Energy Flow Control System with Robot-Accumulator Interfacing Module

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Abstract—This paper is meant to give general explanation of one type of energy recuperation circuits and deeper explanation of its EFCM (energy flow control module). The stresses are put on features which are offered by EFCM, starting from functional and ending with safety and user interface functions. Descriptions of basic algorithms are included.

I. INTRODUCTION

Electrical energy consumption is starting to worry people more and more since prices of it are rising and amount of consumers is also increasing every year. Different energy saving activities is carried out in many levels of economical and geographical organizations. EU has made set of targets that it wants to reach, for example, 20% of energy efficiency by 2020 [1]. So this global target makes all high energy consumers in EU countries to think about energy saving procedures. Automobile manufacturers are companies which consumes lots of energy every day. All actions that are included in car’s production chain starting from different welding, handling, gluing, painting and others sums up in great energy consumption [5]. Local research groups has been analysing energy saving possibilities and found out that great energy savings can be achieved if energy recuperation would be introduced in factory [6].

Energy recuperation system should stop energy dissipation through braking resistances in DC buses of industrial robots and save it in some energy storage, from which the energy could be acquired back later [7]. All recuperation circuit consists of power part and control part. The main task of control part is to allow recuperated energy exchange between industrial robots and energy saving modules as well it should guarantee system safety under any conditions. This paper concentrates on control part which is called EFCM (energy flow control module) development for one type of energy recuperation system, which is categorized as non-isolated energy recuperation system. The task of EFCM is to guarantee safe and reliable only recuperated energy exchange and have easy understandable user interface which includes monitoring possibility of different parameters in all energy saving system.

Current version of EFCM is built to work with connected 2 KUKA (Keller und Knappich Augsburg) industrial robots and one EA (energy accumulator). But very simple adaption of 16 industrial robots can be done by simply changing only one module of EFCM.

For huge factories the target would be to connect as many industrial robots or theoretically any kind of electrical energy consumer devices as possible to one EA. Than EFCM will have different, more complex and distributed topology.

II. GENERAL DESCRIPTION OF SYSTEMS WHICH ENABLE ENERGY RECUPERATION

Industrial robots consist of manipulator, typically with 6 motors, and controller, which contains all necessary elements to implement manipulator powering and control mechanism. This project is more related to KUKA industrial robots and their controllers have internal DC bus line which is used to power motors of manipulator [2]. When motors are accelerating they are taking energy from DC bus, when they are braking energy is put back to the DC bus. During acceleration process voltage in DC bus decreases and during braking process voltage in it rises. When it reaches 688 V, braking resistances are connected in parallel with DC bus in order to dissipate braking energy [7].

Non-isolated energy recuperation system is system which includes few KUKA industrial robots (or similar devices) and one energy accumulator. Connection to industrial robots is done directly at their 550 V (when robot is not moving) DC buses. In between of these connections and accumulator RAIMs (robot-accumulator interfacing module) are put which together with EFCM (energy flow control module) control energy flow between robots and energy saving accumulators [7].

Isolated systems would differ from none isolated ones, with some transformers that would transfer energy to energy accumulator and back by the help of electromagnetic field.

Systems that benefits from energy recuperation can have topologies like ring and star, because of that their control mechanisms are different. Current EFCM is being designed for star topology system. Fig. 1 shows schematically system that is enabled to reuse recuperated energy. There RCI to Rn indicates industrial robots and uniformly dashed lines show communication connections with robots and RAIMs. Line with more dashes is currently using Profinet IO communications protocol and because of that GUI can be implemented as local or distanced, PC or any other Ethernet based module (Fig. 1 shows local GUI). Less dashed connections are used for switch switching in RAIMs, voltage monitoring on DC bus lines and on central EA.

