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COMPLEX MODEL OF LOW-VOLTAGE TRACTION ASYNCHRONOUS DRIVE

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Abstract: *Independent low-voltage traction drives are now used in many application. This paper deals with creation of an exact model of low-voltage traction drive which is used in battery stacker fed from batteries with nominal voltage 24 V. This complex model consists of particular models of induction machine, inverter model, load model and battery model. The model of induction machine is a standard model with considering magnetic circuit saturation. The inverter model includes impact of output voltage distortion by dead times, on-state voltage drops on switching elements and DC-link voltage ripple. The load model is a model of mechanical part of battery stacker considering inertia masses, rolling resistance, air resistance and inclination on slant plane. DC-link is approximated by DC-voltage source with internal resistance and low-pass filter for simulation of a capacitor. All the simulations were done in MATLAB-SIMULINK.*

Key Words: ***Independent Traction/Induction Machine/Modeling/Simulation/Simulink/Low-Voltage Drive***

1. INTRODUCTION

One of the main problems in independent traction is high ratio of weight and capacity of accumulator. For that reason it is important to research losses in the individual parts of the independent traction drive (Fig. 1: battery – inverter – motor – gear – wheel). Decreasing these losses and thereby increasing efficiency is important for usable qualities of the vehicle.

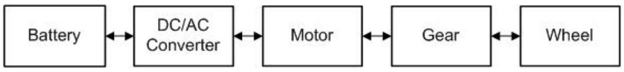

Fig. 1. *Components of the electrical vehicle*

In the article a model of battery stacker drive is described. It contains particular models of drive parts. All the models are connected together. Block scheme of the simulation structure is in Fig. 2.

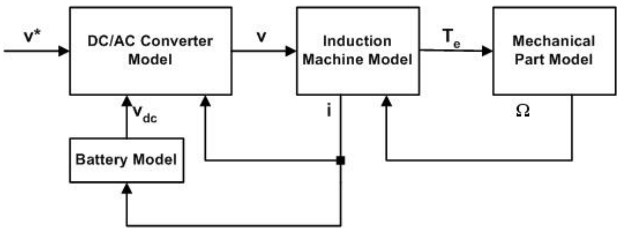

Fig. 2. *Block scheme of the simulation structure of the electrical vehicle*

There is used an induction machine with nominal voltage 14 V which is fed from the accumulator with nominal voltage 24 V. In order for the motor to reach the same torque and power using this voltage as compared to supplying it from the mains, the phase currents have to be much stronger. These currents cause voltage drops on inner resistance of the accumulator and on switching elements of the inverter. These effects have significant influence on features of the whole low-voltage drive.

2. MODEL OF THE INDUCTION MACHINE

The mathematical model of low-voltage induction machine is assembled from voltage equations of the machine in general reference frame, as in [1]:

$$\bar{v}_s^k = R_s \cdot \bar{i}_s^k + \frac{d\bar{\psi}_s^k}{dt} - \omega_k \cdot \bar{\psi}_s^k \tag{1}$$

$$\bar{v}_r^k = R_r \cdot \bar{i}_r^k + \frac{d\bar{\psi}_r^k}{dt} + j(\omega_k - \omega) \cdot \bar{\psi}_r^k \tag{2}$$

where R_s, R_r are stator and rotor phase resistances, $\bar{i}_s^k$, $\bar{i}_r^k$ are stator and rotor current space vectors and $\bar{\psi}_s^k$, $\bar{\psi}_r^k$ are stator and rotor linkage flux space vectors. ω is electrical speed of motor shaft.

