Utilization of Regeneration Energy in Industrial Robots System

Ivars Rankis[1], Davis Meike[2], Armands Senfelds[3], [1-3]*Riga Technical University*

Abstract. **This paper is devoted to the investigation of shared DC Bus systems with common storage capacitor operating on utilization of regeneration energy of electrical drives of industrial robots. The system is elaborated for the connection of the central energy storage capacitor with DC Buses of several robot systems. Simulation of operation of such system has been made with the target to obtain some specific indicators of efficiency of the system at different number of shared DC Buses. Dimensioning of system's parameters as well as some conclusions about necessary principle of control are presented. The results of experimental investigation are presented with the evident operational efficiency of the proposed system.**

Keywords: **robots, supply, capacitor, motors, charge, regeneration, transistor, coil**

I. Introduction

Industrial applications today often require rapid motion control where many fast acceleration/deceleration phases and reversals are presented. Such behavior is typical for industrial robotics and other computerized numerical control machinery [1]. Many existing drive systems today are capable of using regenerative braking of the motors.

However, the recuperative energy is rarely fed back to a network or stored in full extent locally due to AC-DC rectifiers fed supply of frequency converters or increased costs of the storage systems. Previous research shows impressive energy savings potencial using an increased capacitive energy buffer on a drive's DC bus [1].

Common DC link applications using a single rectifier and multiple variable frequency drives have been state of the art for many years. Multiple rectifiers and multiple drives that share the DC links are available from some manufacturers [2]. Some examples are known from wind power turbines [3] and active power filters [4].

Analytical research of shared/common DC bus operation can also be found in [5]. However, in all these cases, synchronized control of the drive switches is required so that these DC links are equalized. In fact, there is actually one synchronized DC bus that is supplied by more than one parallel rectifier. This paper proposes a solution for a recuperative energy exchange approach between drive systems that are controlled independently. The energy is stored in an independent DC subgrid, to which any drive system can ***transfer*** its recuperative excess energy and ***take it back again*** when needed.

An application case in industrial robotics with a shared/common DC bus has been patented recently by the vehicle manufacturer Daimler AG [6].

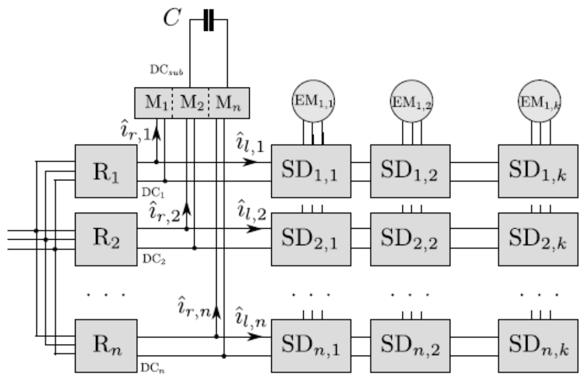

Fig.1. Block diagram of DC subgrid for energy exchange.

Another system for robots' DC subgrid for energy exchange is proposed in [5], where each DC Bus is connected through power converter with adjacent DC Buses of robots. Therefore at regeneration extra power is submitted to the DC Bus of adjacent robots. Such solution utilizes in full extent the capacitors of all DC Buses but the problems may arise when a simulatenous regeneration takes part in different robot drives (then regenerate energy should not be accumulated in capacitors because of lack of their necessary volumes).

II. Energy Exchange within Shared Dc Bus

In the following section, the advantages and main aspects of DC bus sharing principle accepted are discussed. The block diagram is shown in Fig. 1. Here, n drive systems are represented, where each has a DC bus $DC_1 \ldots DC_n$ supplying servo drives $SD_{1,k}$, $SD_{n,k}$ with frequency converters which control the electrical machines $EM_{i,;j}$. Each bus DC_i is connected through power converter modules $M_{1\ldots n}$ to a subgrid DC_{sub}. The central capacitor C determines the size of the buffer. The rectified voltage in the idle circuit of DC bus has a fixed value of

$$U_{dc;idle} = 1.35 U_{rms} \approx 540V \quad (1)$$

with a DC-bus voltage ripple of

$$U_r = \frac{U_{rms}\sqrt{2}}{12 f . R_{dc} . C_{DC,i}} , \quad (2)$$

where $C_{DC,i}$ is the internal capacitance of the DC bus and R_{dc} is the DC bus load. According to (2), short peak loads of about 25kW measured on DC bus [1] can push a voltage as low as

510V. The upper bound of U_{DC} is limited by drive hardware using a brake chopper operating on dissipation resistor. For various drive systems typically the brake chopper is set anywhere within the range of 690 to 790V.

