A Study of Virtual Model of Power Supply Laboratory

Pham Thanh Nhan[1,2], Nguyen Thanh Nghia[1,2], Huynh Xuan Dung[1,2], Quyen Huy Anh[3], Bui Huu Phu[2], and Tran Thanh Trang[1,2,4,5,*]

[1] The Electronics Engineering Department, Cao Thang College of Technology, Ho Chi Minh City, Vietnam
[2] The National Key Lab of Digital Control and System Engineering, University of Technology, Vietnam National University Ho Chi Minh City, Vietnam
trangtranthanh1979@gmail.com
[3] The Electrical-Electronics Engineering Department, University of Technical Education Ho Chi Minh City, Vietnam
[4] The Electrical Engineering Department, Ho Chi Minh City Open University, Vietnam
[5] The Electronics & Telecommunication Engineering Department, Van Hien University, Ho Chi Minh City, Vietnam
trangtt@vhu.edu.vn

Abstract. This paper presented the method of creating virtual models of power supply laboratory in the Matlab environment based on the physical model of LD Didactic GmbH Company. A study created virtual models that had all the features of the physical model. Thus, experiment on the virtual models was similar to experiment on the physical models.

Keywords: Physical model, virtual model, transformer, transmission line, synchronous generator.

1 Introduction

Power supply laboratory is necessary to universities and colleges. Most universities and colleges have invested a lot of money in equipping power supply laboratory with physical models. However, a few universities and colleges had ability to invest, because of the high cost of physical model. Another way to create a power supply laboratory with low cost is building virtual model [1 - 3].

This paper describes the development of the virtual models based on physical models of the LD Didactic GmbH. These virtual models have high flexibility and accuracy that can substitute the physical models.

* Corresponding author.

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2 Materials and Methods

2.1 Experiment on the Physical Models

Synchronous generator model, Three phase transformer model, Transmission line model to collect data.

2.2 The Creation of Mathematical Model of Three Phase Transformer

The equivalent circuit diagram for the transformer operating under load is reproduced in figure 1:

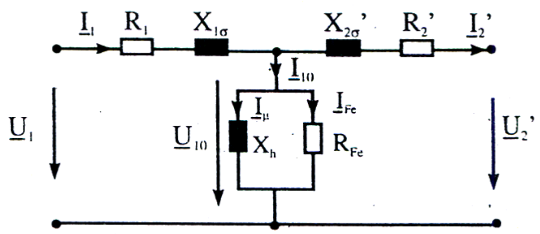

Fig. 1. Equivalent circuit diagram for the transformer operating under load

R_2: Ohmic resistance of the secondary side

R_2': Value of R_2 converted to the primary side in accordance with expression:

$$R_2 = R_2' t^2 \quad (1)$$

$X_{1\sigma}$: Leakage reactance of the primary side

$X_{2\sigma}$: Leakage reactance of the secondary side

$X_{2\sigma}'$: Value of $X_{2\sigma}$ converted to the primary side in accordance with expression:

$$X_{2\sigma} = X_{2\sigma}'.t^2 \quad (2)$$

$$\frac{U_1}{U_2} = \frac{W_1}{W_2} = t \quad (3)$$

To calculate the value showed in figure 1, first of all, experiments with performance at no-load and calculated the following: $cos\varphi_0$, I_{Fe}, I_μ, R_{Fe}, X_h [4].

Then, conduct further experiments with performance at short - circuit, the parameters of the specifications are formulated by:

$$\cos\phi_k = \frac{P_{lk}}{U_{lk}.I_1} \quad (4)$$

$$u_k = \frac{U_{1k}}{U_{1N}} \quad (5)$$

$$u_r = u_k \cos \varphi_k \quad (6)$$

$$u_x = u_k \sin \varphi_k \quad (7)$$

$$R_{lk} = \frac{U_{1k} \cos \phi_k}{I_l} \quad (8)$$

$$X_{lk} = \frac{U_{1k} \sin \phi_k}{I_l} \quad (9)$$

Draw a complete equivalent circuit diagram of the transformer and enter all of the measured or calculated quantities in figure 2. The following applies approximately: $R_1 = R_2^{'} = R_{1k}/2$ and $X_{1\sigma} = X_{2\sigma}^{'} = X_{1k}/2$ [4].

