voltage [kV] (1 – first winding, 2 – second winding), L_{11} is the self inductance of winding 1, L_{22} is the self inductance of winding 2, L_{12} is the mutual inductance between windings 1 and 2, I_1, I_2 is the current [kA] (1 – first winding, 2 – second winding).

Table 3. List of basic parameters of the T1 and T3 unit transformers in HPP Włocławek (Base Power value is 100 MVA

Parameter	**Value**		**Parameter**	**Value**	
Name	T1	T3	Name	T1	T3
Apparent power S [MVA]	72	72	Copper losses ΔP_C [pu]	0.004	0.004
Frequency f [Hz]	50	50	2nd winding voltage U_G [kV]	121	121
Type of conntection [–]	YNd11	YNd11	1st winding voltage U_D [kV]	10.5	10.5
Short-circuit volt. U_x [pu]	0.1057	0.1040	Tap change on side [–]	2nd	2nd
No load losses ΔP_{Fe} [pu]	0.00045	0.00036	Range of the tap changer	$\pm(2 \cdot 2.5\%)$	$\pm(2 \cdot 2.5\%)$

In order to solve for the winding currents, the inductance matrix needs to be inverted:

$$\frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \frac{1}{\Delta} \cdot \begin{bmatrix} L_{22} & -L_{12} \\ -L_{12} & L_{11} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}, \tag{4}$$

where:

$$\Delta = L_{11} \cdot L_{22} - L_{12}L_{12} = L_{11} \cdot L_{22} - \left(1 - K_{12}^2\right),$$

$$K_{12} = \frac{L_{12}}{\sqrt{L_{11} \cdot L_{22}}}\,.$$

2.3. Model of AT2 autotransformer in the Włocławek Azoty substation

Autotransformer AT2 has been modeled as the transformer in the Y-Y configuration using the classic transformer model. Basic parameters listed in the configuration panel are shown in Table 4. Graphical scheme of the autotransformer AT2 is shown in Fig. 1.

Table 4. List of basic parameters of autotransformer AT2 in substation Włocławek Azoty

Parameter	**Value**	**Parameter**	**Value**
Name	AT2	Copper losses ΔP_C [pu]	0.0018
Apparent power S [MVA]	160	2nd winding voltage U_G [kV]	230
Frequency f [Hz]	50	1st winding voltage U_D [kV]	120
Short-circuit volt. U_x [pu]	0.0954	Tap changer on side [–]	2nd
No load losses ΔP_{Fe} [pu]	0.0002	Range of the tap changer	$\pm(10 \cdot 1\%)$

2.4. Model of unit transformer TB2 and unit auxiliary transformers TZ2 and TZ20 of unit No. 2 in TPP Pątnów

Unit transformer TB2 in TPP Pątnów has been modeled like the transformers T1 and T3. In turn, the auxiliary services transformers in TPP Pątnów, TZ2 and TZ20, have been modeled like the autotransformer AT2. Transformer TZ2 has been modeled as the 3-windings transformer. Data for all transformers in TPP Pątnów are listed in Table 5.

Table 5. List of basic parameters of unit transformer TB2, auxiliary services transformer TZ2 and exhaust gases desulfurization system transformer TZ20 in TPP Pątnów

Parameter	**Value**		
Name	TB2	TZ2	TZ20
Apparent power S [MVA]	240	20/10/10	31.5
Frequency f [Hz]	50	50	50
Type of conntection [–]	Yd11	YyO/YO	YyO
Short-circuit voltage Ux [pu]	0.1387	0.0768/ 0.0732/ 0.1905	0.0768
No load losses ΔP_{Fe} [pu]	0.00087	0.00098	0.00098
Copper losses ΔP_{Cu} [pu]	0.0034	0.0064	0.0064
Secondary winding voltage U_G [kV]	250	15.75	15.75
Primary winding voltage U_D [kV]	15.75	6.3/6.3	6.3
Tap changer on side [–]	–	secondary	secondary
Range of the tap changer	–	$\pm(6 \cdot 1.67\%)$	$\pm(8 \cdot 1.25\%)$

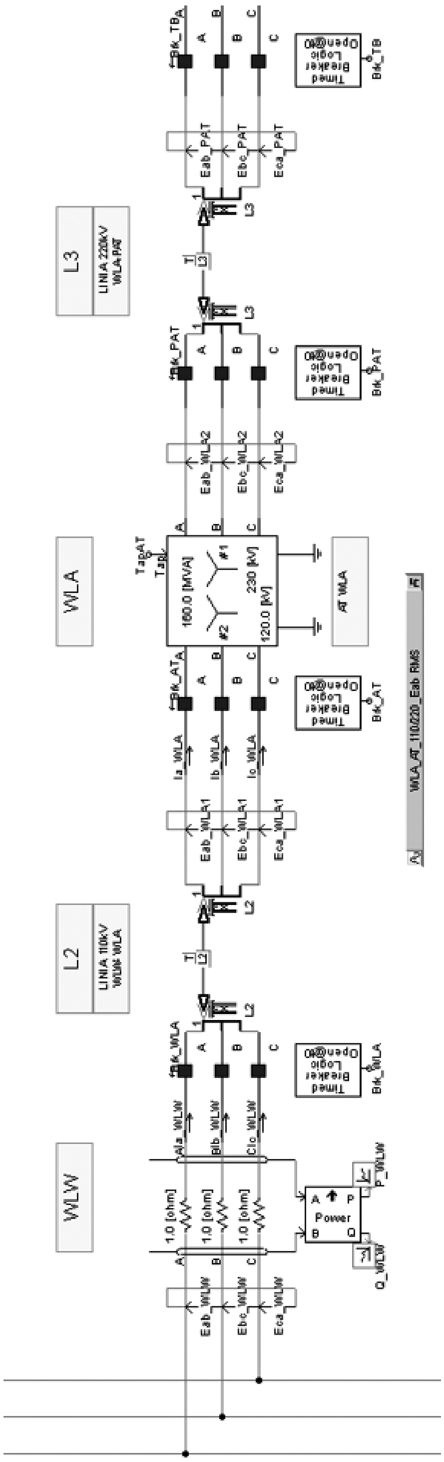

Fig. 1. Section of the PSCAD-based model scheme of starting path from HPP Włocławek to TPP Pątnów: model of autotransformer AT2 and model of 110 and 220 kV transmission lines; 110 kV WLW–WLA line and 220 kV WLA–PAT line

2.5. Models of 110 kV and 220 kV electric power lines for a starting path of HPP Włocławek – Włocławek Wschód – Włocławek Azoty – TPP Pątnów

In the modeled starting path, the 110 kV and 220 kV electric power lines have been modeled using Bergeron's distributed model referring to the line's distributed parameters. It is a model in which the lines inductance (X) and capacitance (B) are distributed along its length whilst the resistance (R) remains lumped. In Table 6, the distributed data of modeled lines in pu/km and the lengths of lines involved in the starting path are shown. Graphical schemes for lines L2 and L3 are shown in Fig. 1.