The proposed DC bus sharing principle allows a relatively large voltage difference between connected DC buses and does not require synchronization of the involved drives. In fact, an independent $[n+1]th$ DC bus as a DC subgrid is created to be used as an energy exchange buffer.

The electrical charge transmitted to the central capacitor C from n drive systems within the time t_t can be calculated assuming that shape of the average current transmitted from each drive system i is triangular with magnitude $\hat{i}_{r;i}$ and duration $t_{r;i}S_{r;i}$ (see Fig. 2), where $t_{r;i}$ and $S_{r;i}$ are respectively the average duty cycle and duty ratio of all recuperation phases respectively. The duty ratio can be expressed as $S_{r,i}=t_{r,i}/T_i$, where T_i is the process cycle for operation of robot number i.

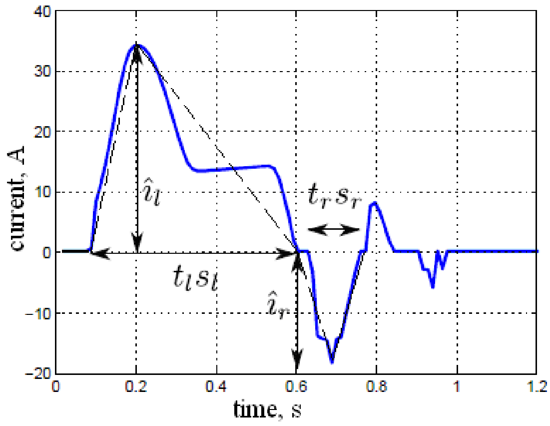

Fig.2. Presentation of current shape at DC input of robot drives.

For energy calculations, the internal capacitance of each DC bus is assumed negligible and that it does not influence the process efficiency. Then the total charge of recuperation is

$$\Delta Q_r = 0.5 t_t \sum_{i=1}^{n} \hat{i}_{r,i} S_{r,i} \quad . \qquad (3)$$

As the average voltage U_C over the evaluation interval t_t is constant, the recuperated energy transferred to C equals the energy received. The motor consumption is the sum of the energy from the AC network and the DC subgrid DC_{sub}. The charge consumed by a motor load can also be calculated, assuming that the load current has a triangular shape with a magnitude $\hat{i}_{l;i}$ and duration $t_{l;i}S_{l;i}$, where $t_{l;i}$ and $S_{l;i}$ are the average duty cycle and duty ratio of all load supply phases respectively. Then, the total charge consumed by all n drive systems is

$$\Delta Q_l = 0.5 t_t \sum_{i=1}^{n} \hat{i}_{l,i} . S_{l,i} \quad . \qquad (4)$$

Typically, $S_{l;i} > S_{r;i}$ and $\hat{i}_{l;i} > \hat{i}_{r;i}$ for each of the examined examples in robot controller drive systems. Depending on the application, cycles t_r and t_l as well as magnitudes of currents may differ. The savings can be estimated in terms of the recuperated charge compared to the consumed charge because the positive (consumed) mechanical power does not depend on the existence of energy-saving device:

$$E_f = \frac{\Delta Q_r}{\Delta Q_l} = \sum_{i=1}^{n} \frac{\hat{i}_{r,i} . S_{r,i}}{\hat{i}_{l,i} . S_{l,i}} \quad . \qquad (5)$$

By adopting different relations $\hat{\boldsymbol{i}}_{r;i}/\hat{\boldsymbol{i}}_{l;i}$ and $S_{r;i}/S_{l;i}$ it is possible to find the savings from the diagram presented in Fig. 3. A smaller duty relation $S_{r;i}/S_{l;i}$ usually results in a smaller recuperation/load current relation $\hat{\boldsymbol{i}}_{r;i}/\hat{\boldsymbol{i}}_{l;i}$ and thus, smaller possible savings. However, even at light loads, the energy to be stored may reach 10% of the consumed energy. If the application is more dynamic the proportion of the recuperated current compared to the supply current is higher, and there is a higher duty ratio proportion in both operation cases, the charge to store rises too. For instance, at a duty ratio relationship of 0.5 the duration of the recuperation interval is half of the charging duration and a current magnitude relationship of 0.7 (magnitude of recuperated current is 70% of that of load), it is possible to save as much as 35% of the energy required for the particular movement phase.

