Configurable Control Systems of Power Converters for Instructional Laboratories

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***Abstract*—This paper describes the configurable control system for instructional laboratories which is currently implemented for direct current and induction machines. The benefits of this type of control system implementation are shown in comparison with simulation and low power solutions. The design of the control system compiler is considered and the example of the generated code for nested loop control system with field weakening is shown.**

Keywords*—*motor control, configurable control system, compiler, education, instructional laboratories

I. Introduction

Practical activity is an essential component of higher education at the undergraduate level particularly in the area of engineering. The main objective of practical activity is to reinforce the students understanding of theory learned from lectures, tutorial and self-studies. The core of practical activity comprises a series of controlled assignments usually referred to as laboratory works where students conduct tests and experiments under academic staff supervision [1].

The study of electrical machines and drives is application-driven requiring a practical demonstration followed by student activity. This suggests that laboratory works have great value in the curriculum of the subject [2]. To reflect rapid changes in the area of electric drive control the curriculum should cover modern industrial applications implementing the variety of motor control DSPs and power converters operating under code development software or real-time control systems e.g. MATLAB, LabView, MexBIOS etc. However the industrial equipment produced by major manufactures are not really appropriate for educational purposes.

Although practical activity focused on tests of embedded control structures can be conducted using standard industrial power converters these devices are black boxes in the context of investigation and understanding of control processes and algorithms. Therefore the industrial equipment is only suitable for basic training or vocational education.

In the last two decades laboratory work execution has been completely reshaped due to introduction of digital computerized systems. Data acquisition systems and automated instrumentation have replaced conventional laboratory instruments to provide better accuracy results and rapid data processing. Computer based simulation has converted most of laboratory works on electric drives into hardware-in-the-loop experiments where computer or DSP board provides real-time control of hardware [3], [4].

The laboratory works based on power converters controlled by DSP kits can perform very detailed analysis of investigated control structures [5]. However these sophisticated systems require students to learn the principles of real-time programming and significantly increase time spent in the laboratory preparing an experiment. Another drawback is that DSP based laboratory works usually use low power converters and machines (up to 1 kW) performing different from industrial installations. The increase in rated power of the converter and motor controlled by a real-time DSP based system may cause an unrecoverable fault due to a software error or mistake in operation.

In fact, a motor control system comprises a number of standard control elements including PI-controllers, adding elements, filters, gains, hysteresis elements, ramps, Clark and Park transforms, observers of the motor state etc. The list of elements to be compiled into a control algorithm depends on tested systems and could be limited for investigation of common and relatively simple control structures. For example, scalar, flux-vector and direct torque control can be built in the same drive using just a few control elements. Therefore, instead of complicate real-time programming a control structure can be easily designed by a limited number of control elements. However these elements must operate under control of the fixed real-time system core ensuring protections of the motor and power converter. This approach provides comprehensive and safe execution of laboratory works and focuses students on achievement of the curriculum learning outcomes.

II. Educational Equipment Hardware Design

There is a tradition of Russian high-school that the students perform their tests in laboratories using special educational equipment. The design of this equipment may be different but usually it is like a kit. So the students can construct some devices or schemes and test their performance. This educational equipment is designed with all kinds of protections so that students can focus on the task and not to think a lot about safety of operation. This approach allows to make more tests in the same time and to cover more system examples in one course.

For motor control system course two types of power converters were designed. One for induction machine and one for direct current motor. The Mitsubishi IPMs were used for inverter due to their excellent protection from short currents. The structure of the converter for direct current motor is shown in Fig.1.

