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SLIP COMPENSATION OF *U/F* CONTROLLED INDUCTION MACHINE THROUGH EDUCATIONAL LABORATORY SETUP

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ABSTRACT

This paper evaluates several slip compensation methods of U/f control of induction machine (IM). At first, most attractive compensation methods are presented theoretically and analysed by means of simulation in MATLAB/Simulink. Then, two compensation methods are implemented and tested in real-time DSP based experimental setup with dSPACE1104 platform after witch proper discussion of the results is given. Educational and didactical aspect of the experimental setup is emphasized through control algorithm developed in Simulink and graphical user interface developed in Control Desk. Users of this application can evaluate different slip compensation techniques, modify them and easily implement and test new compensation algorithms by using an intuitive graphical user interface.

INTRODUCTION

Electric drives control algorithms have experienced sudden blooming with rapid development of power electronic during the last decades. This year we celebrate half of a century since the first commercial frequency convertor appeared in the market. Namely, Danish company Danfoss in 1968 lunched first frequency converter, legendary VLT5 [1]. Since then a vast number of converters as well as AC drives control algorithms was developed. Starting from the classical *U/f* control up to advanced vector control and DTC algorithms all of these AC machine control methods are based on rotating magnetic field speed change inside the machine.

Nowadays, *U/f* control is one of the simplest and most exploited method for the control of the AC machines. Except in cases where high dynamics of the drive is a must, *U/f* control method is thankful for implementation in a vast of applications where variable drive speed is a main demand. Nevertheless, except good characteristic of the *U/f* control method such as simple implementation and small computational burden without closed loop structures and complex machine state observes it has several vital disadvantages. The most important disadvantage (except poor dynamic characteristic) is motor speed weakening (slip) with an increase of the machine load. Moreover, attenuation of the pull-out torque at low speed (frequencies) as a consequence of voltage drop on stator resistance, is another important lack of the *U/f* control method. These effects jeopardise drive system stability at low speed (at frequencies closed to zero) while high frequency operation could easily exceed 1000 Hz without problems.

Favourable characteristics such as the simplicity of the *U/f* control causes huge scientific effort dedicated to dealing with the slip compensation. A large number of authors have suggested and published various slip compensation technics. These solutions are different in terms of complexity and quality. Therefore, several existing slip compensation techniques will be analysed in this paper.

Until few years back, development of control algorithms was a huge time consumer and it required a lot of programming experience. Nowadays there is a considerable number of digitally-based development systems on the market, which allow rapid development and testing of motor control algorithms [2]-[4] while do not require sophisticated programming skills. The literature [5] provides a detailed comparison of these control platforms and their capabilities based on DSP and FPGA processors. Lately, Rapid Control Prototyping (RCP) has become quite popular and attractive in electric drive control algorithms development [6]. Quick and easy design of control algorithms allows engineers to test and enhance control methods and develop final prototypes in simple and effective manner [7].

In this paper RCP technique is used to implement *U/f* control algorithm as well as several different slip compensation techniques. First, a simulation with different slip compensation techniques is developed and obtained results are presented and discussed. Afterwards the slip compensation algorithms are implemented on dSPACE1104 DSP platform and results of experiment are given. GUI interface is developed having in mind an intuitive and didactical aspect of the laboratory setup

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dedicated to students who attend the course of Control of electric drives.

U/F CONTROL – SLIP AND VOLTAGE COMPENSATION METHODS

U/f control belongs to the group of scalar control methods. Unlike the vector control, *U/f* method involves changing the voltage and frequency of the power supply of an AC machine without affecting their current phase position. In order to make the speed change below synchronous speed possible and avoid the saturation of the machine it is necessary to change the voltage proportionally to the stator frequency. For higher speeds, above the synchronous, it is necessary to rise the frequency while the voltage is limited to its nominal value in order to prevent endangerment of the stator winding insulation. The relation between stator voltage and frequency is given by well-known equation (1) and shown graphically in Fig. 1a (red line).

$$u_s = \begin{cases} \dfrac{U_{sn}}{f_{sn}} f_s & , \text{ for } f_s < f_{sn} \\ U_{sn} & , \text{ for } f_s \geq f_{sn} \end{cases} \tag{1}$$

Machine stator flux is determined by machine voltage, frequency and partially by voltage drop on stator resistance according to (2):

$$\psi_s = \frac{u_s - R_s i_s}{2\pi f_s} \tag{2}$$

Where: $\psi_s, u_s, i_s, R_s, f_s$ and are stator flux, voltage, current, resistance and frequency respectively.

