Simulation of Thyristor Operated Induction Generator by Simulink, Psim and Plecs

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***Abstract*-The paper presents simulation results about thyristor operation of a mains connected induction machine, both as a motor and as a generator. The results were obtained by three different simulation packages, Simulink, Psim and Plecs. The co-simulation options between these programs were checked. The performances of these three packages were compared. The simulation results were validated by real experiments.**

I. Introduction

The induction machine is generally used as a motor when it is thyristor operated [1]. Furthermore, the thyristor operation of an induction machine as mains connected generator was also recently reported [2]. Moreover, simulation results obtained by common simulation packages such as Simulink [7], Psim [8] and Plecs [9] and validated by the experimental results, are difficult to find in the literature. The paper presents the comparison results obtained by these simulation programs and also validated by real experiments. Moreover, the paper presents the co-simulation options and limitations between these three programs. The comparison of the programs will be performed on two cases of "star" connected induction machine.

A base illustration of the power control arrangement is shown in Fig. 1. It consists of six thyristors, while each pair of back-to-back connected thyristors is connected between the phase source voltage and the appropriate phase of the induction machine, in the "star" connection. The parameters of the induction machine are: wound rotor type, two pole pairs.

$Rs = 5.2\Omega, Rr = 14.63\Omega, Ls = Lr = 0.055H, Lm = 1.3H$

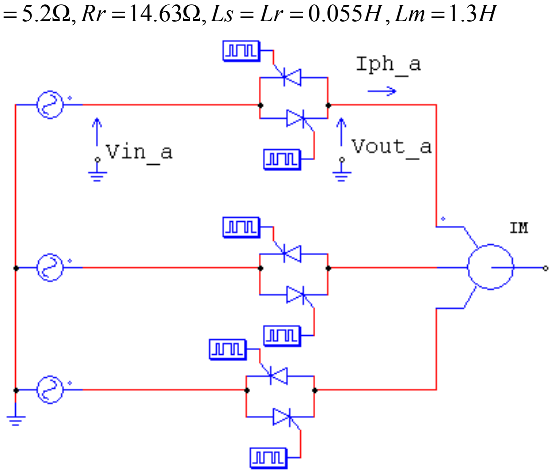

Fig. 1. Induction machine (star connection) controlled by thyristors.

The phase angle ϕ is defined as the angle between the phase voltage and phase current. When the machine will operate as a motor, this angle would be $0 \le \phi \le 90°$. When the machine will operate as a generator, this angle would be $90° \le \phi \le 180°$. The firing angle α is defined as the angle between zero crossings of the phase voltage to the conduction beginning of the appropriate thyristor.

The delay angle γ is defined as the angle between zero crossings of the phase current to the conduction beginning of the next thyristor $\gamma = \alpha - \phi$.

II. Modes of Operation Versus Delay Angle γ

A. *Continuous mode*

The example of continuous mode is shown in Fig. 2, where $\phi = 75°,\ \alpha = 40°,\ \gamma = -35°$.

The firing angle is smaller than the phase angle and the delay angle is negative. Therefore, the machine operates in the continuous mode.

In steady state of continuous mode, the machine would operate as usual, as if there were no thyristors at all, and it would not be influenced by the changes in the firing angle. Fig. 2 shows that the currents and the voltages in the steady state are not influenced by the thyristors.

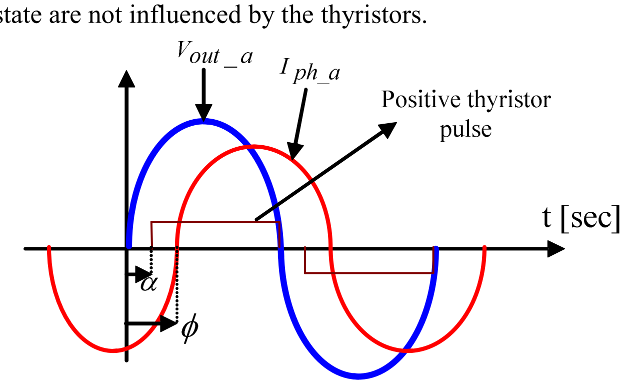

Fig. 2. The waves of phase voltage V_{out_a} and current I_{ph_a} in continuous mode ($\phi = 75°,\ \alpha = 40°,\ \gamma = -35°$).

