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Energy Efficient Use of Robotics in the Automobile Industry

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Abstract— **This paper summarizes various methods of the energy efficient use of medium and high payload industrial robots. Approaches and according savings potential are evaluated for methods like intelligent brake management - release time and power reduction, the temporal storage of the robot's kinetic energy with capacitive energy buffer of controller's DC-Bus, the energy exchange among robot controllers is proposed. Strategic usage alternatives like robot choice, shutdown during the production-free time and setting into a particular stand-by mode are compared. The energy saving potentials per each method are estimated according to real body-shop production characteristics.**

I. Introduction

Over the last decade the electricity prices in many industrial countries have been steady increasing, in some countries like Germany the wholesale prices have fluctuated with a factor 2.3 since year 2000 [1]. The European Union has set a target of saving 20% of primary energy consumption by 2020 in reference to 2007 [3]. These are the basic reasons that have led to a series of energy efficient measures in many manufacturing companies. An automotive industry is a large energy consumer, whereas a significant part of total volume takes the electrical energy consumed by robotics. Dependent on manufacturer, during the vehicle's lifecycle 15-28% of its energy is being consumed in production phase, whereas electrical energy consumed by industrial robots (IR) in production in average is about 8% [4]; therefore an energy efficient use of robotics has a high impact on the production costs and total CO_2 emission of the whole vehicles lifecycle.

According to ISO an industrial robot is an automatically controlled, reprogrammable, multi-purpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications [2]. The most typical industry robot has 6 degrees of freedom, from which the axis 1 to 3 are used for position of tool centre point (TCP), but axis 4 to 6 for the orientation. The original equipment manufacturers (OEM) of the robotics in the last decade have done a significant research increasing the precision, repeatability, speed of the robots; there have been developed various modelling tools [11]. Following the trend in the automation exhibitions [12] and the EU policy on energy use [3], the energy efficiency in automation industry and robotics has become strongly in focus in the recent years. Apart from many other machines, industrial robots power consumption can be characterised as very dynamic - a power of a regular 6 axes 200kg heavy payload industrial robot has a range from 0.5kW in stand-by mode up to 20kW at peak. It is highly dependent from particular robot type, application, tool, work piece, movement trajectory, usage strategy and many other factors, altogether building a complex set of influence variables.

The measurements show that the average 200kg payload robot in body-shop yearly consumes around 8 MWh, if production takes 52 weeks a year in 3 shifts from Monday to Friday. The detailed analysis of measured real pause and standstill times of 20 robots in the 3 shift automotive assembly plant shows that an industrial robot in the movement spends only 19% of annual time considering that the minimum standstill length is 2s. The rest is the sum of the different standstill times and production-free time like weekends and public holidays. Despite of that, 72% of the yearly consumption is spent during the movement . However, it still does not mean that it equals the amount spent for the explicit movement; besides motor consumption, other static loads like PC, cooling fan, mechanical brakes, display and others sums up to about 275W for the whole time, the robot is switched on.

The figure 1 shows the average estimated yearly saving potential per robot broken down by various activities. The sum of all complementary measures are above 31%. In the following there are described all the hardware-related and implementation-close robot usage optimization measures.

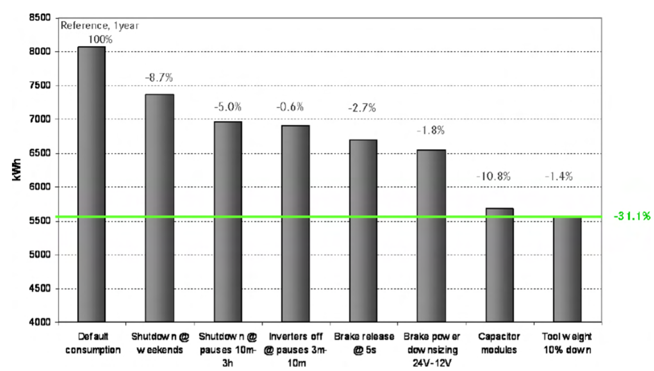

Fig. 1. Energy Savings potential per activity

II. The usage strategy

A. Choice of robot

For the right task the right tool - probably, the most energy savings may be achieved even before the industrial robot has been installed. Because of the largest market share,

