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Analysis of the energy consumption of a novel DC power supplied industrial robot

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Abstract

The energy consumption and electrical characteristics of a novel direct current (DC) power supplied industrial robot prototype are compared and analyzed with a state of the art alternating current (AC) supplied industrial robot. An extensive set of experiments shows an important reduction of the total energy consumption for different electrical power profiles measured in various robot trajectories with specific working temperatures. The recuperated energy is also analyzed in the different scenarios. Experimental results show that a DC type robot can be up to 12.5% more energy-efficient than an equivalent AC type robot.

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Keywords: sustainable manufacturing; AC/DC micro-grids; energy efficient robotics, energy measurements; energy consumption.

1. Introduction

Industry 4.0 leverages digitalization, artificial intelligence and robotics to realize intelligent manufacturing systems and processes. An underestimated drawback of the Industry 4.0 extensive use of industrial robotics and Cyber Physical Production Systems (CPPS) is related with the inevitable drastic rise of the total Energy

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Consumption (EC), which risks to compromise the overall sustainability of the factories of the future. Then, there is a strong need of engineering methods and technologies able to improve the energy efficiency of industrial robots. To this purpose, the AREUS project [1], a European Commission funded research project, developed a novel generation of energy-efficient direct current (DC) supplied robots to overcome current industrial robots energetic limitations and to leverage the exchange, storage and recovery of energy at factory level. In fact, since industrial robots and mechatronic machinery operate on DC, a rectification power conversion stage is necessary with the state of the art alternating current (AC) supply grid, with a consequent loss of energy. For example, state of the art robots actuators are permanent magnet synchronous motors (PMSM). PMSM are controlled by separate servo inverters that are supplied by a common rectifier using a coupled DC-bus [2]. This means that internally, the system is DC supplied already. By using a DC power grid, the rectification stage at AC mains could be eliminated in many applications, thus saving the energy of the power conversion losses. Furthermore, also renewable energy sources operate in DC, then, the adoption of a DC supplied sub-grid would avoid further conversion stages, with the related costs, energy losses and energy quality problem.

DC systems and DC power grids have been extensively discussed in literature, DC sub-grids improve sustainability and energy efficiency by reducing material usage and weight [3], regenerating and recuperating energy and easing the optimization of trajectories and position accuracy for industrial applications [4]. In fact, one of the DC sub-grids main advantage is the capability to recuperate and regenerate energy efficiently, enabling bidirectional DC power flow, as well described with the motor drive system developed in [5], in which the system replicates the dynamics of industrial robot power flow. Furthermore, a DC grid may harvest and store all the recuperated energy, as demonstrated in [6] by using supercapacitor storage and power smoothing. All of these previous works found in literature confirm the systems energy efficiency improvements achievable with DC sub-grids, ideal to recuperate energy from the actuators with regenerative approaches, while in AC systems such recuperation would be harder and more expensive, often with important losses of the AC network quality [7].

Then, the novel DC supplied robots developed with the AREUS project (www.areus-project.eu) may enable DC industrial smart grids, with full regenerative bidirectional DC power flow and seamless integration of renewable energy sources. This paper presents the energy efficiency experimental assessment of a DC supplied KUKA Quantec KR210 R2700 prime DC supplied prototype robot, and the performance are compared with the ones achievable by the same model AC supplied.

The paper is organized as follows: in section 2 the experimental setup is presented, in section 3 the measurement and data acquisition process are described and in section 4 the experimental results are compared and analyzed.

2. Experimental testing setup

Two industrial 6-axes robots, KUKA Quantec KR210 R2700 prime [8], have been tested in different conditions to measure their energy consumption and trajectories power profile. Both robots are identical, excepting for the power supply system. Each robot weights 1100 kg, has a payload up to 210 kg, and a maximum power rating of 22 kW [8, 9]. In the state of the art AC robot version, a single rectifier creates a common DC-bus from which six inverters draw the energy for the motors (Fig. 1), while in the AREUS project robot prototype the rectifier is removed, allowing the direct connection of the internal DC-bus to a prototype factory DC-grid, (Fig. 2). The DC prototype robot, is supplied by an experimental 600 V DC power grid generated by a 55 kW active frond-end unit (AC/DC converter), developed by Riga Technical University [10].

