RIGA TECHNICAL UNIVERSITY

Oskars Bormanis

INCREASING RELIABILITY OF ROBOTIZED MANUFACTURING SYSTEMS

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 6 December 2022 at 13.00 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, 12/1 Āzenes Street, Room 212.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Oskars Bormanis ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, 4 chapters, Conclusions, 157 figures, 18 tables, 14 appendices; the total number of pages is 186, including appendices. The Bibliography contains 170 titles.

CONTENTS

DESCRIPTION OF THE DOCTORAL THESIS

Motivation

Industrial microgrids are a perspective topic in industrial and research environments, included in the innovations introduced by Industry 4.0. Electrical energy consumption reduction in this area has been researched in multiple projects – Daimler AG and Riga Technical University have shown reduced energy consumption by up to 30 %, introducing external energy storage to a state-of-the-art robotized system [1]. This study continues the research, as the demand for direct current microgrid solutions and robotized equipment [2] is increasing.

As the focus of previous studies has been on the reduction of electrical energy consumption by changing layouts, a detailed analysis of suggested robotized manufacturing system layout and control improvements is missing. Various DC microgrid applications and control methods are reviewed in this study by evaluating reliability and other major parameters. Analysis of robotized manufacturing systems should consider reliability. Repetitive load damage wear is application-specific, dependent on mission profile, robot tool weight and robot hardware layout.

To assist the hardware designers in decision making, virtual models of robotized manufacturing hardware are being created. The energy consumption computational model of industrial robots for virtual commissioning software is applied for research and has been extended with addition of thermal and estimated fraction of life consumption simulation capability developed through this study. The study introduces a lifetime improvement tool for specific reliability and lifetime improvements due to a review of robotized equipment application types and robot programs common in the automotive industry.

Computational extension introducing energy consumption and lifetime consumption in a virtual commissioning environment is a novelty supporting the engineering team with data for sustainable robotized hardware design. Toolbox with energy consumption and lifetime estimation capability presented in this study provides the required feedback from the 3D model of manufacturing and robot programs to the engineering team.

Significant motivation to study the topics presented in this work is an industry-standard requirement to maintain the initial functionality of the robotized manufacturing hardware for as long as possible. The concept in general reduces waste and is required for sustainable manufacturing, since effective use of resources is a basis for a sustainable industry being highlighted in the consumer electronics market, where a seven-year smartphone lifespan is considered and demands for improved maintenance options, confirming that reliability requirement and understanding of the related lifetime concepts are essential for product developers, as demanded by the customer and in some cases the government.

The engineering department is expected to adjust the hardware for the needs of the specific application, considering the simulated parameters and the simulation results, while still in development. The developed robot programs are expected to run without major modification for up to 7 years, therefore, software engineers are creating robot programs which will be operational in production for the following years. Energy and lifetime consumption savings or losses are expected to multiply over the duration of the manufacturing.

Reliability in automated factories at the component and material levels has been well researched and documented. Often power electronics converters of industrial robots are designed with a reliability margin, expecting the highest possible load. This reduces the risk of manufacturing downtime due to equipment defects. Similar to the reduction of energy consumption through robotic system-level analysis, improvement of equipment reliability prediction accuracy depends on the application analysis as well. Power electronics equipment is the same and it does not depend on the specific robot application type – either adhesive application or material handling, although the mission profile is different for both tasks.

Sections of the Thesis align with the modelling, assessment and enhancement stages of the study. Results and conclusions are presented within each section and in a summary at the end of the work. Data tables, visualizations in large dimensions are included in the appendices.

Objectives

Missing methodology for power electronics equipment adjustment for actual load and consumption of robotized manufacturing is the main problem solved during this research.

The purpose of the Thesis is to improve reliability of automated robotized equipment by introducing new methods for the development of industrial robot systems and applications.

The objective is to develop a computation tool for junction temperature and lifetime consumption assessment. It is planned to evaluate the assumed relationship between the weight of the industrial robot tool and the lifetime consumption of the power electronics.

As there are multiple use cases of industrial robotized systems, assessment of the connection between robot application type and lifetime consumption is one of the objectives.

Scope of the Work and Research Objects

The scope of the research is current consumption, junction temperature and estimated fraction of life consumed, with focus on isolated gate bipolar transistor (IGBT) module of six degrees of freedom (6-DoF) industrial robot motor drive inverter in various layout and application options. Research objects include inverter IGBT modules, known hardware layouts of industrial robots, control methods and operation principles.

Scientific Novelty

Evaluation of the main reliability differences between alternating current (AC) and direct current (DC) supplied industrial robot systems through theoretical and simulation-based comparison of cost, efficiency, probability of failure and consequence, and other criteria.

A 6-DoF industrial robot motor drive IGBT switch and anti-parallel diode model for junction temperature and estimation of consumed lifetime fraction has been developed. Robot program and application, as well as robot hardware parameters such as tool weight relationship with module junction temperature and lifetime consumption, have been researched.

New analysis method has been created which expands previously researched energy efficiency study with temperature and lifetime evaluation of KUKA industrial robot power electronics modules. A lifetime model has been created for integration into virtual commissioning software.

Practical use scenarios such as analysis of hardware layouts or estimated burn-in testing duration of the developed model have been presented and reviewed to reveal the capabilities of lifetime consumption data availability.

Practical Significance

Applications of the study results include a wider range of inverter lineup, reducing costs and increasing market share. Integration of the wear estimation model in virtual commissioning software has practical application and allows to achieve new technical effects. A predictive maintenance schedule based on mission profile analysis allows for reducing lifetime damage and recognizing any hardware with especially high predicted damage.

Practical applications of this study are wide – the study is expected to improve the reliability and accuracy of reliability prediction for industrial robot manufacturing systems both during development and production.