The target of current energy saving system is to avoid energy dissipation through braking resistances. It is achieved by connecting energy accumulator instead of braking resistance to the DC bus during braking process. When any of robots which are connected to the system wants to accelerate energy which is saved in accumulator is available to them [7].
III. ALGORITHM OF EFCM

EFCM has few basic tasks which have to be executed:

1) Switching IGBTs and Relays of RAIMs.
2) Monitoring voltage at energy accumulator connection and each of robot DC bus connections.
3) Communication with industrial robots and acquiring information of their state.
4) Having user interface to indicate state of system.

To handle these tasks centralized MCU control mechanism was chosen. MCU was chosen from company Microchip with part number PIC24EP512GU810. The main algorithm is planned to have 4 parallel processes as stated before. Their execution during testing phase will be compared in two different manners. One of which is similar to Round-robin scheduling algorithm [8]. Which means that each process will have his time slice in one time period which will be allocated to execution of all processes (Fig. 2). The other algorithm will be simple interrupt driven MCU operation. It is expected to have more predictable MCU behaviour in first case but simpler algorithm in second case.

When Round-robin similar algorithm will be used, time period to execute parts of all 4 processes is not expected to be greater than 1000 μs, because energy flow changes in one DC bus are not expected to happen faster than with 1 kHz frequency. Time slice switching is going to be achieved by dedicated built in MCU timer interrupts every 200 microseconds. Which means that if, for example, MCU instruction cycle frequency is going to be 4 MHz, than each time slice will be capable of executing 200μs × 4M=800 instructions which should be enough for most of processes. If more time will be needed for any of processes, there are 2 ways how their execution can be enabled:

- Increasing MCU working frequency;
- Increasing time slice size of larger processes and reducing time slice size for smaller processes.

When simple interrupt driven MCU operation will be tested, then main program will execute any IGBT or relay switching when interrupts will have been received from DMA channels which will be allocated to ADC or UART modules of MCU.

Sub algorithms:

1) Monitoring voltage at energy accumulator and connection of each robot DC bus. Voltage monitoring is done by the help of 2 ADC converters of MCU. One is used to scan up to 16 analog inputs with 10 bit precision and the other is used to scan voltage on the central energy accumulator with 12 bit precision. Each of ADC modules are powered together with DMA (Direct Memory Access) modules, which enables interrupt generation only after all 16 DC bus analogue voltage values are transformed to digital values [9].

2) Communication with industrial robots and acquiring information of their state. Communication with industrial robot is done by the help of special module which handles Profinet IO communication protocol (Fig 3). But special communication has to be implemented between MCU and Profinet IO communication module. Developers of module have written special drivers to make easier communication with it. Driver has special requirements for MCU memory resources and RAM [3]. Communication from MCU side is also implemented with intermediation of DMA module [9]. Industrial communications interface has also built in WEB server which gives an ability to implement Ethernet based GUI, which enables for example PC or laptop screen to use as user output or input.

3) Switching IGBTs and relays of RAIMs. RAIMs consists of IGBTs which enable high frequency energy flow control and from relays which enable slower energy flow control, that is usually used during robot first connection to accumulator and it's last disconnection from it. Relays also ensure physical isolation of robot in case of
emergency states in system. IGBTs and relays are switched by EFCM. Switch switching is based on information gathered from sensor readings and communication module. There are 3 special cases and conditions which should be separated when switching principles are discussed. All 3 states in future EFCMs are expected to work in parallel in order to enable flexible robot connection and disconnection to the energy saving circuit:

a) System start-up  
b) Normal-working state  
c) System shutdown

**Start-up** is special because central energy saving accumulator has highly capacitive nature and does not have built in current limiting circuit during phase when energy is flowing towards it. This means that direct connection to fully charged DC bus would result in accumulator damage. To avoid damage during first connection accumulator should be charged to fully charged DC bus voltage level. First accumulator charging can be done by connecting it to an industrial robot which is in off state and then turning robot on. During charge of its DC bus it charges also accumulator. And charging current is limited by internal circuit of industrial robot. This fact means that during start-up state all robots (except the one which is charging accumulator) should be disconnected from accumulator physically. Rest of the robots who are meant to work in energy saving system should be connected physically to energy saving circuit only after their DC bus had been fully charged. Now system is ready to switch to normal-working state.

