Experimental Study and Comparative Analysis of Transients of Induction Motor with Soft Starter Startup

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***Abstract* — This paper investigates the influence of the parameters of the machine and of the soft starter on the dynamics of the induction machine start. In order to evaluate the effects of this variation we have used a design of experiments (DOE). The situations may reproduce actual situations occurred in practice, for example the variation of initial voltage U_i, modification of the start time and load value.**

In the present paper we have investigated the relation between the inrush current, voltage dip at the startup of one industrial soft starter. Using an already predefined fire angle characteristic the influence of the initial voltage was also evaluated.

***Index Terms*—AC Motor drives, Converters, Power semiconductor switches, Speed control.**

I. INTRODUCTION

Electrical drives based on induction motors are the most widely used electromechanical systems in modern industry. Due to their reliability, ruggedness, simple mechanical structure, easy maintenance and relatively low cost, induction motors are attractive for use in a new generation of electrical transportation systems, such as cars, buses and trains [1], [2].

From the variety of electric energy consumers in industry one of the largest is without any doubt the induction machine operating as motor. Besides the classical destination of the induction machine as motor this machine is more and more used in the latest period as generator in the conversion chain of wind or micro-hydro-energy into electricity [3], [4], [5].

Variable voltage operation of a squirrel cage induction machine at part load is receiving considerable attention as an energy conservation measure. In particular, the power factor controller has created an interest in energy-saving schemes for all types of electric motors [6]. The switching of three-phase induction machine under different operation conditions is one of the processes frequently performed through speed control, soft starting , energy-saving and in renewable energy applications. It is well-known that the transient behavior associated with frequent switching of induction machines is characterized by high current peaks and pulsating torques. Such performance is most undesirable for both electrical supply and mechanical gearing systems [7].

Direct online induction machine starts have many disadvantages. Torque pulsations are often large and modify from positive to negative values. These torque transients in a motor shaft are transmitted to the load, resulting in mechanical wear in the motor bearings and load couplings. Therefore, properly controlling the starting currents and torques of induction machines is of great importance in many instances. Additionally, the resulting starting currents are high, especially during the first few cycles of a starting transient. This high currents are endured by the motor and power system, causing the heating of the machines windings [8].

In recent years, a variety of power electronics equipment with voltage fed pulse width modulation inverters (VSI - PMW) used widely in industrial applications and power network systems have caused significant inherent problems, such as generation of reactive current and power, as well as higher harmonic distortion in the power sources. The selection of the best PWM technique for most applications is uncertain, which can lead to less than optimum results [9].

Soft starters using silicon-controlled rectifiers (SCRs) are now used extensively in the industry. This starting method essentially allows the control of the voltages applied to an induction motor and hence, control of its torque and the acceleration of a machine during its starting transient [8], [10].

Appearance of soft starters produced a qualitative raise in starting, stopping or braking matter of induction motors with squirrel cage. These equipments are useless at starting-up of induction motors with phase wound rotor. There are numerous producing companies that offer soft starters at low voltages (400 and 690 V) or medium voltages (3.3, 4.2, or 6 kV) [11]. Can be started-up even electric drive systems that have a load torque and an inertia moment of equivalent high values.

The basic way of finding out the inertia moment is through analytic calculation, based on the rotor drawing and materials. Modern design rules take full benefit of the powerful capabilities of computer-aided design (CAD) tools, and once the rotor is entirely defined geometrically and material wise, automatic calculation of the inertia moment for the rotating parts may be easily achieved. Based on the accurate measurements brought by the modern digital-data-acquisition tools, the moment of inertia can be obtained in different manner [12].

The soft starters of switch all three phases are controlled can use the starting-up or shutting-down by means of voltage, current or torque control [13]. At voltage control, is achieved a soft start-up, but it’s not generated any current or torque reaction. The typical quantities for starting-up with voltage raise are the initial voltage U_i and the starting-up ramp’s duration t_p. The currents and voltages versus time variation in this case are presented in fig. 1a and b. By I_{max} was noted the maximum current obtained during the start-up and by I_R the load current [14], [15].

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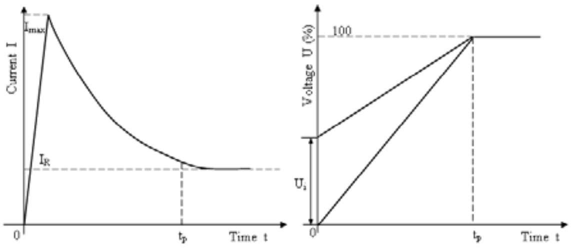
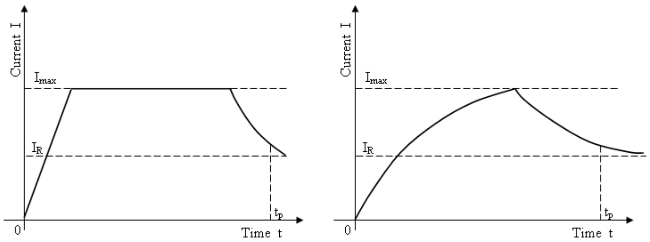


a) b)

Fig. 1. Current and voltage variation form at starting-up with voltage raise



a) b)

Fig. 2. Current's variation form at start-up with current control (a) and with torque control (b).