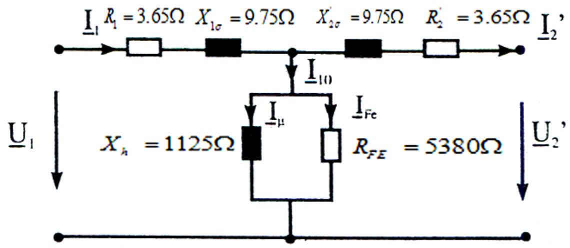

Fig. 2. A complete equivalent circuit diagram for the transformer operating under load

2.3 The Creation of Mathematical Model of Transmission Line

When operating a transmission line with three-phase current, the leakage losses (G) and the inductive and capacitive properties (L and C) of the arrangement, as well as the resistance of the conductor material (R) must be taken into consideration. As these values are evenly distributed along the transmission line in the form of quantities per unit length, the equivalent circuit diagram in figure 3 with concentrated circuit component only applies to short lines [5]:

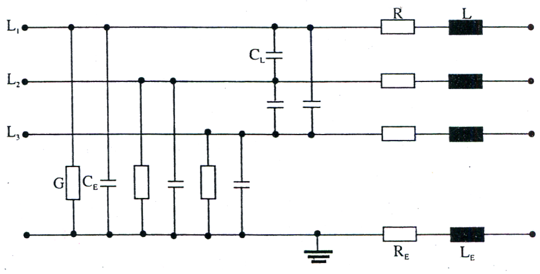

Fig. 3. Equivalent circuit diagram of a three-phase transmission line

$$R = \frac{l}{\chi . A} \tag{10}$$

l : Line length
A : Line cross-section
χ : Specific at a temperature of conductor material

$$L = \frac{1000\mu_0}{2\pi}(\ln\frac{d_{gmi}}{r_B} + \frac{0.25}{n}) \tag{11}$$

d_{gmi} : The geometrical mean value for the conductor spacing. For this the following applies:

$$d_{gmi} = \sqrt[3]{(d_{12}.d_{23}}.d_{31}) \tag{12}$$

d_{12} etc: Spacing of the conductor cables from each other
n : Number of subconductors
r_B : Equivalent radius for multiple conductor lines

$$r_B = \sqrt[n]{(n}.r.a^{n-1}) \tag{13}$$

r : Radius of a conductor cable
a : Spacing of the subconductors of a multiple conductor line
μ_0 : Permeability of free space =1,257.10^{-6} Vs/Am

$$C_L = \frac{1000.2\pi.\varepsilon_0.\ln\frac{2h}{d_{gmi}}}{3\ln\frac{2h}{d_{gmi}}\ln\frac{2h}{\sqrt[3]{r_B.d_{gmi}^2}}} \tag{14}$$

$$C_E = \frac{1000.2\pi.\varepsilon_0}{3(\ln\frac{2h}{\sqrt[3]{r_B.d_{gmi}^2}} - \frac{(\ln\frac{h+h_0}{d_0})^2}{\ln\frac{2h_0}{r_0}})} \tag{15}$$

$h = \sqrt[3]{(h_1}h_2h_3)$: Geometrical average of the line height
h_0 : Medium height of the earth wire
$d_0 = \sqrt[3]{d_{10}.d_{20}.d_{30}}$: Geometrical average distance from earth wire to the other conductors
r_0 : Radius of the earth wire

r_B : Equivalent radius as in calculation of the inductance

ε_0 : Permittivity of free space = 8,86.10^{-12} As/Vm

In the transmission line model, condensed circuit element was used to simulate a transmission line with three possible lengths: 144km, 216 km, 360 km, as indicated in table 1:

Table 1. The technical data of transmission line

Length in Km	360	216	144
Length in %	100	60	40
R in Ω	13	8	5
L in mH	290	174	116
C_B in nF	5000	3000	2000

2.4 The Creation of Mathematical Model of Synchronous Generator

The circuit is based on a star configuration of the stator (see figure 4):

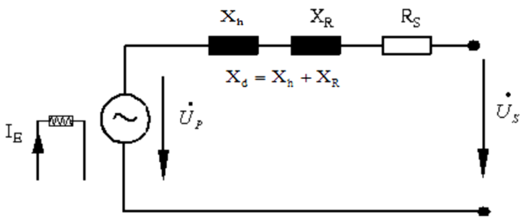

Fig. 4. Single-phase equivalent circuit diagram of the turbo generator in stationary operating mode

I_E : Exciter current in rotor

$\dot{U}_P$: Synchronous generated voltage in stator

$\dot{U}_S$: Stator voltage

X_h : Main field reactance of the stator winding

X_R : Leakage reactance of the stator winding

R_S : Resistance of the stator winding

Accordingly the two reactances are defined X_h and X_R, the two in conjunction constitute the synchronous reactance X_d, which is also referred to as armature reactance [4].

$$X_d = X_h + X_R \tag{16}$$

The resistance R_S of the stator winding is designed as small as possible by selecting the appropriate diameter for the copper windings. Thus, for rough observations, R_S can be ignored in comparison with the synchronous reactance X_d.

The value of the synchronous reactance X_d is obtained by performing current and voltage measurements during a short-circuit experiment whereby the resistance of the stator winding is neglected. The measurement is carried out with reduced exciter current and with all three phases of the stator winding short-circuit currented. There is an almost linear relationship between the exciter current and the short-circuit current. Furthermore, unlike the no-load voltage, the short-circuit current is nearly independent of the machine's speed, as both the synchronous generated voltage and the synchronous reactance are proportioned to the frequency, thus making the quotient of both quantities frequency-dependent.

The curve of a no-load and a short-circuit characteristic is reproduced in figure 5:

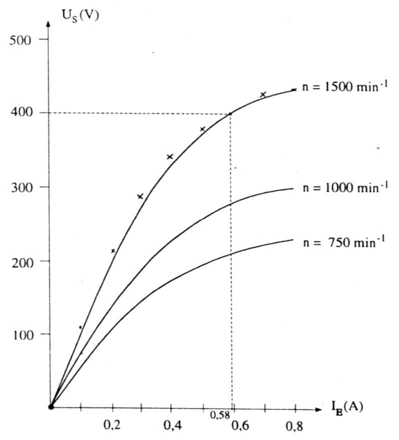

Fig. 5a. No-load characteristic of the turbo generator

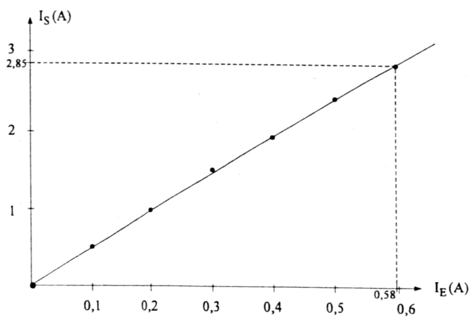

Fig. 5b. Short-circuit characteristic of the turbo generator

The no-load nominal exciter current I_{E0} = 0.58 (A) is that particular current in the rotor which supplies the nominal voltage during generator operation under no-load condition. If the machine is short-circuited at this current level, then the so-called no-load steady short-circuit current I_{K0} flows in the stator. The synchronous reactance can be determined. For a star connection of the stator this amounts to:

$$X_d = \frac{U_N}{\sqrt{3}.I_{K0}} = \frac{400}{\sqrt{3}.2.85} = 81\Omega \tag{17}$$