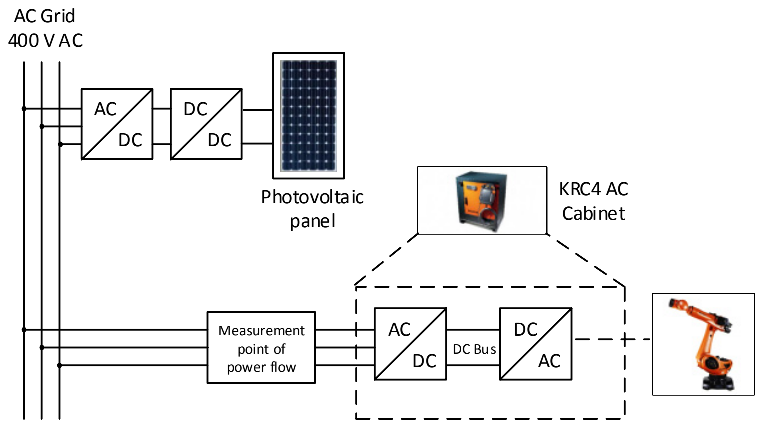

Fig. 1: Example of the state of the art AC supplied industrial robot system

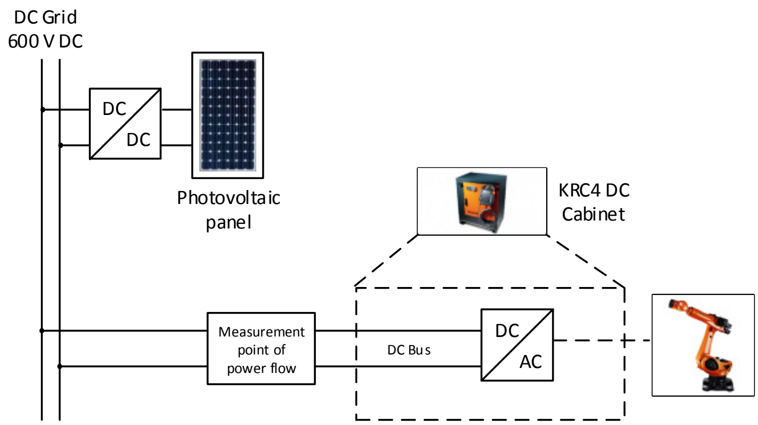

Fig. 2: Example of the DC supplied industrial robot system

3. Methodology

3.1. Measurement setup

During the experiments, the two robots have run the same code, following a trajectory designed to simulate typical motions on a production line. Power consumption curves were logged at different velocities (40%, 60%, 80% and 100% of the maximum velocity) to determine its influence. Furthermore, two different temperature conditions have been considered, called "warm" and "cold", where the "warm" has a five hours warm-up phase before the measurements in order to emulate the real working conditions and to differentiate the power profiles from different friction losses, while "cold" is the robot working after a brief transient. 80 measurements have been acquired: 5 repetitions for each velocity percentage at both temperature condition.

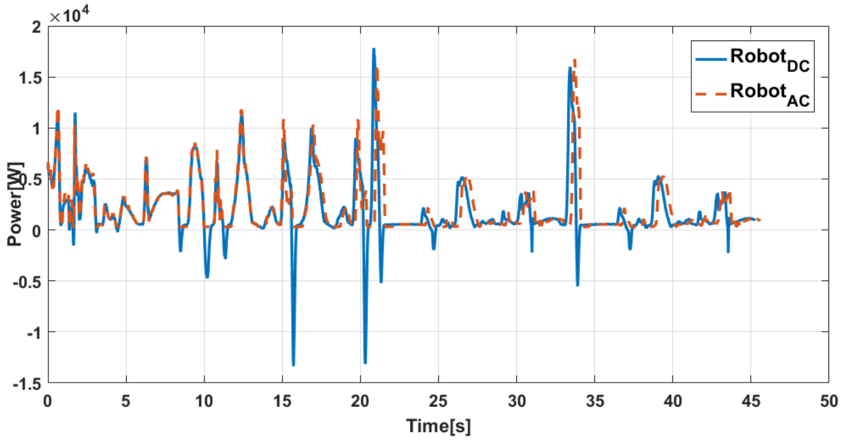

Fig. 3. Test cycle power profiles (W) at 100% execution velocity of the AC (dotted) and DC (line) robots.