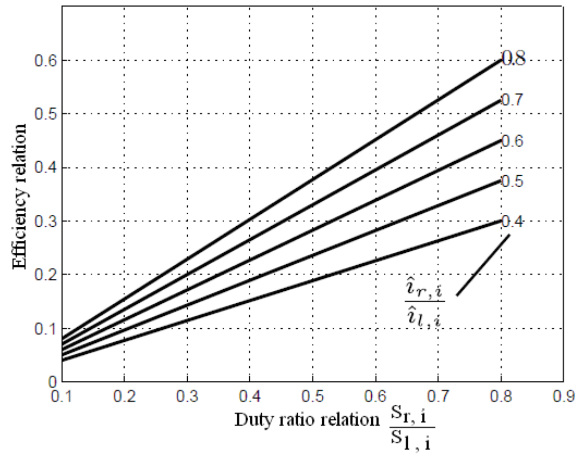

Fig. 3. Estimation of energy savings as a function of the duty ratio and recuperation and loading current magnitude relation.

III. The Proposed Circuit

Fig. 4 shows a connection principle of two power transducer modules M_i and M_{i+1}.

Each of the power modules has 4 power terminals a_i, b_i, c_i and d_i. Terminals a_i and b_i (Fig.4) are to be connected accordingly to the positive and negative terminals of a particular DC bus DC_i. Terminals c_i and d_i of each module are to be connected to the c_{i+1} and d_{i+1} terminals of the other module, noting here that the terminals $d_{1:::n}$ are the common ground of all modules $M_{1:::n}$ and DC buses $DC_{1:::n}$. Note that this is not an earth ground of AC supply system.

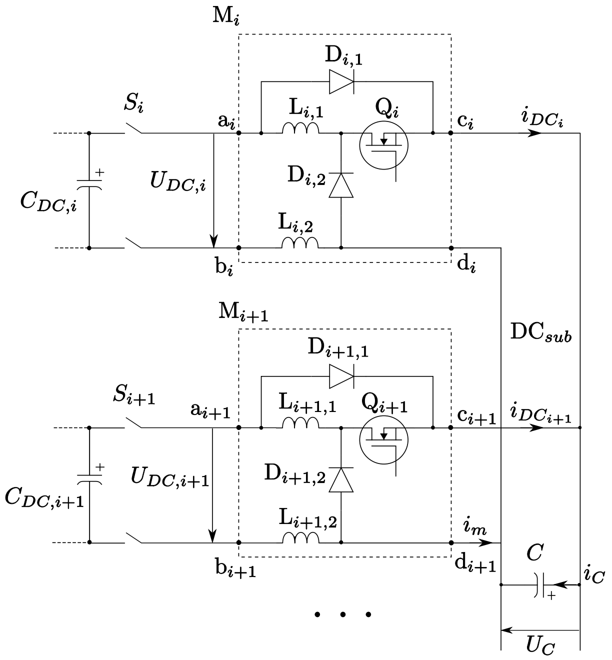

Fig.4. Electrical scheme of connections between sub-buses and the central capacitor.

A central capacitor C is connected between all terminals $c_{1:::n}$ and $d_{1:::n}$ and used as a temporary energy storage device.

The voltage fluctuations of U_{DCi} from the viewpoint of the module M_i can be described as stochastic. Whenever the voltage $U_{DC;i}$ is slightly higher than U_C, the current flows through the power diode $D_{i;1}$ charging the central capacitor C. Switch Q_i blocks the current flow in the opposite direction. Whenever the voltage $U_{DC;i}$ drops below U_C the diode $D_{i;1}$ is reverse biased and the control of current flow from point c_i to a_i is taken over by the switch Q_i. The inductance $L_{i;1}$ and $L_{i,2}$ limit the maximum current stresses. The diode $D_{i;2}$ has a function to eliminate the effects of arc discharge and overvoltage spikes.

In difference from electrical scheme presented in [7] there are 2 coils in each module. Such solution is accepted for supression of circulating currents in common ground wires between supply rectifiers' anode groups diodes (thyristors). By the way the accepted solution allows increase the reliability of switches operation.

IV. Component Dimensioning

The total charging current if all the modules are recuperating must be noted:

$$i_C = i_{DC;1} + i_{DC;2} + : : : + i_{DC;n} \qquad (6)$$

that has to be lower than the maximum charging current of the buffer capacitor

$$i_C \le C\left(\frac{du}{dt}\right)_{\max} \quad . \qquad (7)$$

The capacitor bank is dimensioned accordingly. If the recuperation current is assumed to have a triangular shape with a decreasing slope, i.e., the current is described as $\hat{i}_{r;i}(1\text{-}t/t_{r;i})$ noting that any selected time frame $t \ll t_{r;i}$, then the capacitor voltage change is

$$u_C = \frac{ng}{C}\int \hat{i}_{r,i}\left(1-\frac{t}{t_{r,i}}\right)dt \quad , \qquad (8)$$