2.5 The Creation of Virtual Model

Building the electric circuit of the physical model on Simulink with all the information have been received from the mathematical model [6 - 7] (see figure 6, figure 7, figure 8):

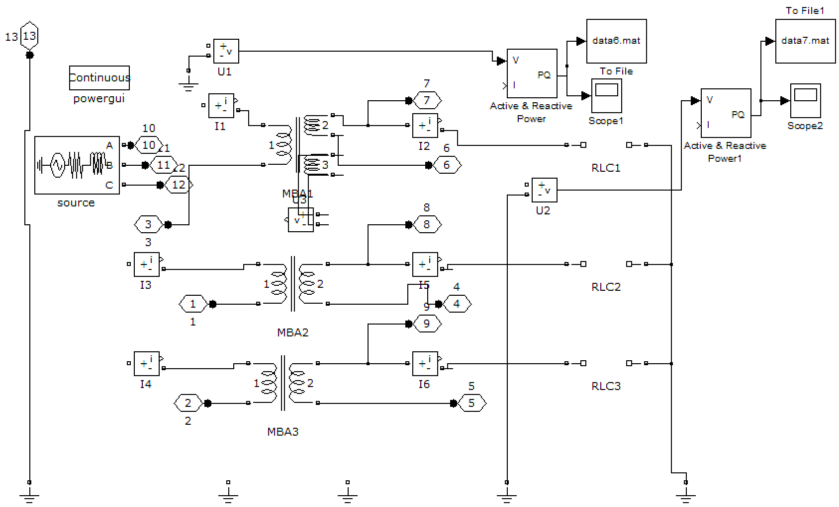

Fig. 6. Circuit diagram of three-phase transformer model

In figure 6, the circuit used the Transformer models and Three-Phase Source model, Series RLC Branch models, these models used varying parameter to from mathematical models and physical models. The Transformers model connected to Three-Phase Source model, Series RLC Branch models was correspondent with each cases of experiment selected from the interface of the virtual model. The Voltage Measurement models, Current Measurement models, and Active & Reactive Power models were measured currents, voltages, powers and results would displayed in the interface model. The circuits in figure 7, 8 show the same.