B. *Discontinuous mode*

The example of discontinuous mode is shown in Fig. 3, where $\phi = 80°, \alpha = 100°,\ \gamma = 20°$.

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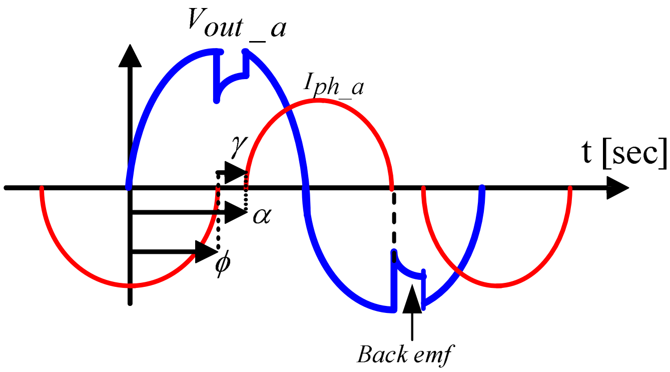

Fig. 3. The waves of phase voltage V_{out_a} and current I_{ph} in discontinuous mode ($\phi = 80°$, $\alpha = 100°$, $\gamma = 20°$).

The phase angle is smaller than the firing angle and the delay angle is positive. The phase voltage and current become discontinuous.

When the phase current is zero, there would be a delay, until the positive current is enabled. During this delay, the phase voltage gets the value of the back emf voltage of the machine. The duration of this delay is defined by the delay angle.

III. Simulation by Simulink

The Simulink simulation circuit, for "star" connected stator, is shown in Fig. 4. The Simulink model includes three phase voltage source, an induction machine, six thyristors, a firing system for the thyristors and the measurement arrangements. The firing system is implemented by the synchronized 6-pulse generator.

The Simulink simulation results for $\alpha = 110°$, n=1500 rpm, "star" connection, are shown in Fig. 5. The Simulink simulation results for $\alpha = 110°$, n=1533 rpm, "star" connection, are shown in Fig. 6.

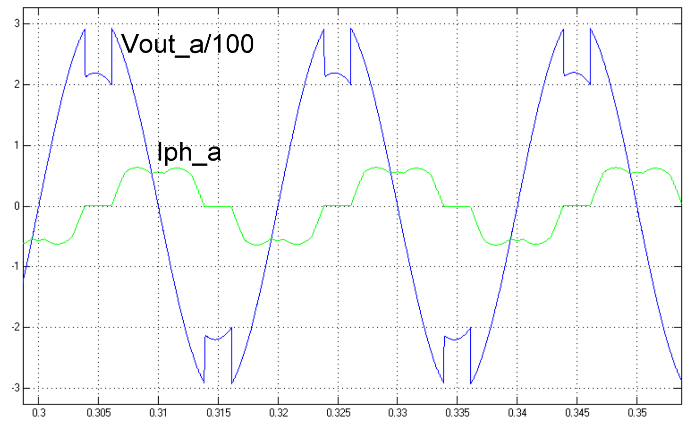

Fig. 5. Simulink simulated phase voltage of the machine- V_{out_a} /100 [V] and the phase current I_{ph_a} [A], for $\alpha = 110°$, n=1500 rpm, "star" connection. (X- 5 msec/div, Y1- 100V/div, Y2- 1A/div)

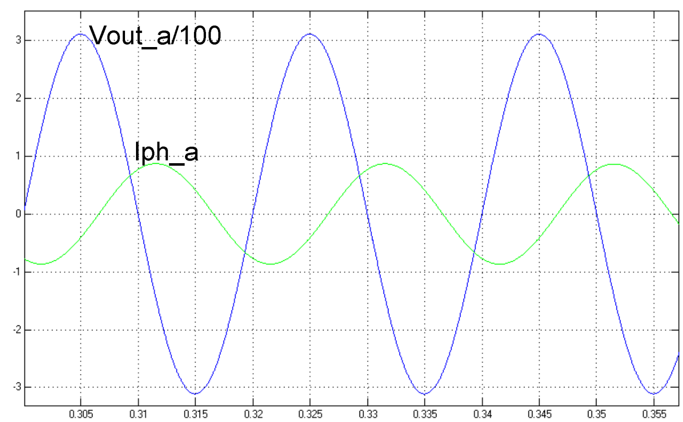

Fig. 6. Simulink simulated phase 'a' voltage- V_{out_a} /100 [v] and the phase 'a' current I_{ph_a} [A], for $\alpha = 110°$, n=1533 rpm, "star" connection. (X- 5 msec/div, Y1- 100V/div, Y2- 1A/div)