**Normal-working** state is the one in which system should be able to work most of the time. In this state principle that robots can exchange only with recuperated energy should be followed. This is achieved by energy flow towards any of robots when voltage in accumulator is higher or equal to the fully charged DC bus voltage. If there is set only one voltage limit which is compared to the actual voltage across accumulators than IGBT switching could be very often in case many robots would be connected to the accumulator. To enable IGBT switching frequency change two voltage limits will be considered in testing circuit and sensor-switch system will operate by hysteresis principle. If voltage across accumulator is greater than higher limit, than energy flow towards any of robots is allowed. If decreases under lower limit, energy flow towards robots is cancelled. In this state only energy flow towards accumulators is allowed.

Shut down of any robot can be executed any time without stopping robot system. In case of robot shut down, energy flow to it should be stopped (opening IGBT) and also physical disconnection from accumulator should be done. Rest of the system can continue to work without any disturbances. When all robots are disconnected from RAIMs than energy saving accumulator can be discharged through resistances (built in the energy accumulator).

4) **User interface to indicate state of system.** EFCM will have 2 types of user interfaces. One is simple LCD display (2 rows and 16 columns) in combination with 3 pushbuttons. LCD will show amount of connected robots and their status, voltage level in DC bus of each robot and it will have an ability to set earlier mentioned voltage reference values. However, this interface will back up only the main GUI and will assist in system start-up and will be useable even if no industrial Ethernet connection will be present.

The main GUI is supported by industrial communications module, which enables any Ethernet device to serve as GUI. There will be shown all important system variables that need to be monitored during testing phase. These variables include energy transfer of different industrial robots and EM, real time voltage changes at DC bus connections, switch states and other information which is needed for system diagnostics. Manual switch switching and safe system start-up control will also be enabled from this GUI [4].

User interface also includes RS-232 connection which can be used for UART communication diagnostics between MCU and industrial communications module.

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**Fig. 4. Block diagram of normal-working state.**

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**IV. CURRENT VERSION OF EFCM AND PLANNED TESTS**

Current version of EMC is planned to work with 2 robots. Its main task is to test circuit design in the field where real industrial environment is present. EFCM is modular circuit, which has 3 parts:

a. **Input module.** It has terminals for 2 DC bus voltage inputs and 1 terminal for accumulator input. The last
one is connected to 2 types of sensors to enable comparison of their outputs. One sensor type is Hall Effect sensor and another is optocoupler based sensor. The same voltage signal will be measured with both of the sensors and their response will be compared in different frequencies. During testing phase also low pass input filter values for sensor inputs should be found. In the next development phase this module can be exchanged with module that supports 17 DC bus input terminals to enable tests with 16 robots and one energy accumulator.

b. **MCU and user interface module.** This module continues user interface and MCU, with all necessary connections, like programming interface, reference voltage and others. It has built in RS-232 interface for debugging purposes. On the MCU and user interface module, will be compared simple interrupt driven algorithm with Round-robin like scheduling algorithm, tested their energy consumption, efficiency and safety for energy saving process control.

c. **Output and Communications module.** This module includes connections related to Communications module and outputs which are used to drive IGBT drivers that are located in RAIM. This module together with IGBTs in RAIM will be checked for response times and IGBT switching process control quality. This module is very important for safety requirements, because it can receive error signals from industrial robot system or any other device from industrial network.

V. **CONCLUSIONS**

Although EFCM design plan is ready, real module is still under construction. Things that are described in this paper have already been tested on the breadboard separately, so full functionality tests are still to be executed. Also Ethernet based GUI functionality has not been fully tested yet.

Despite of these drawbacks, expectations of possible energy savings reaches 20% from current energy consumption depending on industrial robot programs which will be activated during testing phase [7]. And process of saving energy will be safe and well monitored, which will enable further experiments and energy saving circuit analysis and development.

**REFERENCES**