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among all, the 150kg-250kg payload range heavy load 6axes industrial robots today are the most low-cost ones [11], which is a reason why they are often chosen for applications that do require far lighter load. A recent measurement of energy consumption between Kuka KR16 and KR210 evaluating identical process points with the 16kg load and identical cycle time showed that the KR210 required in average 2.2 times more energy per cycle time. Because the proportion of the own weight of the larger robot is higher, accordingly the consumption results higher. However, because there are no explicit software tools available that might evaluate such comparison, it is hard to examine the proper choice of robot type, based on energy consumption of the actual work, so that the hardware for the application is not overdimensioned. The exact energy savings are determinable only knowing the specific application, but, according to series of comparisons, the optimal robot choice may result in energy savings of as high as 50-65%. Since these energy savings are highly variable, they are not considered in the figure 1.

B. Various stand-by modes during the production free-time

The Mercedes-Benz plant in Sindelfingen is the first one worldwide to implement the automatic shut-down and start-up of the robots during the production-free time on weekends [5]. The following sample calculation shows the potential annual energy savings per type of standstill frame.

1) Shutdown during the production-free time: Saving the *stand-by* default consumption of 275 W over the weekends only, delivers in average 700kWh a year per robot or 8,7% of its total consumption.

2) Shutdown during the standstill times above 10 minutes: At SIEMENS AG developed protocol PROFIenergy based on ProfiNET [6] today enables the controlled shutdown, leaving only the power supply necessary only for the machine's network communication. Applying it for shorter standstill times like 10 minutes to 3 hours, would deliver another 400kWh savings or 5% of total yearly consumption.

3) Low consumption stand-by mode: The PROFIenergy protocol enables also setting the machine in to known stand-by state in cases, when pause length is below minimum equipment restart time. In IR with this is turning off the robot's servo motor amplifiers, which would deliver additional 50kWh or 0.6% a year.

The challenge and difference between last two points and shutdown during the weekends lies behind the fact that often the short-term pauses and standstill times are not known in advance, which reduces the usable potential.

III. Intelligent Mechanical Brake Management

Articulated robots require motors with accurate response characteristics and dynamic behaviour- fast starts, stops and reversals. To fit these requirements, the permanent magnet (PM) synchronous machines today is de-facto industry standard for robotic applications. They are usually normally equipped with mechanical normal-close brakes. According to measurements, the 6 axis medium and heavy duty industrial robot's motor brakes require around 140W to keep them opened during the movement.

A. Release time reduction

The typical articulated robot by reaching its target position is being kept in a still state by it motors' stator currents. If there is no movement command continuing after a certain amount of time (differs from one manufacturer to another) the mechanical brakes are released and the voltage from stator windings removed the robot is in a type of stand-by mode, waiting for next movement command. For *KUKA KRC2* and *KRC4* controllers this time delay default value is $t_r = 20s$. According to measurements on *KRC2*, the states are accordingly about 650W - 800W, depending on actual robot position, when motors are supplied and 275W (for *KRC4*- 210W) when brakes are released, which is a difference of minimum 375W. Evaluating a range of statistical values, if the time delay were decreased to $t_r = 2s$, it would result in extra 3.1 hours/day spent in stand-by mode with released brakes, which sums up to 300kWh savings per robot a year. However, this would result in additional 9.5 million switching cycles in 14 years. In another calculation example, releasing the brakes after 5 seconds it would result in saved 214kWh per year per robot with total switching cycles below 5 million. Since the movement profiles of the robots strongly differ, the actual limit is to be adjusted individually. The figure 2 shows the trade-off curves between energy savings and mechanical brake lifetime (considered 14years) switching cycles.

