Graphical user interface for self-commisioning of induction motor drive insuring high-efficiency of electrical vehicle

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Abstract – This paper presents the graphical user interface (GUI) created to support self-commissioning procedure of unknown 48V battery driven three-phase induction motor for Golf Cart application. GUI application is created for PC, it has options to setup the self-commissioning procedure, to retrieve, display and off-line change the resulting motor and controller parameters. Finally, the application offers the option to write the parameters to the EEPROM of unknown induction motor drive and consequently to setup the drive control module and make it ready to perform robust and efficient control of induction motor. This application uses CAN Open interface to communicate with Nidec/Kinetek induction motor vector drive developed for the electrical vehicle application which has the STM32F303 microcontroller firmware version IFOC V1012 ATUN 1.09 or higher.

1. INTRODUCTION

Electrical vehicle application of digitally controlled drives is gaining momentum and it is attractive for many researchers. The focus is on performance and overall system efficiency. That is why vector control of three-phase induction motor is utilized, insuring good dynamic response and steady state performance.

Yet, the vector controlled drive has to be properly tuned in order to give the expected performance. Even more, with motors working on the edge of their safety operating area, in deep saturation (heavy torque start at low speeds) or deep field-weakening (high cruse speeds) the vector controller parameters are becoming even more important. Finally, with vehicle as dynamic system, the model based procedure have to be used for both development of Maximum Torque Per Ampere (MTPA) or for minimization of motor loses using Loss Model Control (LMC) [1]–[6]. That is why different procedures were developed for self-commissioning of unknown 48V battery driven three-phase induction motor and drive [7]. All of the relevant parameters are retrieved and available in the controller's memory.

In this paper, the GUI application developed to control and support the self-commissioning procedure [7] is described. When self-commissioning procedure is successfully finished, GUI is designed to retrieve the parameters from the controller memory to allow their inspection and editing. The GUI application is developed in C sharp using Visual studio 17 and 19 for Windows operating system. Some aspects of GUI application will be described in more details in the following chapters.

2. SETTING UP SELF-COMMISIONING OF INDUCTION MOTOR

Autotuning procedure can be initialized, started and monitored via the Autotuning Command window, presented in Fig 1. This window is designed to allow the operator to setup some system parameters and voltage, current, speed limits for the autotuning procedure. At this point, operator has to know the voltage, current and speed range in which the motor has to be tested.
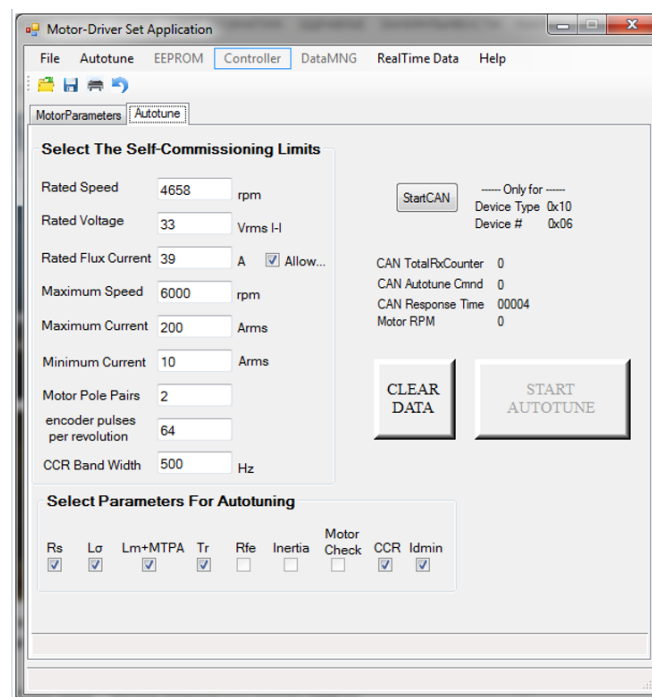

Fig. 1. Window for setting the limits and parameters for pending self-commissioning procedure

From the Fig. 1 the one can distinct three status/control groups:

1. First Group box named **Select Self-Commissioning Limits**: Contains Self-Commissioning advanced parameters for proper handling the overall estimation process. These include various limits (Maximum Current, Speed max, Minimum Current, speed rated, Minimum Voltage, number of encoder pulses per revolution, etc.) which must be set by the user before autotuning starts.
2. Second Group box named **Select Parameters For Autotuning**: Contains List of Parameters that can be selected for autotuning (stator resistance Rs, total leakage inductance Lσ, magnetizing and optimal characteristic Lm +MTPA, rotor time constant Tr, iron loss resistance

Rfe, mechanical Inertia, motor Check phase, current regulator tuning CCR). By checking/unchecking the Parameter box, the user can select/unselect the parameters, which are going to be estimated. Rfe plot and Inertia result are still not included in the program.

3. Third group is a status/control group around the bottom START button, designed to start CAN communication and if no errors, to start self-commissioning procedure.

2.1. Select Self-Commissioning Limits

The following table describes the self-commissioning parameters and their defaults values.

ATUN INPUT VARIABLE	DESCRIPTION	DEFAULT VALUE
Rated speed	Rated motor mechanical speed in rpm. The speed at which most of the parameters (the ones for which the rotation is mandatory) will be measured (*Lm*, MTPA and Tr curves).	4658 rpm
Rated voltage	Rated line–to–line rms voltage in Volts. This voltage will be used for Idmin detection. It will be applied during scalar open loop run test at rated speed. After rated speed it will be kept constant.	For 48V battery the rated voltage is 48/1.41 = 33Vrms
Rated flux current	Current level at which Lm slope starts to descend in Amps. At that level the rated rotor time constant value will be measured. (If corresponding check box selected, Lm+MTPA algorithm will suggest rated flux current value and change the value in the box accordingly)	39 A – motor dependent
Maximum speed	Maximum allowed mechanical motor speed in rpm. At that speed the Idmin will be measured.	6000 rpm
Maximum current	Maximum allowed rms value of motor line current in Amps. Within this range, Lm and MTPA curves will be defined. Must be lower than motor and drive maximum current.	200 A
Minimum current	Minimum magnetizing current rms value allowed during the autotuning. Units Amps	10A
Motor pole pairs	Integer number regarding the construction of the EV motor	2 typical
Encoder pulses per revolution	Integer number regarding the resolution construction of the encoder	64 (typical 32, 64)
CCR BandWidth	Desired current regulators bandwidth for the proper current control	500 Hz

One example of how to set those parameters is given for the motor with the nameplate data presented in Fig. 2

Fig. 2. Example of motor nameplate data

Input parameters to the ATUN can be calculated by using the previously given considerations:

- **Rated speed**: If not specified, use $n_{rated\ ATUN} = 0.33n_{max} = 1666\ rpm$ where $n_{max} = 5000\ rpm$ (1/3 is experiential value)
- **Rated voltage**: $V_{rated} = V_{DC}/\sqrt{2} = 33\ V$ for $V_{DC} = 48\ V$
- **Rated flux current**: $I_{d\ rated} = 0.5I_{rated} = 40\ A$ where $I_{rated} = 80\ A$
- **Maximum speed**: $n_{max\ ATUN} = 2n_{rated\ ATUN} = 3400\ rpm$
- **Maximum current**: $I_{max} = 3I_{rated} = 240\ A$ at least since no data for inverter ratings are given
- **Minimum current**: $I_{dmin} = 0.2I_{rated} = 16\ A$
- **Motor pole pairs**: $P = ceil(60f_{max}/n_{max}) = 2$ where $f_{max} = 170\ Hz$
- **Encoder pulses per revolution**: $R = 32\ pulse/rev$
- **CCR Bandwidth**: $\omega_{bw} = 500\ Hz$

2.2. Select Parameters For Autotuning

The autotuning can perform the separate measurement of different motor parameters. Within the Group box – **Select Parameters for Autotuning** the user can arbitrary setup the autotuning state machine flow.

If some measurements are not necessary, or maybe already determined by the a priori knowledge of the motor, the user can uncheck the proper box below and the parameter estimation procedure will not be called.