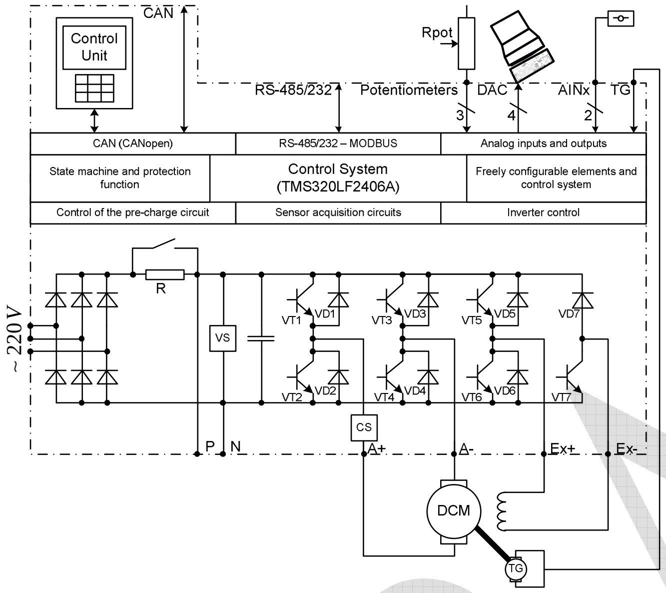

Fig. 1. Structure of the power converter for DC motor

The control system is designed on TMS320LF2406A microcontroller from Texas Instruments and has 4-channel DAC. So it is possible to display any internal variable on the oscilloscope. There is voltage sensor in DC-link and current sensor for armature current. Also a signal from tachogenerator can be used for speed feedback. The control unit is connected via CAN. The converter for induction motor has the same structure and contains two current sensors in phases and the brake circuit for DC-link voltage control.

III. REQUIREMENTS FOR SOFTWARE CONTROL SYSTEM

The motor control system course has to cover different types of the control structures such as:

- closed-loop PI-control with nested loops;
- open-loop control;
- hysteresis control;
- field weakening control and other types.

The number of control structures is large and it is not easy to predict all connections, switches and settings we need to implement in the software. So it was decided to implement configurable structure which will operate with a number of the standard elements. These elements can be combined together by a student in any possible way using control unit or computer with special software. After configuration is finished the control system must compile a control core into a program where all connections will be replaced with data copy instructions and execution of elements by function call instruction.

This approach allows us to compile a control system core which will be executed inside the PWM interrupt routine. This core operates with hardware via input and output variables without low-level methods. This allows us to implement all protection outside the core in real-time PWM interrupt. So the main demand is that inverter must be durable for short currents if the designed control system core has rude mistakes (for example positive feedback in the current loop). That is the reason to use Mitsubishi IPM in the inverter circuit.

Every element of the control core can have four data types:

data sources or the output variables which have read-only access and can be connected to the inputs of other elements (for example, the output of the PI-controller unit);

settings for tuning of the elements (for example, gains of the proportional and integral channels of the PI-controller);

data consumers or input variables which can be linked with data sources (for example, the reference or feedback of PI-controller);

data consumers / settings which works like settings if the input is not linked with the source and like data consumers if it is (for example, the saturation of the PI-controller can be define by setting or by another variable if we need to change it during the operation).

The links between the elements are defined on the consumer side. This allows to link data source with different data consumers if necessary. The following elements were determined for direct current motor, they are:

- inverter control subsystem (gains voltage references for armature and excitation windings);
- DAC control element (gains data from any sources);
- subsystem of internal microcontroller ADC (provides an information about current, speed from tachogenerator, references signals from potentiometers and auxiliary analog inputs);
- 8 programmable variables;
- 5 PI-controllers with tunable gains and output limits;
- 5 adding elements with three inputs of programmable polarity;
- 5 gain elements with tunable gain and offset;
- 3 hysteresis elements;
- 5 filters;
- 4 multiplexers for signal switching;
- ramp generator.

The control system for induction machine has some extra alternating current elements:

- 3-phase inverter control subsystem (gains voltage references in stationary frame and support four different types of PWM like sinusoidal and space vector modulation);
- v(f) function;
- frequency to angle integrator;
- Clarke transform;
- inverse Park transform
- 3 Park transforms;
- transform from stationary frames to magnitude and angle;
- state observer of rotor flux for flux-vector control (using speed and currents);
- state observer of stator flux for direct torque control.

The example of the control system for direct current motor with field weakening using described set of the elements is shown in Fig. 2. This structure contains current and speed loops with PI-controllers. The field weakening contains a hysteresis controller with feedback from the current controller output. It is possible to set the speed reference and current limit separately from the potentiometers.