To the model the equation for linkage flux space vectors in general rotating reference frame are added:

$$\bar{\psi}_s^k = \left(L_h + L_{s\sigma}\right) \cdot \bar{i}_s^k + L_h \cdot \bar{i}_r^k \tag{3}$$

$$\bar{\psi}_r^k = \left(L_h + L_{r\sigma}\right) \cdot \bar{i}_r^k + L_h \cdot \bar{i}_s^k \tag{4}$$

2.1. Impact of temperature on motor resistances

To include impact of temperature on motor resistances, constant resistances were replaced by variables depending on temperature by equation:

$$R_2 = R_1(1+\alpha\Delta\vartheta) \tag{5}$$

where α is thermal coefficient of resistance and $\Delta\upsilon$ is thermal difference.

2.2. Saturation of main magnetic circuit

Considering saturation of main magnetic circuit is done by replacing constant value of main inductance L_h in equations 3 and 4 by approximated curve dψ/di according to figure 3b. Based on knowledge of instantaneous magnetizing current is taken off instantaneous main inductance.

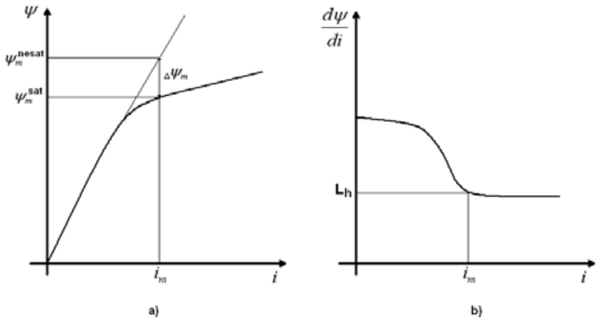

Fig. 3. *Magnetizing curve (a) and its derivation by magnetizing current (b)*

3. MODEL OF THE LOAD

On battery stacker affect many mechanical forces and inertia masses which are necessary to consider for getting an exact model. In the model are considered: force by inclination on slant plane, wheels rolling resistance, air resistance and losses in the gearbox. Moments of inertia are transferred on motor shaft and by adding motor moment of inertia we get the total moment of inertia of the whole drive J_l. After converting forces in torques on the rotor shaft T_l and inserting it in the moving equation 6 is the model of load done.

$$T_e - T_l = J_l \frac{d\omega_m}{dt} \tag{6}$$

4. MODEL OF THE INVERTER

In the model of the inverter special attention was focused on description of impact of dead time and on-state voltage drops on switching elements. Voltage drops on inverter switching elements and dead times cause distortion of inverter output voltage and affect magnitude of the first harmonic of output voltage. It can significantly affect machine torque.

Voltage drop on transistor is described by threshold voltage V_{pT} and dynamic resistance R_{dT}.

$$V_T(t) = V_{pT} + R_{dT} \cdot i_T(t) \tag{7}$$

The similar situation occurs with voltage drop on diode:

$$V_D(t) = V_{pD} + R_{dD} \cdot i_D(t) \tag{8}$$

V_{pD} is threshold voltages and R_{dD} is dynamic resistances of the diode.

Introduction of dead time into switching sequence of top and bottom transistor causes a distortion of inverter pole output voltage and affects voltage applied on the motor. Sign of distortion depends on phase current.

Two models of inverter were created. Both of them allow a choice of considering of impact of on-state voltage drops and dead times. By this is possible to research their impact at the whole drive system.

4.1. Pulse model of the inverter

The scheme of pulse SIMULINK model of inverter is shown in figure 4.

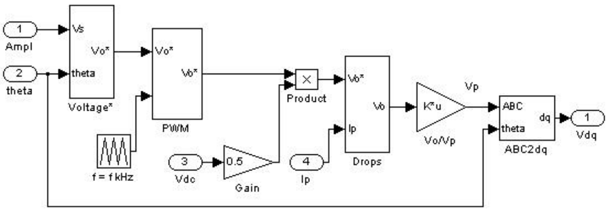

Fig. 4. *Scheme of pulse model of inverter*

From desired value of magnitude and frequency are created three desired pole voltages which are modulated in PWM block and multiplied by instantaneous value of DC voltage and shifted. In "Drops block" are computed distorting voltages from instantaneous phase currents by equations 7 and 8 and they are added to output pole voltages. After it these output voltages are converted into phase voltages and transformed in *dq* reference frame.