2.3. Status/control group

This group is used to initiate the CAN communication and motor self-commissioning. It consist of the various status/control actions that will be described in the continuation of the section. This group is depicted in Fig. 3. The control buttons of interest within this group are:

- **CLEAR DATA** button – used to reset the motor parameter data within the **MotorParameter** tab; recommended to initiate prior to changing the motor within the drive,
- **StartCAN** button – activate the CAN communication bus; a priori action to autotuning process; if CAN adapter is not attached to the driver the following warning pops out: *Open USB-CAN adapter error – no adapter*; if adapter is attached the following message is presented: *CAN started OK*,
- **START AUTOTUNE** button – initiate the autotuning process (active button only if *StartCAN* was previously pressed)
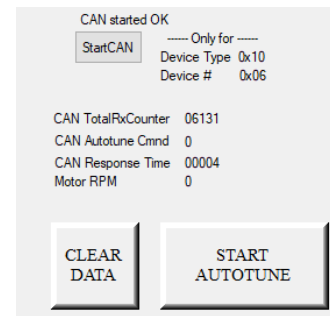

Fig. 3. If CAN communication is detected, the START button is enabled

3. MONITORING AND PROCESSING OF COMMISSIONED MOTOR PARAMETERS

The first result of self-commissioning process are parameters of equivalent circuit of induction motor. The second result are FOC induction motor drive parameter characteristics, such are Lm(Id) and MTPA Id(Iq) curves. These are as follows:

1. **Rs** – stator resistance parameter corresponding to *Rs* within the IM equivalent circuit; value given in Ohms – under the **Motor Parameters** field,
2. **Lσ** – stator equivalent leakage inductance, as a sum of stator and rotor leakage inductances within the IM equivalent circuit in uH – under the **Motor Parameters** field,
3. **1/Tr Inverse rotor time constant parameter** – The DSP value of this parameter is recorded at the specific magnetizing current level represented at the knee point of the magnetizing Lm(Id) curve. Scaling to the rotor time constant in ms is also presented– under the **Motor Parameters** field,
4. **Lm (Id)** – motor magnetizing curve denotes magnetizing characteristic within the IM equivalent circuit,
5. **MTPA Id(Iq)** curve – The d-axis stator current Id value that gives maximum torque per amp for given Iq,
6. **1/Tr (Temp)** – the rate of change of rated *1/Tr* with temperature; this characteristic is closely related to the temperature change of rotor resistance parameter within the IM equivalent circuit,
7. **Idmin(Speed)** – magnetizing current curve for rated voltage and different speeds,
8. **CCR Parameters** field: Include the DSP values of PI current regulator gains, proportional gain Kp, integral gain Ki and gain Shift parameter.

Curves Lm(Id) and MTPA Id(Iq) have a possibility for the advanced edition and modification. The editing window for each figure can be accessed by double clicking on the corresponding characteristic window. This software functionality is essential for acquiring the correct dependency of the critical characteristics within the IM drive.

3.1. Displaying of the self-commissioning results

When the self-commissioning phase of induction motor drive is completed, the retrieved parameter are automatically displayed at parameters dashboard, located in separate MotorParameters tab, depicted in Fig 4.

In the upper left corner, the measured value of stator resistance Rs , at 20ºC, and the value of leakage inductance Lσ are displayed.

Inverse rotor time constant 1/Tr is also displayed in the same area. This parameter is given per unit, but also in [ms]. Due to expected variation of Inverse rotor time constant with level of heating, the value of field current that corresponds with 1/Tr value is also provided.