At current control, the voltage raise can be used, but by monitoring the current, in such way that, when reaching the prescribed I_{max} limit, the voltage increase to be limited. The current versus time variation is presented in fig. 2a [14].

Starting-up by torque control has maximum efficiency, because the soft starter monitors the torque demand and allows the start-up with the lowest current possible. If a torque control is not made, the motors will start-up or shut-down much earlier than set, especially at reduced start-up loads. In fig. 2b is presented the current's variation form in this case [14].

II. Mathematical Model of the System

Induction motors are represented in power system studies as constant power loads. Although this is a valid representation for steady-state operation under certain conditions, induction motors do not always operate under constant power, especially when large deviations of voltage occur. In reality induction motors in steady-state operate at a point where the electro-mechanical torque of the motor equals the mechanical torque of the load. As the voltage at the terminals of the induction motor changes, the operating point will change.

In this paragraph the dynamic equations of induction machine and the soft starter in the natural reference frame abc are presented. These equations are written using fluxes as state-variables.

A. Mathematical Model of the Induction Machine

The differential equations of the induction machine stator and rotor windings described in vector mode and in dq reference frame rotating by angular speed ω_k are [16]:

$$\bar{u}_{sdq} = \bar{i}_{sdq} R_s + \frac{d\bar{\psi}_{sdq}}{dt} + j\omega_k \bar{\psi}_{sdq}, \tag{1}$$

$$\bar{u}_{rdq} = \bar{i}_{rdq} R_s + \frac{d\bar{\psi}_{rdq}}{dt} + j(\omega_k - \omega)\bar{\psi}_{rdq}, \tag{2}$$

where: ω – electric angular rotor speed.

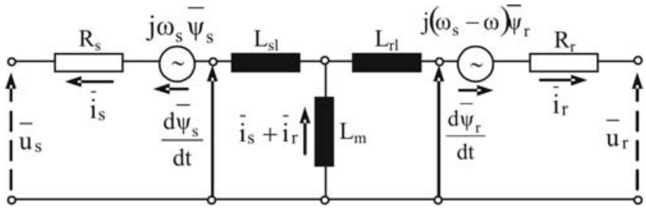


Fig. 3. Equivalent diagram of the induction machine for dynamic states

$$\bar{\psi}_{sdq} = L_s \bar{i}_{sdq} + L_m \bar{i}_{rdq}, \tag{3}$$

$$\bar{\psi}_{rdq} = L_m \bar{i}_{sdq} + L_r \bar{i}_{rdq}. \tag{4}$$

With the magnetic fluxes of stator $\bar{\psi}_{sdq}$ and rotor $\bar{\psi}_{rdq}$ from (3) and (4) we have:

$$\bar{u}_{sdq} = \frac{d\bar{\psi}_{sdq}}{dt} + \left(\frac{1}{T_s'} + j\omega_k\right)\bar{\psi}_{sdq} - \frac{k_r}{T_s'}\bar{\psi}_{rdq}, \tag{5}$$

$$\bar{u}_{rdq} = \frac{d\bar{\psi}_{rdq}}{dt} - \frac{k_s}{T_r'}\bar{\psi}_{sdq} + \left(\frac{1}{T_r'} + j(\omega_k - \omega)\right)\bar{\psi}_{rdq}. \tag{6}$$

The equivalent diagram of the three-phase induction machine for dynamic states, given from equations (1) to (4), is shown in fig. 3.

The parameters presented in equations (1) to (4) are:

$$\begin{gathered} L_s' = \sigma L_s,\ L_r' = \sigma L_r,\ \sigma = 1 - \frac{L_m^2}{L_s L_r}, \\ k_s = \frac{L_m}{L_s},\ k_r = \frac{L_m}{L_r},\ T_s' = \frac{L_s'}{R_s},\ T_r' = \frac{L_r'}{R_r}. \end{gathered} \tag{7}$$

Equation of electromagnetic torque of induction machine expressed in base quantities is:

$$T_e = \frac{k_r}{L_s'}\left(\psi_{sq}\psi_{rd} - \psi_{sd}\psi_{rq}\right). \tag{8}$$

B. Power Electronic Soft Starter's Model

The operation modes of a soft starter depend on the extinction angle ξ and the limit angle α_{lim}, both dependent on the phase angle φ. Depending on the firing angle α, two different modes of operation of the soft starter can be distinguished when a star or delta connected resistive load is used:

• Mode 1: $\varphi \le \alpha \le \alpha_{lim}$ two or three SCRs are conducting;

• Mode 2: $\alpha_{lim} \le \alpha \le 150^0$ - none or two SCRs are conducting, where α is the firing angle for the soft starter.