3.2. DC/AC energy flow measurement

In both the DC and AC supplied robots, the overall energy consumption can be assessed directly measuring the electrical power flowing into the cabinets. In the AC version, the electrical power can only flow into (positive) the robot cabinet since the energy recuperated during brakes is mainly dissipated into an internal resistor. In the DC version instead, the power can also flow out (negative) from the cabinet to the DC grid allowing for direct measurements of the recuperated braking energy. Such regenerative approaches, extended to the whole cell or plant, may lead to important energy and CO2 emission reduction, as well as contribute to new sustainability assessment methods [11].

In literature are found different approaches to monitor the electrical energy consumption [12]. In this study an AC/DC InLine Bi-direct Energy sensor has been used for data acquisition. This device has been specifically designed to measure instantaneous power values in both consumption and recuperation modes with high accuracy. In previous studies [13], such AC/DC InLine Bi-Direct Energy sensor provided very fast, precise and stable measurements: compared with an expensive calibrated power analyzer (Newtons N4L), the power measurements of over 1kW experienced a deviation under 5%. A single energy sensor module has three current transducers and is capable of measuring a 3-phase 400 V AC grid and a 600 V DC grid [14].

3.3. Data acquisition and analysis

The experimental data have been analyzed, comparing AC cold robot with DC cold robot, AC warm with DC warm, AC cold with AC warm and DC cold with DC warm.

The data analysis has focused on:

- Efficiency of the DC robot in both cold and warm states comparing with the AC robot,
- Energy consumption at different velocities,
- Energy recuperation at different velocities,
- Recuperated energy difference between cold and warm DC robot,
- DC robot energy consumption in both states: cold and warm,
- AC robot energy consumption in both states: cold and warm.

As explained, the AC robot recuperative energy cannot be measured by the Bi-direct energy sensor [15], because such energy is not fed back to the AC grid but internally dissipated in the braking resistors and partly stored in the robot cabinet internal capacitors.

4. Power consumption analysis

4.1. AC/DC robot energy consumption

Analyzing the acquired power profiles of AC and DC robots, some little differences can be noted (e.g. Fig. 3), especially in the power peaks. The cause of such differences can be related with the unavoidable mechanical and electrical construction tolerances between the two robots. The power differences are more accentuated at higher velocity while the curves tend to overlap in the lower ones.

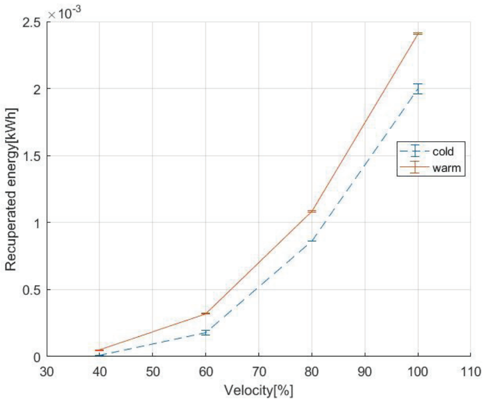

Fig. 4. Recuperated energy of the DC robot at different velocities (“cold” and “warm” state).

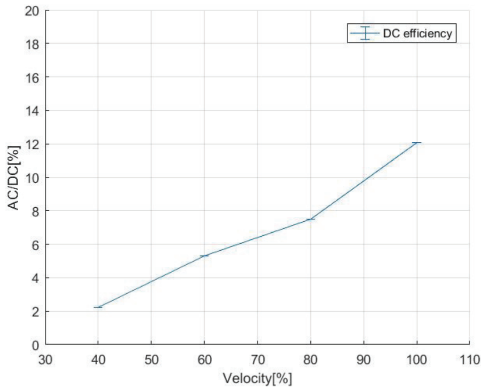

Fig. 5. Energy savings of the DC robot compared to the AC robot (“warm” state).

The energy savings have been evaluated comparing the energy consumption of the AC and DC robot performing the same trajectory at different velocities using (1), the results are presented in Fig. 4.

$$\eta\ [\%] = (1 - \frac{E_{DC}}{E_{AC}}) * 100 \tag{1}$$

In the Fig. 5 it is possible to see that at 40% of velocity the DC robot consumes 2,24% less energy than the AC robot, while at maximum velocity the difference is 12,52%. The increased efficiency in DC robots is due to the capability to recuperate the braking energy, sending it back to the network instead of dissipating. The higher the velocity, the higher the recuperated energy.

4.2. DC robot energy consumption in warm and cold state

An important objective of this study is the evaluation of the DC robot energy consumption by measuring with the Bi-direct energy sensor the energy flow recuperated back to the grid.

