

Application of Induction Machine U/f Control Through the Educational Laboratory Setup

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Abstract: *This paper gives a description of a laboratory setup based on dSPACE1104 DSP board which allows development and testing different control algorithms of AC machines. A detailed description of the laboratory setup components as well as realization of the U/f control algorithm for an induction machine (IM) is presented in the paper. U/f control of IM is enabled by developed Graphical User Interface (GUI) application. The GUI provides observation of characteristic quantities during U/f control and emphasizes didactic character of the laboratory setup. The laboratory setup is intended for students who follow the course of control of electric drives and should enable more quality knowledge gain as well as enhance student's practical skills in the laboratory. At the end, obtained experimental results characterizing the IM operation under U/f control are presented.*

Keywords: *U/f control; dSPACE1104; induction machine; Rapid Control Prototyping; electric drive, laboratory setup, MATLAB/Simulink*

1. INTRODUCTION

The number of AC motors is much higher than number of DC motors in nowadays electric drive systems. This expansion of AC motors usage was due to their design robustness and the sudden fall in prices and dimensions of drive controllers caused by the rapid development of power electronics in the last few decades [1]. Hand by hand with power electronics expansion as well as the appropriate power converters dynamical growth of various AC machine control algorithms came as well.

Until few years back development of control applications was a huge time consumer and it required a lot of programming experience. Nowadays there is 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. Most of these platforms, nowadays, are usually based on Rapid Control Prototyping (RCP) techniques which allow testing the control system on real-time machine with real I/O interfaces connected to real-world systems. RCP decreases application development time by allowing corrections to be made early in the developing process. By giving engineers an insight to the product early in the design stage, mistakes can be corrected and changes can be made while they are still inexpensive.

Lately, Rapid Control Prototyping becomes 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.

Modern advanced control algorithms such as vector control (FOC – *Field oriented control*), Direct torque control – DTC in their essence are based on stator rotating magnetic field speed control i.e. changing the frequency of AC machine power supply. These advanced control methods are mostly deployed in systems with high dynamics characteristic. However, in systems where sudden and quick speed reversal is not required, U/f control method also known as scalar control can be an optimal solution having in mind control complexity and overall drive price. The U/f method is one of the simplest control methods and the most represented in modern power converters and drives. This method is considered as “plug-n-play” since very little motor data is needed by the drive. The U/f control method is often used when there is a demand for high frequency operation which could easily exceed 1000 Hz. Most machine tool and spindle applications use the U/f control method for this advantage [7].

In this paper the development of a U/f control algorithm based on dSPACE 11104 DSP board is described. Complete laboratory setup is developed in Laboratory of Electrical Machines, Drives and Regulation at Faculty of Technical Sciences in Čačak, University of Kragujevac, Serbia [8]. The setup (experiment) is intended for students who

follow the course of Control of Electric Drives at bachelor as well as master studies level. The paper describes each element of the setup as well as development process of control application. Didactical approach of the laboratory setup is particularly accentuated through application's graphical user interface as well as overview of obtained experimental results.

2. BACKGROUND THEORY OF U/F CONTROL

Until twenty century late sixties control of induction machine and AC machines in general was very unpractical from reason of lack of the power supply with variable frequency. Speed control of induction machine was done by change of the additional resistance in the machine rotor circuit, switch of the stator pole pairs and similar. Since these AC machine control methods were very limited, DC machines were dominated in the industry applications where precise and continuous torque and speed control were demanded. Unsatisfied with the circumscribed use of the induction machine engineers focused their scientific effort on development of frequency converters which should enable variable speed of AC motors in general. This year completes half a century since Danish company Danfoss was launched first commercial frequency converter [9]. It was legendary VLT5 (VLT - VeLoTtrol abbreviated form velocity control) with rated power of 4 kW weighted slightly more than 50 kg. Technologically, it pushed the limits of what was feasible at the time and held 14 patents. The device attracted significant interest and even won an Industrial Design Award. Thanks to exponential development of power electronics nowadays equivalent with the same rated power weights a little less than 5 kg with many more possibilities and higher efficiency rate as well.