In the upper right corner of Fig. 4, the suggested parameters of current regulators are given. The parameters are given per unit, with suggested shift (gain) value.
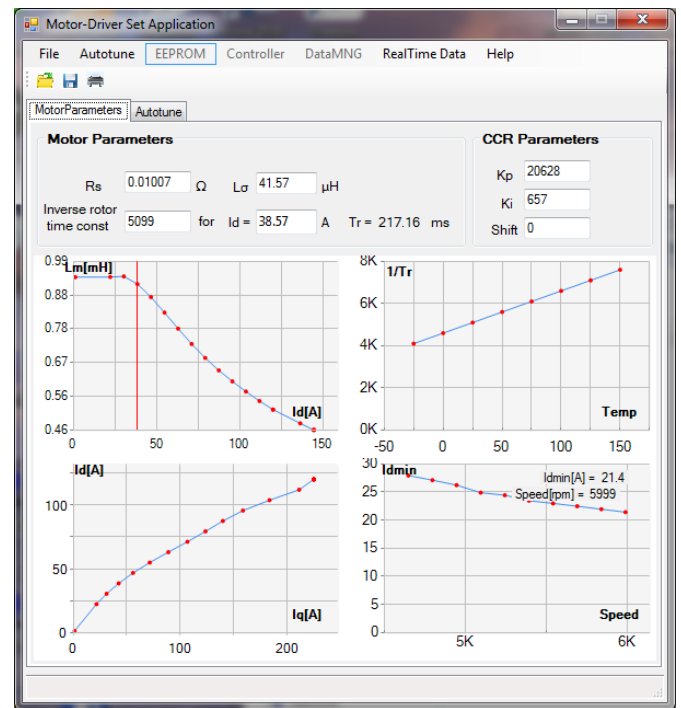

Fig. 4. Motor parameter dashboard in separate window

3.2. Modifying of the self-commissioning results

The self-commissioning results are prone to measurement and system noise. The best way is to inspect the results, and if needed, perform necessary data correction and trimming. All that is offered by this GUI application.

Parameters Rs, Lσ and 1/Tr can be changed directly in the corresponding field labels, if needed, before the parameters are saved on the disk or send back to controller EEPROM. The parameter can be changed by directly entering the new value in the label box.

Magnetizing Lm(Id) characteristic and optimal MTPA curves can be modified in separate advanced widows. By using this option, possible shortcomings and drawbacks of the introduced self–commissioning methods and imperfections of the measuring equipment used in the process of tuning the drive can be avoided by the operator action.

3.2.1. Modifying of Lm curve

The motor magnetizing Lm(Id) characteristics is received from the controller for the purposes of editing in separate window. Before editing, the user must cope with the few additional details regarding the magnetizing conditions within the real drive:

1. The magnetizing characteristics must be *smooth* and *monotonically decreasing* throughout the entire Id range
2. The upper threshold defines the constant magnetizing inductance before the first saddle point (point of zero second order derivative)
3. Second saddle point is in the area of deep saturation

Due to measurement imperfection, especially at very low voltage level, raw Lm curve usually does not have perfect upper threshold around zero, and it is not smooth as anticipated.

Typical Lm result is shown on Fig 5.

3.2.2. Modifying of MTPA curve

Maximum torque per ampere is the control mode mostly used during the typical electrical vehicle operation. That is the reason why rotor time constant and MTPA curve are the most important parameters to be tuned to insure energy efficient operation of electrical vehicle.

The GUI application can define the MTPA curve of unknown induction motor in two ways: 1. It can simple receive it from drive after the self-commissioning is finished. The drive is using the method described in [1], 2. GUI can also calculate analytical MTPA, based on the polynomial fit of Lm curve. Also described in [1]. The curves are always similar, but it is up to operator to design which curve is more accurate. In that process, one must know that optimal MTPA characteristics must be 1. smooth and monotonically increasing throughout the entire Iq range, 2. The curve angle in the vicinity of the point (0,0) must be 45º. 3. At some point MTPA curve has to saturate, reach maximum Id current value. Separate MTPA curve window is opened by double clicking the Id(Iq) chart within the Motor Parameter tab, Fig 4.

Typical MTPA Id(Iq) curve (blue and red) is shown in Fig 7. Identified maximum and minimum Id current values are also shown using green vertices. For convenient reasons, mostly for backward compatibility with old firmware, the linear fit of MTPA curve is also shown. Linear fit approximates MTPA curve using $Id = K_0 + K_1 \cdot Iq$. GUI calculates the K0 and K1 parameters as a best fit candidate to presented MTPA curve.