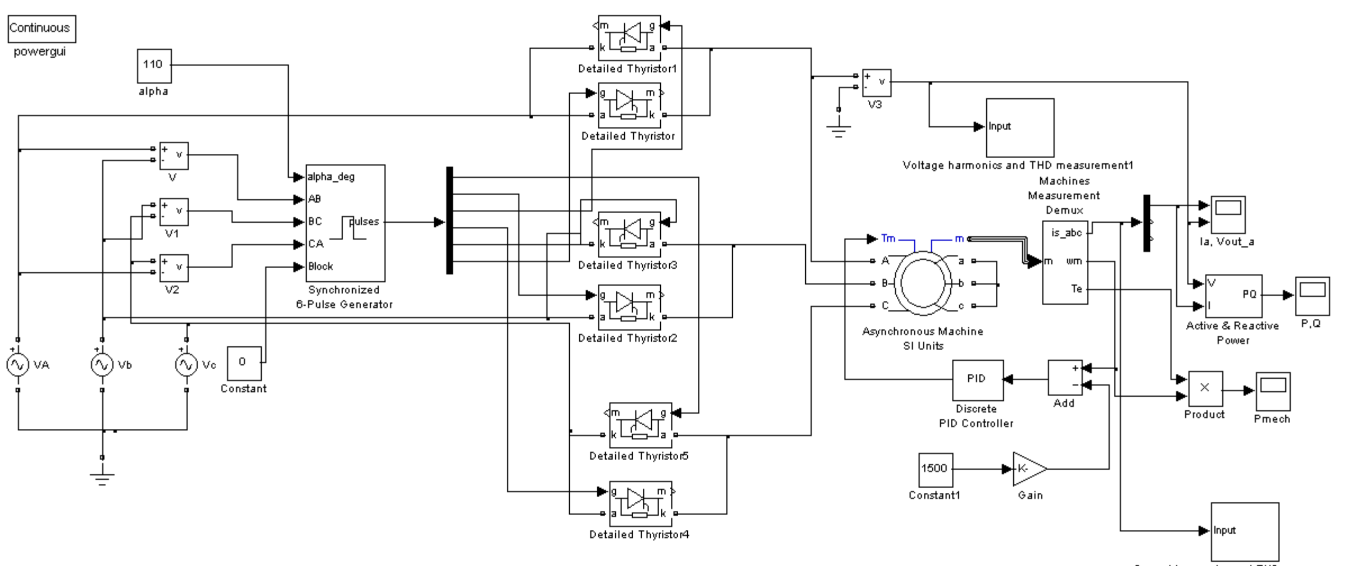

Fig. 4. The Simulink simulation circuit for "star" connected stator.

The desired machine speed is regulated by feedback control which is performed by PID controller. The measurement of harmonics and THD of the phase current and voltage is performed inside subsystems "Voltage harmonics and THD measurements" and "Current harmonics and THD measurements". These subsystems include "Fourier" and "Total Harmonic Distortion" blocks.

In the first case, when the machine speed is 1500 rpm (the synchronous speed of the machine), the input power from the grid and the mechanical power developed at the machine shaft are very close to zero. They are intended to cover the electrical, magnetic and mechanical losses of the machine. This is the transition point between the motor and the generator modes. The phase angle is 89.3 degrees and the delay angle is 20.7 degrees. The phase current is discontinuous and includes higher harmonics. When the phase current is zero, the phase voltage gets the value of the back emf voltage. In the second case, when the machine speed is 1533 rpm, the machine operates as generator. The slip is negative and it causes the phase angle to be 119 degrees. The delay angle is -9 degrees. Therefore, the mode is continuous. There are no higher harmonics in the phase current.