Table 6. List of basic parameters of modeled electric power lines (Base Power value is 100 MVA)

Name	Line	U [kV]	R [pu/km]	X [pu/km]	B [pu/km]	I [km]
L1a	HPP–WLW	110	0.001311	0.003380	0.000334	2.50
L1c	EW–WLW	110	0.001311	0.003380	0.000334	2.50
L2	WLW–WLA	110	0.001027	0.003355	0.000342	18.00
L3	WLA–TPP	220	0.000149	0.000880	0.001437	75.30

The research used a distributed model due to the fact that transient processes were simulated. The distributed model performs better on them, especially in an electromagnetic field.

2.6. Induction motors of unit services' loads (PW) of unit No. 2 in TPP Pątnów

The TPP Pątnów's auxiliary services, i.e. the exhaust gas desulfurization system (IOS) and the auxiliaries (PW) being the loads for the transmitted start-up power have been presented in the form of the induction motors models with the EMTP Type 40 input data. In such a type, the parameters are introduced referring to the steady state of the motor's mechanical curve. Fundamental data of the started-up motors are given in Table 7.

Table 7. List of the fundamental parameters started–up when testing the greatest asynchronous motors

Parameter	Value					
Name	PWZ-2A	PWCh-2	WC-2A	WP-2A	WS	PC1 and PC2
Active power P [MW]	3.15	1	0.7	0.5	5.25	1.45
L–L voltage U [kV]	6	6	6	6	6	6
Current I [kA]	0.353	0.127	0.088	0.059	0.598	0.198
Frequency f [Hz]	50	50	50	50	50	50
Power factor cos φ [–]	0 91	0 815	0 88	0 89	–	–

2.7. Switches for starting path development, simulation control panel

To control the simulation, switches have been installed in the entire model to switch-on the individual path components with a preset time delay. In addition, to simplify their setting procedure, a control panel for the time delay setting regulation (i.e. indicating the instant the individual switch is being switched-on) has been developed.

3. Scope of simulation-based investigations of operation of starting path from HPP Włocławek to TPP Pątnów

Due to the PSCAD application, the simulation-based investigation of bringing voltage (starting path development) and start-up power from the start-up source to the thermal power plant's activated unit can be precisely carried out. Simultaneously, the instantaneous transient phenomena (electromagnetic and electromechanical ones) such as those accompanying the energizing of the transformers and electric power lines under the no-load conditions as well as switching-on the unit's auxiliaries can be monitored.

3.1. Starting path development process – bringing voltage to TPP Pątnów

The switching sequences, assumed in turn in the simulative investigations on bringing voltage to the 6 kV unit auxiliaries' distribution station of unit No. 2 in TPP Pątnów, have been reported in Tables 8, 9 and 10 [7]. The successive switching sequences in the model have always been carried out after having attenuated the accompanying electromagnetic and electromechanical phenomena.

The main goal of the first stage of the simulation investigation was to find the voltage levels across the distribution substations and electric power substations (PS) during the starting path construction. The assumed generator voltage was 10 kV. Due to the investigations, the substation's busbar voltage levels during the starting path construction have been determined by choosing the transformation ratio of the transformers taking part in the test; thus, the test was accomplished effectively. Also, the level of the reactive power generation by the lines operating with no-load has been determined (Fig. 2). The calculation results are reported in Table 8.

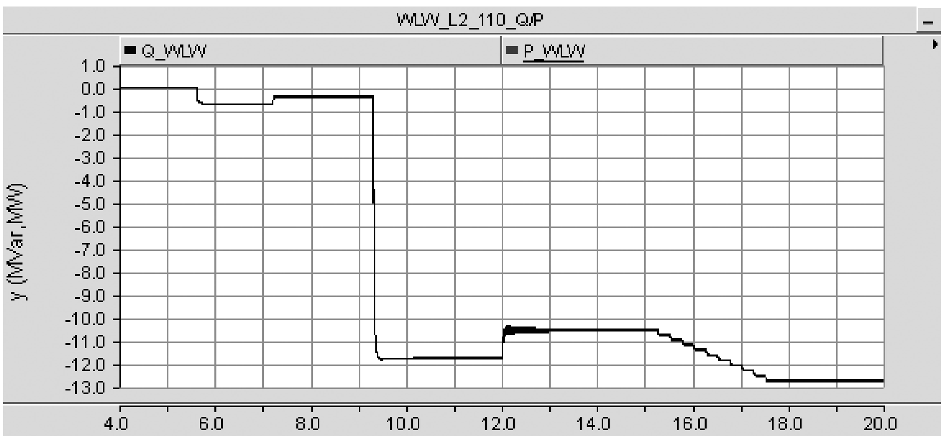

Fig. 2. Reactive power control range by changing the ratio of AT2 at Włocławek Azoty (Table 8)

Finding the voltage regulation capabilities across the R-6 kV substations of unit auxiliaries of unit No. 2 in TPP Pątnów was the main problem. Finally, it has been accomplished by changing the tap changer's position on the auxiliary services transformer, TZ2, and the exhaust gases desulfurization system's transformer, TZ20, obtaining the satisfactory voltage levels. The calculation results are presented in Tables 9 and 10.