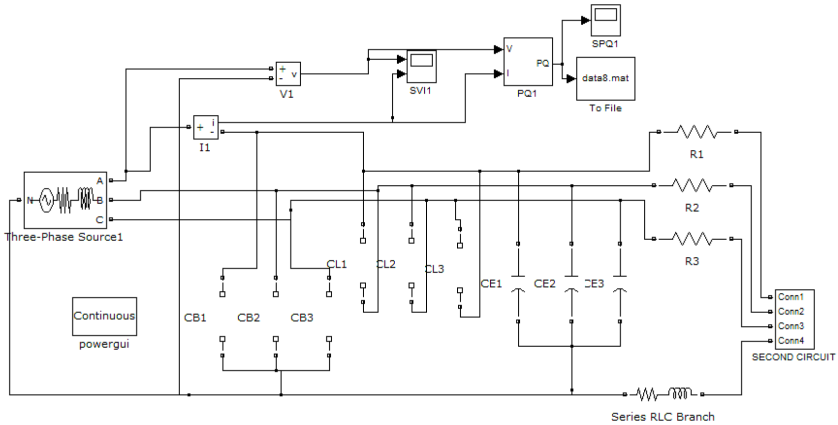

Fig. 7a. First circuit diagram of transmission line model

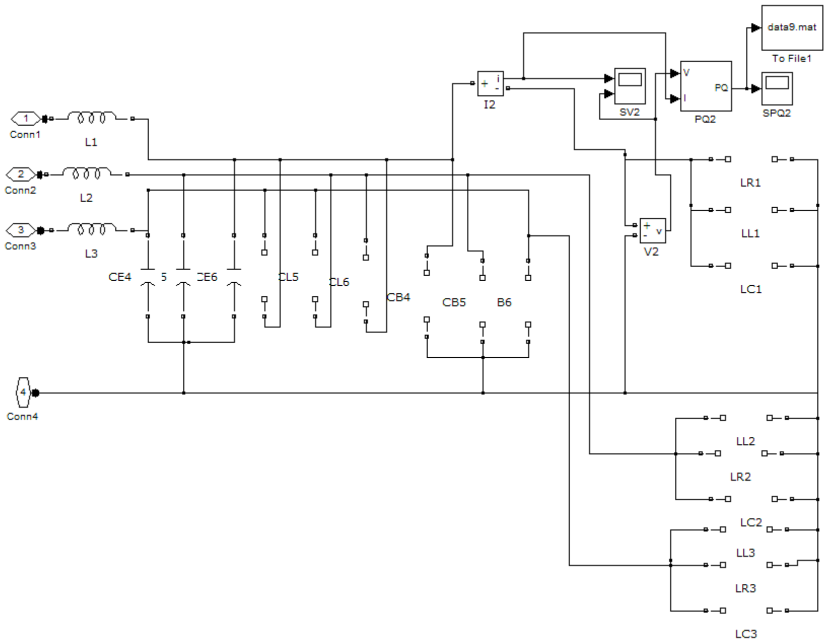

Fig. 7b. Second circuit diagram of transmission line model

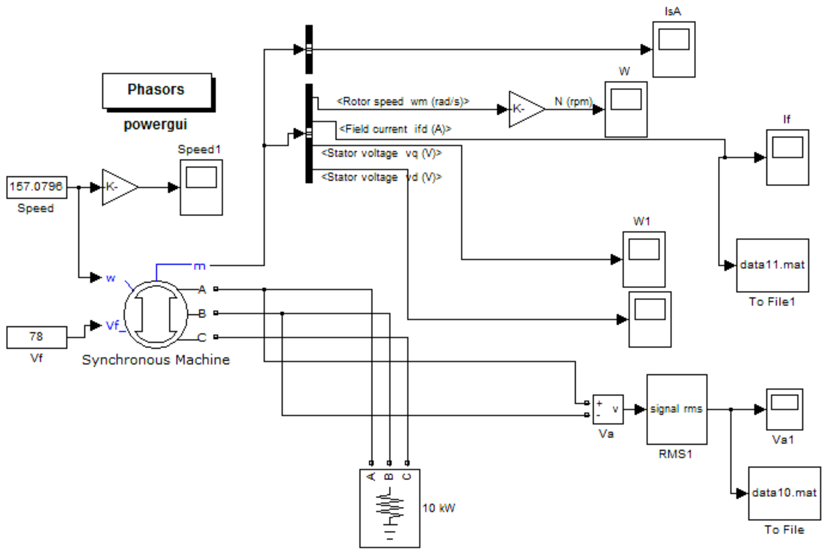

Fig. 8. Circuit diagram of synchronous generator model

The interface of virtual model was created by GUI function (see figure 9, figure 10, figure 11):