IV. Simulation by Psim

The simulation in Psim is performed in co-simulation with Simulink. The co-simulation consists of Psim and Simulink files. The Psim simulation circuit is shown in Fig. 7. The Psim simulation results for $\alpha = 110°$, n=1500 rpm, "star" connection, are shown in Fig. 8. The Psim simulation results for $\alpha = 110°$, n=1533 rpm, "star" connection, are shown in Fig. 9. The results, which were obtained by the Psim simulations, are identical to the results, which were obtained by the Simulink simulations.

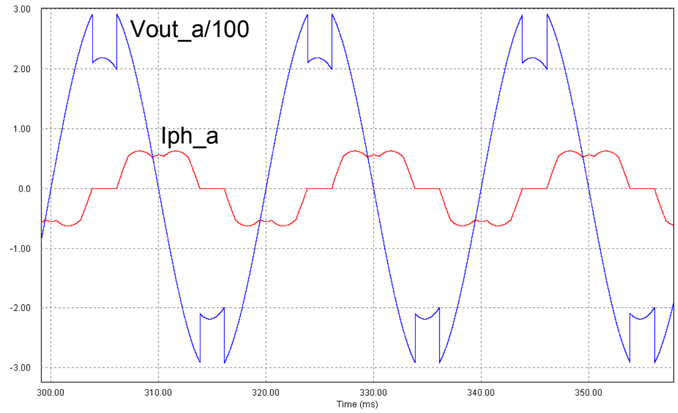

Fig. 8. Psim simulated phase voltage of the machine- $V_{out\_a}/100$ [V] and the phase current I_{ph_a} [A], for $\alpha = 110°$, n=1500 rpm, "star" connection. (X- 10 msec/div, Y1- 100V/div, Y2- 1A/div)

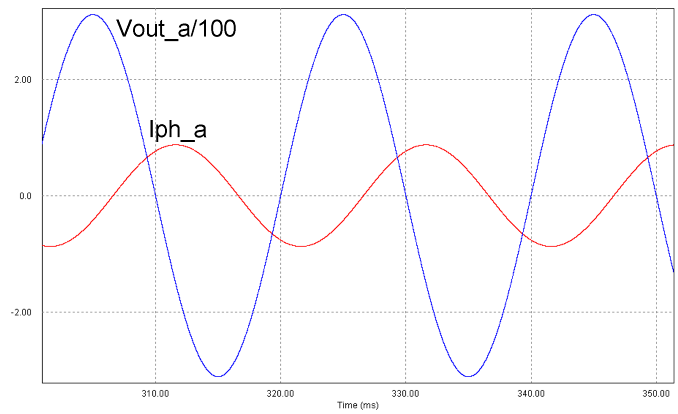

Fig. 9. Psim simulated phase 'a' voltage- $V_{out\_a}/100$ [v] and the phase 'a' current I_{ph_a} [A], for $\alpha = 110°$, n=1533 rpm, "star" connection. (X- 10 msec/div, Y1- 100V/div, Y2- 1A/div)