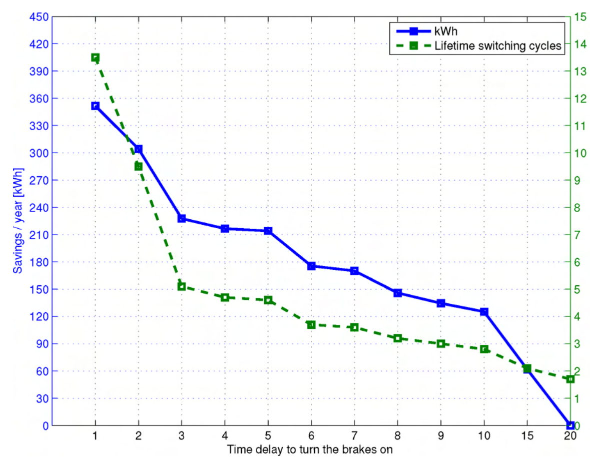

Fig. 2. Energy savings vs. brake switching cycles

B. Power adjustment

The peak power required to open the brakes and power to keep them opened significantly differs. Universal timer-based power reducers known on market are often used for types of valves for applications, where they are open for a relatively long time. The maximum voltage is delivered only for a power peak required for switching-on the valve, which after a significant time (some hundred milliseconds) is decreased on PWM basis. This principle, however, is not known in industrial robotics, whereas the recent calculation shows, that it can deliver additional energy savings. According to measurement, to keep the brakes of 6 motors of *KR210* open after they've been switched on, it is satisfactory with just 50% of currently used amount of power to achieve the same holding moment, accordingly 102W at 24V and 47W at 16V. This can deliver 55 W power savings over the whole time, when robot's motors are supplied. Yearly it results in 150kWh or 1.8% energy savings per robot.

IV. Tool Weight Reduction

The tool weight has a proportional and linear impact on total consumption, which results in higher axes' and motor torques. A typical welding program has been tested to compare the energy consumption of KR210 for a reduced tool weight. The weight centre point in this case has been set to $X = 100mm, Y = 100mm, Z = 100mm$ in the tool coordinate system. The results are shown in the figure

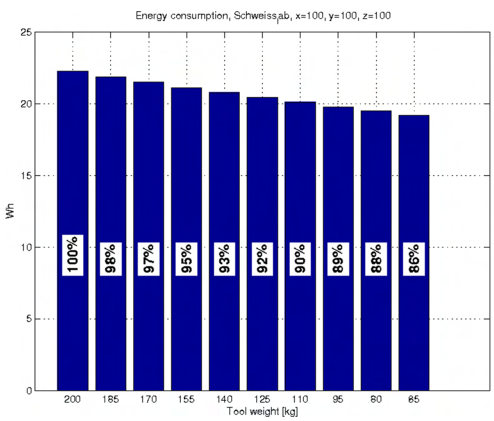

Fig. 3. Energy consumption with reduced tool weight

3, where reduction of every 15kg results in about 0.4Wh less consumption per cycle time. Influence of the position of the tool weight centre must also be considered - as closer it is to base of the tool-coordinate system, as lower the motor torques and therefore the consumption per cycle time. Assuming that a tool weight may be reduced of about 10% or 15-20kg, this would deliver 1.4% of annual consumption per robot.

V. Reuse of the Kinetic Energy

Because of the highly dynamic robot's motor behaviour, most of the robot controllers while decelerating run the servo motors in recuperative mode, thus enabling an energy exchange among other servo motors that are all supplied from single DC-Bus. However, in a case, when several axes brake, the DC-Bus voltage increases above rectified AC supply voltage $\sim 565V$ and the excess overvoltage is dissipated on brake choppers. To reuse otherwise wasted energy, there are several options:

- increase the capacitance of dc-bus,
- use a dynamic energy storage,
- share the DC-bus among several robots, creating a robot *EnergyTeam*,
- use of bidirectional rectifier.