In [17] the equivalent model of the soft starter was presented by means of a matrix based on three switching functions S_{WA}, S_{WB}, and S_{WC} in two levels can be introduced in modeling of the SCRs and defined as equal to one when a given thyristor is conducting and equal to zero. In our case the soft starter connection is a star connection. Analyzing connection topology of the applied per-phase voltages at the machine terminals can be written as:

$$\begin{bmatrix} u_{UX} \\ u_{VY} \\ u_{WZ} \end{bmatrix} = \begin{bmatrix} S_{WA} & -S_{WB} & -S_{WC} \\ -S_{WA} & S_{WB} & -S_{WC} \\ -S_{WA} & -S_{WB} & S_{WC} \end{bmatrix} \begin{bmatrix} u_{AN} \\ u_{BN} \\ u_{CN} \end{bmatrix}, \tag{9}$$

where : $[u_{UX} \quad u_{VY} \quad u_{WZ}]$ are the phase voltages of the machine; $[u_{AN} \quad u_{BN} \quad u_{CN}]$ are the phase-to-ground supply voltages and are the switching functions for each phase.

III. Experimental Investigations

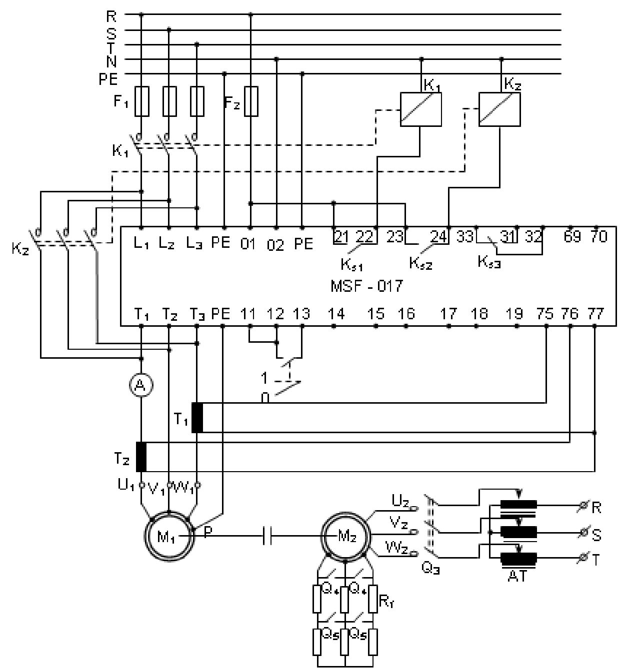


Fig. 4. Experimental diagram

TABLE I

Quantity	Value
Rated current	17 A
Rated voltage	400 V
Motor's recommended power	7.5 kW
Maximum current	150÷500% I_N
Power loss	50 W
Mass	6.7 kg
Cooling	By convection
Bussman ultra-rapid fuses	80 A

TABLE II

Characteristics \ Electric machine	M_1	M_2
P_N [kW]	3	3.5
U_N [V]	380/220	380/220
I_N [A]	12.6/7.26	17.8/10.3
Connection	Δ/Y	Δ/Y
cosφ	0.77	0.75
n_N [rot/min]	945	910
U_{rotor} [V]	-	204
I_{rotor} [A]	-	12.2

In fig. 4 is presented the experimental diagram for measuring the currents, voltages and start-up time, and were made the following notations [15]:

- F_1 –ultra-rapid fuses for the power part;
- F_2 – control fuses;
- K_1 – main contactor;
- K_2 – bypass contactor;
- Q_3 – main switch M_2 to the grid;
- Q_4, Q_5 – resistance steps' short-circuit switches;
- K_{s1}, K_{s2}, K_{s3} – soft starter relays;
- T_1, T_2 – curent transformers;
- R_f – braking rheostat;
- A – ampermeter;
- M_1, M_2 – induction motors.

In table I is presenting the MSF-017 soft starter's characteristics from the company Emotron from Sweden, used for experiments [14] and in table II the catalog data of the motors M_1 and M_2.

Fig. 5. Industrial softstarter MSF-017 test stand set up

Figure 5 presented soft starters MSF-017 during the tests.

The industrial soft starter we have considered is used to revalue the stability of the system due to the variation of the above mentioned parameters. The rule of experimentation was based on the basis of a DOE experiment.

Several tests were made with the experimental stand: with unrestricted ramp voltage start, current limited voltage ramp and torque control. We have measured peak currents during each time starts and then closes the bypass contactor K_2, ordered the relay soft starters K_{S2} when voltage reaches the nominal value. With machine M_2 and by modifying the R_f rheostat have obtained different values of engine load at startup of the soft starter driven machine shaft M_1. Also, at a given value of load we have changed the initial voltage value U_i.

IV. Experimental Results

In table III the values of measured maximum values of the absorbed current during the start-up process , compared with the setted ones are presented.