By keeping linear dependence between the stator voltage and frequency (*U/f*=const.) relating mechanical characteristic ($T_e(n)$) of the induction machine (IM) in constant field and field weakening zone is shown in Fig.1b.

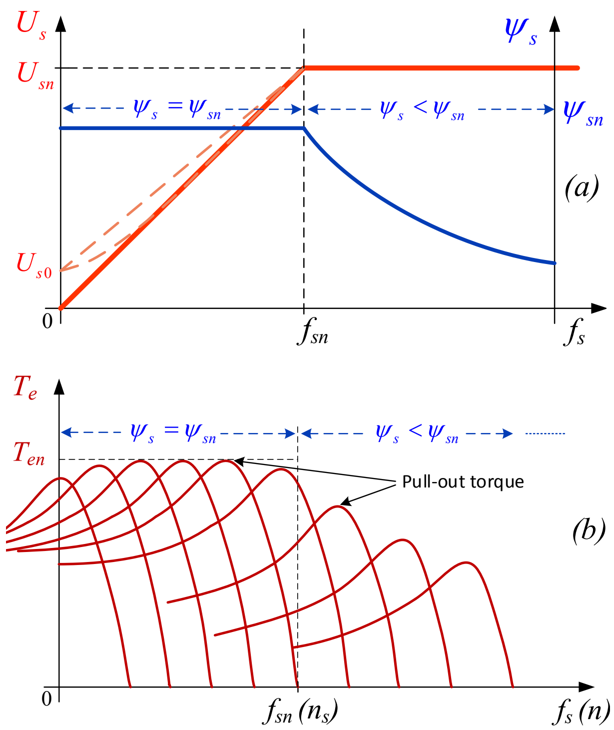

Fig. 1. Mechanical characteristics (Te(n) curves) of IM during U/f control (top) and voltage and flux dependence on frequency (bottom)

At frequencies close to zero voltage drop on stator resistance is nearly comparable to back electromotive force (EMF) and it can't be neglected. This further results with the stator flux reduction (machine filed weakening) as a consequence of *U/f* linearity degradation. Reduction of the machine filed further downgrade the pull-out torque (maximal torque) as can be noticed in Fig.2. At the medium and high speed, voltage drop is covered by EMF and doesn't have significant influence on the machine field. In order to minimize or completely remove diminution effect on the machine pull-out torque at low speed it is necessary to compensate the voltage drop on the stator resistance which depends on the machine load (stator current). One of the simplest methods to compensate the voltage drop on stator resistance and ensure nearly constant machine filed at low frequencies is to violate the *U/f*=const. principle. This violation of the *U/f* principle reflects in adding small voltage value U_{s0} at zero frequency (Fig.1a - orange line). Afterwards stator voltage (up to its rated value) changes linearly with respect to stator frequency or by following some quadrat or exponential shape depending on the load type i.e. voltage drop on stator resistance $R_s i_s$.

To increase machine speed and ensure slip compensation with different machine load an additional frequency („fcomp.") should be summed up with a reference frequency according to the Fig. 2. In this way the speed weakening can be compensated and the resulting motor speed will be dependant only on the reference frequency.

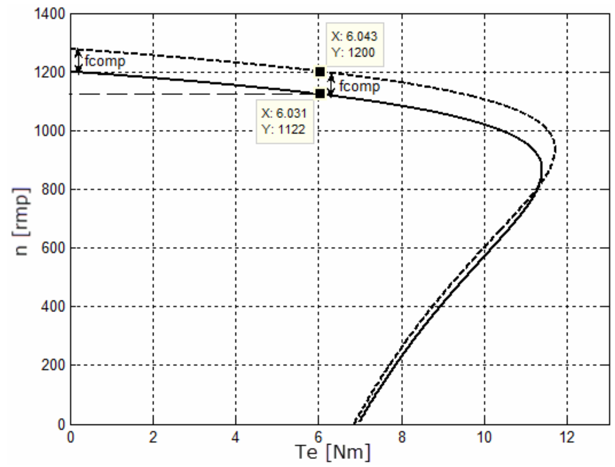

Fig. 2. Mechanical characteristic with compensated slip

Some of the calculation methods for obtaining additional frequency „fcomp." (slip frequency) are described below.