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 possible endangerment of the machine insulation. The relation between stator voltage and frequency is given by well-known equation (1) and shown graphically in Fig. 1 (red line).

$$u_s = \begin{cases} \frac{U_{sn}}{f_{sn}} f_s & , \text{ for } f_s < f_{sn} \\ U_{sn} & , \text{ for } f_s \geq f_{sn} \end{cases} \quad (1)$$

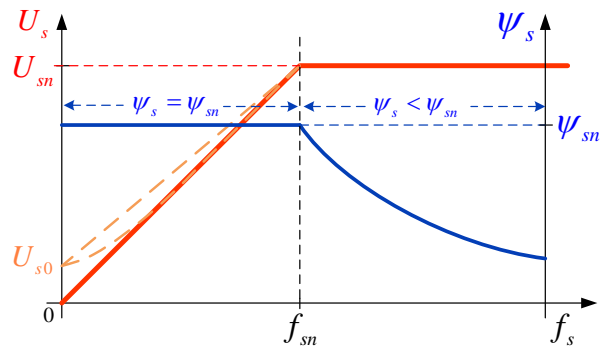


Figure 1. U/f characteristic of freq. converter

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

$$\psi_s = \frac{U_s - R_s i_s}{2\pi f_s} \quad (2)$$

Where: ψ_s , U_s , i_s , R_s and f_s 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 IM machine in constant field and field weakening zone is shown in Fig.2.

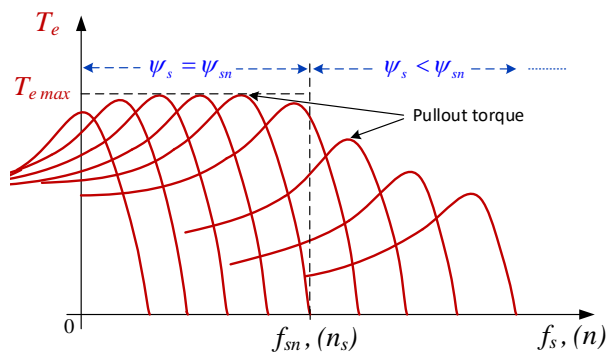


Figure 2. Mechanical $T_e(n)$ characteristic of IM

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 results with the stator flux reduction (machine filed reduction) as a consequence of U/f linearity degradation. Reduction of the machine filed further downgrade the pull-out torque (maximal torque) as can be notice in Fig.2. At the medium and high speeds, 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 methods to compensate the voltage drop on stator resistance and ensure constant machine filed at low frequencies is to violate the U/f=const. principle.

This violation of the U/f principle reflects in small voltage value U_{s0} added at zero frequency (Fig.1 - orange line). Further, stator voltage 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_{sfs} .

Commercial frequency converters usually dispose of several options for stator resistance voltage drop compensation. Moreover, beside this compensation, frequency converters by default have possibility of slip compensation i.e. compensation of speed reduction originating from rise of the motor load. With these two compensations induction motor speed can be satisfactory regulated by using the U/f control without speed (position) sensor mounted on the motor shaft. This makes U/f method very attractive and widely implemented in modern electric drives across the globe. Very simple algorithm without current regulators and complex mathematical calculations makes the U/f control method quite popular in scientific literature which asks for further improvements of its characteristics and ways which will rise the quality of speed regulation [10]-[12].

Nevertheless, in the electric drive systems where demands for high dynamics are strong the use of power converters drove by control methods with more complex mathematical calculations based on vector control are still mandatory.