Table 8. List of simulative investigation results for voltage levels and reactive power value regulation by changing the tap changer position of AT2 autotransformer in the Włocławek Azoty substation

Operation	The time of switching on in the simulation	Setting turns ratio			Voltage levels registered during simulation tests; the value of reactive power flowing through the L2 line LW–WLA								
		T1 EW	AT WLA	TZ20 PAT	1GA	EW 110	WLW		WLA 110	WLA 220	PAT 220	PAT 15	PAT 6
	s				kV	kV	Mvar	kV	kV	kV	kV	kV	kV
reg AT2	16.25		+5%	+0%		116.52	−11.63	116.84	117.53	238.20	238.85	15.04	6.01
	17.00		+5%	−1.25%		116.50	−11.59	116.83	117.53	238.20	238.83	15.04	6.09
	17.25		+5%	−2.50%		116.50	−11.59	116.83	117.53	238.20	238.83	15.04	6.17
	17.50		+5%	−3.75%		116.50	−11.59	116.83	117.53	238.20	238.83	15.04	6.25
reg TZ20	17.75	+0%	+5%	−5.00%	10.00	116.50	−11.59	116.83	117.53	238.20	238.83	15.04	6.33
	18.00		+5%	−6.25%		116.50	−11.59	116.83	117.53	238.20	238.83	15.04	6.42
	18.25		+5%	−7.50%		116.50	−11.59	116.83	117.53	238.20	238.83	15.04	6.50
	18.50		+5%	−8.75%		116.50	−11.59	116.83	117.53	238.20	238.83	15.04	6.59
	18.75		+5%	−10.00%		116.5	−11.59	116.83	117.53	238.2	238.83	15.04	6.68

Table 9. List of results of simulation tests of the voltage levels and reactive power value regulation by changing the position of the tap changer of auxiliary services transformer TZ2

Operation	The time of switching on in the simulation	Setting turns ratio			Voltage levels registered during simulation tests; the value of reactive power flowing through the L2 line LW–WLA									
		T1 HPP	AT WLA	TZ2 PAT	HG1	HPP 110	WLW		WLA 110	WLA 220	PAT 220	PAT 15	PAT 6
	s				kV	kV	Mvar	kV	Mvar	kV	kV	kV	kV
						115.4	–	–	–	–	–	–	–
turn on L1a	4.00					115.5	0. 0	115.5	–	–	–	–	–
turn on L2	5.60					115.5	−0.7	115.6	115.6	–	–	–	–
turn on AT2	7.20		0%			115.5	−0.4	115.5	115.5	221.4	–	–	–
turn on L3	8.50		+0%			116.6	−11.8	116.9	117.6	227.0	227 8	–	–
turn on TB2, P2A, P28, P20	12.00	0%		0%	10.0	116.4	−107.0	116 7	117 4	226.4	227.1	14.3	–
reg AT2	15.25	+0%	+1%	+0%	10.0	116.5	−10.8	116.7	117.4	228.7	229.4	14.4	5.8
	15.50		+2%			116.5	−10.8	116.7	117.4	231.1	231.7	14.6	5.8
	15.75		+3%			116.5	−11.2	116.8	117.5	233.4	234.1	14.7	5.9
	16.00		+4%			116.5	−11.4	116.8	117.5	235.8	236.5	14.9	6.0
	16.25		+5%			116.5	−11.6	116.8	117.5	238.2	238.9	15.0	6.0
	16.50		+6%			116.5	−11.9	116.9	117.6	240.6	241.2	15.2	6.1
	16.75		+7%			116.6	−12.1	116.9	117.6	242.9	243.6	15.3	6.1
	17.00		+8%			116.6	−12.3	116.9	117.7	245.3	246.0	15.5	6.2
	17.25		+9%			116.6	−12.5	116.9	117.7	247.7	248.4	15.6	6.3
	17.50		+10%			116.6	−12.8	117.0	117.7	250.1	250.8	15.8	6.3

Table 10. List of results of simulation tests of the voltage levels and reactive power value regulation by changing the position of the tap changer of the exhaust gas desulfurization system transformer TZ20

Operation	The time of switching on in the simulation	Setting turns ratio			Voltage levels registered during simulation tests; the value of reactive power flowing through the L2 line LW–WLA								
		T1 EW	AT WLA	TZ20 PAT	1GA	EW 110	WLW		WLA 110	WLA 220	PAT 220	PAT 15	PAT 6
	s				kV	kV	Mvar	kV	Mvar	kV	kV	kV	kV
reg AT2	16.25	+0%	+5%	+0%	10.0	116.52	−11.63	116.84	117.53	238.2	238.85	15.04	6.01
reg TZ2	17.00		+5%	−1.67%		116.5	−11.59	116.83	117.53	238.2	238.83	15.04	6.12
	17.25		+5%	−3.33%		116.5	−11.59	116.83	117.53	238.2	238.83	15.04	6.22
	17.50		+5%	−5.00%		116.5	−11.59	116.83	117.53	238.2	238.83	15.04	6.33
	17.75		+5%	−6.67%		116.5	−11.59	116.83	117.53	238.2	238.83	15.04	6.44
	18.00		+5%	−8.33%		116.5	−11.59	116.83	117.53	238.2	238.83	15.04	6.56
	18.25		+5%	−10.00%		116.5	−11.59	116.83	117.53	238.2	238.83	15.04	6.68

Referring to the described investigations on the starting path development from HPP Włocłwek to TPP Pątnów, the following has been done:

– Retaining of a reduced generator voltage of 10 kV by the group regulator has been recommended; with the recommended 10 kV of the generators in HPP Włocławek, the construction of the tested starting path will be safe.
– Insufficient possibilities of voltage regulation of the AT2 autotransformer in the Włocławek Azoty substation has been stated. To obtain 6.3 kV across the bus of the R6 kV substation, the tap changer must be set in the extreme position at which the upper side voltage attains a dangerously high level of 250 kV. Therefore, an additional voltage regulation on the auxiliary services transformer as well as on the exhaust gas desulfurization system transformer in TPP Pątnów will be necessary during the test.
– Constant transformation ratio of the unit transformer TB2 in unit No. 2, TPP Pątnów (250/15, 75 kV) results in the need for increasing the voltage in R-220 kV substation of Pątnów up to 240 kV. The voltage regulation in the 220 kV network has been carried out by changing the position of the tap changer of AT2 in the Włocławek Azoty substation. The optimum initial transformation ratio of the autotransformer has been found: the tap changer in position No. 6. To obtain the desired voltages across the R6 kV bus of the exhaust gas desulfurization system substation P20 and R-6 kV auxiliary service substations P2A and P2B, the regulation on the transformers TZ20 (position of the tap changer 9–15) and TZ2 (positon of the tap changer 7–12) should be provided.