Research Methods

The main research method is based on computational analysis of electrical and thermal processes through base equations and damage estimation methods, while the results and simulations are mostly controlled through computer modelling methods in MATLAB. Mathematical computations are directed towards the change of junction temperature value and the created impact on the estimated fraction of consumed life. The study is supported by the literature analysis.

Hypothesis

The main hypothesis is that the accuracy of automated robot manufacturing system reliability estimations can be improved considering application-specific parameters. Robotized equipment costs can be reduced on the basis of system hardware layout and mission profile.

The hypothesis of this work is supported by research presented in Sections 2, 3 and 4. Section 2 reflects the modelling stage of the study by presenting the developed mechatronic translation from robot language code to lifetime estimation. Layout options of industrial robot electrical cabinet hardware are evaluated and compared in Section 3, and Section 4 investigates various available methods to estimate the reliability of the robotized manufacturing hardware.

Approbation

Related research of the author has been published and presented in international conferences and scientific journals.

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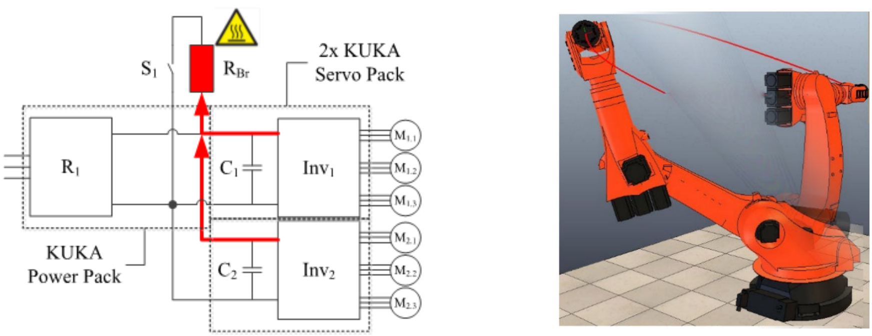
8. **Bormanis, O.**, Ribickis, L. Mission Profile based Electro-Thermal Model of Robotic Manufacturing Application. In: *2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe) Proceedings, Ghent, 2021*. IEEE, 2021, pp. 1–6. ISBN 978-1-6654-3384-6. e-ISBN 978-9-0758-1537-5. Available from: doi: 10.23919/EPE21ECCEEurope50061.2021.9570547.

1. LIFETIME CONSUMPTION MODEL

1.1. Introduction

Virtual commissioning software (VCS) tools of various industry leaders [3], [4], [5] enable simulation of process flow and robot trajectories during the development phase of the production cell. If the launched virtual machine plugin [6] of given VCS includes vendor-specific robot control simulation (RCS) module, then the output simulated trajectory is expected to match with actual movement trajectory and timing on site. Robotics Toolbox for MATLAB [7], [8] is a software tool on which virtual model of robot mechatronic hardware and further transformations to electrical power losses is based (Fig. 1.1 (b)) following the path generated earlier by the vendor specific RCS module. Electric circuit and electrical processes of the industrial robot cabinet (Fig.1.1 (a)) and the hardware layout are reflected in this section.



(a) (b)

Fig. 1.1. (a) Simplified electrical circuit layout of industrial robot ; (b) robot visualization.

Sample welding program was simulated with RCS module, and axis torque has been calculated. Output torque values through the robot program duration are an input to further calculations, such as phase current. The value of phase current changes through the acceleration and deceleration of robot (see Fig. 1.2). Values of Axes 1–3 are higher due to supported weight.

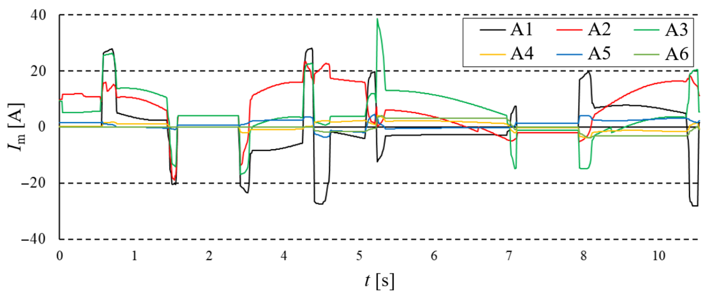


Fig. 1.2. Phase current of robot motors during sample robot program.

Power consumption fluctuates (see Fig. 1.3) as the robot is accelerating and decelerating. DC bus voltage increase is limited by threshold voltage at which brake chopper resistance is connected – resulting in a voltage decrease.

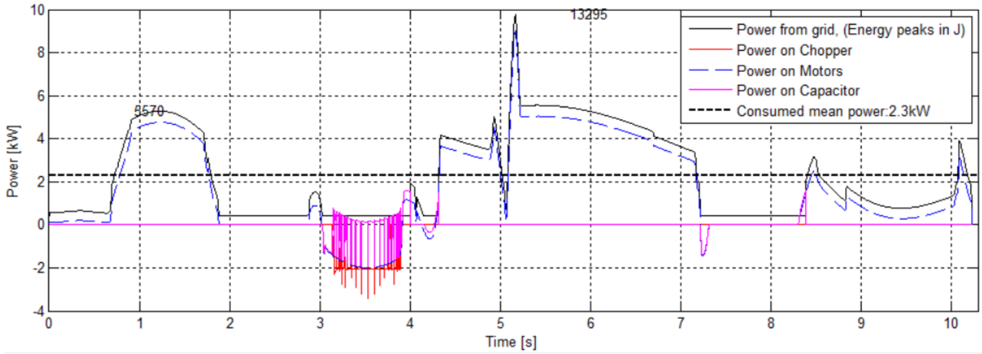


Fig. 1.3. Power consumption of motors, brake chopper resistance and capacitor through sample movement with 2 standstill points (at 2 s and 7 s).

Input current is considered a mission profile for the IGBT junction temperature computation (see Fig. 1.4), estimated for both anti-parallel diode and the IGBT semiconductor switch. Each of the two power switching module components follow different relationship of load current and junction temperature at different operation states of permanent magnet synchronous motor (PMSM).