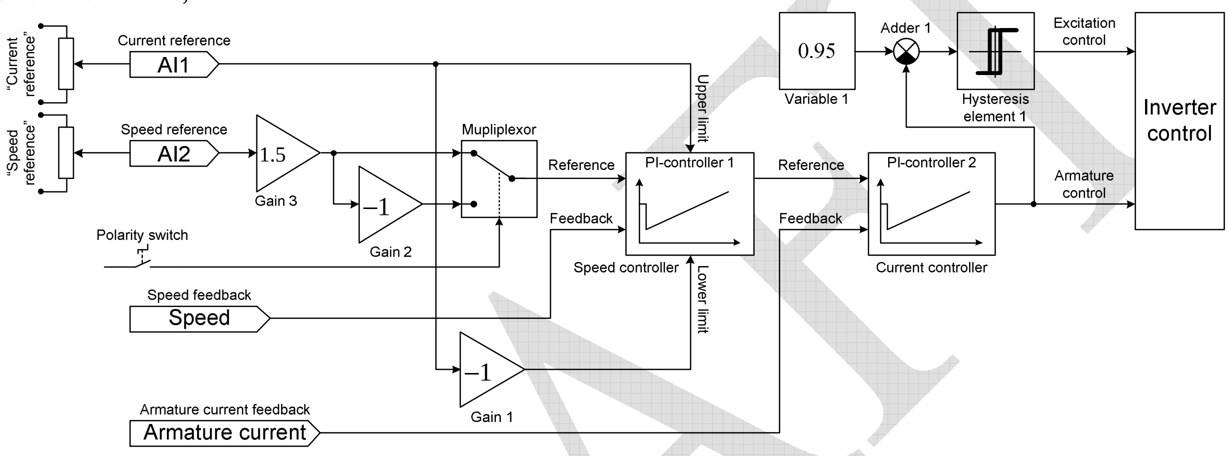

Fig. 2. The example of control system for direct current motor

IV. Compilation of the Control System Core

After control system links configuration is finished the build-in compiler should compile control core. It is possible to find all presented links and build a code for data copy between sources and data consumers and then to insert function calls for every element included to control system structure. But this method will give the significant delay of one PWM cycle on every element so this will result in a poor system response time.

Another way of compilation is to determine the sources which are already have the input data available and to make data copy from this sources first. For example, it is possible to copy data from AI1 to Gain1 and PI-controller1 upper limit. But the data for PI-controller1 lower limit is not currently ready so this data copy operation must be done on one of the next steps.

After that compiler can insert calls for those element functions which are currently have the full set of input data. For example, Gain1 now has all input data and its function can be executed. After execution of Gain1 function the data for PI-controller1 lower limit is ready and can be copied on the next step.

Sometimes if the control structure contains the loop there may be no solution with the consequent data copy and function execution. In this case the compiler should produce function execution code regardless the input data is not ready.

All the elements described in the data area "elements" (see Table I). Each element has the execution address in the program memory and a ready flag. If the compiler places the execution code for this element in the control core he sets this flag.

TABLE I. Description of the Elements

# of the element	Address in the program memory	Ready flag
0	doNothing	0
1	piController1	0
2	piController2	0
…	…	…
16	hysteresis1	0
…	…	…
24	filter5	0
…	…	…

All data sources are described in the data area "sources" which is shown in Table II in in a short form. The first column the number of source is used to define the link in the link table (see Table III). The second column contains information about the physical address of this variable in data memory of the microcontroller. The next column contains the information about the corresponding element which must be executed to produce this data. The last one is the ready flag which is set by compiler when the element execution function is placed to the control core code and the source data is ready for use. Some of the sources which are always available like speed, variables, currents and so on contains 1 in this field.

TABLE II. DESCRIPTION OF THE DATA SOURCES

# of the source	Address in the data memory	# of parent element	Ready flag
0	main_null	0	1
1	variable1	0	1
…	…	…	…
9	main_speed	0	1
…	…	…	…
13	PIcontroller1_out	1	0
…	…	…	…
26	hysteresis1_out	16	0
…	…	…	…
35	main_ai1	0	1
…	…	…	…

The connections between elements are defined in the “links” data area (see Table III). This area is configured via control unit or special MATLAB library and CANopen software and represents all links in control system structure. Every link can be set to a data source (#0 or 1) or disconnected if the input is optional (#2) or the corresponding element is not used (#10 in Table III). The optional flag is set in the links like PI-controller limits. If the link is defined then the data is taken from the data source and if the link is undefined then the data is taken from setting.

TABLE III. DESCRIPTION OF THE LINKS

# of the link	Destination address in the data memory	# of the data source	# of the element	Optional flag	Ready flag
0	PIcontroller1_xSet	29 (mux output)	1	0	0
1	PIcontroller1_xFdb	9 (speed)	1	0	0
2	PIcontroller1_max	35	1	1	0
…	…	…	…	…	…
10	PIcontroller3_xSet	0 (disconnected)	3	0	0
…	…	…	…	…	…

The compiler was written in accordance with the diagram from Fig. 3. The compiler runs the search of the links with ready data to produce the data copy code and then the search of the elements with ready inputs to produce execution code for elements. These operations repeat until the search of the elements returns zero result. This means that the compilation of the control core is over. The algorithm is presented in a shortened form and the block “Search for partially connected elements” is not disclosed.