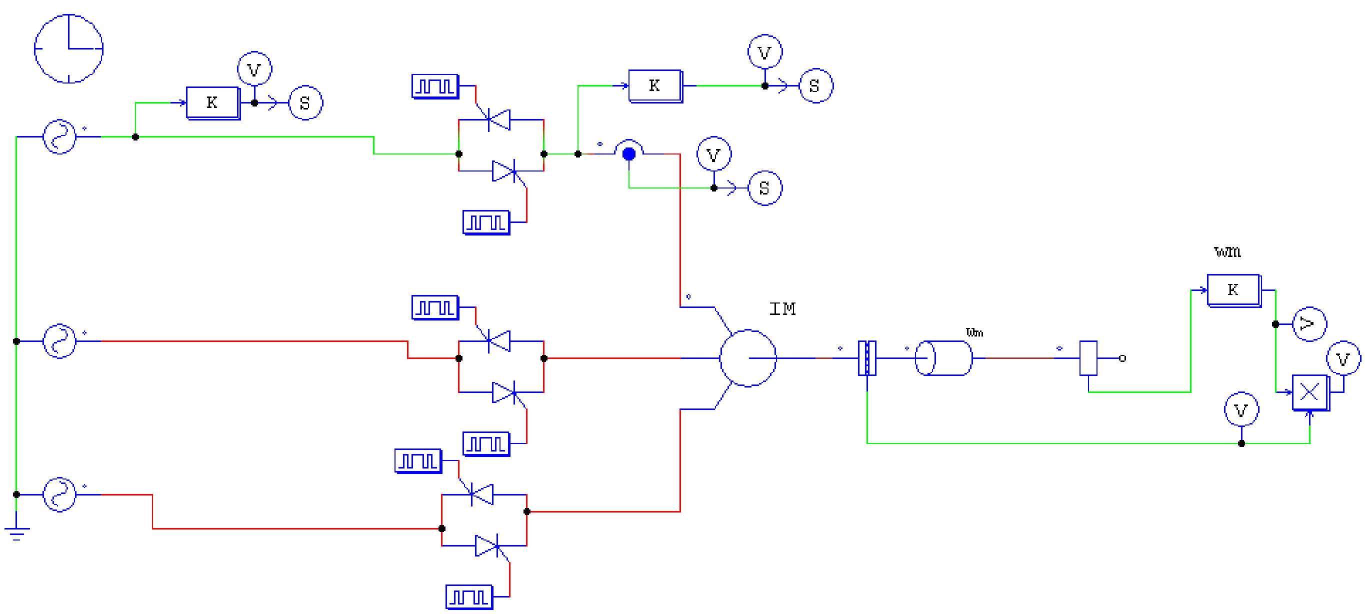

Fig. 7. The Psim simulation circuit.

The simulation of the power circuit is performed in Psim. The signals that are sent to the Simulink are the phase current, phase voltage before and after the thyristors. These signals are transferred to the Simulink file by Simcoupler block, which is shown in Fig. 10. The parameters that are measured by the Simulink are the RMS, THD and harmonics of the phase current and phase voltage and the phase active and reactive power. The mechanical power of the induction machine is measured in PSIM.

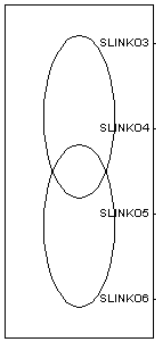

Fig. 10. The Simcoupler block.

V. Simulation by Plecs

The Plecs program can not work alone. It runs under the Simulink program. Plecs is presented in Simulink as subsystem with inputs and outputs.

The goal is to simulate the thyristors inside the Plecs program and the induction machine, firing control and measurements inside the Simulink program. The Plecs and Psim co-simulation file is shown in Fig. 11.

The contents of the Plecs block are shown in Fig 12.

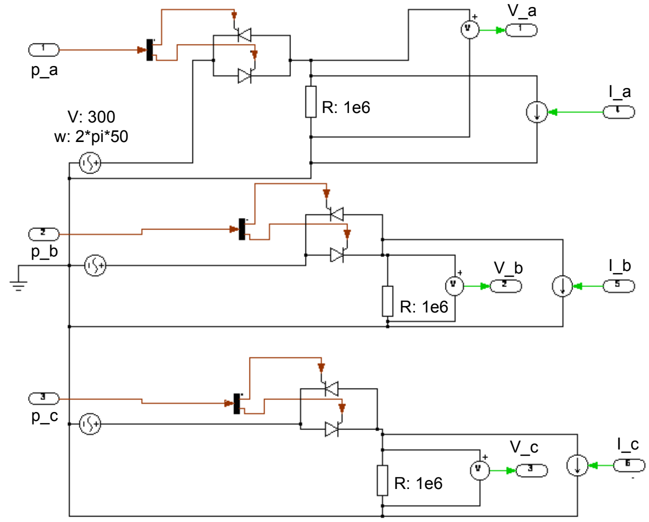

Fig. 12. The contents of the Plecs block.

The firing pulses for the thyristors are generated inside the Simulink circuit. Through the ports p_a, p_b and p_c, the Plecs block receives these firing pulses. Each port carries pulses for one phase.

The Plecs block can receive or export only Simulink signals. It can not receive or export currents or voltages. In order to overcome this problem, signal controlled voltage and current sources must be used.

The measured stator currents I_a, I_b and I_c are fed back to the Plecs block as signals. These signals must be converted to the Plecs currents.