With positive voltage and positive current values (PMSM consumption) IGBT module semiconductor switch conducts the current and its switching and conduction power losses heat up the device significantly. As current is negative during PMSM operation in generator mode, the current path is closed through anti-parallel diodes and semiconductor switch power losses are insignificant.

In the developed electro-thermal model, ambient environment and heatsink temperatures are stabilized by forced airflow. Thermal transient process is ignored in this computation. In this initial study, heatsink temperature is considered constant due to active cooling. Power losses of IGBT is the power which is dissipated in module and therefore directly influences the junction temperature change in time, as shown in Eq. (1.1):

$$T_{\mathrm{j}}(t) = P_{\mathrm{inv_{IGBT}}}(t) \cdot \left(Z_{\mathrm{th_{j-c}}} + Z_{\mathrm{th_{c-h}}} + Z_{\mathrm{th_{h-a}}}\right) + T_{\mathrm{a}}(t), \quad (1.1)$$

where T_{j} is the junction temperature [K] of inverter semiconductor power module; $P_{\mathrm{inv_{IGBT}}}$is power losses [K] of IGBT; $Z_{\mathrm{th_{j-c}}}$ is the junction to case thermal impedance of semiconductor module [K/W]; $Z_{\mathrm{th_{c-h}}}$ is the case to heatsink thermal impedance of semiconductor module [K/W]; $Z_{\mathrm{th_{h-a}}}$ is the heatsink to ambient environment thermal impedance [K/W]; and T_{a} is ambient temperature of robot hardware cabinet, [K].

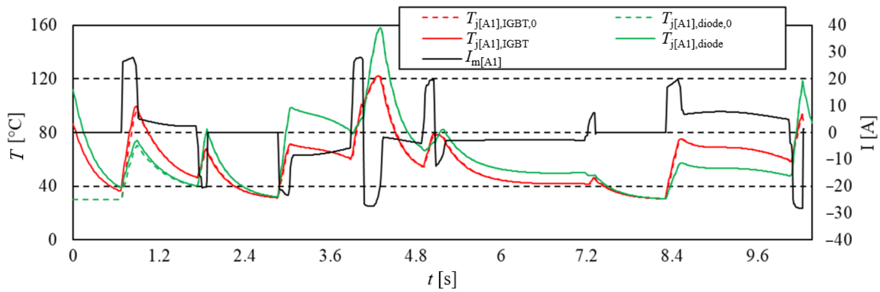


Fig. 1.4. Junction temperature of anti-parallel diode and IGBT (A1 robot axis), illustrating motor phase current and junction temperature relationship.

Input junction temperature data formatting for Rainflow counting application is completed in a sequence as shown in Fig. 1.5 [9]. Positive and negative peak values are sorted. Close peaks are filtered with a 5 % hysteresis filter. Remaining values are discretized and arranged in data bins, processed by Rainflow-counting algorithm. Output data are analyzed through range histograms and processed to reveal lifetime consumption of the cycles and half cycles.

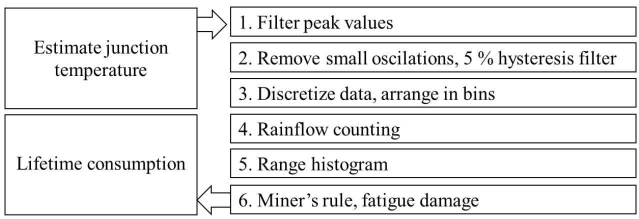


Fig. 1.5. Junction temperature data translation to lifetime consumption through Rainflow-counting algorithm and application of Miner's rule.

Histogram of junction temperature swing cycles can be generated for each of the analyzed mission profiles (see Fig. 1.6).

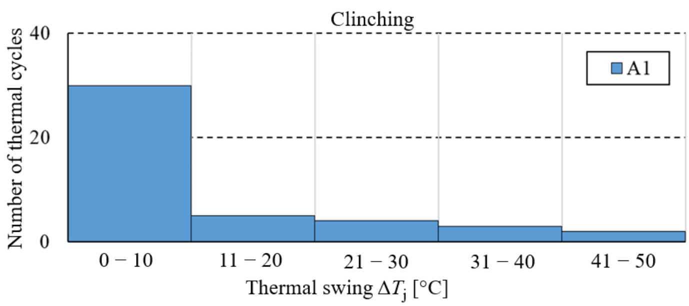


Fig. 1.6. Range histogram of Robot Axis A1 inverter IGBT junction temperature swing and cycles during sample clinching operation.

The total fatigue damage is estimated by Palmgren-Miner linear damage hypothesis, Miner's rule. Damage is a ratio between service load cycles and permissible value calculated assuming that each cycle with the same amplitude range consumes fraction of the total lifetime, is proportional to load cycle number, and when reaching value 1.0 the device is expected to be fatigue damaged. Number of cycles to failure are calculated, where parameter values are obtained using bond wire fatigue damage model [10], [11] and Palmgren-Miner linear accumulation rule [12]. Some of the drawbacks are: the rule does not consider the effect of a low versus high stress sequence and inability to recognize the probabilistic nature of fatigue.

1.2. Tool Mass Change

The research evaluates the assumption that changing tool mass of industrial robot has a direct impact on lifetime consumption of the hardware semiconductor components. A welding robot program of KUKA KR220 six degrees of freedom manipulator was simulated with no load (0 kg) and 56 % (125 kg) of the maximal load (220 kg). Simulation results confirm the change of maximal temperature with increased load weight between 15–23 % for IGBT of Axes 1–3 and between 9–17 % for anti-parallel diode junction temperature of Axes 1–3 inverter. Minimal temperature increase in semiconductor module junction temperature is between 0–9 % for Axes 1–3 and between 0–18 % for diodes of Axes 1–3 inverter of IGBT modules.