Looking at Fig. 4, experimental results show that increasing robot velocity increases the recuperated energy even more if the robot is warm. This effect is reasonably expected due to the reduction of the viscous friction losses in the robot reducers. The most efficient robot execution velocity has been measured around 80% of the full speed. At this speed, DC warm robot is almost 15% more efficient (less consuming) than cold robot. At the maximum velocity, such difference decreases to 12%, as shown in Fig. 6. Efficiency has been calculated using the equation (2). Fig. 4

shows that at 100% velocity warm robot recuperates about 0,002405 kWh per cycle, that is 9% of the total energy consumption, but in case of cold robot it is approximately 7% of the total energy consumption.

$$\eta\ [\%] = (1 - \frac{E_{DC_{cold}}}{E_{DC_{warm}}}) * 100 \tag{2}$$

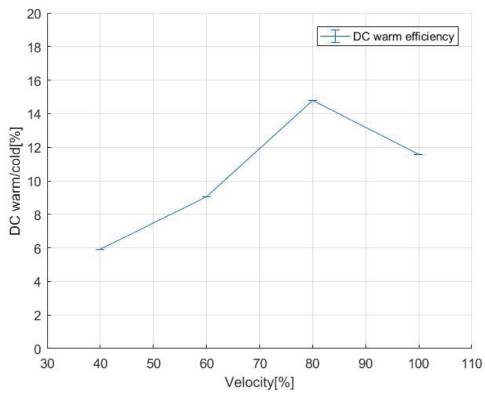

Fig. 6. Energy savings of the DC robot in the warm state compared to the cold state.

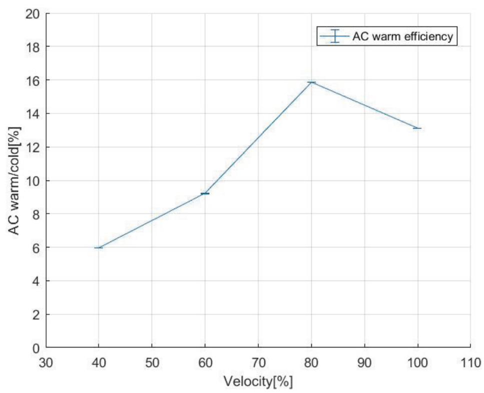

Fig. 7. Energy savings of the AC robot in the warm state compared to the cold state.

4.3. AC robot energy consumption in warm and cold state

As expected, the AC robot energy savings in the warm state (Fig. 7) are very similar to the DC robot ones since the mechanical and electrical systems are ideally identical, excepting for some differences due to inevitable manufacturing tolerances. Warm robot reaches the maximum efficiency at execution velocity of 80% . At this speed warm robot is about 16% more efficient than cold robot, at 100% of execution velocity percentage drops to 13%.

4.4. Measurement relative error analyzes

As it can be seen in figures 4-7, the measurements relative errors are on average under 1%, then the difference between the samples is negligible. Few measurements resulted less accurate, probably for the small scale of the acquired data. The maximum relative error of 8.33% has been obtained in the measurements of the DC robot recuperated energy, at 40% of velocity and in cold state. At the maximum velocity, the relative error is 1.88%. The main cause of such errors can be attributed to the Bi-direct energy flow sensor, which is not suitable to measure precisely low energy levels (less than ~100 watts). In warm state the relative error is smaller, from 3,37% to 0,17% with velocities from 40% to 100%.

Relative error has been calculated with the following method: firstly, it has been calculated an average of the sample measurements (3), such average has been used to calculate the absolute error (4), which is then multiplied by student's t-distribution coefficient (5) to get the systematic error (6). Finally, the systematic error has been divided by the average, obtaining the relative error (7). For indirect measurements equation (8) has been used.

$$x_{vid} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

$x_{vid} - average\ of\ sample\ measurements$

$x_i - sample\ measurement$

$$s_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x_{vid})^2}{n(n-1)}} \tag{4}$$

$S_x - Aboslute\ error$

$$t_\beta(n) = 2{,}78 \tag{5}$$

$t_\beta(n)$-student's t-distribution coefficient

$$\Delta x_s = s_x t_\beta(n) \tag{6}$$

$x_s - systematic\ error$

$$\varepsilon = \frac{\Delta x}{x_{vid}} * 100\% \tag{7}$$

$\varepsilon - relative\ error$

$$\Delta y = \sqrt{(\Delta y_1)^2 + (\Delta y_2)^2 + \ldots + (\Delta y_3)^2} \tag{8}$$