The following figures present the waveforms of currents and voltages acquired by the experimental stand tests. Figure 6 represents a voltage and a current of one phase in the time immediately following the start of the soft starter ordering. The waveforms over approximately 60 ms before the actual start, shown in figure 7, and serves to identify the machine by soft starter. In figure 8 is observed reduction phase currents with increasing engine speed. Figure 9 shows the current, respectively, the voltage of a phase during the starting process.

Figure 10 shows the moment when the bypass contactor K_2 is closed. It is noted that both current and voltage are perfectly sinusoidal phase at the time. Figure 11 was surprised when giving a stop command (STOP) of the system, bypass contactor opens and the engine braking is taken by soft starter.

From the test result the interaction plot for the selected parameters was obtained and load value (figure 12). The interaction between the initial voltage is not present as it may be observed from first chart of the interaction plot. This is not the same when a current control is used or a torque controller which give a minim value of the inrush current.

TABLE III

Load current [A]	Initial voltage at START [%]	Maximum absorbed current [A]		
		Voltage raise without current limitation	Voltage raise with current limitation	Torque Control
3.4	30	15	13.4	12
	60	19.6	18.5	12.1
	90	21.3	20.5	11.1
3.9	30	20.3	19.1	15.9
	60	28.1	24.8	15.7
	90	32.9	29.1	15.3
5.2	30	23.8	21.3	20.7
	60	29.2	27	20.6
	90	35.3	32.4	20.6

Measured start-up time [s]			Set start-up time [s]	Set maximum current [A]
Voltage raise without current limitation	Voltage raise with current limitation	Torque Control		
6.3	7	6.2	6	30
5.8	6.8	6.1	6	30
5.2	6.5	6	6	30
6.5	6.8	6.1	6	30
6.1	6.5	6	6	30
5.4	6.3	5.9	6	30
6.6	6.9	6.1	6	30
6.3	6.6	6	6	30
5.7	6.2	6	6	30

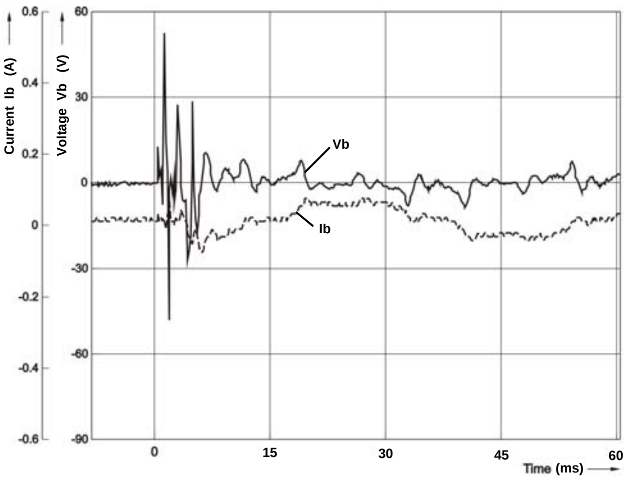


Fig. 6. Initial variation of the phase current and voltage when START command is given