which leads to

$$u_C = t_{r,i}\frac{ng\hat{i}_{r,i}}{2C} + U_{dc,idle} \quad , \qquad (9)$$

where g is a coefficient of coincidence of recuperation processes for n drive systems, but $U_{dc;idle}$ is as in Eq.(1). If $n = 1$ then $g = 1$, as n increases, g decreases. Approximately based on experience it can be assumed that

$$g = 1/\sqrt[3]{n^2} \quad . \qquad (10)$$

Taking such a value into account, the maximum permitted value of capacitor voltage $U_{C;max}$ can be reached if capacitance C is

$$C = \frac{\sqrt[3]{n^2}\,\hat{i}_{r,i}.t_{r,i}}{2\left(U_{C,\max} - U_{C,idle}\right)} \quad . \qquad (11)$$

For instance, $\hat{i}_{r;i}$ = 20A, $t_{r;i}$ = 0.3s , $U_{C;max}$ = 670V, $U_{C;idle}$ = 560V, then

- for $n = 4 \longrightarrow C = 43.3$ mF,
- for $n = 3 \longrightarrow C = 39.3$ mF,
- for $n = 2 \longrightarrow C = 34.3$ mF,
- for $n = 1 \longrightarrow C = 27.3$ mF.

V. Control Strategy

There are three different operational modes of the device as summarized in Table 1.

Table 1. Various working modes

	Energy flow	$D_{i,1}$ bias	Q_i bias	Q_i state	Voltages
1	From DC_i to DC_{sub}	forward	reverse	any	$U_{DC_i} > U_C$
2	From DC_{sub} to DC_i	reverse	forward	ON	$U_{DC_i} < U_C \ge U_{ref}$
3	None	reverse	forward	OFF	$U_{DC_i} \le U_C \le U_{ref}$

1. The energy is flowing from any module M_i to the subgrid DC_{sub} and is controlled passively.

2. The energy flow from DC_{sub} is controlled with switch Q_i and the current is limited by L_i. Here, a variable U_{ref} is introduced - a minimum voltage that has to be sustained on the DC subgrid. The state of Q_i is *fully on* if U_C is higher than U_{ref} and *fully off* if it falls below U_{ref} . Setting U_{ref} to above $U_{dc;idle}$ means that C never discharges below the voltage of idle DC bus. The charging, as mentioned, is possible only if $U_{DC;i} > U_C$. Thus, it is assured that only the recuperative excess energy is being exchanged in DC_{sub}.

3. An idle state is possible when no energy is being exchanged. This is the case when U_C drops below U_{ref} . All the switches Qi equally depend on UC, thus in normal operation their states are changed simultaneously. (For functional and safety purposes, any of the modules may also be disconnected separately. This, as well as the initial charging of C, however, is not discussed here). In practice, the reference voltage $Uref$ is implemented with a hysteresis and is set in the range

$$U_{ref} = \left[U_{off}\,; U_{on}\right] \quad . \qquad (12)$$

VI. Experimental Validation

Many short acceleration/deceleration phases are typically present but not limited to industrial robotics. Therefore, the application tests are made on industrial robot manipulators with permanent-magnet synchronous servo motors and their drive systems with three-phase full-bridge diode-rectifiers. High-payload robots *RB*1 and *RB*2 of type KUKA KR200-KRC2 have been selected to execute various applications. Their drive DC links have been shared according to the power circuit in Fig. 4 using a central capacitor of size C = 45mF.

Various U_{ref} modes have been tested. Figs. 5 and 6 show the crucial difference between low and high U_{off}. Positive current represents the energy flow towards *DCsub*. Fig. 5 illustrates the case when *off* voltage is low (520 V) and switches Q_i are permanently *on*. Here, the robot *RB*1 is accelerating while *RB*2 is in standstill. *RB*1 causes a temporary voltage drop on its DC bus that is partly compensated by current flow from DC_{sub} and a preceding voltage drop on U_C. Since the both Q_1 and Q_2 are *on*, the voltage drop on C is passively compensated by *RB*2 with a positive current flow I_{DC2} over the diode $D_{2;1}$.

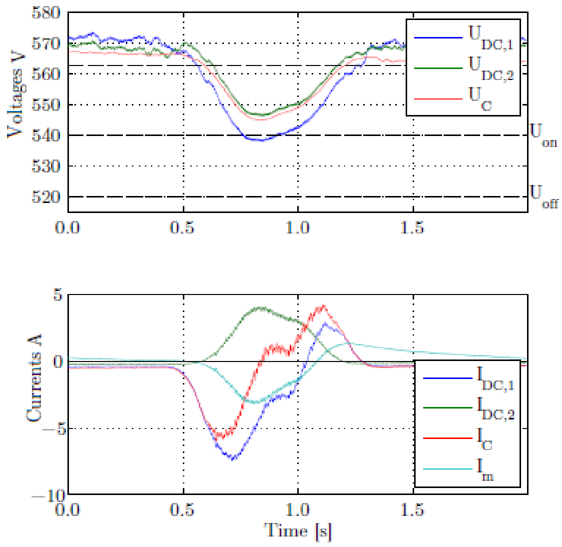

Fig. 5. Working modes with U_{on} = 540V, U_{off} = 520V.