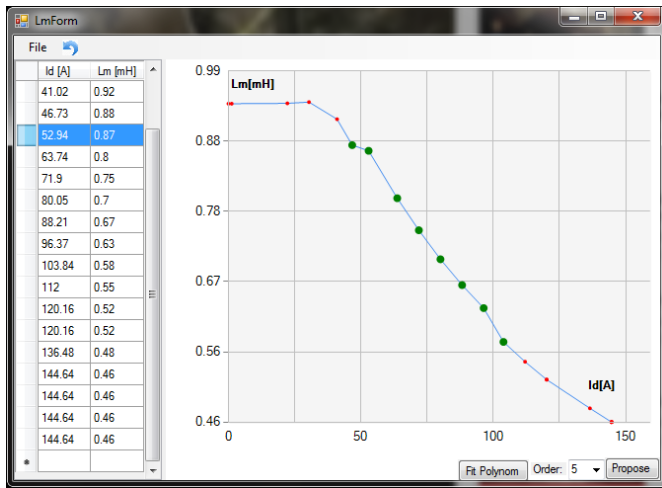| Id [A]	Lm [mH]
41.02	0.92
46.73	0.88
52.94	0.87
63.74	0.8
71.9	0.75
80.05	0.7
88.21	0.67
96.37	0.63
103.84	0.58
112	0.55
120.16	0.52
120.16	0.52
136.48	0.48
144.64	0.46
144.64	0.46
144.64	0.46
144.64	0.46

Fig. 5. Typical Lm curve after the self-commissioning

Of course, even with those imperfections, Lm curve trends are quite clear and it carries enough information about saturation of induction motor magnetic circuits. At this point, operator can use two options 1. to fit the Lm(Id) data manually (simply change the position of individual data points of Lm curve) and 2. to using Polynomial Function:

1. User can choose Order of Polynomial, from the dropdown menu,
2. When button Propose is clicked, the Green line will be shown, this is only proposed line for fit,
3. If the user is satisfied with the proposed Green line fit, then he should press button Fit Polynom,
4. If the user is in some way not satisfied with the proposed dependency, he is able to move points, and press button Propose, as many times as he wants; when finally, he is satisfied with the proposed line, he should press button Fit Polynom,
5. When button Fit Polynom is pressed, data at Lm(Id) are changed,
6. If Lm curve is changed, the MTPA curve proposal, according to [1], is also updated accordingly within the Charts and Tables.
7. User can repeat this process indefinitely,

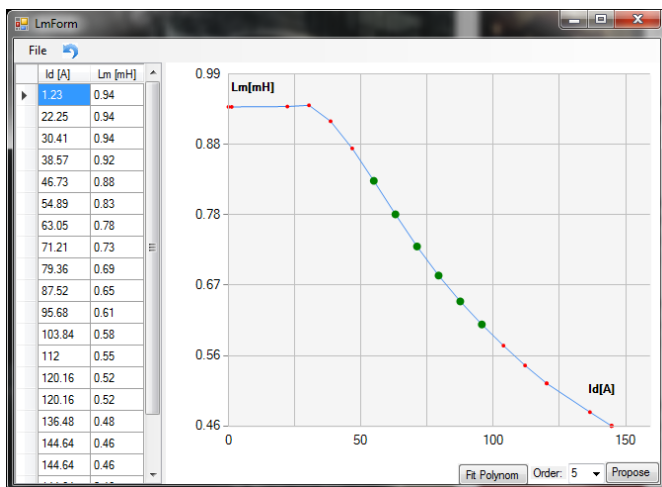| Id [A]	Lm [mH]
1.23	0.94
22.25	0.94
30.41	0.94
38.57	0.92
46.73	0.88
54.89	0.83
63.05	0.78
71.21	0.73
79.36	0.69
87.52	0.65
95.68	0.61
103.84	0.58
112	0.55
120.16	0.52
120.16	0.52
136.48	0.48
144.64	0.46
144.64	0.46

Fig. 6. Lm curve after polynomial fitting

Example of Lm curve after the fitting is shown in Fig 6. One can find that after the fitting of the all the measured points, the systematical errors will be removed and magnetizing curve will be more appropriate for the future use.