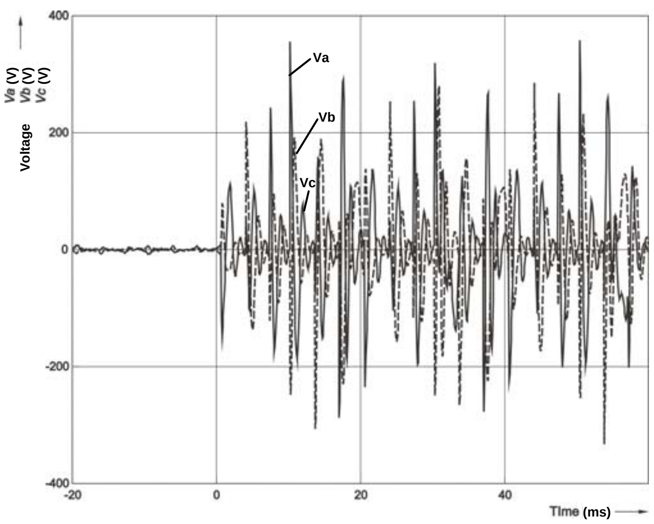


Fig. 7. Waveforms of voltages at the start-up the motor

itself

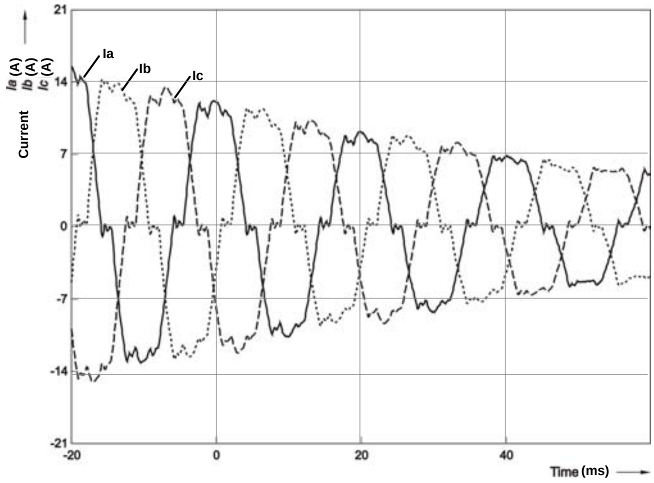


Fig. 8. Current waveform when the motor accelerates

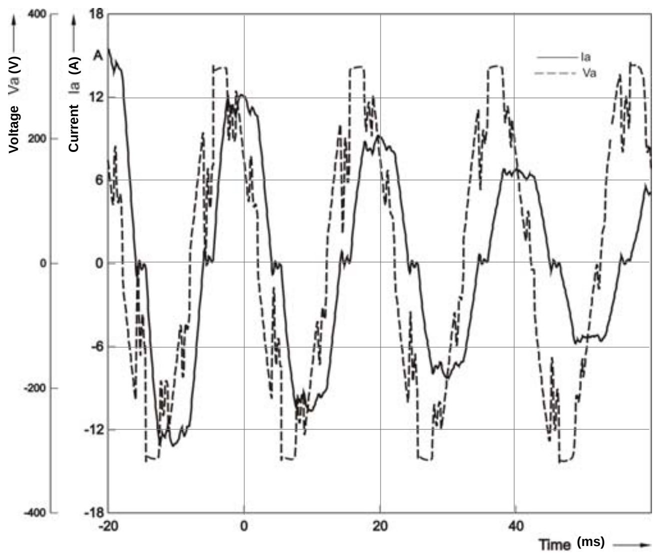


Fig. 9. Phase current and voltage transient waveform

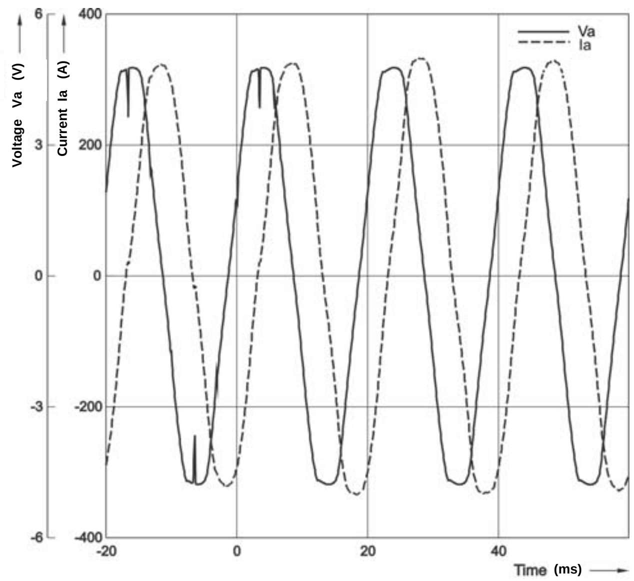


Fig. 10. Waveform of phase current and voltage when the

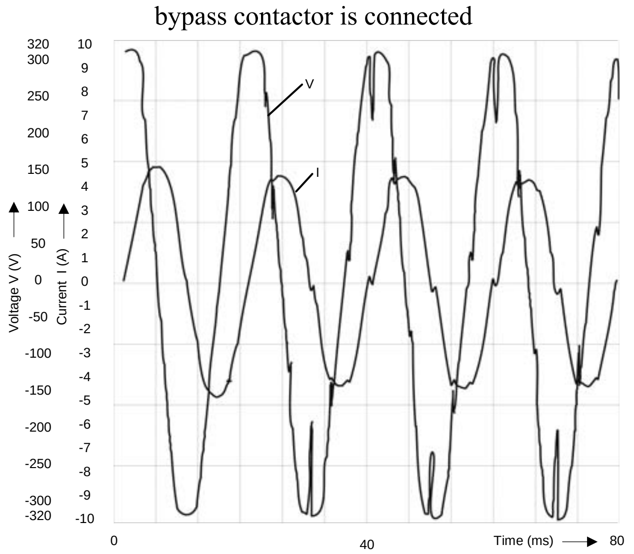


Fig. 11. Phase current and voltage waveform when the command STOP is given

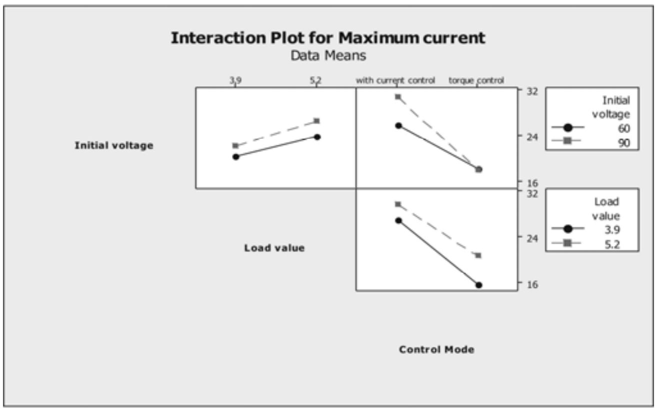


Fig. 12. Interaction plot of the initial voltage load value and control mode

Since the initial value of the voltage it seems to have an influence we will analyze by means of simulation the influence of this parameter over the transients of the induction machine.