4.2. Discrete model of the inverter

The scheme of discrete SIMULINK model of inverter is shown in figure 5.

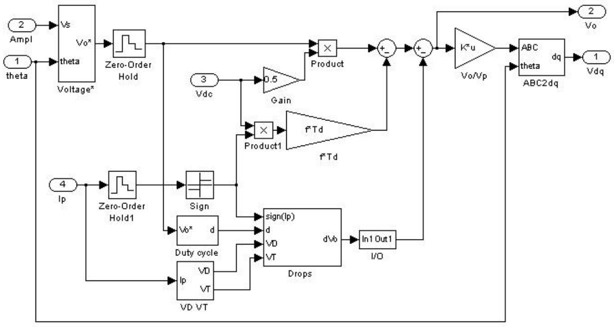

Fig. 5. *Scheme of discrete model of inverter*

From desired value of magnitude and frequency are created three desired pole voltages which are sampled with switching frequency. They are decreased by distorting voltages which simulate on-state voltage drops and dead time effect.

Distorting voltage by dead time is computed in each switching period by:

$$V_{DT} = f \cdot T_D \cdot V_{DC} \cdot \mathrm{sgn}(i_p) \tag{9}$$

where f is switching frequency, T_D is dead time, V_{DC} is DC-link voltage and i_p are individual phase currents. Similarly, voltage drops are computed by equation 7 and 8 and distorting voltage is given by following equations [2]:

$$\Delta V_o = V_D + d(V_T + V_D) \qquad i_p > 0 \tag{10}$$

$$\Delta V_o = -V_T + d(V_T + V_D) \qquad i_p < 0 \tag{11}$$

Symbol d is duty cycle in particular pole.

After correction pole voltages by both of these effects are again computed phase voltages and transformed into *dq* reference frame.

5. MODEL OF THE WHOLE DRIVE

By connection of previously described particular models we get a model of the whole drive which is shown in figure 6. The model of DC-link (Battery) allows computing instantaneous value of DC-link voltage V_{DC}, when we know instantaneous DC-link current.

$$V_{DC} = V_{DC0} - R_i \cdot i_{DC} \qquad (12)$$

V_{DC0} is internal battery voltage and R_i is its internal resistance. I_{DC} is instantaneous current of DC-link. The model allows switch between constant or computed DC-link voltage and also can be switched on or off effect of dead times and on-state voltage drops.

Block of Discrete Furrier Transform DFT, as in [3] for possibility of comparison simulation results was added into both of these models.

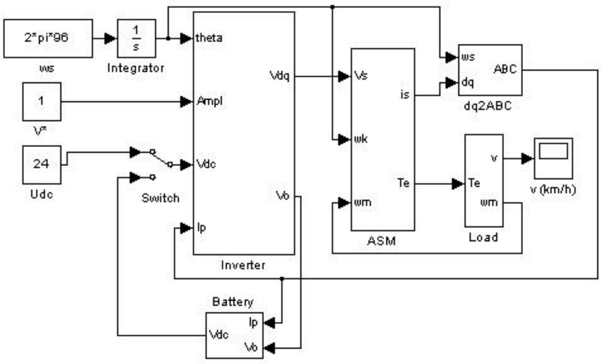

Fig. 6. *The whole drive model*

6. SIMULATION RESULTS

The four-pole induction machine with nominal voltage 14 V and nominal frequency 96 Hz was simulated. System was fed by battery with nominal voltage 24 V with internal resistance 0.005 Ω. Threshold voltage of inverter transistor was 0 V and diode 0.4 V. Dynamical resistances were 7.5 and 6 mΩ. Inverter switching frequency was 4 kHz.