3. DESCRIPTION OF LABORATORY SETUP BASED ON DSPACE1104 PLATFORM

For implementation of the U/f control algorithm in this paper dSPACE1104 DSP board [13] was used. dSPACE 1104 is a complete real-time control system based on a 603 PowerPC 64-bit floating-point processor running at 250 MHz. For advanced I/O purposes the platform includes slave DSP subsystem based on the TMS320F240 DSP microcontroller (16-bit, 150 MHz). For purposes of rapid control prototyping (RCP), specific interface connectors and connector panels provide easy access to all input and output signals of the board. A/D and D/A inputs and outputs are provided through BNC connectors, I/O and PWM signals through dSUB 37-pin and incremental encoder interface through dSUB 15-pin connectors. dSPACE platform has enabled communication with models created in the MATLAB/Simulink environment. Simulink model can be easily converted to a code suitable for dSPACE processor that further, in real time, controls the application or I/O units. It extends the C code generator Simulink Coder™ (formerly Real-Time Workshop - RTW) for the seamless, automatic implementation of Simulink and Stateflow models on the real-time hardware as it is shown in Fig.3. This significantly simplifies the process of iterations in the development of control

prototypes and applications, without requiring specific programming skills from users.

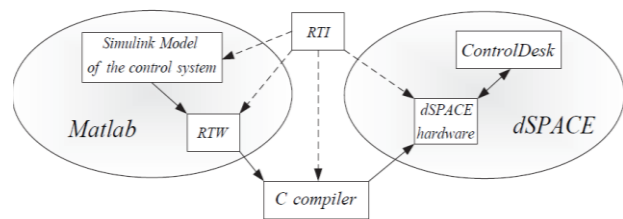


Figure 3. MATLAB – dSPACE communication [14]

The following resources of dSPACE1104 board are utilized in the setup:

- PWM control unit;
- 2*A/D converters for current measurement;
- 1*A/D converter for DC voltage measurement;
- INC unit for measuring the motor speed.

The laboratory setup on which scalar U/f control was implemented besides dSPACE1104 board consists of following parts:

- Isolated power supply;
- 3-ph power converter (inverter) up to 1 kW;
- 2 current sensors CMS3005;
- Signal conditioning and isolation board;
- Isolated DC power supply;
- IM with encoder;
- PC with ControlDesk software installed.

The U/f control algorithm was tested on two pole IM with parameters given in the appendix. Block structure of the overall laboratory setup is presented by Fig. 4.

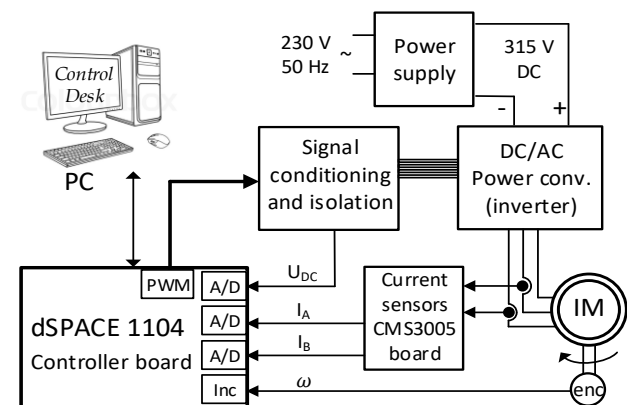


Figure 4. Block structure of the laboratory setup

dSPACE 1104 board provides PWM signals which are through signal conditioning and isolation board passed to 3-ph voltage source inverter. Isolation board consist of seven TLP2200 optocouplers which unlike the majority of standard commercial optocouplers provide positive logic i.e. output signal with the same polarity as the input signal. The maximal switching speed depends on the optocoupler bandwidth which is 2.5 MBd. Measured results show that the board transition time for rising edge (turn on) is 250 ns and for falling edge (turn off) is 400 ns. The signal isolating board is shown in Fig. 5a.

Current sensors CMS3005 are used for current measurement in two motor phases. The CMS3000 current sensor family is designed for highly dynamic electronic measurement of DC, AC, pulsed and mixed currents with integrated galvanic isolation. CMS3005 has very high dynamic response (bandwidth up to 2 MHz) without the hysteresis that is present in iron core based designs. This type of sensors is particularly suitable for high dynamics current measurement application such as in AC electric drives. The current sensor board is shown in Fig. 5b. Incremental encoder HEDSS HKT3006 with 500 pulses per rotation in

two phases (2000 pulse/rotation after generation of quadrature-clock and direction signals) and zero phase with reference pulse was used for the speed measurement and positioning. Fig. 5b shows the board with current sensors.