The highest temperature peak of Axis 1 diode has increased by 20 °C (see Fig. 1.7) due to the tool mass change from 0 kg to 125 kg. The temperature change rate is not equal and ranges between 10 °C and 20 °C. Changing tool weight does not create new turning points, with an exception that at higher load, the previously filtered, small temperature peaks become more significant and are not removed by threshold filter.

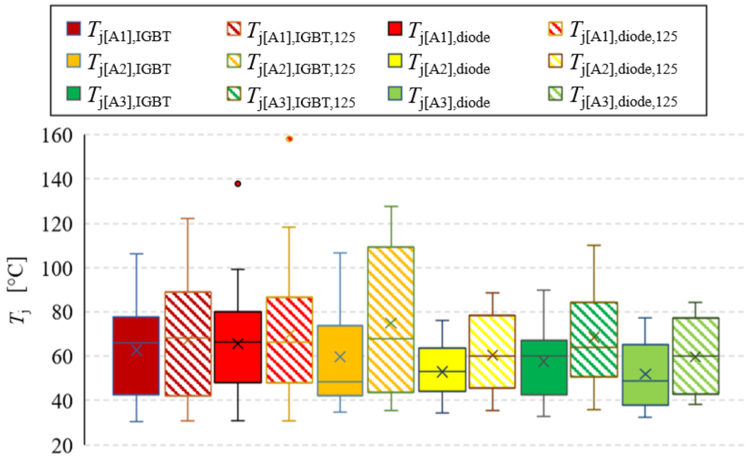


Fig. 1.7. The highest peak value, temperature change amplitude and mean value of robot axis inverter IGBT and anti-parallel diode during sample handling program at changing load mass.

Proportional lifetime consumption (see Fig. 1.8) increase between the simulated 0 kg and 125 kg load weights is evident for IGBT and anti-parallel diode of Axis 1, while absolute values between axes reveal significant difference. The largest reduction of lifetime is caused by higher amplitude temperature swings introduced by increased load weight.

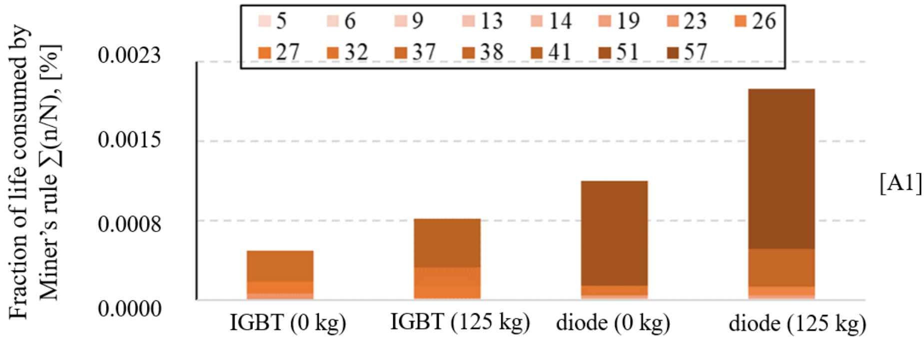


Fig. 1.8. Estimated lifetime consumption of 0 kg and 125 kg tool weight handling program on IGBT and anti-parallel diode of A1 robot axis inverter IGBT module.

Due to different operation modes and characteristics, lifetime consumption difference is expected between IGBT, which is powered through acceleration, and anti-parallel diode which reach the highest temperatures during deceleration.

1.3. Changing Application Type

Lifetime consumption dependance of robot axis drive inverter power switching module on robot application type (handling, adhesive bonding, clinching, spot welding) has been evaluated as well as possible program adjustment or predictive maintenance as available reliability improvement options. Thermal cycle and thermal swing (see Fig. 1.9) data reveal that values observed in programs differ.

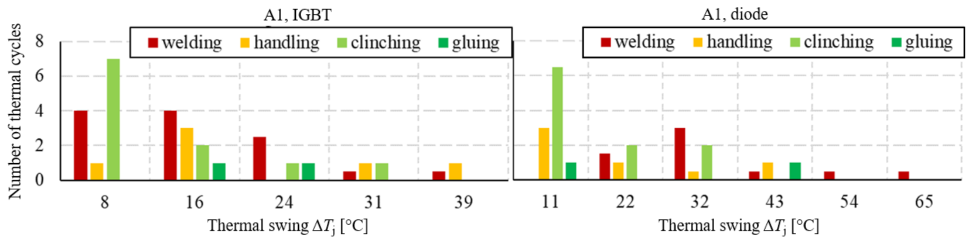


Fig. 1.9. Quantity of IGBT and anti-parallel diode junction temperature cycles and half cycles for A1 of each simulated robot program type after Rainflow counting – spot welding, handling, clinching and adhesive bonding (gluing).

Lifetime consumption data per IGBT semiconductor switch and anti-parallel diodes of robot Axes 1–3 (see Fig. 1.10) reveal differences in LC data depending on robot program. The data follow trends seen in thermal cycle and thermal swing analysis. Less fraction of lifetime consumed is expected in one program operation cycle of clinching or adhesive bonding.

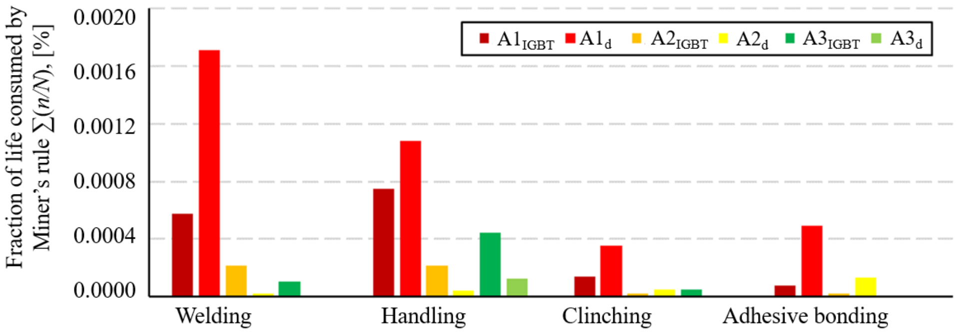


Fig. 1.10. Total lifetime consumption for Axes 1–3 for sample welding, handling, clinching and adhesive bonding robot programs.