3.2. Process of bringing voltage from HPP Włocławek to TPP Pątnów

The goal of the second stage of the simulation investigations was to check the capabilities to start-up the devices of the exhaust gas desulfurization system (IOS) and the unit auxiliaries (PW) of unit No. 2 in TPP Pątnów when energized from HPP Włocławek, including determination of the voltage surges and frequency during the start-ups of the biggest devices over 500 kW. In the scope of the test, the following was started-up:

– IOS devices (P20 substation):
  • First IOS circulation pump (PC1) of rated power $P_n = 1450$ kW,
  • second IOS circulation pump (PC2) of rated power $P_n = 1450$ kW,
  • IOS support fan (WS) of rated power $P_n = 5\,250$ kW,
– PW devices (substations P2A and P2B):
  • Cooling water pump (PWCh-2) of rated power $P_n = 1000$ kW,
  • Exhaust gas fan (WC-2A) of rated power $P_n = 700$ kW,
  • Air fan (WP-2A) of rated power $P_n = 500$ kW,
  • Feeding water pump (PWZ-2A) of rated power $P_n = 3150$ kW.

In Figs. 3, 4 and 5, examples of the voltage, frequency and power curves obtained in the simulation tests are presented. The switching sequences according to Table 11 have been followed.

The accomplished simulation tests of starting-up the high power ($P_n \geq 500$ kW) IOS and PW devices of electric power unit No. 2 in TPP Pątnów authorized the statement that the startup of the mentioned devices should not imply any problems for the hydro-electric sets HZ1 and HZ2 as well HZ5 and HZ6 operating in parallel in HPP Włocławek. The watched changes in

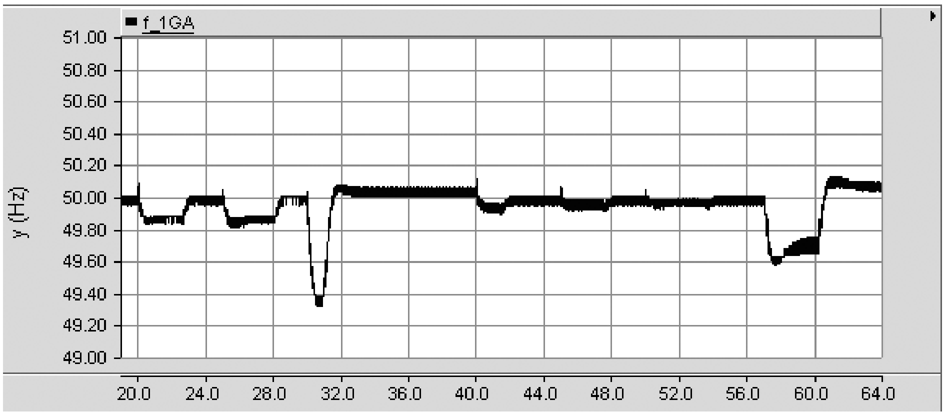

Fig. 3. Changes in frequency on R-10 kV substation bus of hydro-electric set HZ1 in EW Włocławek when bringing start-up power from HPP Włocławek to TPP Pątnów and start-up of IOS and PW devices of electric power unit No. 2 in TPP Pątnów

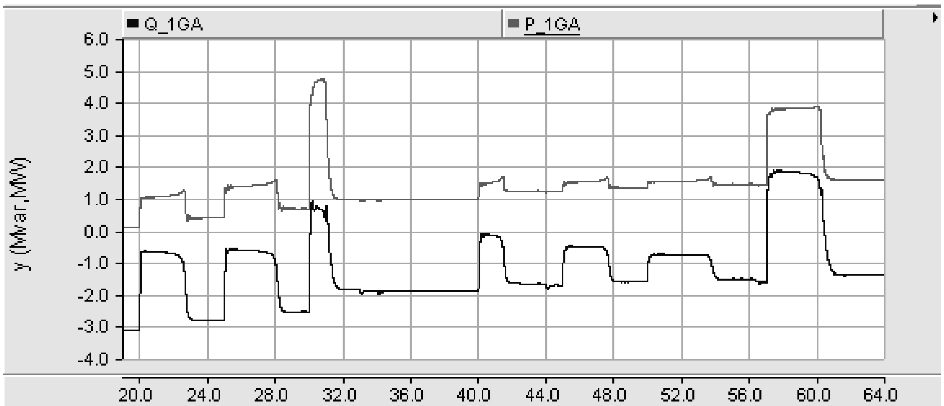

Fig. 4. Changes in active power value (lower plot) and reactive power (upper plot) on R-10 kV substation bus of hydro-electric set HZ1 in HPP Włocławek when starting-up the IOS and PW devices of electric power unit No. 2 in TPP Pątnów

the voltage as well as frequency across the bus of the substation R-10 in HPP Włocławek have been properly regulated by the voltage and rotational speed governors of the hydro-electric sets working for the starting path. The greatest voltage dip appearing during the tests did not exceed 1 kV. Therefore, the conclusion can be drawn that, for the set starting path parameters, there is no risk for motor stalling. In turn, the changes in frequency appearing when the starting path elements are being switched on, fall into the range from 49.4 Hz to 50.6 Hz. The simulation tests have shown that the system test of the start-up of unit No. 2 in TPP Pątnów, including both the bringing voltage and the start-up of the IOS and PW devices can, probably, be run in the problem-free way.