Slip compensation method 1

Starting with a mathematical model of the IM in synchronous reference frame it can be shown that slip frequency is proportional to the machine torque:

$$\omega_{slip} = K \cdot T_e, \quad K = \frac{\omega_{slip\ n}}{T_{e\ n}} \tag{3}$$

Having in mind a linear torque-slip relationship (3) compensation frequency can be given as (4), according to [8]:

$$\omega_{comp.} = \begin{cases} \omega_{sn} \dfrac{i_{qs}}{I_{sn}} s_n & \text{, for } \omega_s < \omega_{sn} \\ \omega_s \dfrac{i_{qs}}{I_{sn}} s_n & \text{, for } \omega_s \geq \omega_{sn} \end{cases} \tag{4}$$

Finally:

$$\omega_e = \omega_s + \omega_{comp.} \tag{5}$$

Slip compensation method 2

A little more complex way to calculate compensation frequency is derived in [9] starting form simplified Kloos equation with neglected stator resistance:

$$f_{comp} = \frac{1}{2}\left(\sqrt{f_s^2 + s_{lin} P_{em}} - f_s\right) \tag{6}$$

where:

$$s_{lin} = \frac{2p}{\pi} \frac{s_n f_n}{T_n}$$

$$P_{em} = 3U_s I_s \cos\varphi - 3I_s^2 R_s - P_{Fe}$$

$$P_{Fe} = \frac{1}{2}\left(\frac{1+s}{1+s_n}\left(\frac{f_e}{f_n}\right) + \frac{1+s^2}{1+s_n^2}\left(\frac{f_e}{f_n}\right)^2\right) P_{Fen} \tag{7}$$

$$P_{Fen} = 3U_n I_n \cos\varphi_n (1-\eta_n) - 3R_s I_{sn}^2 - \frac{s_n}{1-s_n} P_{meh}$$

Slip compensation method 3

Slip frequency (according to [10]) can be calculated if machine parameters are known and machine flux is estimated:

$$\omega_{comp} = \frac{L_m}{T_r} \frac{\psi_{dr} i_{qs} - \psi_{qr} i_{ds}}{\psi_{dr}^2 + \psi_{qr}^2} \tag{8}$$

where Tr is the rotor the time constant and Lm is the machine mutual inductance.

Slip compensation method 4

If machine dynamic can be neglected and stator current can be decoupled to excitation (iqs) and torque component (ids), slip compensation can be calculated according to (9):

$$\omega_{comp} = \frac{1}{T_r} \frac{i_{qs}}{i_{ds}} \tag{9}$$

Stator voltage drop compensation

Starting with voltage stator equations of the IM in synchronous reference coordinate system with reference frame aligned to the direct axis (i.e. the quadrature component is zero) the steady state orthogonal voltage components are:

$$\begin{aligned} u_{ds} &= R_s i_{ds} \\ u_{qs} &= R_s i_{qs} + \omega_e \psi_{ds} \end{aligned} \tag{10}$$

In order to avoid operational problems at zero speed and in the field weakening zone as well as estimation of the stator flux ψds, authors in [8] suggest that equation (10) should be modified according to (11):

$$\begin{aligned} u_{ds} &= R_s I_{sn} \\ u_{qs} &= R_s i_{qs} + u_s \end{aligned} \tag{11}$$

Where us is defined by (1). This method of voltage compensation together with slip compensation method 1 makes very simple compensation algorithm that requires only information available at motor nameplate.

Another way to compensate voltage drop on stator resistance is proposed in [11]. By analysing the phasor diagram of stator voltage and inducted EMF (Es), following expressions of stator voltage can be made:

$$U_s = I_s R_s \cos\varphi + \sqrt{E_s^2 - (I_s R_s)^2 - (I_s R_s)^2 \cos^2\varphi} \tag{12}$$

Stator voltage calculated according to equation (12) keeps the Es/f proportion constant enabling constant pull-out torque at low speed.

SIMULATION MODEL AND EXPERIMENTAL SETUP

All four described slip compensation methods together with the voltage drop compensation given by (12) are modelled in MATLAB/ Simulink (Fig. 3).

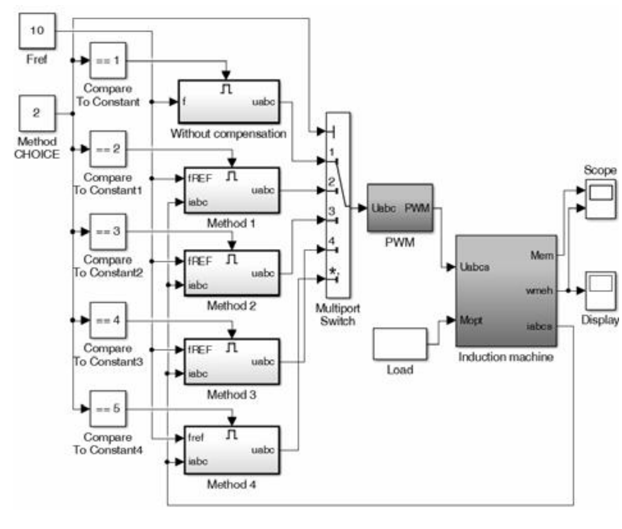

Fig. 3. Simulation model with 4 slip comp. methods

Realized Simulink model allows user to choose which slip compensation method should be simulated and analysed. By choosing a number from 1 to 4 in block “Model CHOICE” user can choose the corresponding method for slip compensation. Each of four described slip compensation methods (mathematically described in the previous section) are modelled in blocks with corresponding names. Each compensation block has two inputs: reference frequency and motor (stator) currents.