Initial assumption that each type of robot program has a unique inverter current mission profile, which leads to wide spread in junction temperature values for robot axis inverters. The current and junction temperature difference is translated into number of thermal cycles and thermal swing amplitudes. Final result of the computation model is an order of magnitude differences of lifetime consumption estimations per each program type.

1.4. Conclusions

The developed model has been reviewed and analyzed taking into consideration automotive industry specifics. Added thermal and lifetime consumption estimation models have been developed and presented. Conclusions regarding operation and reliability of state-of-the-art robot hardware have been made for various robotized manufacturing scenarios, therefore, the study has managed to estimate the junction temperature of IGBT and establish the relationship between robot hardware, robot operation and drive inverter damage.

2. ASSESSMENT OF CONTROL AND TOPOLOGY

2.1. Introduction

The efficiency of AC/DC voltage converters have increased over time [13], [14] and currently is considered sufficient for most of the applications, while review of hardware applications has the potential for further improvements. Currently installed power electronics systems mostly support unidirectional power flow, consist of high number of avoidable converters, and use brake chopper without utilizing the storage and energy exchange possibilities. One of the examples is the most recent industrial applications recovering brake chopper energy [15] and enabling support for energy exchange within the system consumers and generators.

Drawbacks and challenges of shared DC link systems (DC microgrids) include the required reliability evaluation, technological barriers (limited availability of hardware solutions and high specialization), as well as economic and legal barriers. Challenges include establishing of DC voltage standards for various types of microgrids.

Single robot and multiple robot hardware layouts are compared through different characteristics and parameters. Several reliability and lifetime related parameters are evaluated, such as redundancy, probability of failure, and consequence of failure (see Fig. 2.1).

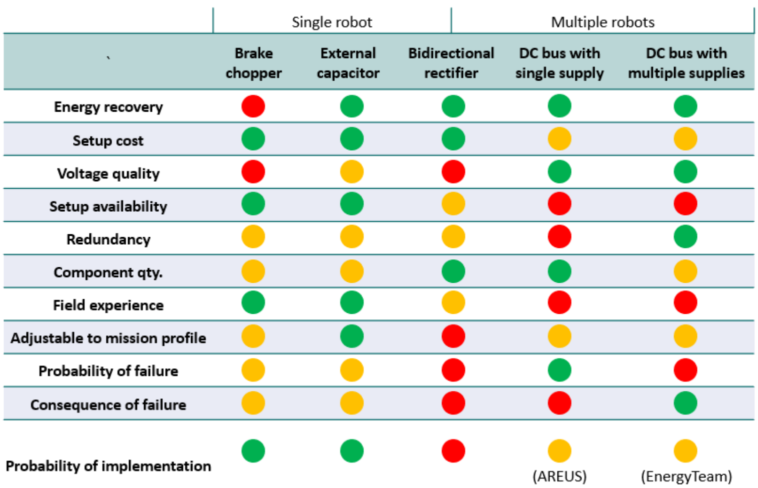


Fig. 2.1. Comparison of multiple parameters of recuperative energy hardware applications.

As a general conclusion, probability of implementation is evaluated for single robot and multiple robot systems. Analysis reveal that a single robot system with state-of-the-art hardware layout, upgraded with a additional capacitor, and selected for the specific robot program is the most recommended option.

2.2. Common DC Link Layouts, Single Robot Setup with Capacitor

Energy flow, including brake chopper, capacitance and total regenerated amount during one deceleration peak of the simulated sample robot program is visualized in Fig. 2.2. As shown, in 2.01 sec, about 25 % of the regenerated energy (W_{regen}) is stored in capacitance (W_{cap}), while 75 % of the energy has been dissipated in brake chopper resistance (W_{br}).

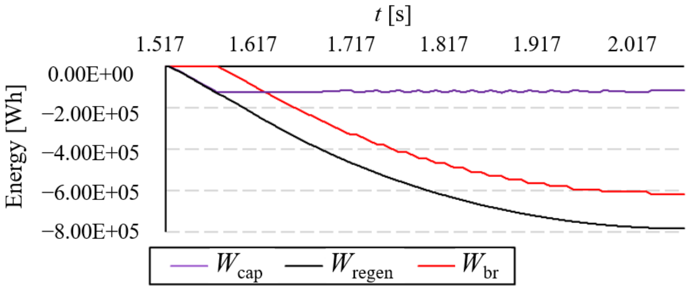


Fig. 2.2. Deceleration of sample robot program with state-of-the-art hardware layout.

Current state-of-the-art circuit (see Fig. 2.3) is viewed as a reference layout, with majority of deceleration energy being dissipated. External capacitor is well documented and recommended for storage of recuperated energy [16]–[18] yet not common in industrial robot systems, therefore, this addition has been studied in the Thesis. Due to mission profile differences, one capacitance does not fit all programs [19].

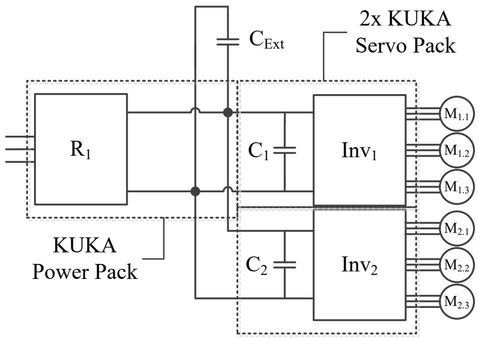


Fig. 2.3. Schematic of KUKA industrial manipulator system with external capacitor for storage of recuperated energy [20].