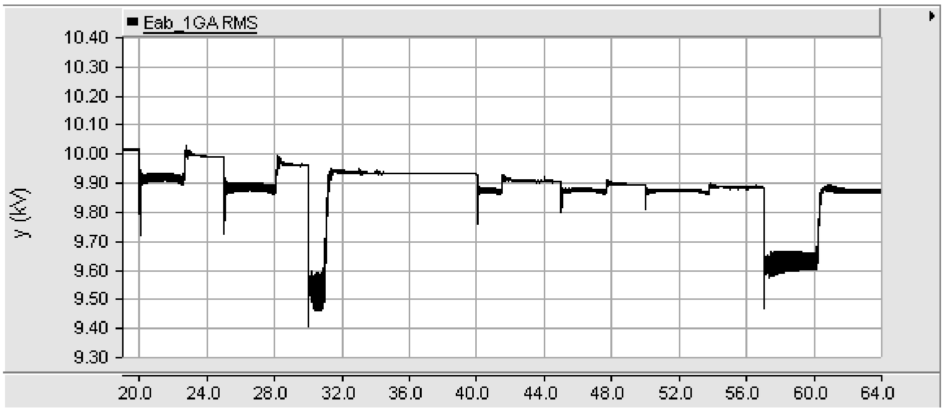

Fig. 5. Changes in phase-to-phase voltage (RMS values) on R-10 kV substation bus of hydro-electric set HZ1 in HPP Włocławek when starting-up the IOS and PW devices of electric power unit No. 2 in TPP Pątnów

Table 11. List of switching sequences when starting-up the IOS and PW devices of electric power unit No. 2 in TPP Pątnów

No.	**The time of switching on in the simulation [s]**	**Switching part of the start-up path**
1	To 15.0	The switching sequences are the same as in Table No. 8
2	15.25–16.5	Voltage regulation in the start-up path using an autotransformer AT2 in WLA station, changing the position of the tap-changer from No. 11 to No. 6
3	17.0–18.5	Voltage regulation in the start-up path using the transformer TZ20, changing the position of the tap changer from No. 9 to No. 16
4	20.0	Switching of the first circulating pump with rated power $P_n = 1450$ kW
5	25.0	Switching of the second circulating pump with rated power $P_n = 1450$ kW, changing position of the tap changer of TZ20 from No. 16 to No. 17
6	30.0	Switching of the exhaust fan with rated power $P_n = 5250$ kW, changing position of the tap changer of TZ20 from No. 17 to No. 15
7	35.0	Switching of P2A and P2B switching stations, changing position of the tap changer of TZ2 from No. 7 to No. 12
8	40.0	Switching of the cooling water pump PWCh-2 with rated power $P_n = 1000$ kW
9	45.0	Switching of the draft fan WC-2A with rated power $P_n = 700$ kW
10	50.0	Switching of the blow fan WP-2C with rated power $P_n = 500$ kW
11	57.0	Switching of the feed water pump PWZ-2A with rated power $P_n = 3150$ kW

4. Computer model verification: true power system test results versus computer simulation results

Regarding conclusions from the described simulation investigation, a program/procedure of the system test including bringing voltage and start-up power from HPP Włocławek to unit No. 2 in TPP Pątnów has been developed. According to the program, a true system test has been carried out and the characteristic waveforms have been recorded. Due to the obtained real measurements, the verification of the computer model became possible.

4.1. Verification of process of bringing voltage from HPP Włocławek to TPP Pątnów

The parameters and switching sequences in the simulation adequate to the true phenomena have been set. In Table 12, the instants of the individual events appearing in the true system test

Table 12. List of switching sequences during process of bringing voltage: true recordings versus simulation results

<table>
<tr><th rowspan="2">No.</th><th colspan="2">The time of event</th><th rowspan="2">Event</th><th colspan="2">The time of meter</th><th colspan="4">Tap changer</th></tr>
<tr><th>Real test [hh:mm:ss]</th><th>Simulation [s]</th><th>Real test [hh:mm:ss]</th><th>Simulation [s]</th><th>T1 and T3 in HPP</th><th>AT2 in WLA</th><th>TZ20 in PAT</th><th>TZ2 in PAT</th></tr>
<tr><td>1</td><td>–</td><td>4.00</td><td>giving voltage to WLW</td><td>09:52:40</td><td>5.5</td><td rowspan="19">0%</td><td rowspan="6">0%</td><td rowspan="12">0%</td><td rowspan="19">0%</td></tr>
<tr><td>2</td><td>09:52:55</td><td>5.60</td><td>turn on line 110 kV WLW–WLA</td><td>09:55:30</td><td>7.1</td></tr>
<tr><td>3</td><td>09:56:10</td><td>7.20</td><td>turn on AT2</td><td>09:58:40</td><td>8.4</td></tr>
<tr><td>4</td><td>09:58:55</td><td>8.50</td><td>turn on line 220 kV WLA–PAT</td><td>10:02:30</td><td>11.9</td></tr>
<tr><td>5</td><td>10:02:50</td><td>12.00</td><td>turn on TB2</td><td>10:04:10</td><td>14.9</td></tr>
<tr><td>6</td><td>10:02:50</td><td>15.00</td><td>turn on P20</td><td>10:04:10</td><td>15.2</td></tr>
<tr><td>7</td><td>10:04:20</td><td>15.25</td><td>regulation AT2 11→10</td><td>10:04:50</td><td>15.4</td><td>+1%</td></tr>
<tr><td>8</td><td>10:05:00</td><td>15.50</td><td>regulation AT2 10→9</td><td>10:05:30</td><td>15.7</td><td>+2%</td></tr>
<tr><td>9</td><td>10:05:40</td><td>15.75</td><td>regulation AT2 9→8</td><td>10:06:00</td><td>15.9</td><td>+3%</td></tr>
<tr><td>10</td><td>10:06:10</td><td>16.00</td><td>regulation AT2 8→7</td><td>10:07:20</td><td>16.2</td><td>+4%</td></tr>
<tr><td>11</td><td>10:07:30</td><td>16.25</td><td>regulation AT2 7→6</td><td>10:08:30</td><td>16.4</td><td>+5%</td></tr>
<tr><td>12</td><td></td><td>16.50</td><td>end of regulation AT2</td><td>10:10:00</td><td>16.9</td><td>+5%</td></tr>
<tr><td>13</td><td>10:12:20</td><td>17.00</td><td>regulation TZ20 9→10</td><td>10:12:30</td><td>17.2</td><td>+5%</td><td>−1.25%</td></tr>
<tr><td>14</td><td>10:12:40</td><td>17.25</td><td>regulation TZ20 10→11</td><td>10:12:50</td><td>17.4</td><td>+5%</td><td>−2.50%</td></tr>
<tr><td>15</td><td>10:13:00</td><td>17.50</td><td>regulation TZ20 11→12</td><td>10:13:10</td><td>17.7</td><td>+5%</td><td>−3.75%</td></tr>
<tr><td>16</td><td>10:13:15</td><td>17.75</td><td>regulation TZ20 12→13</td><td>10:13:25</td><td>17.9</td><td>+5%</td><td>−5.00%</td></tr>
<tr><td>17</td><td>10:13:30</td><td>18.00</td><td>regulation TZ20 13→14</td><td>10:14:00</td><td>18.2</td><td>+5%</td><td>−6.25%</td></tr>
<tr><td>18</td><td>10:14:10</td><td>18.25</td><td>regulation TZ20 14→15</td><td>10:15:00</td><td>18.4</td><td>+5%</td><td>−7.50%</td></tr>
<tr><td>19</td><td>10:15:10</td><td>18.50</td><td>regulation TZ20 15→16</td><td>10:22:00</td><td>18.9</td><td>+5%</td><td>−8.75%</td></tr>
</table>