Power supply of the IM is modelled in “PWM” block. Block “Induction machine” represents complete mathematical model of the machine in stationary αβ reference frame. Numerical and graphical representation of the obtained results can be observed with Scope and Display.

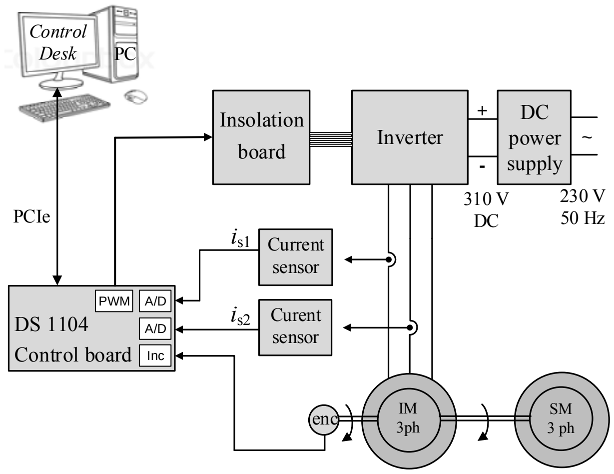

Fig. 4. Block diagram of the experimental setup

Experimental setup is realised based on the DSP dSPACE104 platform as a control device. Block scheme of the laboratory experimental setup is shown in Fig.4. Signal form the encoder (mounted on IM shaft) and stator currents in two motor phases (high bandwidth current sensors CMS3005) are passed to the A/D unit of the dSPACE1104 control board. Generated PWM signals as a board output are conditioned, galvanically isolated and passed to the voltage source inverter. All components of the experimental setup are shown in Fig.5 in a laboratory environment.

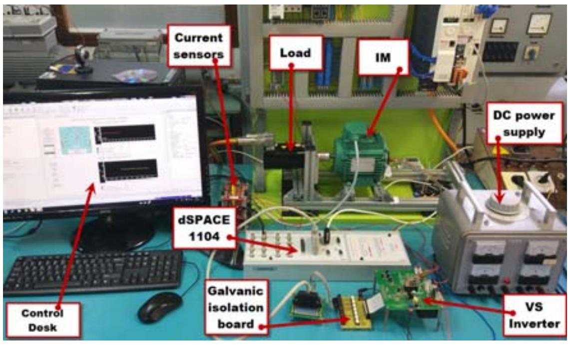

Fig. 5. Experimental setup

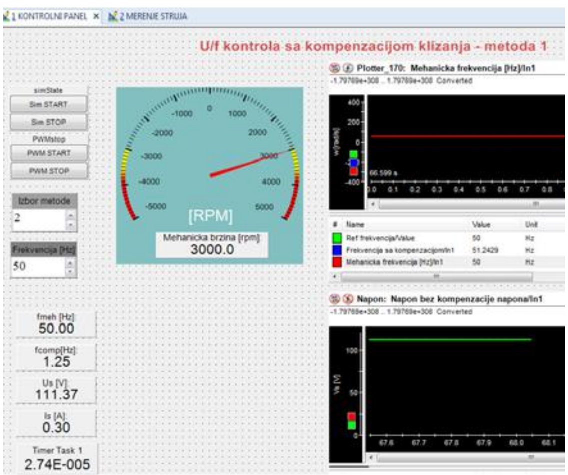

Fig. 6. GUI with controls and measurements

GUI – CONTROLS AND MEASUREMENTS

The graphical user interface is realised in Control Desk software which is a part of dSPACE platform. All attributes of the GUI communicate with Simulink model and the user have complete control of the application. The user can start and stop simulation as well as PWM generation, choose the method of compensation, set the reference frequency and observe the motor speed and time waveforms of the stator currents as it is shown in Fig.6.

The GUI can also be easily modified and rearranged. User can add control or observe any model parameter or quantity of interest.