The effect when a drive system supplies power to a DC link that does not have a load in its own system, is undesirable and can cause certain control errors. To eliminate this effect the criterion

$$U_{off} > U_{dc;idle} \tag{13}$$

must be satisfied. The operating mode of U_{ref} =[560; 600] is shown in Fig. 6. Various processes are to be recognized here:

_ t = 0:2s recuperation of *RB*1,
_ t = 0:8s power requirement of *RB*1,
_ t = 1:5s recuperation of *RB*1,
_ t = 1:7s recuperation of *RB*2,
_ t = 2:6s power requirement of *RB*2,
_ t = 2:8s recuperation of *RB*2,
_ t = 4:3s recuperation of *RB*1.

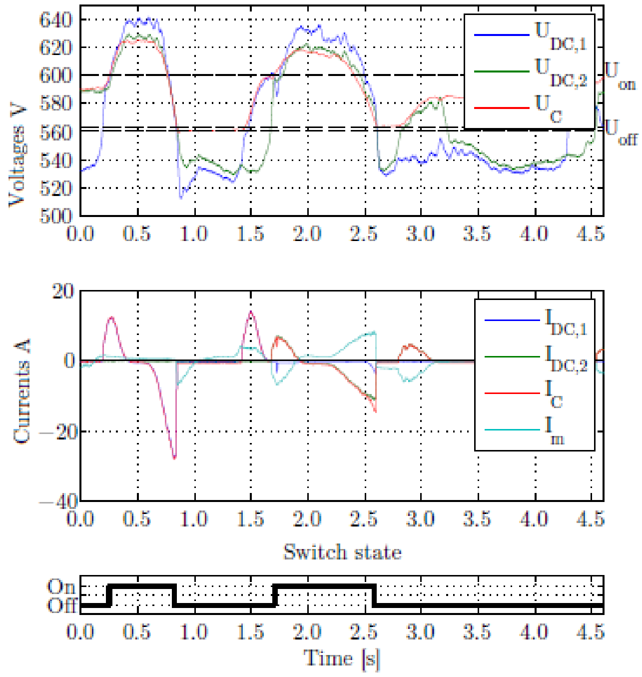

Fig. 6. Working modes with U_{on}= 600V, U_{off} = 560V.

The current flow of the positive terminal is cut whenever $U_C < U_{off}$. Since at experiments the negative terminals were directly connected, an equalizing circular current I_m is present at the negative terminal and

$$I_{m;i+1} > 0; \text{ if } U_{DCi+1} > U_{DCi} . \tag{14}$$

Value of Im at common negative wire depends on the difference of resistances of the lower half-bridge of drive rectifiers. In the experiments, a minimum circular current $I_{m;min}$ has been determined when *RB*1 is in idle mode but *RB*2 is in operation.

Energy consumption of industrial robots highly depends on many parameters such as load, application type, acceleration profiles, etc. [7]. The estimated savings of the DC bus sharing approximately equal the otherwise wasted energy at the brake chopper. Since movements of all robot manipulators are not synchronized, consumption also depends on how much the supply-requirement and regenerative phases overlay as described by coincidence factor $\boldsymbol{g}$ in (10).

Table 2. Energy measurements of robotic applications

Application type	DC bus sharing	Consumption [kVh]	Difference [%]
Welding	none	3.66	-
Welding	√	3.45	-5.6%
Handling	none	6.44	-
Handling	√	5.11	-20.6%

Table 2 summarizes the energy requirement for 1 hour operation of two KUKA KR200-KRC2 robots with a load of approximately 30 kg running two types of programs, in each case with and without DC bus sharing. During the whole measurement, none of the DC links reached the brake chopper threshold voltage. The reference voltage was set to $Uref$ = [560; 600]. Previous experiments have shown the energy-saving potential of using capacitive energy buffers per industrial robot drive system [1]; the proposed DC bus sharing enables the same potential to be reached using just one buffer within a DC subgrid.