Capacity of the capacitor is selected through power consumption profile analysis. From the combined power consumption profile, energy dissipated in brake choper is used as a reference to estimate the required additional capacitance (see Fig. 2.4 b)). For sample program, an additional external capacitor capacitance of 7.3 mF (see Fig. 2.4 a)) was calculated, providing recovery of 1.5 %.

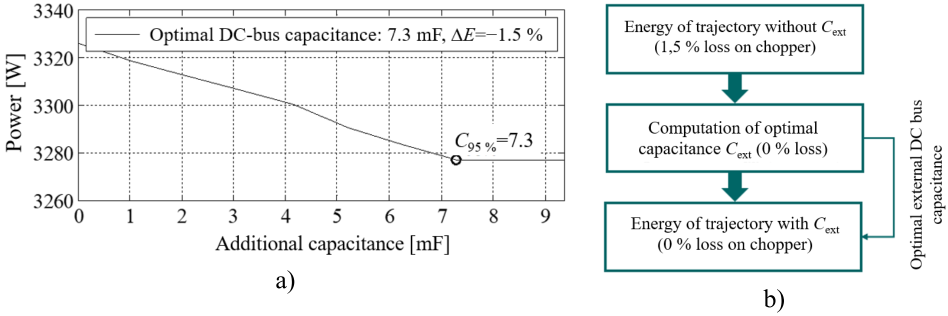


Fig. 2.4. a) Change of power consumption from AC grid through increase of additional DC bus capacitor capacitance; b) implementing of optimal capacitance.

The added external DC bus capacitor capacitance (W_{cap}) is able to store most of the regenerated energy (W_{regen}) and reuse it (see Fig. 2.5) with a capacitance value selected to store at least 95 % of the largest dissipated brake chopper energy (W_{br}) peak.

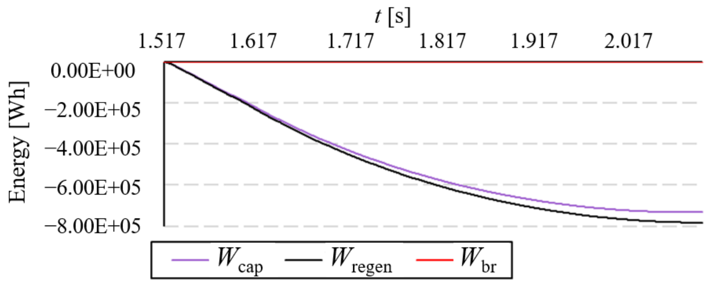


Fig. 2.5. Deceleration of sample robot program with added optimal capacitance.

Motor drive and inverter current values of the sample simulated program for layouts with and without external capacitor are simulated with absolute and relative current value difference being plotted in Fig. 2.6. With brake energy introduced during deceleration, the most significant difference of the current profiles is also at the decceleration.

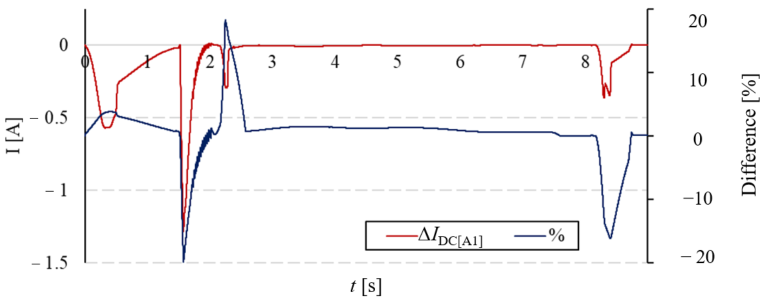


Fig. 2.6. Comparison of relative and absolute value differences for Axis A1.

The current difference is sufficient to change the amplitude of temperature peak values resulting in lifetime consumption values (see Table 2.1). The assumption that addition of external capacitor might improve lifetime of the reviewed robot motor drive inverter semiconductor switch components has been confirmed, as results reveal more than 10 % (12.73 % for IGBT and 14.67 % for anti-parallel diode) difference when comparing the two options.

Table 2.1

Change of Lifetime Consumption Values with and without Added External Capacitor

	A1, $C_{ext} = 7.3$ mF	A1, $C_{ext} = 0$ mF	Change
Lifetime consumption, IGBT	7.12 E – 06 %	8.03 E – 06 %	12.73 %
Lifetime consumption, anti-parallel diode	7.41 E – 06 %	8.49 E – 06 %	14.67 %

The probability of implementation of the state-of-the-art layout with additional capacitor is high. The demand is created by the promised energy consumption reduction. The drawbacks include the limited possibility to estimate the required capacitance before installation on site.

2.3. Multiple Interconnected Robot System Layouts, Shared DC Bus

Sample setup of single high power rectifier and multiple industrial robots sharing a DC bus are shown in Fig. 2.7. The most significant advantage over previous systems is that if a manipulator linked to the same DC bus accelerate during deceleration of another robot, energy can be used before storage in capacitor [21]. The main challenge is the high power rectifier.

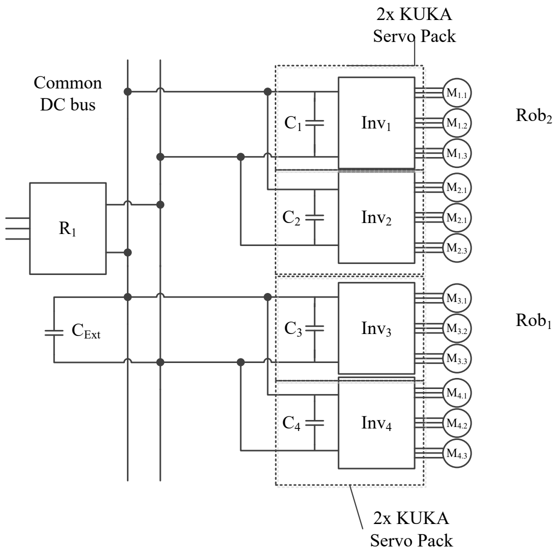


Fig. 2.7. Connection of multiple industrial robots to a shared DC bus with centralized supply and an external capacitor for additional energy storage [22].