Complete laboratory setup is shown in Fig. 6. Laboratory setup realised in this way (with closed current and speed loops) is suitable for implementation and examination of advanced AC drives control methods as well, such as FOC or DTC methods.

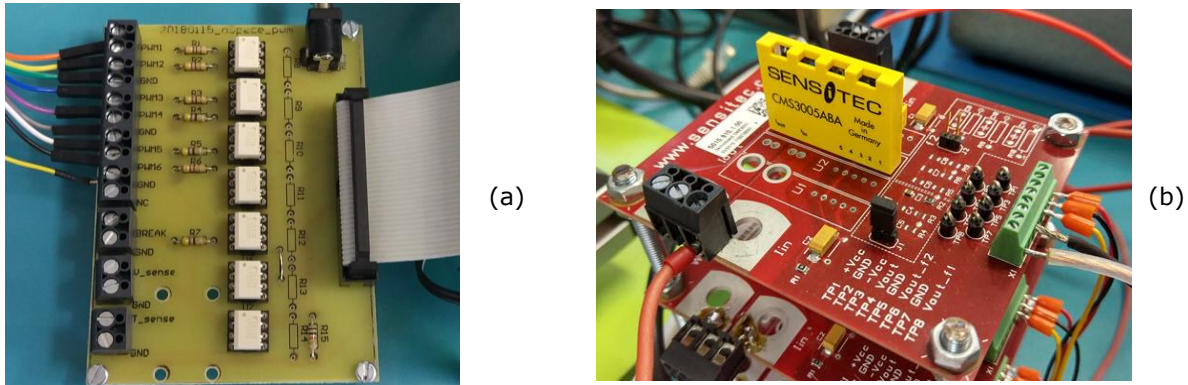


Figure 5. (a) Signal conditioning and isolation board and (b) currents sensors board