SIMULATION AND EXPERIMENTAL RESULTS

Results obtained for two reference frequencies (50 Hz and 25 Hz) and two compensation methods (method 1 and method 2) are shown in Fig.7 in terms of simulation. The results show expected speed reduction at higher loads in case without slip compensations (Fig.7 – black line). Blue and red lines represent part of Te(n) characteristics with compensation method 1 and method 2. At light machine load speed is almost constant (3000 rmp and 1500 rpm). At higher loads it can been seen that small speed weakening is present at 50 Hz and small speed growth at 25 Hz regime. This is a consequence of nonideal slip compensation due to introduced neglects and machine parameter mismatch.

Experimental results obtained for the same compensation methods are shown in Table 1.

Table 1. Experimental results of slip comp. method 1 and method 2 compared to the results without compensation at 50Hz and 25Hz of reference frequency

T/T_n [%]	*Reference frequency 50Hz*			*Reference frequency 25Hz*		
	Without comp.	**Method 1**	**Method 2**	**Without comp.**	**Method 1**	**Method 2**
0	3000	3030	3000	1530	1530	1470
5.7	3000	3030	3000	1530	1530	1500
11.3	3000	3030	3000	1500	1530	1500
17.0	2970	3030	3000	1500	1530	1500
22.7	2970	3000	3030	1500	1530	1500
28.3	2940	3000	3000	1470	1530	1500
34.0	2940	3000	3000	1470	1530	1500
39.7	2910	3000	3000	1440	1530	1530
45.3	2880	3000	3000	1440	1530	1530
51.0	2880	3000	3000	1410	1530	1530
56.7	2880	3000	3000	1380	1530	1530
62.4	2850	3000	3000	1380	1530	1530
68.0	2850	3000	3000	1380	1530	1530
73.7	2790	3000	3000	1350	1530	1560
79.4	2790	2970	3000	1350	1530	1560
85.0	2760	2970	3000	1320	1500	1560
90.7	2760	2940	2970	1290	1530	1560
96.3	2730	2940	2940	1230	1530	1560
102.0	2700	2910	2940	1200	1500	1560
107.7	2670	2910	2910	1170	1500	1560
113.4	2670	2790	2880	1110	1500	1560
119.0	2640	2760	2850	1020	1500	1560

The experimental results are recorded for step load change from 0 % up to 120 % of rated (nominal) torque of the machine. It can be seen that speed drop at high machine load is compensated significantly in comparing to the results without compensation involved.

Moreover, it can be seen that experimental results confirm the simulation results to a great extent. With small loads the motor speed is pretty much constant and close to synchronous speed, while at a high load motor speed slightly decreases for 50 Hz and slightly increase for 25 Hz of reference frequency.

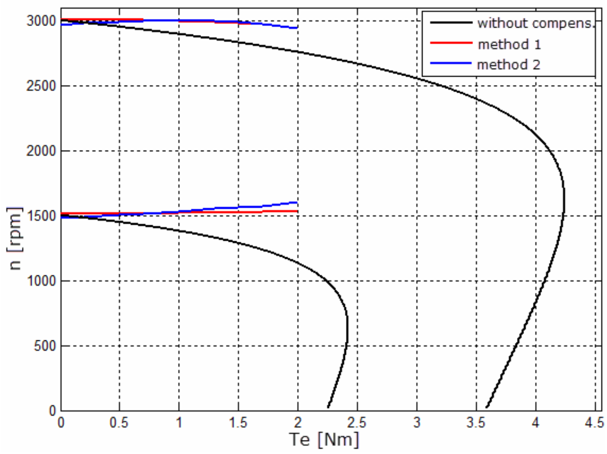

Fig. 7. Simulation results of two compensation methods

CONCLUSION

In this paper several slip compensation technics for U/f induction machine control have been presented. At first, theoretical background with basic U/f control disadvantages are presented. Afterwards four slip compensation methods and stator resistance voltage drop compensation are described. The U/f control algorithm with described compensation methods are modelled in Simulink and results of simulations are presented and discussed.

Experimental setup with graphical user interface is realised with dSPACE platform and experimental results are presented. Experimental setup with GUI is developed with accentuated educational and didactical aspect of use. Users (students) of this laboratory setup can test any of the implemented compensation methods. Through GUI effects and quality of compensation methods can be observed depending on the machine load. Moreover, users are allowed to change the method of the compensation, modified them or implement and test a new compensation method in relatively quick manner.

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APPENDIX

Table 2. Induction motor parameters - SIEBER L71

U_n [V]	400	R_s [Ω]	24.6	L_s [H]	1.48
I_n [A]	0.95	R_r [Ω]	16.1	L_r [H]	1.48
P_n [W]	370	n_n [min^{-1}]	2860	L_m [H]	1.46

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