of bringing voltage versus those in the simulation are listed. Also, the instants at which the values have been read are presented.

The curves for true changes in voltage and reactive power during starting path development from HPP Włocławek to TPP Pątnów [7] are shown. In the Fig. 6 corresponding curve recorded in the simulation tests is reported. To compare the results obtained in two ways, the numbers read at the same instants have been taken and listed in the same table, and the error curve has been calculated. In Fig. 7, an example of the plot comparing the voltage value across the hydro-electric set HG1 in HPP Włocławek during the starting path construction process is shown. The results of both types of voltage registration are listed and the relative error of the voltage level registration

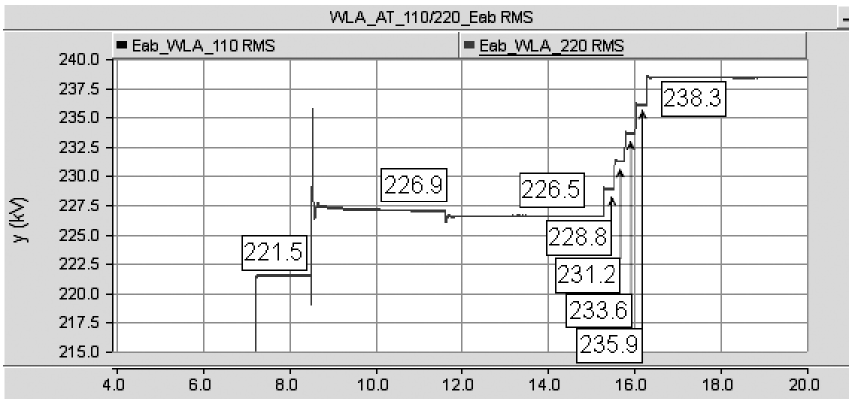

Fig. 6. Changes in phase-to-phase voltage (RMS values) on the R-220 kV substation bus in Włocławek

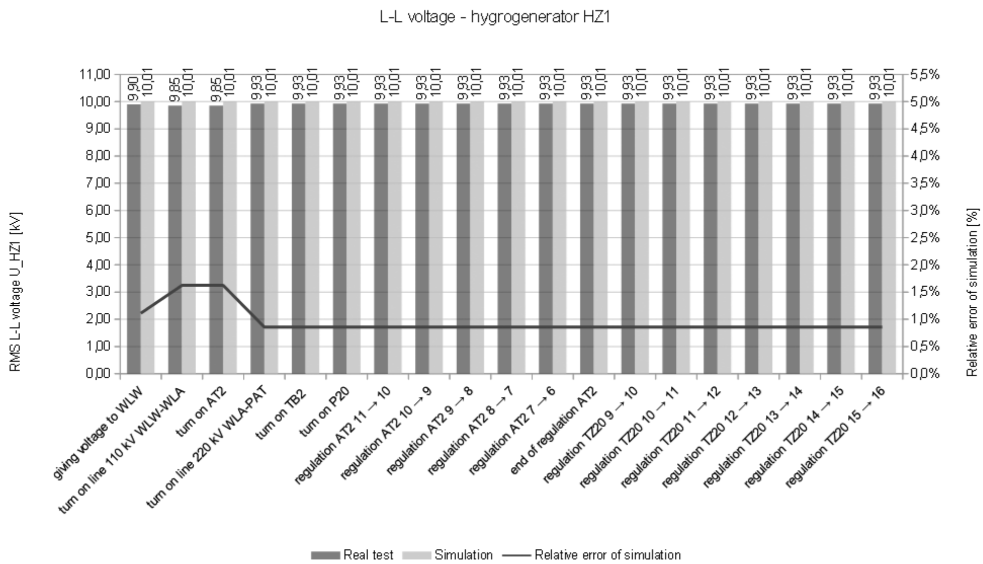

Fig. 7. Comparison of voltage on HG1 (RMS values): true recordings vs computer simulation results

is plotted. The simulation relative error is here from 0.5% to 1.5% referring to that recorded in the true system test. It means that the developed model of the starting path provides very good mapping of the true process of bringing voltage from HPP Włocławek to TPP Pątnów.

Azoty (WLA2) substation during starting path development (switching sequences acc to Table 12); voltage regulation process using AT2 is shown, voltage values recorded in the simulation are introduced

4.2. Verification of bringing the start-up power from HPP Włocławek to TPP Pątnów

In Table 13, the time instants when the individual events occur in the true system test of bringing start-up power are shown versus those from simulation; in addition, the time instants for which the numeric values have been read are shown.

In Fig. 8, the records of the voltage levels registered during the simulation tests of the start-up of the IOS and PW devices of greatest rated power are reported.