A. Capacitive energy buffer

Currently each of the motor drive of the KUKA KRC2 robot controller has either 2 or 4 internal capacitors C_i, each 330μF, that are connected either in series for *KSD1-16* or series-parallel for *KSD1-48*, that on DC-Bus makes up the total capacitance of:

$$C_{org} = 3C_i + 3\frac{C_i}{2} = 1.49mF$$

In the given maximal voltage range of 490V-640V it results in the saveable energy:

$$Q_{org} = \frac{C_{org}U_2^2}{2} - \frac{C_{org}U_1^2}{2} = 125.4J$$

For the external capacitive energy buffer electrolytic capacitors were chosen as a best alternative because of their robustness and fast energy absorption. The test assembly was constructed from four capacitors C_e, each 18mF, 400V. To achieve the voltage requirements, the series-parallel connection was chosen.

$$C_{ext} = C_{org} + \frac{C_e}{2} + \frac{C_e}{2} = 19.48mF$$

$$Q_{ext} = \frac{C_{ext}U_2^2}{2} - \frac{C_{ext}U_1^2}{2} = 1650.9J$$

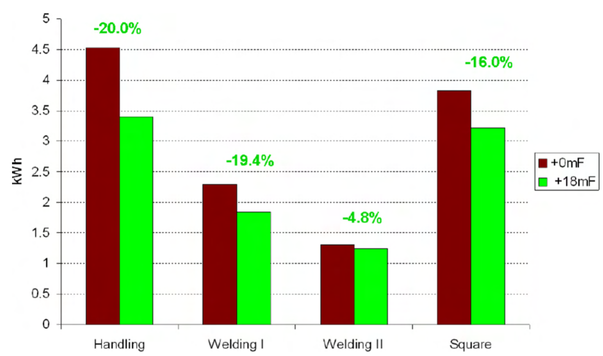

Fig. 4. Use of capacitive energy buffer- program comparison

The extended capacitor bank increases the total capacitance more than 13 times. For testing purposes several robot programs were run, representing the typical welding or handling applications. The power consumption was measured for the whole system, including all static loads like PC, cooling fan, mechanical brake supply, etc. Programs were executed at 100% override setting (maximal speed and acceleration), the weight of the tool- 45kg. The peaks of the measured DC-Bus voltage with original 1.48mF capacitance reached 690V, which is within the working range of the brake chopper. With the attached capacitor bank the peaks are rounded and are about 40V lower, which leaves less working space for the brake chopper. The comparison results (figure 4) show large energy savings, when using the capacitor bank. Since the feed-in power was measured, deducting the approximate 400W of static load during the movement, the actual percentage savings from the explicit movement energy are even higher:

- program *Handling*: -33.7%
- program *Welding I*: -36.8%
- program *Welding II*: -35.5%
- program *Square*: -26.5%

The savings may estimated to be higher also because the DC-bus voltage still did reach the brake chopper working range. Considering the production characteristics and the time spent in movement, the estimated average annual energy savings from total consumption would range between 10-11% with external capacitor buffer or about 870kWh. Assuming that the list price of an according capacitor bank ranges between €700-1000 [8] it would still take more than 8 years[1] to return the investments.

B. Energy exchange between robot controllers in a robots' EnergyTeam

The potential savings by reusing the recuperated energy are in detail analysed in the previous chapter. The reason that the robot spends relatively less time in the movement, leads to the need for option to share such capacitive energy buffer among several robots to sink its costs per IR. Like 6 motor drives for each axis are coupled on a common DC-bus, the similar approach is applied by coupling several robots on a common DC-bus, creating a robot *EnergyTeam*. There are