6.1 Inverter model

In figures 7 – 12 are shown inverter output pole voltages and their harmonic analysis produced by pulse and discrete model. Both models are simulated without and with considering voltage drops on switching elements. It is shown in “pulse inverter” the impact of DC-voltage ripple on the course of output pole voltage. There is also shown in “discrete inverter” the impact of dead time on the course of output pole voltage.

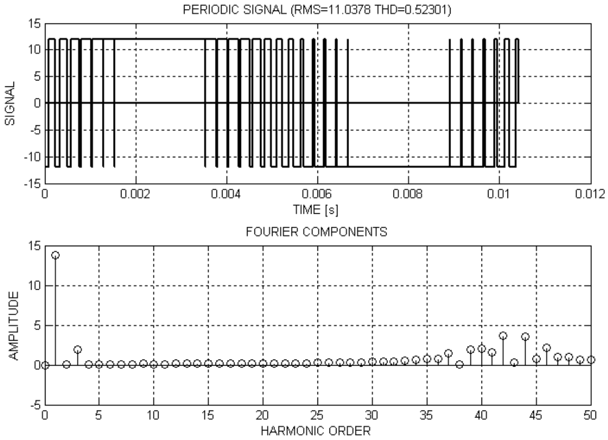

Fig. 7. *Inverter output pole voltage and harmonic analysis in inverter pulse model. Switching elements voltage drops are not considered*

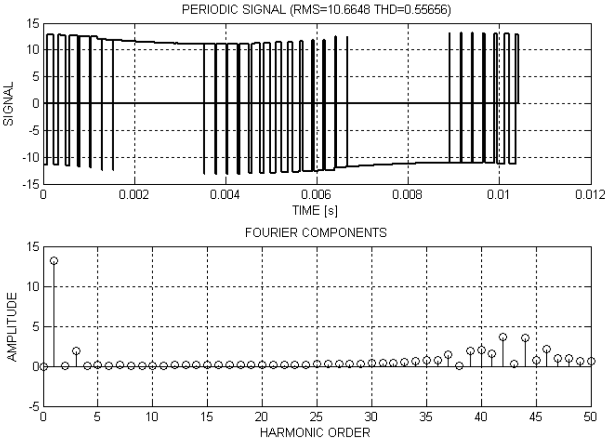

Fig. 8. *Inverter output pole voltage and harmonic analysis in inverter pulse model. Switching elements voltage drops are considered*

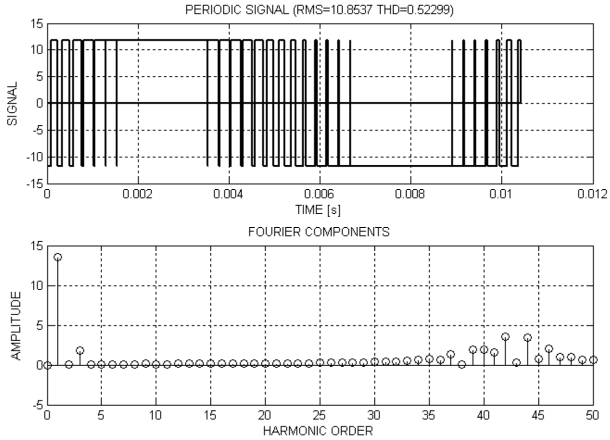

Fig. 9. *Inverter output pole voltage and harmonic analysis in inverter pulse model. DC-voltage ripple is considered*

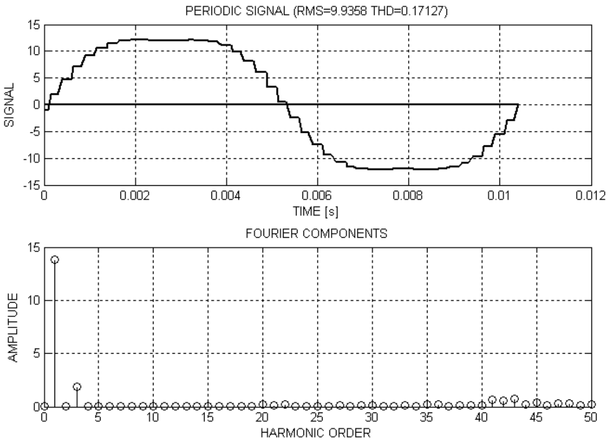

Fig. 10. *Inverter output pole voltage and harmonic analysis in inverter discrete model. Switching elements voltage drops are not considered*