V. Simulation Results

Figure 13 represents the Matlab Simulink soft starter model with integrated control system necessary for controlling the three phase AC voltages of the induction motor. A complete soft starter firing control circuit had to be designed and its output had to be connected to the gate of each of the above thyristors. The soft starter model includes the switches for the bypass connection. The bypass simulated transient is presented in figure 14. Since the firing angle duty cycle and pulse width of the firing angle are playing a major role in the performance different firing characteristics angle were designed, simulated and analyzed.

From the transient simulation we have evaluated the influence of the fire angle characteristic on the dynamics of the induction machine. Using a predefined different design of fire angle will cover almost all approaches of varying the voltage ramp wise. This is the standard practice in the existing higher rating soft starter.

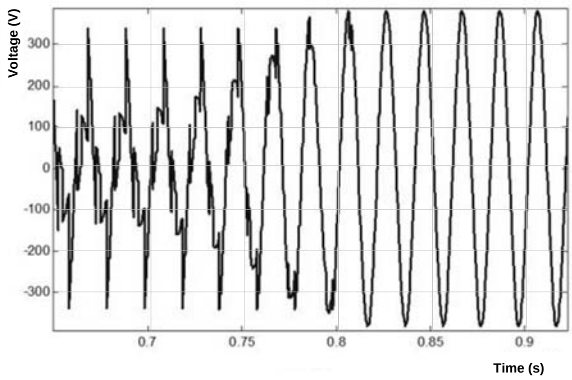


Fig. 14. Simulated bypass moment

One objective of the simulation investigations was to analyze the evolution of the maximum inrush current when varying the firing angle characteristic. Following reference [10] we have selected one optimal fire angle characteristic as a slowly decreasing amplitude function on the time domain, except the last time interval when the characteristic function has a steeper descent. The method proposed here rests on the decomposition of the alpha angle versus slip characteristic function as a piecewise linear function with N pieces having the form:

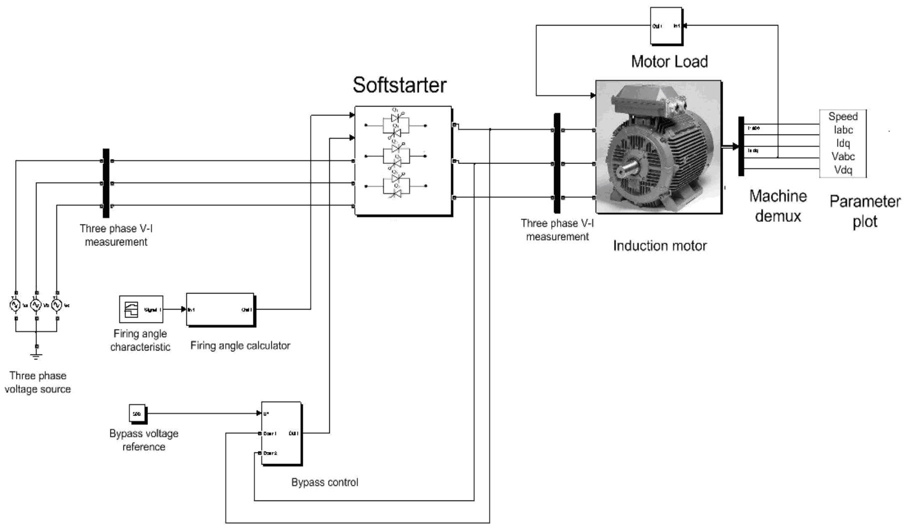


Fig. 13. MATLAB Model of the soft starter

$$\Lambda^i(t) = \alpha^k(\theta^i) + (t - t_j)tg(\theta^i)$$
$$i = 0..N,\quad j = 0..N-1 \qquad (10)$$
$$\alpha_k = \begin{cases} \alpha_{max}, & k = 0 \\ 0, & k = N-1 \\ \Lambda^k(t_k, \theta_i), & k = 1..N-2 \end{cases}$$

where t is the time variable, $tg(\theta^i)_{i=1..N}$ represent the piecewise slopes, $\{\alpha^k\}_{k=0..N-1}$ are the characteristic intercepts on y-coordinate depending on the piecewise slopes and $\{t_j\}_{j=0..N}$ represent the uniform grid on the time domain with $t_0 = 0$, $t_N = t_p > 0$. The shape of the firing angle was predetermined based on a previously determined optimization test [10].