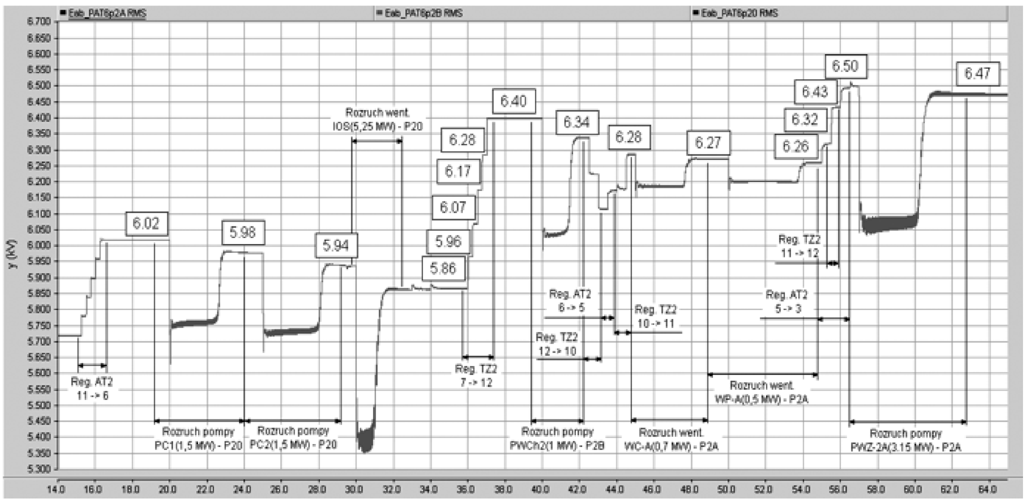

Fig. 8. Start-up of the IOS and PW devices of power unit No. 2 in TPP Pątnów. Changes in voltages (RMS value) across substation obtained by simulation

In Fig. 9, the curves recorded during the system test are reported [6]. To simplify the comparison, the RMS voltage values for the substations R-6 kV P2B and P2A for special points of the bringing start-up power process are shown. In the paper, the example listing of voltages across the auxiliary services substation R-6 kV P2B in TPP Pątnów has been chosen.

In Fig. 10, the plots comparing values of the considered voltage in the process of bringing the start-up power is presented. The results for both types of voltage registrations are listed and the relative error of the voltage level registration is found. The simulation error did not exceed here 1.75% in reference to the values registered during the system's true test.

Table 13. List of switching sequences during process of bringing start-up power in the true system test and in simulation

No.	The time of event		Event	The time of meter		Tap changer			
	Real test [hh:mm:ss]	Simula-tion [s]		Real test [hh:mm:ss]	Simula-tion [s]	T1 and T3 in HPP	AT2 in WLA	TZ20 in PAT	TZ2 in PAT
1	10:23:00	20.00	turn on pump PC1 (1.5 MW)	10:25:00	24.9	0%	+5%	−8.75%	0%
2	10:30:30	25.00	turn on pump PC2 (1.5 MW)	10:31:00	29.4			−8.75%	0%
3	10:31:20	29.50	regulation TZ20 16→17	10:33:00	29.9			−10.00%	0%
4	10:34:00	30.00	turn on fan FGD inst. (5.25 MW)	10:36:00	32.9			−10.00%	0%
5	10:40:00	33.00	regulation TZ20 17→16	10:40:20	33.9			−8.75%	0%
6	10:40:30	34.00	regulation TZ20 16→15	10:40:50	34.9			−7.50%	0%
7	10:45:20	35.00	turn on P2A	10:45:50	35.9			−7.50%	0%
8	10:46:00	36.00	regulation TZ2 7→8	10:46:10	36.2			−7.50%	−1.67%
9	10:46:20	36.25	regulation TZ2 8→9	10:46:30	36.4			−7.50%	−3.33%
10	10:46:40	36.50	regulation TZ2 9→10	10:46:50	36.7			−7.50%	−5.00%
11	11:02:10	36.75	regulation TZ2 10→11	11:01:50	36.9			−7.50%	−6.67%
12	12:02:10	36.75	regulation TZ2 11→13	11:03:00	39.9			−7.50%	−8.33%
13	11:03:50	37.00	turn on PWCh-2 (1 MW)	11:05:00	42.4			−7.50%	−8.33%
14	11:05:20	42.50	regulation TZ2 12→11	11:05:40	42.9			−7.50%	−6.67%
15	11:05:50	43.00	regulation TZ2 11→10	11:05:55	43.4			−7.50%	−5.00%
16	11:06:00	43.50	regulation AT2 6→5	11:06:20	43.9		+6%	−7.50%	−5.00%
17	11:06:30	44.00	regulation TZ20 15→14	11:09:00	44.4		+6%	−6.25%	−5.00%
18	11:09:20	44.50	regulation TZ2 10→11	11:11:00	44.9		+6%	−6.25%	−5.00%
19	11:12:00	45.00	turn on WC_A (700 kW)	11:13:00	49.9		+6%	−6.25%	−6.67%
20	11:13:15	50.00	turn on WP_A (500 kW)	11:16:00	54.9		+6%	−6.25%	−6.67%
21	11:18:45	55.00	regulation AT2 5→4	11:19:00	55.4		+7%	−6.25%	−6.67%
22	11:19:10	55.50	regulation TZ2 11→12	11:19:20	55.9		+7%	−6.25%	−8.33%
23	11:19:30	56.00	regulation AT2 4→3	11:20:00	56.4		+8%	−6.25%	−833%
24	11:20:05	56.50	regulation TZ20 14→13	11:20:10	56.9		+8%	−5.00%	−833%
25	11:20:15	57.00	turn on PWZ_A (31.5 MW)	11:21:00	59.9		+8%	−5.00%	−8.33%