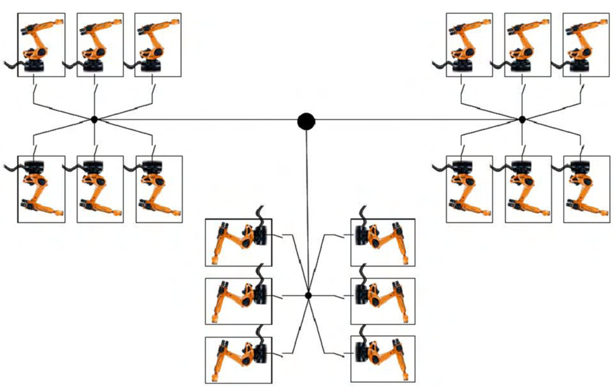

Fig. 5. The *EnergyTeam* principle

basically 2 implementation alternatives:

- a single, centralized rectifier + several robots,
- several decentralized rectifiers + several robots.

In the case of the first scenario, a sophisticated production planning would be necessary to estimate the required power for the whole DC network. The second approach promises to use the robot as apart or to connect it to the *EnergyTeam*. The figure 5 represents the principal connection- the robots from a single workcell are connected with the DC-link, but several workcells may be interconnected to join larger groups of robots. The multi-star connection is chosen, so that each particular robot may be detached from the DC-network, if a failure occurs or the IR is shut down.

The simulation of several typical welding programs have been realized. The program's cycle time is 70s and it has 22 process points, each 2-2.5s long. As a source data a power

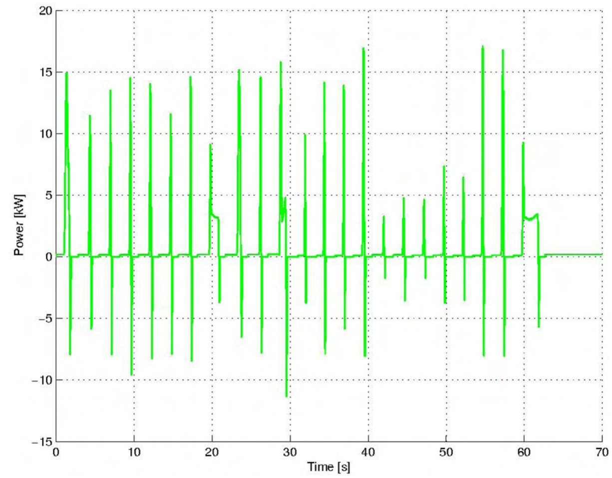

Fig. 6. Energy consumption of single robot

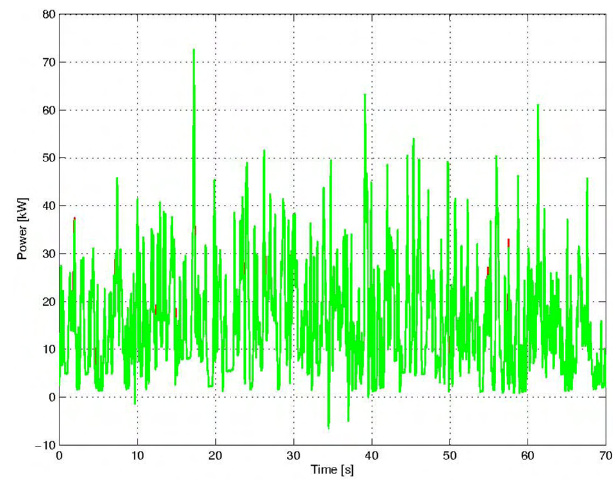

Fig. 7. Energy consumption of 20 robot EnergyTeam

measurement of a rectifier and the brake resistances were used; no external capacitor banks were used. The power curve of a single robot is plotted in the figure 6 (explicit movement energy, no static loads). The negative peaks represent the total power either saved in external capacitors or dissipated on the balancing resistors, which is the energy to be captured. There were simulated *EnergyTeams* within the size from 1 to 20 robots with a random generated program's start shift in the range $0 - \frac{cycletime}{2}$.