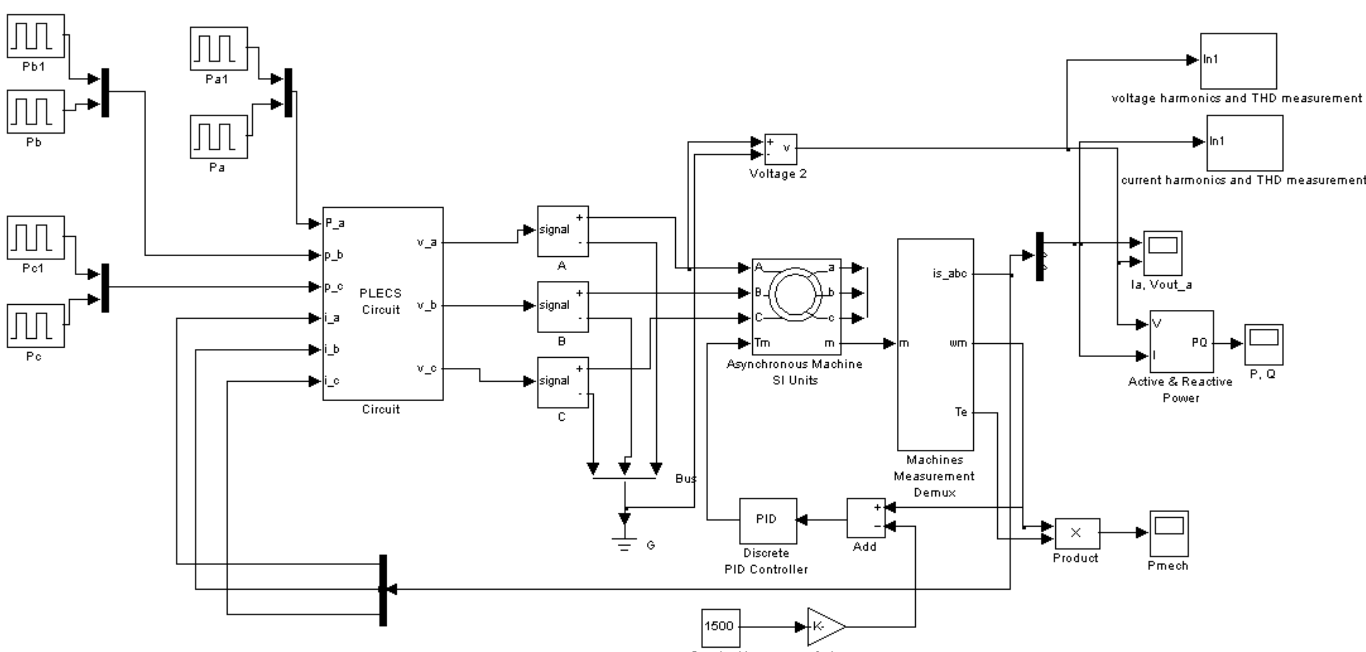

Fig. 11. The Plecs and Simulink co-simulation file.

This conversion is done by the signal controlled current sources, which close the currents loops in the Plecs block.

Three resistors of 1M ohm are inserted for the phase voltages measurement. The measured phase voltages V_a, V_b and V_c have to be fed into the induction machine, in Simulink. The phase voltage signals are converted to the Simulink voltages by signal controlled voltage sources. By the help of controlled current and voltage sources, the Plecs circuit operates as if the induction machine was connected directly to the thyristors inside the Plecs.

The Plecs simulation results for $\alpha = 110°$, n=1500 rpm, "star connection", are shown in Fig. 13. The Plecs simulation results for $\alpha = 110°$, n=1533 rpm, "star connection", are shown in Fig. 14.

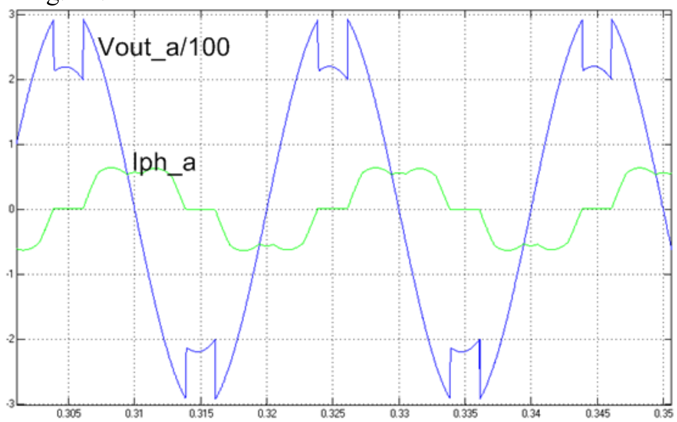

Fig. 13. Plecs simulated phase voltage of the machine- V_{out_a} /100 [V] and the phase current I_{ph_a} [A], for $\alpha = 110°$, n=1500 rpm, "star" connection. (X- 5 msec/div, Y1- 100V/div, Y2- 1A/div)