Id [A]	Iq [A]
38.57	42.49
46.73	55.94
54.89	71.58
63.05	88.98
71.21	106.88
79.36	123.74
87.52	140.01
95.68	158.83
103.84	183.71
112	211.45
120.16	225.1
120.16	225.1
120.16	225.1
120.16	225.1
120.16	225.1
120.16	225.1

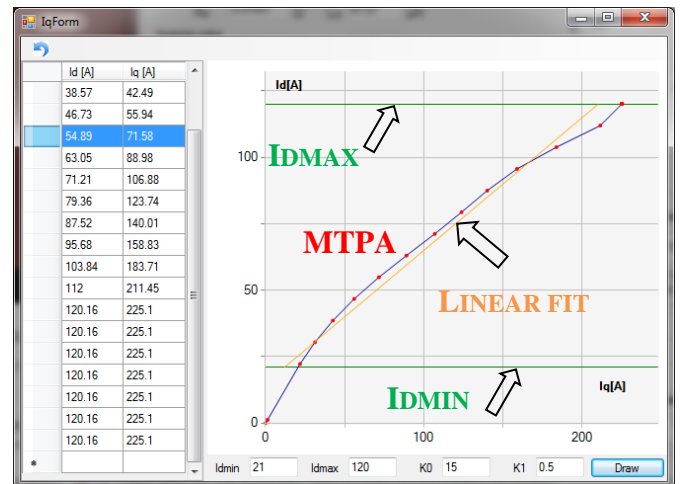Idmin 21 Idmax 120 K0 15 K1 0.5 Draw

Fig. 7. MTPA curve after self-commissioning and fitting

MTPA data can be changed in various ways:

1. In IqForm window, user can directly change the Table with MTPA data. When user clicks Enter, the MTPA graphic is changed accordingly.
2. In the MTPA chart, user can select one (by clicking on the point) or multiple points (by selecting the area where they are situated) of the Chart, and to change the values by moving and dragging them,
3. Additionally, user can generate linear interpolation fit of the MTPA curve regarding predefined flux current limits. *Fig7* depicts this process:

i. Enter the propositions for the minimum *Idmin* and maximum *Idmax* flux currents, current offset *K0* and slope *K1*

ii. Click on the button *Draw* to generate the linear curve of the proposed parameters

4. CONCLUSION

In this paper newly developed self-commissioning GUI application is presented. The application is created to support the self-commissioning process of unknown induction motor drive using vector control. The application controls the autotuning process via CAN bus, and reads and displays the resulting data from controller. GUI has powerful tools for data editing, and even mathematical tools to support data fitting and theoretical MTPA curve proposal. Finally, the application offers motor and controller data to be saved on the disk, and/or written in EEPROM memory. With current globalization, this application is attended to be used at different motor factories around the globe, to retrieve the data to distant research centers for further analysis and inspection. Moreover, all this allows operator to tune the controller to unknown motor and perform some initial onsite demos with new electrical vehicles. Still, this is an early stage of this program development, some settings and suggested input values are currently under the test and with each new test data from the field the program is learning and evolving.

5. LITERATURE

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Садржај – Овај рад описује графички кориснички интерфејс који је начињен као подршка за аутоматско подешавање параметара непознатог трофазног асинхорног мотора напајаног са 48V батеријом. Апликација је направљена за персоналне рачунаре са Windows оперативним системом и има опције да подеси и покрене процедуру за аутоматско подешавање параметара мотора. Такође, по завршетку процедуре апликација преузима параметре и нуди њихову инспекцију и корекцију, по потреби. Апликација користи CAN Open интерфејс да комуницира са Nidec/Kinetek погоном за електрична возила који ради са STM32F303 процесором чији програм има верзију IFOC V1012 ATUN 1.09 или већу.

ГРАФИЧКИ ПРОГРАМ ЗА АУТОМАТСКО МЕРЕЊЕ ПАРАМЕТАРА АСИНХРОНОГ МОТОРА ЧИМЕ СЕ ОМОГУЋУЈЕ ВИСОКА ЕФИКАСНОСТ ЕЛЕКТРИЧНОГ ВОЗИЛА

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