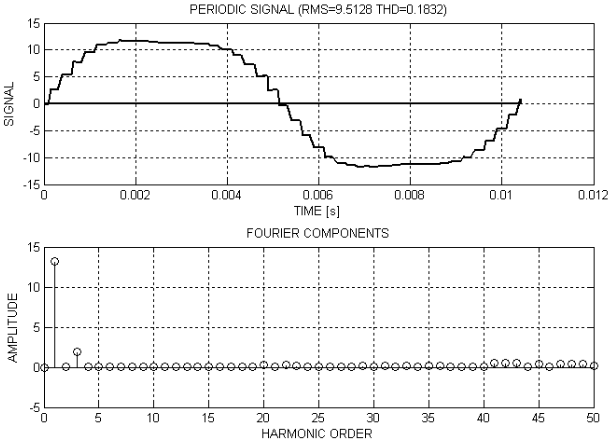

Fig. 11. *Inverter output pole voltage and harmonic analysis in inverter discrete model. Switching elements voltage drops are considered*

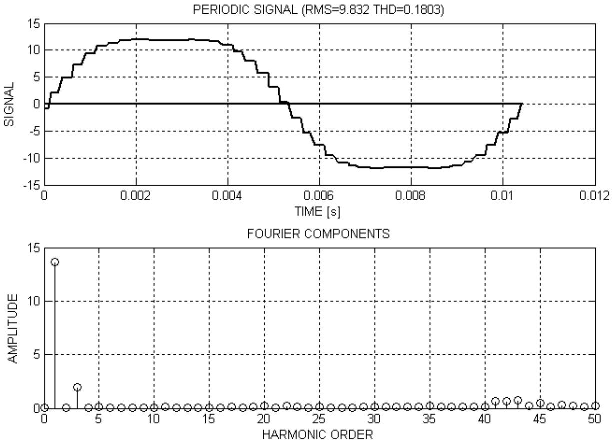

Fig. 12. *Inverter output pole voltage and harmonic analysis in inverter discrete model. Dead times (T_d = 2e-6 s) is considered*

Following table presents values of first and third harmonic of pole voltages in cases of both types of models. There is shown, that the including of non-idealities of inverter decreases first harmonic of pole voltage and also of phase voltage, because both are identical. It is evident, that results are the same for both types of model and both can be used for simulation of low-voltage drive. An advantage of "discrete model" is much faster computing.

Table 1. *Values of first and third harmonic of pole voltages*

		First Harmonic	Third Harmon.	
Pulse model	Ideal	13.83	1.89	V
	Volt. Drops	13.18	1.97	V
	With battery model	13.60	1.86	V
Disc. Model	Ideal	13.85	1.87	V
	Volt. Drops	13.23	1.96	V
	Dead time	13.68	1.93	V

6.2. Modelling of whole drive

Parameters of battery stacker are shown in table 2:

Table 2. *Parameters of load*

Motor moment of inertia	0.00105	kg.m^2
Gear moment of inertia	0.000244128	kg.m^2
Wheels moment of inertia	0.028733	kg.m^2
Gear efficiency	90	%
Driving wheel radius	0.11	m
Gear ratio	30	-
Weight of vehicle	800	kg
Slope	3	%
Front area of vehicle	2	m^2