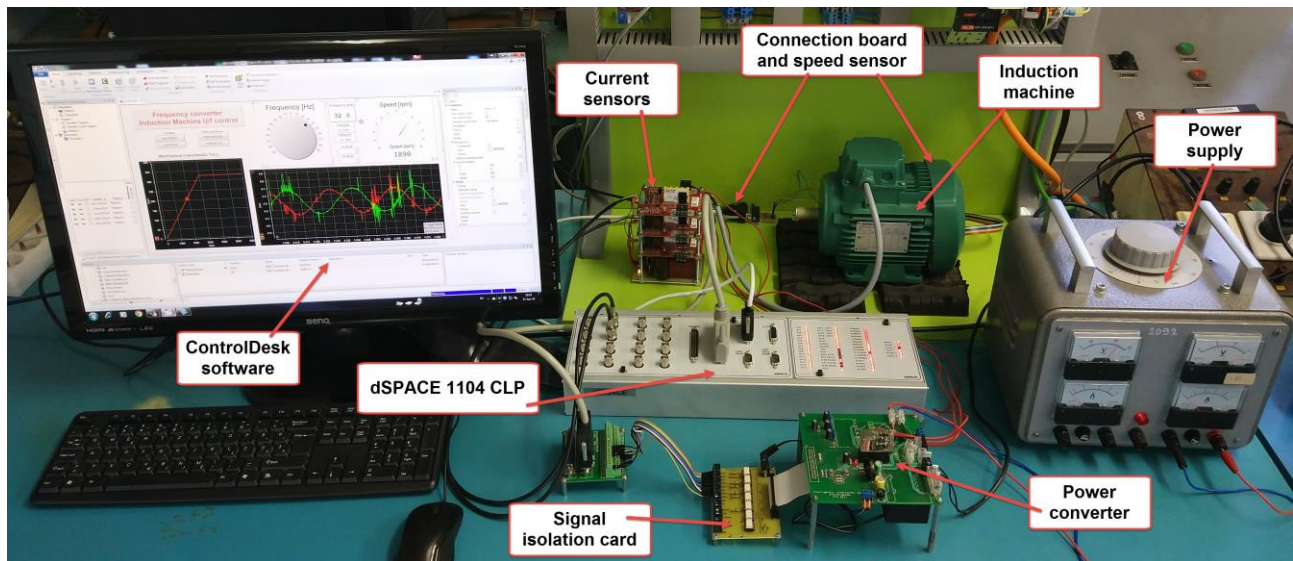


Figure 6. Complete experimental laboratory setup for testing different AC machine control algorithms

4. APPLICATION OF U/F CONTROL OF IM

Application of U/f control described in section 2 consist of two main parts: Control algorithm (MATLAB/Simulink) and graphical user interface (Control Desk). These two parts of the U/f application communicate through the RTI (Fig.3) allowing read/write control of every quantity in the application (Simulink model). All I/O specifications for RTI can be defined within the Simulink environment. RTI modifies the code generated by RTW according to these I/O specs and processes it to load the DSP system automatically. Supported

by RTI, block-diagram parameters in the real-time program (Control Desk) can be changed through Simulink's external simulation facility without regenerating code.

4.1 Simulink model of control application

In order to implement control application in DSP of the dSPACE1104 board, control application should be developed first. Control application is developed in MATLAB/Simulink. Application sample frequency as well as PWM frequency is set to 20 kHz which makes 50 μs available for all algorithm calculations.

Determination of PWM duty cycles (stator voltages) is related to stator frequency reference and defined by equation (1). The calculations have been done in synchronous reference coordinate system. The stator voltage is determined by U_d and U_q voltage components in synchronous $d-q$ coordinates. Then, by using inverse Park transformation, stator voltage references (in all three phases) are obtained in respect to the frequency reference as it is shown in Fig. 7.

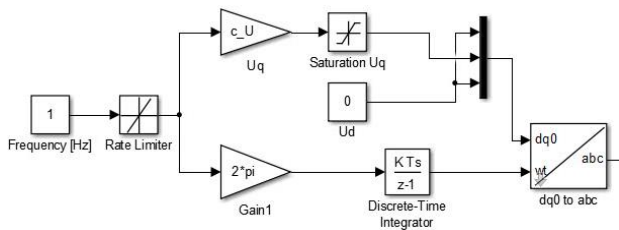


Figure 7. Calculation of stator voltages

Stator current measurement was realized through the interrupt routine which happens at the middle of the PWM cycle. In this way more accurate current measurement in a and b motor phases was obtained. Protection from unwanted excessive currents is realized by software. In case the stator current values exceed the maximal allowed value, the generation of the PWM signal stops.

Speed and position measurement is realized by processing obtained encoder signals within the Speed Measurement block. Since mechanical time constant is several times higher than electrical time constant, frequency of the interrupt routine which calls speed measurement is set to 1 kHz. This means that speed values are updated every 1 ms which is 20 times slower than PWM update (50 μ s).