We study the current behavior of the for a couple of sets of piece wise functions defined by angles $\Theta^1 = \{\theta_1, ..., \theta_N\}_{1=1..m}$ in a simulation analysis [10].

As it is presented in [10] for small values of α, from 0 up to 30 the speed torque characteristics are very similar. This can be explained by the fact that for values of the firing angle smaller or equal to the load impedance angle φ, there is a continuous conduction. Thus, changing the firing angle within that limit will have no effect on the voltage applied to the motor; hence, the torque and speed values are kept unchanged. The Matlab Simulink program is run several times with a fixed firing angle characteristic. The steady state value of the speed is calculated after each run. The same procedure is repeated for different values of the firing angle (figure 15).

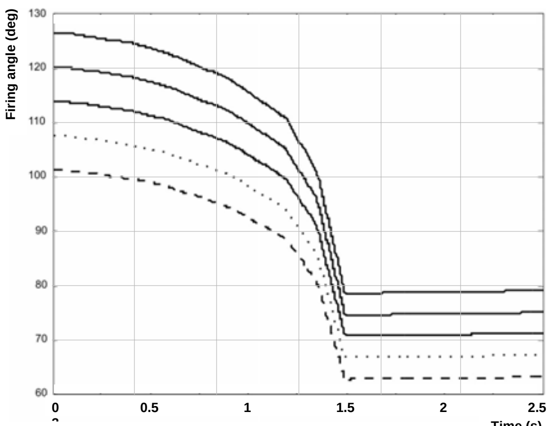


Fig.15. Firing angle variation

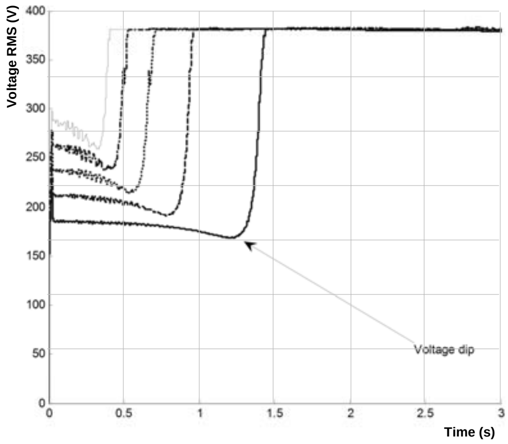


Fig.16. Softstarter voltage transient dip

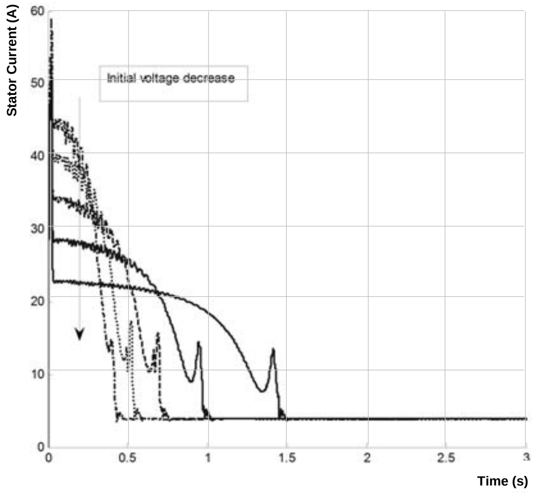


Fig.17. Inrush current transient variation

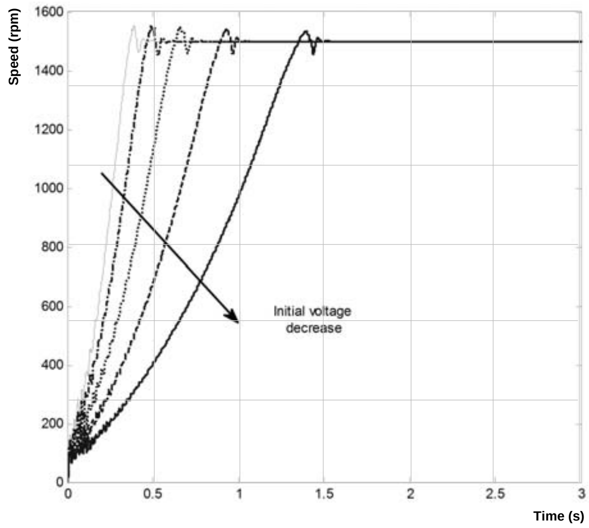


Fig. 18. Speed variation

VI. CONCLUSION

From the correlated experiments and simulations one may draw the following conclusions upon the influence of the considered parameters in the dynamic response of the soft starter based start of the induction machine.

As the initial voltage was decreased the inrush current decreased as it may be observed from figure 18. As the initial starting voltage was increased the results improved. This led us to have shorter inrush times and inrush current. A 90% of an initial voltage is better than 80% for example.

There was a linear relationship between initial voltage increase and the inrush time period decrease. So, we can say that if we decrease the initial voltage we will have: less inrush current and more inrush time period.