The power curve of 20 robot consumption is shown in figure 7- it clearly shows that the negative peaks are much less than in the case of single robot. The percentage of energy needed to capture on energy buffer depending on different *EnergyTeam* sizes is shown in the figure 8. For a single robot the dissipated energy is as high as 24%, which approximately matches the energy savings gained by the capacitor banks, but it sinks rapidly with each additional robot on *EnergyTeam*. Already with 5 robots the dissipated energy is about 2.5% of total consumption, but with 20 robot team it is below 0.5%. The recuperated energy of one robot braking phase is reused by the robots that in other case

[1] Used price per kWh: €0.11

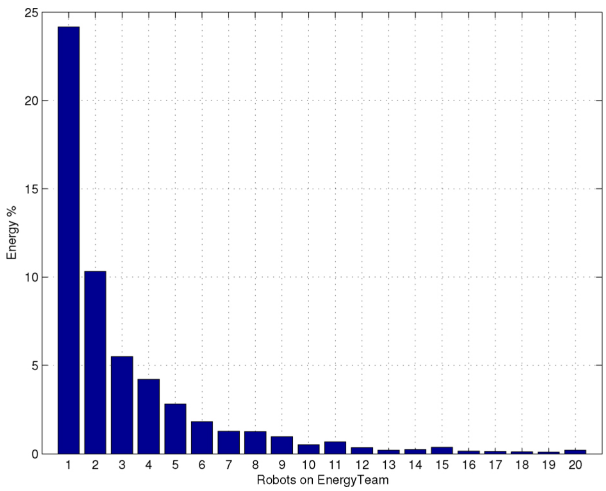

Fig. 8. Energy proportion of total consumption dissipated on balancing resistors, dependency of number of robots coupled

would take it from the AC network. Differences between different randomly generated shifts do not exceed 1%. The peaks of single robot power exceed 15kW, but at 20 robot team maximal peak is below 75kW. These simulation results leads to two conclusions:

- within the *EnergyTeam* of size of 10 IR the recuperated energy is reused as effective as with the use of the external capacitors,
- if a single, centralized rectifier would be used for the whole robot team, it's power requirements should not be as high as the sum of all the currently used decentralized rectifiers, which may eventually deliver additional savings on hardware.

The implementation of *EnergyTeam* involves additional hardware requirements: a bidirectional DC/DC converter for each IR, which controls the energy flow from controller's DC-Bus to the shared DC-network, safety features like disconnecting the particular robot from the DC-network at malfunction or particular stand-by mode. Different topologies of DC/DC converters are known in the literature[9]-[10], however, no known topology is directly applicable to *EnergyTeam* requirements.

VI. Conclusions

The steady increasing electricity prices have strongly set the energy efficiency of the automation technologies in the focus. In the automobile industry, where more than 95% of work in the body-shop is done by robotics-related applications which are known by their cyclically reparative behaviour, even little efficiency improvements of their systems may result in significant energy and CO_2 emission reduction in the whole production.

In this paper there are described *hardware related* energy saving approaches that generally may be arranged in 2 types:

- Activities during the standstill times by setting machine's hardware in lower consumption stand-by modes like the strategy of releasing the mechanical brakes, switching off the servo motor controllers or shutting the machine down at production free times. Here, the greatest challenge is the prediction of the length of standstill.
- A relatively high saving potential lies in the reuse of recuperated kinetic energy, however, there is a challenge to find cost-effective and safe solutions. Promising alternatives are the capacitive energy buffer and the robot *EnergyTeam* - a dynamic energy exchange among robot controllers without the necessity to temporary store it.

Combining all the described hardware usage/optimization measures, the total energy savings in 3-shift production of automobile body-shop in average will reach 31% from yearly consumption. The implementation complexity and cost-effectiveness of each activity must be taken into consideration and the actual savings are hardly application dependent, thus one method may as rise as decrease the influence of others.

VII. Acknowledgments

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