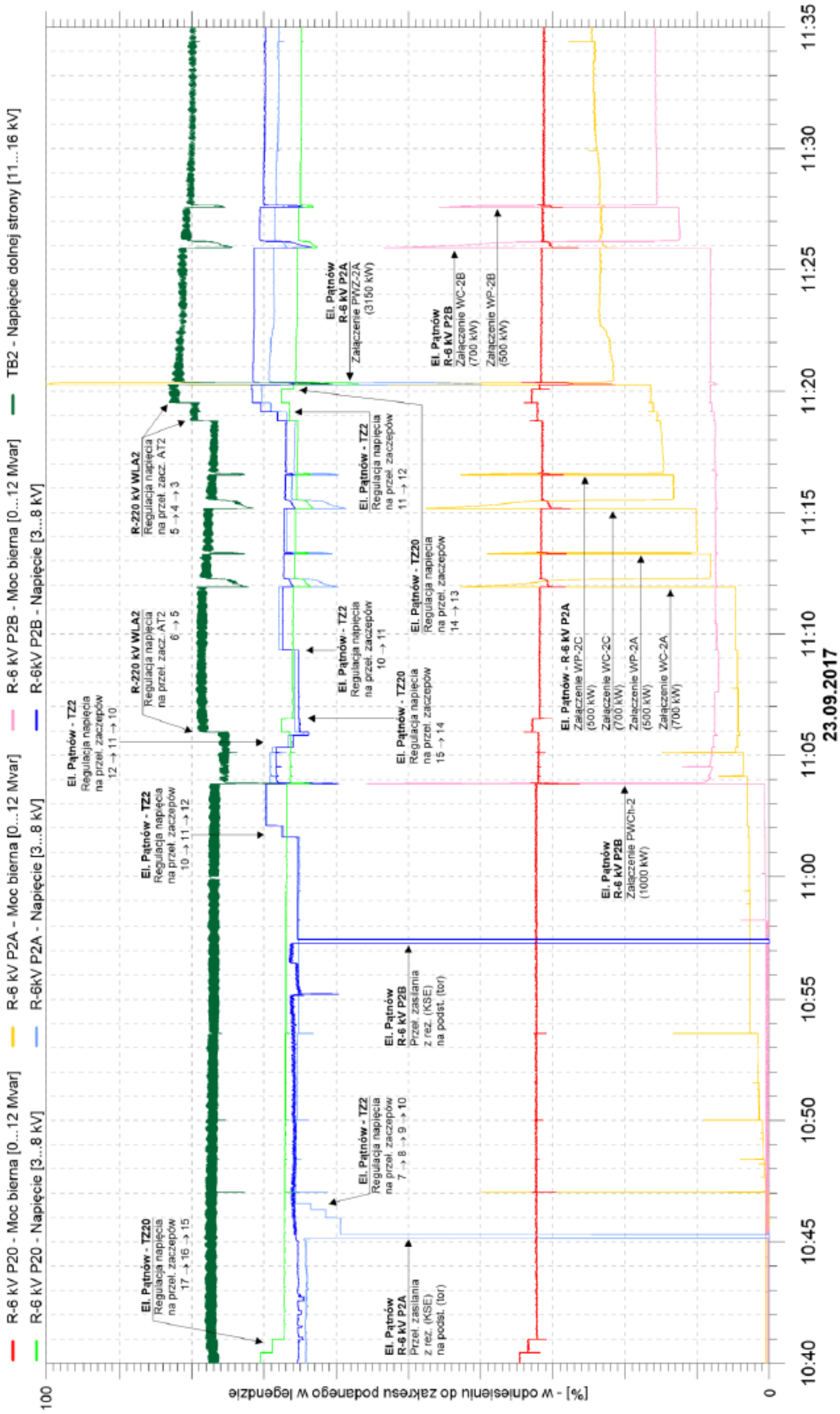

Fig. 9. Start-up of the IOS and PW devices of power unit No. 2 in TPP Pątnów. Voltages and reactive power across the bus of substations P2A and P2B as well as P20

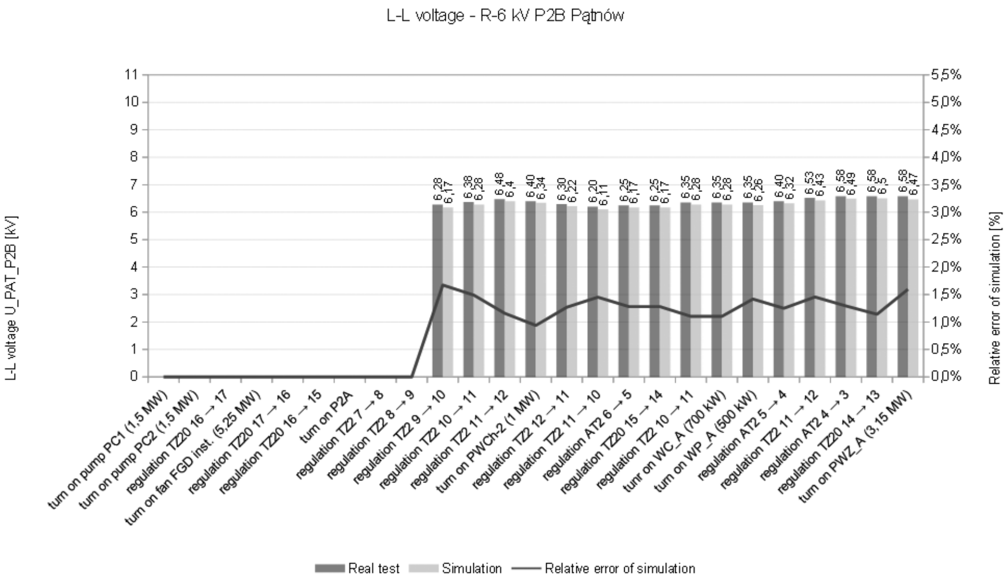

Fig. 10. Comparison: voltage (RMS) across substation bus R-6 kV PW P2B in TPP Pątnów obtained in true recording and computer simulation

5. Conclusions

Referring to the simulation results, the system test of starting-up the power unit No. 2 in TPP Pątnów from HPP Włocławek, including bringing voltage as well as starting-up the IOS and PW devices, is expected to run with no significant problems.

The analysis of the obtained recordings of changes in the voltage levels, active power and reactive power during both the true test and the simulation ones indicates that both ways give almost identical results.

The developed starting path model provides a very high approximation of the true process of bringing voltage from HPP Włocławek to TPP Pątnów.

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