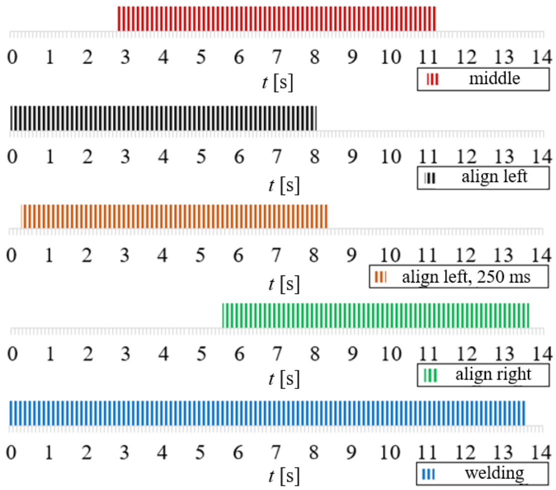


Fig. 2.8. Alignment of handling and welding robot programs.

The assumption of maximal energy recovery considers robots accelerating and decelerating simulatenously, therefore, scheduling of programs has an important role. Spot welding program was selected as a base program, handling program as an overlay program, changing the alignment as shown in Fig. 2.8, to evaluate the scheduling effect on lifetime consumption.

Regarding the current mission profiles (see Fig. 2.9), one of major challenges is the peak value at the beginning of program during initial acceleration. For single robot it is 20 A, while combined peak values for a layout with single power source can reach 43 A. The left alignment with 250 ms offset (see Fig. 2.8) reveals that the initial current demand has decreased from 43 A to two separate peaks of 20 A and 30 A.

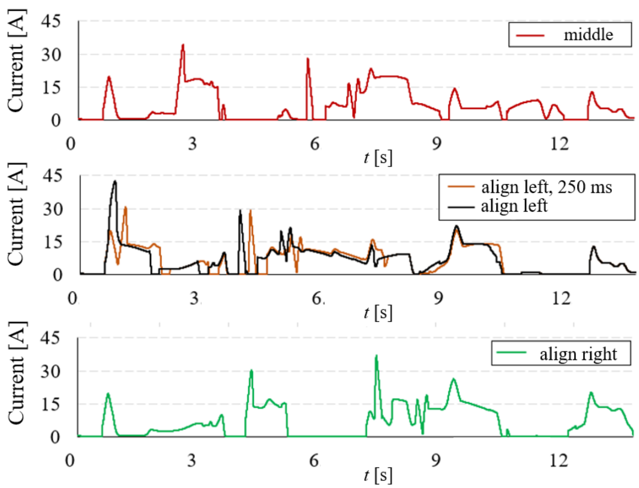


Fig. 2.9. Current consumption from AC grid through central rectifier.

Lifetime consumption analysis for the simulated junction temperature data confirms that both alignment scenarios are not equal, as shown in Table 2.2. Handling program in right alignment is expected to have 10.21 % more damage on IGBT and 45.58 % more damage on anti-parallel diode of drive inverter power electronics switch components of the analyzed axis.

Table 2.2

Change of Lifetime Consumption Values for Right and Middle Alignment of Welding and Handling Robot Programs (see Fig. 2.8)

	Align middle	Align right	Decrease
Lifetime consumption, IGBT	7.89 E – 06 %	8.78 E – 06 %	10.21 %
Lifetime consumption, anti-parallel diode	8.68 E – 06 %	15.9 E – 06 %	45.58 %

The probability of implementation is average, not expecting to become a mainstream option. The demand is supplied by a requirement to have a DC grid with additions of capacitance, inverter, solar power, and DC/DC converter for larger energy storage. The challenge is to manage the optimal efficiency when reducing energy dissipation in brake chopper by scheduling. Drawbacks include high engineering effort for the setup, availability of electrical consumption data during design and development, and costly redundancy of central rectifier unit.

2.4. Conclusions

Robotized manufacturing power supply topologies have been reviewed comparing regenerated energy, failure probability and consequence of failure (see Table 2.3). Detailed comments and analysis of the discussed layouts are included in the relevant sections. Probability of implementation is rated as a general conclusion of the reviewed layout.

Table 2.3

Comparison of Types of Industrial Manipulator Hardware Layout

Indust. manipulator hw layout type	Rank	Average score – Probability of implementation
State-of-the-art w/brake chopper	3	3.33 – available, cost effective, not efficient
State-of-theart w/external capacitor	1	1.66 – available, more expensive, more efficient
Bidirectional AC/DC converter	2	2.33 – questionable cost effective and practical
DC link w/centralized rectifier	4/5	3.83 – rectifier – questionable dimensioning and reliability
DC link w/redundant rectifiers	4/5	3.83 – still in development, therefore expensive

State-of-the-art single robot system is the most commonly installed layout. If energy efficiency improvements are required, a capacitor upgrade, simulated for the specific robot program, has the highest probability of implementation, considering the lifetime of the introduced capacitor. Multiple robot systems linked with DC bus have higher initial development costs, benefits are robot program dependent, but some of the required hardware has not been transferred from research to production environment.

3. DEVELOPMENT AND TESTING OF ROBOT HARDWARE

3.1. Introduction

In the electronics industry, reliability of system or a device is defined commonly as “the probability that a piece of equipment operates under specified conditions and shall perform satisfactorily for a given period of time”. One of reliability engineering objectives is to apply various methods to estimate reliability of designs and analyze data, which is also in the focus of this Thesis.