$y - indirect\ measurements$

5. Conclusions

The energy consumption and regenerative characteristics of a novel DC power supplied KUKA Quantec KR210 R2700 prime prototype industrial robot have been measured and compared with the state of the art AC supplied KUKA Quantec KR210 R2700 prime industrial robot. The tests have been performed with various robot trajectories and different working temperatures. The results confirm that the DC energy supply is more efficient up to 12,52%. As expected, the best results have been achieved in the more demanding application cases whit the robots running at maximum velocity. The DC power supplied robots developed in the AREUS project confirm to be reliable and cost efficient, then can enable a full DC Factory.

Further tests will be performed to better assess the performance gains and cost savings in different applications.

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References

[1] M. Pellicciari, A. Avotins, K. Bengtsson, B. Lennartson, G. Berselli, N. Bey, D. Meike, AREUS - Innovative hardware and software for sustainable industrial robotics, IEEE International Conference on Automation Science and Engineering, vol. 2015-October (2015)

[2] C. Hansen, J. Öltjen, D. Meike, and T. Ortmaier, Enhanced approach for energy-efficient trajectory generation of industrial robots, IEEE Int. Conf. Autom. Sci. Eng., pp. 1–7, 2012.

[3] J. Brombach, T. Schröter, A. Lücken, and D. Schulz, Optimized cabin power supply with a / 270 v DC grid on a modern aircraft, 2011 7th Int. Conf. Compat. Power Electron. CPE 2011 - Conf. Proc., pp. 425–428, 2011.

[4] M. Pellicciari, G. Berselli, F. Balugani, and M. Gadaleta, Increasing position accuracy and energy efficiency of servo-actuated mechanisms, IEEE Int. Conf. Autom. Sci. Eng., vol. 2015–Octob, pp. 1339–1344, 2015.

[5] R. A.Paugurs, A.Senfelds, Design of a Motor Drive System for Bidirectional DC Power Flow Control, RTUCON, pp. 7–10, 2015.

[6] A. Senfelds, M. Vorobjovs, D. Meike, and O. Bormanis, Power smoothing approach within industrial DC microgrid with supercapacitor storage for robotic manufacturing application, IEEE Int. Conf. Autom. Sci. Eng., vol. 2015–Octob, pp. 1333–1338, 2015.
[7] D. Meike, A. Senfelds, and L. Ribickis, Power converter for DC bus sharing to increase the energy efficiency in drive systems, IECON 2013 - 39th Annu. Conf. IEEE Ind. Electron. Soc., pp. 7199–7204, 2013.
[8] Kuka Roboter Gmbh, KR QUANTEC prime Spezifikation, 2014.
[9] Kuka Roboter Gmbh, Kr C4 Na ; Kr C4 Ck Na Operating Instructions, p. 227, 2015.
[10] A. Senfelds, O. Bormanis, and A. Paugurs, Modelling of AC / DC Power Supply Unit for DC Microgrid, pp. 5–8, 2015.
[11] T. J. Dijkman, J. M. Rödger and N. Bey, How to assess sustainability in automated manufacturing, 2015 IEEE International Conference on Automation Science and Engineering (CASE), Gothenburg, 2015, pp. 1351-1356.
[12] D. Meike and L. Ribickis, Recuperated energy savings potential and approaches in industrial robotics, IEEE Int. Conf. Autom. Sci. Eng., pp. 299–303, 2011.
[13] P. Apse-Apsitis, A. Avotins, and L. Ribickis, A different approach to electrical energy consumption monitoring, 2014 16th Eur. Conf. Power Electron. Appl., pp. 1–5, 2014.
[14] P. Apse-Apsitis, A. Senfelds, A. Avotins, A. Paugurs, and M. Prieditis, Power Measurement and Data Logger Device with High-Resolution for Industrial DC-Grid Application, Sci. J. Riga Tech. Univ. - Electr. Control Commun. Eng., vol. 9, no. 1, pp. 36–42, 2015.
[15] P. Apse-apsitis, A. Avotins, and L. Ribickis, Bidirectional DC / AC energy flow measurement, vol. 5, pp. 1–4.
[16] D. Meike, A. Senfelds, and L. Ribickis, Power converter for DC bus sharing to increase the energy efficiency in drive systems," IECON Proc. (Industrial Electron. Conf., pp. 7199–7204, 2013.