The compiler produces relatively good code which contains data copy operations and element function execution code as shown in Listing 1. At first compiler form data copy code using “ldp” and “bldd” instructions for all currently available data sources. When the ready data sources are over compiler produce code for execution of the element functions using “call” instruction for those elements which have the full data at the inputs. After that compiler form data copy code and then execution code until the structure will be fully compiled. The result of the operation of the control system from Fig. 2 is shown in Fig. 4. The field weakening starts at the moment when the speed curve begins to lose the acceleration rate.

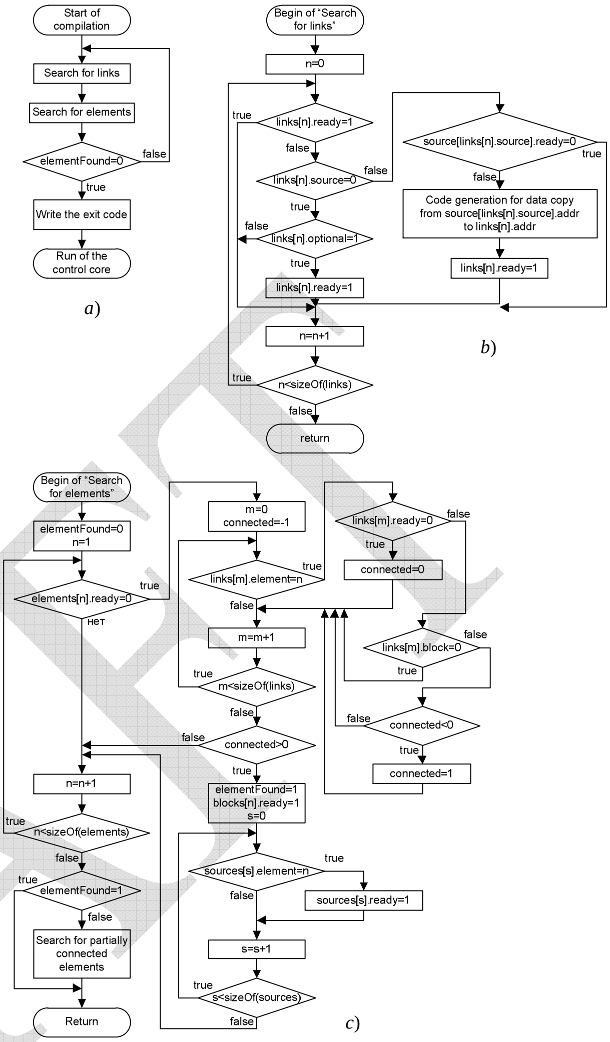

Fig. 3. Algorithm of the control core compiler

Listing 1. Example of the control core code for structure from Fig. 2

```
prog:
        ldp     #main_ai1
        bldd    main_ai1, #PIcontroller1_max
        ldp     #main_ai1
        bldd    main_ai1, #gain1_in
        ldp     #main_ai2
        bldd    main_ai2, #gain3_in
        ldp     #main_speed
        bldd    main_speed, #PIcontroller1_Fdb
        ldp     #main_iA
        bldd    main_iA, #PIcontroller2_Fdb
        ldp     #variable1
        bldd    variable1, #adder1_in1
        call    gain1
        call    gain3
        ldp     #gain1_out
        bldd    gain1_out, #PIcontroller1_min
        ldp     #gain3_out
        bldd    gain3_out, #gain2_in
        ldp     #gain3_out
        bldd    gain3_out, #mux_in1
        call    gain2
…
        b       returnToT1Int
```

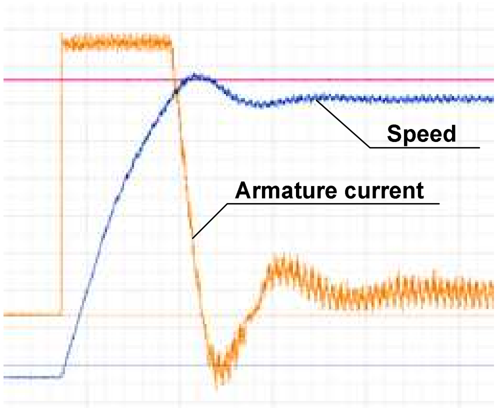

Fig. 4. The example of the operation of the control structure from Fig. 2

V. CONCLUSIONS

The described configurable control system was implemented on TMS320LF2406A microcontroller and now is used in the educational laboratory of the Electric Drive Department of National Research University “Moscow Power Engineering Institute”. This approach was highly appreciated by the students and lectures. The similar system was designed for induction machine so it is now possible to test flux-vector control and direct torque control using the same power converter. It is used in the course of Motor Control Systems for 4 years and showed its benefits. This approach can be implemented on different types of power converters and microcontrollers.

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