For more estmations a computer simulation of robot system operating with common energy storage capacitor and individual bus of robot connection through the scheme of intermediate module according to Fig.4 has been made. Five robot supply rectifiers with common for them AC network have been applied operating with different frequency f_1=0.5 Hz for robot N1; f_2=0.7 Hz for N2; f_3=0.6Hz for N3; f_4=1Hz for N4 and f_5=0.6Hz for robot N5. Respectively duty ratios of loading with averaged current 28 A for each robot were 0.278; 0.305; 0.278; 0.333; 0.278. Averaged meaning of regenerated current was 20 A for each of robots. Simulation process lasts for time interval of 20 s operation in two different situations – without the central capacitor of 45 mF and with central capacitor applying connection modules switches of which have been operated at U_{off}=540 V and U_{on}=550 V.

In table 3 the results of simulation are summarized for operation of all 5 robots and for operation in 3 another cases when each later robot was not activated, i.e. for 4, 3 and 2 robots operation cases.

TABLE 3
VOLUMES OF CONSUMED FROM SUPPLY ENERGY (kJ)

case	Rob.1	Rob.2	Rob.3	Rob.4	Rob.5
without	89.33	99.0	89.2	107.2	89.2
with C	56.9	55.0	66.0	66.4	66.1
With C	59.34	58.5	54.74	73.37	
With C	63.38	60.12	61.17		
With C	69.26	64.5			

As it can be seen without energy storage system total consumption of energy by 5 robots is 473.93 kJ; consumed energy with storage device is 310.4 kJ, i.e. 34.5% of energy is saved. Calculated by (5) saving amount is 30.3%.

In case of operation of 4 robots saving level is 36%; for 3 robot case saving level is 33.5%; for 2 robot case – saving level is 29%. Calculations show very close results.

VII. Prospective Scheme of Converter Module

Presented previous scheme anticipates common connection of DC busses through non-insulating modules to the central storage capacitor. Such solution has certain drawback of introducing extra electrical alignment contours. Better way should be in connection of individual busses with storage central capacitor through their modules with insulating transformers (Fig.7). Primary winding of transformer has to be connected with individual bus through switching converter SC1, but secondary – to the central capacitor through switching converter SC2 of the module. Therefore at regeneration at the bus its converter SC1 will be activated at 180^0 conductivity of its switches but SC2 operates as a rectifier through its diodes. At loading of the bus its module converter SC2 is activated at 180^0 conductivity of its switches but SC1 works as BOOST element with reduced duty ratio of its switches providing reverse flow of power from the storage capacitor to the loaded bus [8].

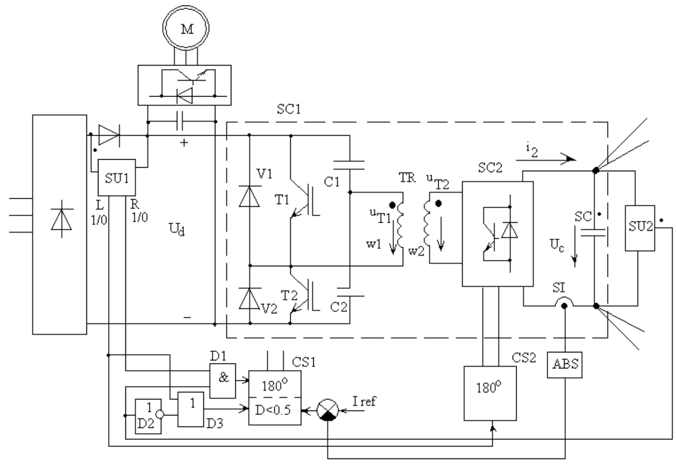

Fig.7. Scheme of the bidirectional power flow module with insulating transformer between DC bus and storage capacitor.

Control of the system can be provided using measurement diode in DC bus circuit with digital sensor SU1 (Fig.7). When regeneration takes place the diode is reverse biased and output R of the sensor is at its high logical level activating through D1 converter SC1 operate with 180^0 conductivity. Output L is at its zero level and switches of converter CS2 are stopped. Transfer of regenerated energy to the storage capacitor takes place. When motors unit of the DC bus is activated through measurement diode current is passing and digital signal exist on SU1 output L; this signal activates converter SC2 on 180^o conductivity of its switches and provides decreasing of duty ratio for switches of SC1, with control of process with current limitation.