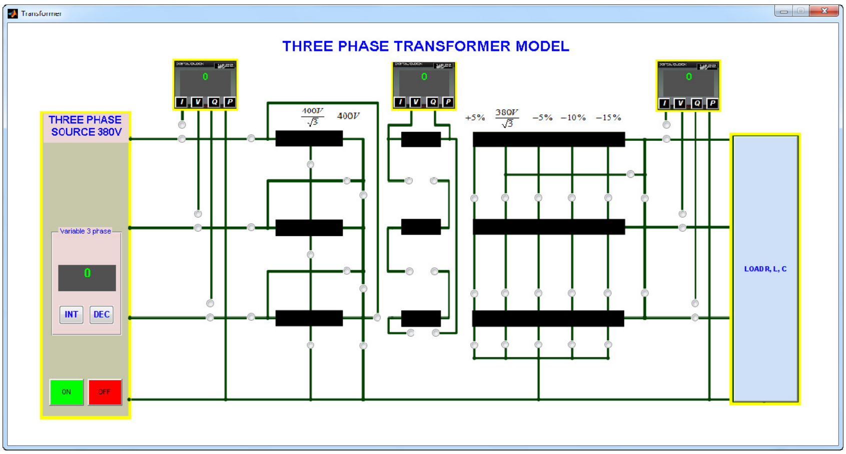

Fig. 9. The interface of three-phase transformer virtual model

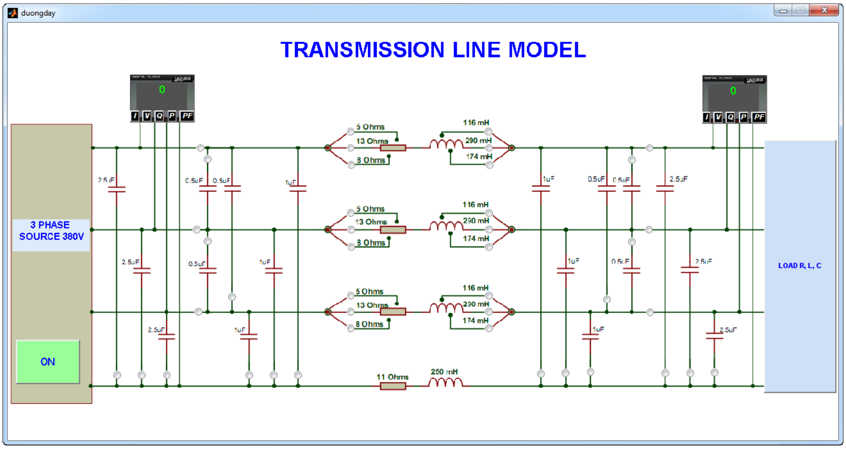

Fig. 10. The interface of transmission line virtual model

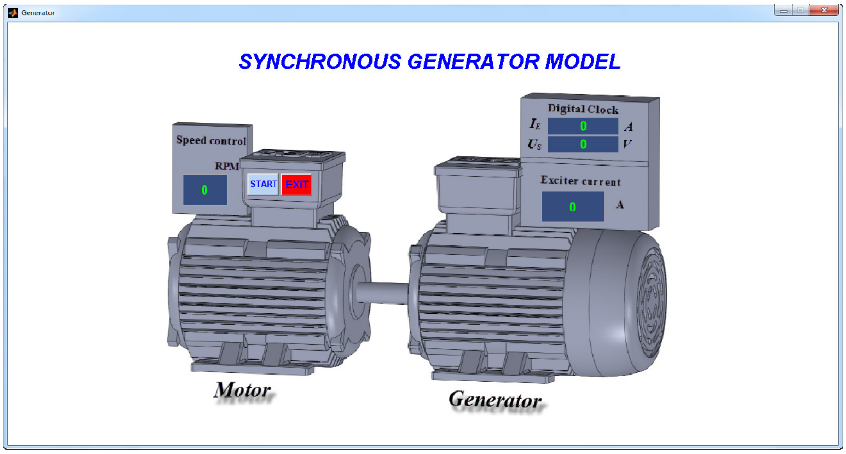

Fig. 11. The interface of synchronous generator virtual model

3 Results and Discussion

3.1 Three Phase Transformer Virtual Model

Can be carry out experiments on transformer virtual model:

• Performance at no-load: Determining the voltage transformation ratio of a transformer operating at no-load as well as measuring the consumed active and reactance power, determining equivalent circuit quantities based on these measurements.

• Performance at short-circuit: Measuring voltage, current, and active power when there is a short-circuit on the secondary side of the transformer and determining the equivalent circuit quantities based on these measurements.

• Performance at load operation: Measuring the effect of load type and magnitude on the performance of the secondary voltage and comparing this to the theoretically anticipated value, determining the efficiency.