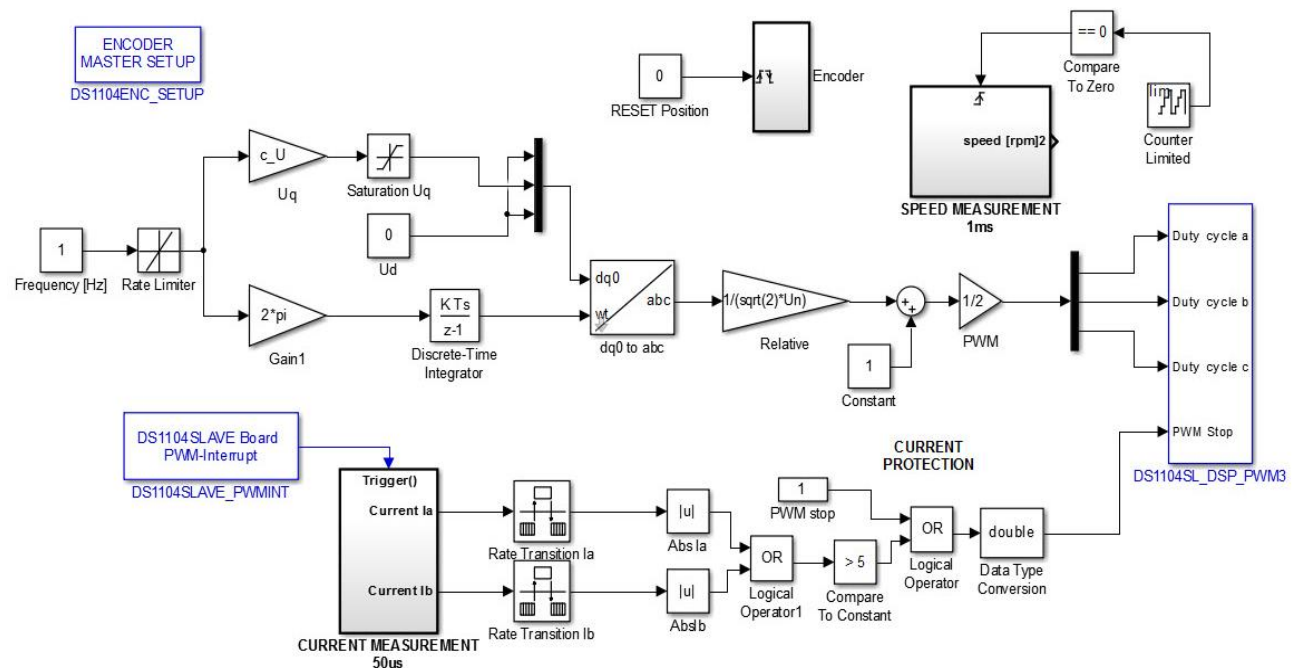


Figure 8. Complete Simulink model of the U/f control algorithm

Fig. 8 shows complete Simulink model of the U/f control algorithm ready to be implemented on the dSPACE board. At the end, the application is automatically built to C code using MATLAB RTW and downloaded to dSPACE1104 control board ready for use. In such applications it is a must to prevent uncontrolled application start after the download on DSP was performed as well as set initial conditions of the application. In order to prevent unstrained application run the *Initial simulation state* option (*Code generation/RTI Simulation option*) in *Model configuration parameters* of the Simulink model should be set to STOP. This variable should be controlled through the GUI as *simState* variable.

4.2. Control environment and results

Graphical User Interface (GUI) has been developed in Control Desk software. The Control Desk enables making objects for control and measurement (plot) characteristic quantities in the control application. The objects are linked to the quantities of interest and their values can be changed/observed in real time. The developed GUI allows setting up the reference frequency as well as observation of electrical and mechanical parameters of the motor such as motor speed, stator currents, U/f and ψ/f characteristics etc.

Before application start, current offset fields should be adjusted in order to remove DC component in the motor current measurement. After this, application can be started (*simState* variable) and PWM outputs can be resumed (*PWM stop* variable) by selection appropriate buttons. Complete GUI is shown in Fig. 9.