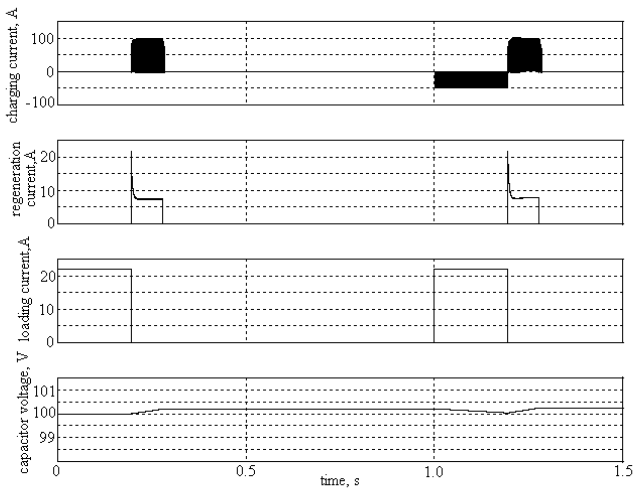

Fig.8. Simulated diagrams of currents and voltage of storage capacitor of 100μF.

Fig.8 presents the diagrams of currents and storage capacitor voltage obtained in way of computer simulation experiments. In very first loading cycle voltage of capacitor is at its lowest threshold level and output of the sensor SU2 is at zero level disallow discharging of the capacitor.

CONCLUSIONS

1. Regeneration energy of several robot system can be efficiently utilized using one central storage capacitor of sufficient high its capacity.
2. For proper operation of the system each robot's DC bus has to be connected with the storage capacitor through bidirectional power flow converter module.
3. The converter module can be realized with electrically non-insulated connections with other converters as well as with insulated by transformers circuits.
4. The experimental results with industrial robots show energy savings of up to 20% for each system.
5. Computer simulation of robot system with number of involved robots up to 5 shows that it does not depend on the number of robots an operating saving effect can reach up to 30%.
6. Further work includes DC subgrid extension with optional super-capacitor based storage system and electrically mutually insulated DC buses of robots.

REFERENCES

[1] D. Meike, L. Ribickis, *Recuperated energy savings potential and approaches in industrial robotics, IEEE 15th Int. Conf. on Automation Science and Engineering,* 2011, pp. 299–303.
[2] Allen-Bradley, *PowerFlex AC Drives in Common Bus Configurations, Rockwell Automation,* 2011.
[3] L. Meng, W. Yong, *Research on the parallel technique for the direct-drive wind power converter, Electrical Machines and Systems (ICEMS),* 2011 International Conference, 2011, pp. 1 – 4.
[4] P. N. Enjeti Lucian Asiminoaei, E. Aeloiza, F. Blaabjerg, *Shunt active-power-filter topology based on parallel interleaved inverters, IEEE Transactions On Industrial Electronics,* 2008.
[5] A.H. Wijenayake, T. Gilmore, R. Lukaszewski, D. Anderson, G. Waltersdorf, *Modeling and analysis of shared/common dc bus operation of ac drives, Industry Applications Conference, Thirty-Second IAS Annual Meeting, IAS '97., Conference Record of the 1997 IEEE,* Oct. 1997, vol. 1, pp. 599 – 604.
[6] M. Lebrecht, T. Schneider, *Robotersystem, patent P817837, Deutsches Patent- und Markenamt,* 2010.
[7] D. Meike, I. Rankis, *New Type of Power Converter for Common-Ground DC Bus Sharing to Increase the Energy Efficiency in Drive Systems. 2nd IEEE ENERGYCON, Advance in Energy Conversion Symp.,* 2012, pp.263-268
[8] I. Rankis, J. Zakis, *Investigation of Supercapacitor Bidirectional Power Flow System, Pow. And El. Engin.,*vol..30, Riga:RTU, 2012, pp.35-40

Ivars Rankis, professor, Hab.Dr.sc.eng. He graduated from Riga Polytechnic institute in 1960 as an engineer electromechanician. He defended his first degree of Dr.sc. (candidate of technical sciences) in 1970. Defended his second degree Hab.Dr.sc.eng. in 1992 at Riga Technical university. From 1958-1966 he worked as an engineer at Riga Electrical machine building company. From 1966 he started studies as a doctoral student, but from 1970 – as a lecturer of different subjects in electrical engineering at Riga Technical University. Research interests are connected with Power electronics and Industrial automation. Now he is a professor at the department of Industrial electronics and electrical technologies of Riga Technical University. Riga Technical University, Institute of Industrial Electronics and Electrical Engineering

Address: Kronvalda 1, LV1048,Riga. Phone +371 67 089 917, rankis@eef.rtu.lv

Dāvis Meike, M.sc.eng., doctoral student. He graduated Riga Technical university in 2009 . Address: Kronvalda 1, LV1048,Riga. Phone +371 67 089 917

Armands Senfelds, M.sc.eng., doctoral student. He graduated Riga Technical university in 2010. Address: Kronvalda 1, LV1048,Riga. Phone +371 67 089 917, armands.senfelds@rtu.lv