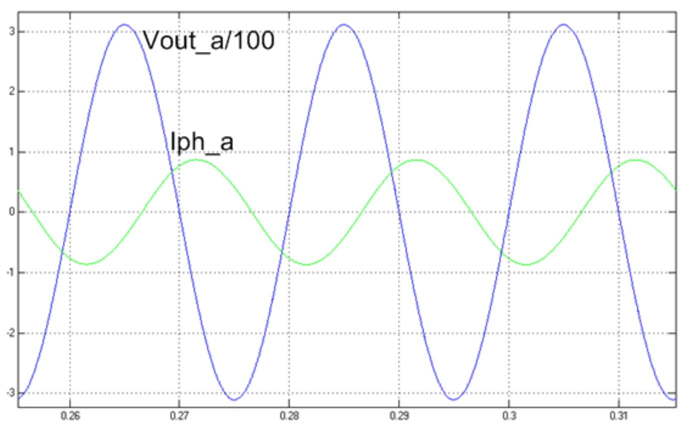

Fig. 14. Plecs simulated phase voltage of the machine- V_{out_a} /100 [V] and the phase current I_{ph_a} [A], for $\alpha = 110°$, n=1533 rpm, "star" connection. (X- 10 msec/div, Y1- 100V/div, Y2- 1A/div)

The results, which were obtained by the Simulink, Psim and Plecs simulation programs, are identical.

VI. Validation of Simulations by Experimental Results

The experimental results for $\alpha = 110°$, n=1500 rpm, "star" connection, are shown in Fig. 15. The experimental results for $\alpha = 110°$, n=1533 rpm, "star" connection, are shown in Fig. 16.

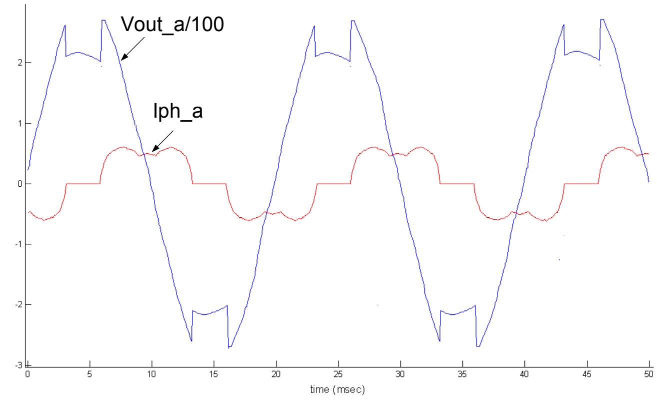

Fig. 15. Measured phase voltage of the machine- V_{out_a} /100 [V] and the phase current I_{ph_a} [A], for $\alpha = 110°$, n=1500 rpm, "star" connection.

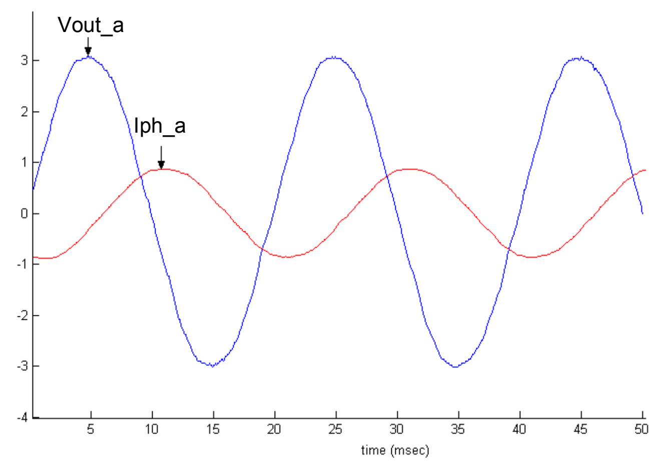

Fig. 16. Measured phase voltage of the machine- V_{out_a} /100 [V] and the phase current I_{ph_a} [A], for $\alpha = 110°$, n=1533 rpm, "star" connection.