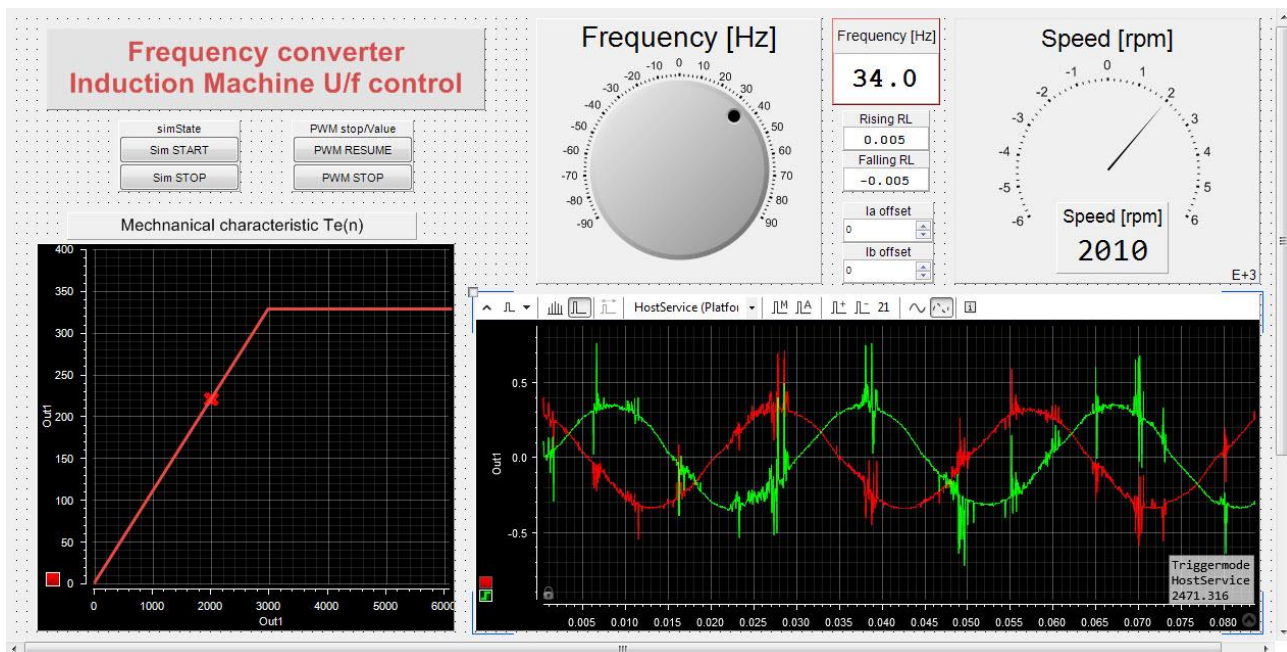


Figure 9. GUI for U/f control of IM

Beside the possibility to set up the appropriate current offsets user can define rising and falling edge limiter of the reference frequency (frequency soft start). The frequency can be set by "Frequency [Hz]" radio button or numerically edited in the corresponding field. The resulting speed is provided graphically as well as numerically at the top right part of the GUI. Dependence of the stator voltage and speed (frequency) is provided graphically in the bottom left corner. The user can observe current value of speed and stator voltage in two zone operation (constant field and field weakening zone) by changing the stator reference frequency. Stator currents in stationary d - q coordinate system are shown in bottom left corner of the GUI. The currents in Fig. 9 are plotted in time domain. Currents are plotted in raw format measured with the highest sensor bandwidth without any using any filtering option.

This GUI can help students to better comprehend working principle of the U/f control application and relation between characteristic quantities of IM during the operation. The GUI is quite easy to edit so new measurement and graphs of interests can be added very simply.

5. CONCLUSION

The paper presented a laboratory setup for testing various control methods of AC machines. Every part of the setup was described in detail as well as developed application of U/f control. Firstly, the basic theoretical overview of U/f control was given after which complete system based on dSPACE 1104 board is described. Control application made in Simulink was properly described and discussed. In the end, GUI interface for U/f control method is

presented together with its control functions and graphs.

The laboratory setup is dedicated to students who follow the course of Control of Electric Drives and should aim for them to gain knowledge and practical skills in the laboratory. This laboratory setup allows its users to perceive all aspects of an AC machine control method in modern electric drive applications such as:

- Current and speed measurement and regulation;
- Implementation of necessary matrix (Clarke and Park) transformations;
- Determination of the necessary voltage and current references and PWM generation;
- Flux estimation techniques;
- Protection implementation;
- 2Q or 4Q machine operation, etc.

Moreover, the setup consists of all necessary parts which enable implementation and testing of different advanced control methods such as FOC or DTC control.

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APPENDIX

Table 1. Induction motor SIEBER L71 parameters

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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