Figure 13 shows mechanical speed during vehicle start with above presented load

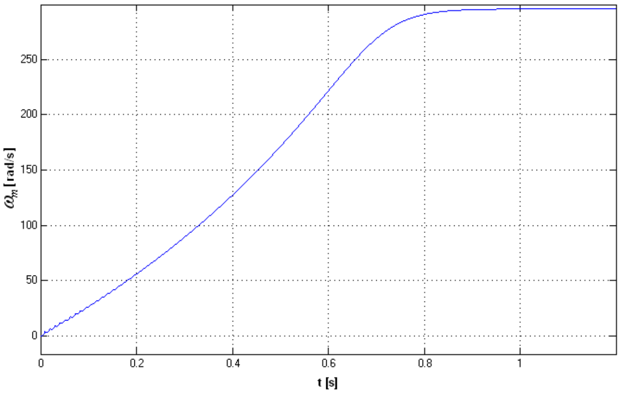

Fig. 13. *Mechanical speed course during vehicle start*

There is possible to watch distribution of power and losses in the model. Figure 14 shows course of total losses in mechanical part ΔP and input and output power P_1 and P_2 during acceleration.

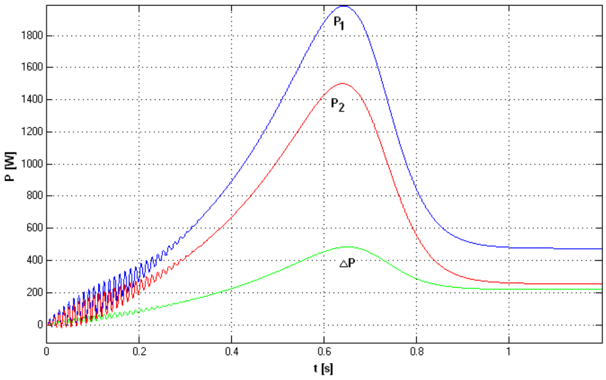

Fig. 14. *Input and output power and total losses course in drive mechanical part during vehicle start*

Figure 15 presents particular compounds of losses in mechanical part. There it is possible to see instantaneous power consumed in acceleration of rotating mass of inertia (gear ΔP_{jp}, motor ΔP_{jm} and wheels ΔP_{jk}). ΔP_t and ΔP_p are losses by rolling and gear friction resistance and ΔP_v are losses by air resistance. ΔP_s is power consumed in inclination on slant plane.

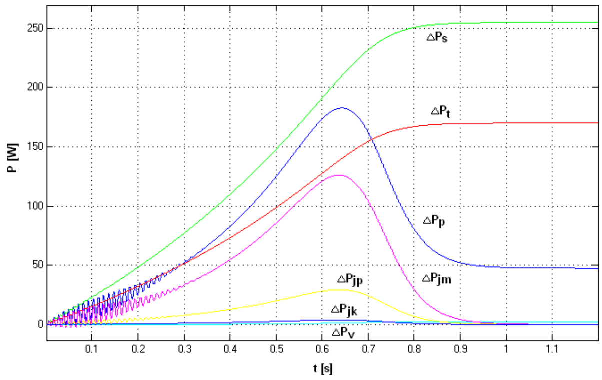

Fig. 15. *Losses distribution in mechanical part of the drive*

7. CONCLUSION

In the article the complex model of low-voltage traction asyncronnous drive for baterry stacker is described. Model considers mechnical part (wheels, gear and motor) losses and allows simulation of load for battery stacker dynamic parameters testing upon inclination on slant plane. Electromagnetic model of the motor considers saturation of main magnetic circuit. Inverter model incudes impact of dead times and on-state voltage drops on inverter switching elements. Last, model of accumulator is simulated as DC voltage source with internal resistance.

For computing speed increasing was created “discrete model” of inverter which has the same qualitative results for whole drive simulation.

Thanks to this complex model is possible observing of drive feature during an operation. The knowledge of behavior of the whole system (instantaneous value of DC-link voltage, magnitude of first harmonic of inverter output voltage, course of load torque and inner machine torque) can serve for optimization of inverter control processes and for optimized design of driving system.

8. REFERENCES

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