The simulated and experimentally measured values for $\alpha = 110°$, n=1500 rpm, "star" connected induction machine, are shown in TABLE I. The simulated and experimentally measured values for $\alpha = 110°$, n=1533 rpm, "star" connected induction machine, are shown in TABLE II.

TABLE I

SIMULATED AND MEASURED VALUES FOR $\alpha = 110°$, N=1500 RPM

Case/ parameters	Simulink, Psim and Plecs Simulation	Experiment
I_{ph_a} [A]	0.46	0.45
$I_{ph\_a\_1}$ (first harmonic) [A]	0.63	
$I_{ph\_a\_3}$ (third harmonic) [A]	0	
$I_{ph\_a\_5}$ (fifth harmonic) [A]	0.13	
$I_{ph\_a\_7}$ (seventh harmonic) [A]	0.04	
$I_{ph\_a\_THD}$ [%]	22.4	
P_{in_3ph} (3-phase grid active power) [W]	7.8	7
Q_{3_ph} (3-phase grid reactive power) [VAR]	297	
P_{mech} (shaft mechanical power) [W]	3.7	
V_{out_a1} (first harmonic) [V]	271.94	
V_{out_a3} (third harmonic) [V]	33.6	
V_{out_a5} (fifth harmonic) [V]	23	
V_{out_a7} (seventh harmonic) [V]	10.5	
V_{outa_THD} [%]	16.7	

TABLE II

SIMULATED AND MEASURED VALUES FOR $\alpha = 110°$, N=1533 RPM

Case/ parameters	Simulink, Psim and Plecs Simulation	Experiment
I_{ph_a} [A]	0.61	0.6
$I_{ph\_a\_THD}$ [%]	0	0
P_{in_3ph} (3-phase grid active power) [W]	-192	-191
Q_{3_ph} (3-phase grid reactive power) [VAR]	357	
P_{mech} (shaft mechanical power) [W]	-201	
V_{outa_THD} [%]	0	

VII. CONCLUSIONS

A. *User interface of the programs*

In Simulink elements, more parameters can be defined than in Psim or Plecs elements. This includes induction machine, switching devices and other elements. Therefore, the Simulink elements can be better fitted to the behavior of the devices than Psim or Plecs elements.

B. *Control options*

The control of switches is simpler in Simulink and Plecs than in Psim. Moreover, unlike Simulink, Psim library does not have PID controller.

C. *The signals processing and measurement options*

In Simulink, there is an option to measure fluxes and rotor currents of the machine. Psim does not have these options.

In Simulink, the terminals of the stator of the induction machine cannot be directly accessed. The stator could be connected only in "star". This fact limits the options for simulation of induction machine connected in "delta" or other topologies. However, in Psim, the terminals of stator and rotor could be accessed directly and connected in any desirable way.

Simulink has more options for signal processing and measurements than Psim or Plecs. Therefore, Simulink is often used in co-simulation with other programs. However, in simulation of machines with different connections of stator and rotor, it is preferable to use Psim.

D. *Run time of the simulation*

Psim has the fastest run time. It took about 10 seconds to simulate the circuit of case 1. Simulink is slower than Psim. In Simulink, it took about 1 minute to simulate the circuit of case 1. In Plecs and Simulink co-simulation, it took 1 minute to simulate the circuit of case 1. In demo version of Plecs and Simulink co-simulation, it took 1 hour to simulate the circuit of case 1.

E. *Co-simulation with Simulink*

In Plecs and Simulink co-simulation, the power circuit was divided into two circuits: the thyristors (Plecs file) and the induction machine (Simulink file). This division was possible because Plecs is designed especially for co-simulation with Simulink. Any Plecs circuit can be co-simulated with Simulink, including the option of dividing of the power circuit by controlled current and voltage sources. The same division can not be done in Psim and Simulink co-simulation because there is a problem of time delays between the programs.

Psim should be co-simulated with Simulink only in the case of the signals passing. It is not recommended to divide the Psim power circuit by controlled current and voltage sources.

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