The tolerance between experiments on virtual model and physical model, as indicated in table 2, table 3 and table 4.

Table 2. Performance at no-load

Tolerance	U_N+5%	U_N	U_N-5%	U_N-15%
U_1 (%)	0.27	0.27	0.27	0.27
U_2 (%)	1.05	0.64	0.22	0.87
U_3 (%)	-	0.63	-	-
P_{10} (%)	-	0	-	-
I_{10} (%)	-	1	-	-

Table 3. Performance at short-circuit

Tolerance	U_{1k} (%)	I_1 (%)	P_{1k} (%)
	4	0	0

Table 4. Performance at load operation

Tolerance	U_{20} (%)	U_2 (%)	I_2 (%)	P_1 (%)	P_2 (%)
R_1	0.40	1.07	5	3.30	3.60
R_2	0.40	0.39	4	4.60	3.40
R_3	0.40	0.39	4	4.40	3.30
R_4	0.40	0.70	4	4.60	3.30
R_5	0.40	1.09	4.30	4.30	4

3.2 Transmission Line Virtual Model

Can be carry out experiments on transmission line virtual model:

• Performance at no-load: Measurement of the voltage increase and charging power in lines of different lengths in no-load operation. Explanation of the concept of operating capacitance. Different performance characteristics of overhead transmission line and cable.

• Performance characteristics for three-phase short-circuit: Measuring and interpreting the current and voltage ratios of a transmission line during a three-phase short-circuit.

• Performance characteristics of an ohmic-inductive and pure inductive load: Measuring and interpreting the current and voltage ratios of a transmission line with mixed ohmic-inductive and pure inductive loads.

• Performance characteristics of an ohmic-capacitive and pure capacitive load: Measuring and interpreting the current and voltage ratios of a transmission line with mixed ohmic-capacitive and pure capacitive loads.

The tolerance between experiments on virtual model and physical model, as indicated in table 5, table 6.

Table 5. Performance at no-load

Tolerance	U_1 (%)	U_2 (%)	Q_C (%)
144 km	0.05	0.03	1.5
216 km	0.36	0.02	1.6
360 km	0.70	0.40	1.2

Table 6. Performance at load operation: An ohmic-inductive and pure inductive load

Tolerance	U_1 (%)	I_1 (%)	P_1 (%)	U_2 (%)	I_2 (%)	P_2 (%)
	1	2	0	1.2	2	3.5
	0.8	1.6	0	1.2	2.1	2.8
	1	1.9	0	1.1	3	3.5
	1.3	1.6	0.6	0.6	2.6	2.7

3.3 Synchronous Generator Virtual Model

Can be carry out experiments on synchronous generator virtual model:

• Performance at no-load: Measuring the exciter current and the corresponding stator voltage at various speeds. Determining the no-load nominal exciter current from the measured values.

The tolerance between experiments on virtual model and physical model, as indicated in table 7.

Table 7. Performance at no-load

P=750 (RPM)	I_E (A)	0.1	0.2	0.3	0.4	0.5	0.6
Tolerance	U_S (%)	2	2.7	3.6	2.9	2.6	2
P=1000 (RPM)	I_E (A)	0.1	0.2	0.3	0.4	0.5	0.6
Tolerance	U_S (%)	2.7	2.2	3.2	2.3	2	1.8
P=1500 (RPM)	I_E (A)	0.1	0.2	0.3	0.4	0.5	0.6
Tolerance	U_S (%)	2.5	1.8	2.2	2.	2.4	2.25

4 Conclusion

The virtual models were built with high homology with the physical models, the results of experiment on the virtual model and the physical model had low tolerance, the physical models were replaced by virtual models. Can perform the experiments on the virtual model similar to perform the experiments on the physical models and can be extended to the case of experiments, other practices by change information's the settings of the virtual model. Can be equipped the virtual models for universities, colleges cannot equipped yet with the physical model to conduct experiments.

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