The voltage dip was improved by about 15% and it kept on improving as we got closer to the rated current figure 17. The current curves figure 16 and 17 the voltage curves indicate that as the current increased the voltage dip is increasing (figure 16) increased in almost a linear relationship. This means that if we improve the current peak the voltage dip will improve in the long-term. As mechanical stress on the shaft occurs for a fraction of a second (500 ms), it will not have a negative impact on the life of the motor.

The experimental and simulation results are similar.

REFERENCES

[1] M. Bounadja, A.W. Belarbi, and B. Belmadani, "A High Performance Space Vector Modulation-Direct Torque Controlled Induction Machine Drive based on Stator Flux Orientation Technique", Advances in Electrical and Computer Engineering, Volume 9, No 2, 2009, pp. 28-33.

[2] A. Tahour, H. Abid, and A.G. Aissaoui, "Speed Control of Switched Reluctance Motor Using Fuzzy Sliding Mode", Advances in Electrical and Computer Engineering, Volume 8, No 1, 2008, pp. 21-25.

[3] T. Tudorache, and L. Melcescu, "FEM Optimal Design of Energy Efficient Induction Machines", Advances in Electrical and Computer Engineering, Volume 9, No 2, 2009, pp. 58-64.

[4] G. Raţă, M. Raţă, I. Graur, and D.L. Milici, „Induction Motor Speed Estimator Using Rotor Slot Harmonics", Advances in Electrical and Computer Engineering, Volume 9, No 1, 2009, pp. 70-73.

[5] K. Laroussi, M. Zelmat, and M. Rouff, "Implementation of a Fuzzy Logic System to Tune a PI Controller Applied to an Induction Motor", Advances in Electrical and Computer Engineering, Volume 9, No 3, 2009, pp. 107-113.

[6] T.M. Rowan, and T.A. Lipo, "A Quantitative Analysis of Induction Motor Performance Improvement by SCR Voltage Control", IEEE Transactions on Industry Applications, vol. IA-19, no. 4, July/August 1983, pp. 545-553.

[7] W. Deleroi, J.B. Woudstra, and A.A. Fahim, "Analysis and Application of Three-Phase Induction Motor Voltage Controller with Improved Transient Performance," IEEE Transactions on Industry Applications, vol. 25, no. 2, March/April 1989, pp. 280-286.

[8] M.G. Solveson, B. Mirafzal, and N.A.O. Demerdash, "Soft-Started Induction Motor Modeling and Heating Issues for Different Starting Profiles Using a Flux Linkage ABC Frame of Reference", IEEE Transactions on Industry Applications, vol. 42, no. 4, July/August 2006, pp. 973-982.

[9] O. Ursaru, C. Aghion, M. Lucanu, and L. Ţigăeru, "Pulse Width Modulation Command Systems Used for the Optimization of Three Phase Inverters", Advances in Electrical and Computer Engineering, Volume 9, No 1, 2009, pp. 22-27.

[10] Gastli, A.; Ahmed, M.M.; „ANN-Based Soft Starting of Voltage-Controlled-Fed IM Drive System", IEEE Transaction on Energy Conversion, Volume 20, Issue 3, Sept. 2005 pp. 497-503.

[11] S.I. Deaconu, G.N. Popa, C. Diniş, and I. Popa, "Comparative Study of the Methods for Starting-Up the Induction Motors by Softstarter", Proceedings of the 14th National Conference on Electrical Drives, September 25-26, 2008, Timişoara, Romania, pp. 93-96.

[12] R. Babău, I. Boldea, T.J.E. Miller, and N. Muntean, "Complete Parameter Identification of Large Induction Machines From No-Load Acceleration-Decelaration Tests", IEEE Transactions on Industrial Electronics, vol. 54, no. 4, August, 2007, pp. 1962-1972.

[13] G.N..Popa, I. Popa, and S.I. Deaconu, „PLCs in applications", „Mirton" Publishing House, Timisoara, Romania, 2006 (in Romanian), ISBN 973-661-911-7.

[14] ***, "MSF. Hardware and Software Manual", Emotron AB, Sweden, 2000.

[15] S.I. Deaconu, G.N.Popa, I. Popa, and C. Diniş, „Study of the Influence of the Initial Start-Up Voltage on the Bypass Contactor's Connecting Time", National Conference – Dorin Pavel, the founder of the Romanian hydroenergetics, Sebes, May 30-31, 2008, vol.13, pp. 263-268.

[16] S.D. Sudhoff, B.T. Kuhn, D.C. Aliprantis, P.L. Chapman, "An Advanced Induction Machine Model for Predicting Inverter-Machine Interaction", PESC 32nd Annual Conference, 2001, pp. 2043-2052.

[17] G. Zenginobuz, I. Cadirci, M. Ermis, C. Barlak, "Soft Starting of Large Induction Motors at Constant Current with Minimized Starting Torque Pulsation", IAS Record Conference, 2000, pp. 1593-1604.