Ivars Raņķis, Dāvis Meike, Armands Šenfelds. Reģenerācijas enerģijas utilizācija industriālo robotu sistēmā
Publikācijā aplūkoti robotu grupas piedziņu elektromotoru reģenerācijas enerģijas utilizācijas iespējas, izmantojot kopēju lielas kapacitātes enerģijas uzkrāšanas kondensatoru. Piedāvāts tehniskais risinājums ar individuālo robotu līdzstrāvas kopņu tiešu sasaisti caur pusvadītāju divvirziena jaudas plūsmas moduli ar centrālo enerģijas uzkrāšanas kondensatoru . Aprēķināta šī kondensatora nepieciešamā kapacitāte atkarībā no robotu skaita sistēmā. Sistēma aprobēta ekspluatācijas apstākļos un iegūti labi enerģijas taupīšanas rezultāti, kas gan atkarīgi no robota veiktās tehnoloģiskās operācijas, bet ietaupījums var sasniegt pat 30% no enerģijas, kas nepieciešama darbā bez uzkrāšanas ietaises. Ieviešot zināmus tuvinājumus, teorētiski aprēķināta iespējamā elektroenerģijas ekonomija robotu grupai atkarībā no robota darba un reģenerācijas intervalu laiku relatīvās attiecības periodiskajā darba procesā un darba un reģenerācijas strāvu amplitūdu attiecības. Parādīts, ka, samazinoties šīm attiecībām, enerģētiskā efektivitāte pieaug un ekonomija var sasniegt būtiskus lielumus. Teorētiskie aprēķini labi sasaka\nojas ar praktiskos eksperimentos iegūtajiem. Parādīts, ka ļoti būtisks moments ir saistīts ar pareizu sistēmas darbības vadību, kura reducēta uz kondenstaora sprieguma vērtību izmaiņu diapazona ierobežošanu. Izveidotā sistēma tomēr nav pilnīga, jo tiešā līdzstrāvas kopņu sasaiste rada strāvas nevēlamas cirkulācijas kontūrus, kurus jāierobežo ar speciāliem reaktīvajiem elementiem. Lai novērstu šo trūkumu, tiek likts priekšā veidot ar transformatoru izolētu sasaisti ar centrālo kondensatoru, kurā iespējams izmantot superkondensatoru ar daudz zemāku spriegumu nekā robota līdzsprieguma sistēmai. Izveidota shēma, kurā transformators no abām pusēm atdalīts no robota kopnēm un kondensatora ar diviem tranzistoru invertoriem, kuri var darboties divos virzienos, nodrošinot enerģijas plūsmu gan robota motoru reģenerācijas laikā - no kopnēm uz kondensatoru, gan robota slogošanas laikā - otrādi.

Иварс Ранкис, Давис Мейке, Армандс Шенфелдс. Утилизация регенерированной энергии в системе промышленных роботов
В публикации рассмотрены возможности утилизации энергии в ходе регенеративного торможения группы электроприводов роботов, используя конденсаторы большой емкости для накопления энергии. Предложено техническое решение, в котором индивидуальные шины постоянного тока каждого робота непосредственно через полупроводниковый модуль двунаправленного потока мощности напрямую соединены с центральным энергонакапливающим конденсатором. Рассчитана необходимая емкость этого конденсатора в зависимости от числа роботов, подключенных к конденсатору. Система апробирована в условиях эксплуатации и достигнуты хорошие результаты по экономии электроэнергии, которые все же зависят от технологического цикла, выполняемого роботом, но возможно достичь до 30% экономии от энергии, потребляемой без энергосберегающего устройства. Введением некоторых упрощений получены теоретические выражения для расчета возможной экономии энергии для группы роботов в зависимости от отношения длительностей интервала активной работы робота и интервала регенерации в периодическом режиме работы, а также отношения амплитуд токов нагрузки и регенерации. Показано, что при уменьшении этих отношений энергетическая эффективность возрастает и экономия может быть существенной. Теоретические расчеты хорошо согласовываются с экспериментально полученными. Показано, что очень существенным является принятый закон управления, который в данной системе редуцирован к ограничению диапазона изменения напряжения энерго накапливающего конденсатора. Все-таки разработанная система не является полноценной, поскольку принято непосредственное соединение шин постоянного тока отдельных роботов и при этом возникают контуры для циркуляционных токов, которые необходимо ограничить реактивными элементами. Предложен новый вариант реализации системы с изолирующим трансформатором между отдельными роботами и центральным конденсатором, в качестве которого может быть использован суперконденсатор с пониженным по отношению к шинам роботов напряжением. Разработана схема, в которой обе стороны трансформатора подключены через индивидуальные инверторы, способные работать в двух направлениях.