While development costs increase rapidly with more engineering effort to increase reliability, cost of replacement parts, maintenance staff and spare equipment decrease (see Fig. 3.1). There is a demand for methods and techniques for design of more reliable systems from existing components [23].

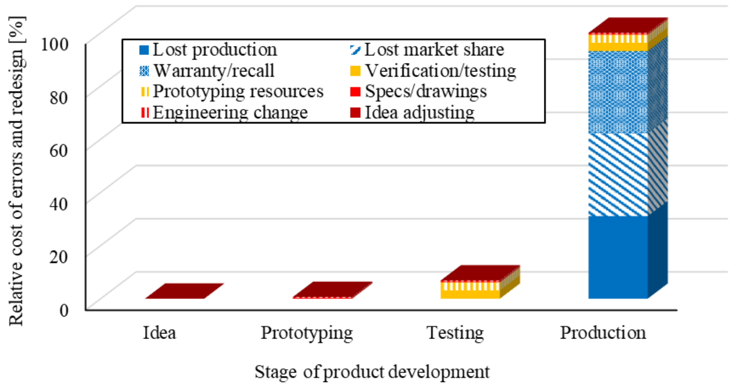


Fig. 3.1. Costs due to reliability and engineering errors at various discovery stages [24].

Unreliable products result in loss of market share, resource demanding recalls and warranty repairs, lost or scrapped production materials, wasted verification and testing time, as well as prototyping materials, engineering effort and idea phase. Postproduction service is required to monitor product life, customer complaints and repair quantities, especially significant during the first production batches, helping to discover deviations and errors ahead of the next productions. Some of the expected failure categories are illustrated in Fig. 3.2.

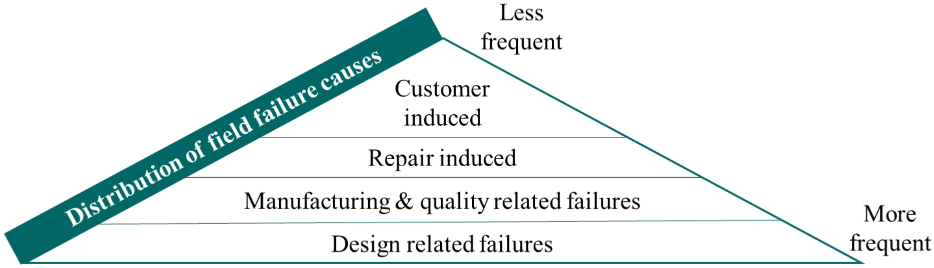


Fig. 3.2. Generalized structure of field failures for electronics applications.

3.2. Program for Development and Manufacturing

Development team has to balance between product launch window limitations, as profit and market cap are affected by delayed launch [25] and the product reliability and issues recognized late in the process are resource demanding [26].

Automotive, aerospace, and military industries require proof of reliability. Reliability program of a development and production cycle includes series of tests during all stages of product life cycle [27]. Feasibility, development, qualification and launch – multiple significant stages of the reliability program are illustrated in Fig. 3.3.

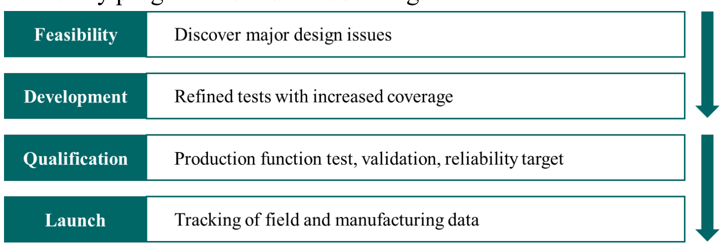


Fig. 3.3. Stages of reliability testing thorough product development.

Development is divided into concept, design, prototype and manufacturing phases. Sample robot drive inverter reliability program and improvement methods are illustrated in Fig. 3.4.

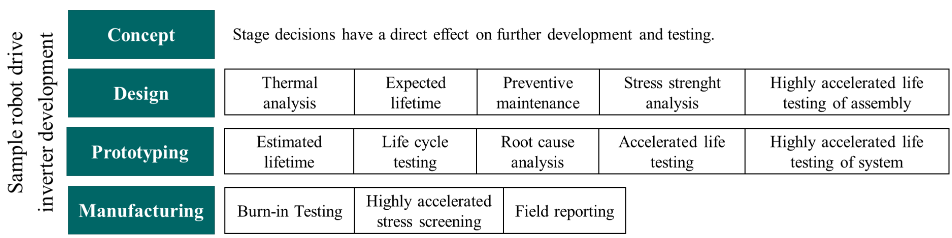


Fig. 3.4. Reliability improvement during robot drive inverter product development.

The role of the outgoing quality control program is to assure that the manufactured product meets the specification requirement and functions properly and that the quality does not decline over time. Stress screening is one of the tools applied to eliminate early failure rate by decreasing the useful life of each production unit in order to improve the reliability of the produced batch as marginal products with defects are discovered.

3.3. Stress Testing and Failure Modes

One of the root causes for early life product failures are variables of the material manufacturing and component assembly process, usually not equally distributed through the life cycle as shown in Fig. 3.5.

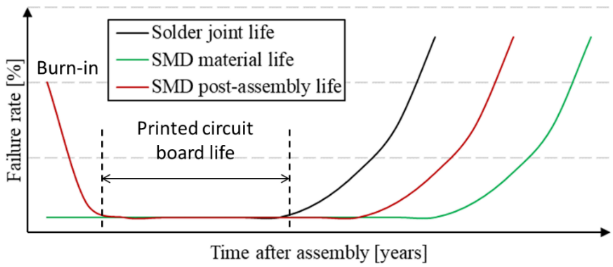


Fig. 3.5. Stages of printed circuit board assembly life cycle.

Two categories of life assessment tests are considered – qualitative and quantitative, focusing either on the trigger of failure mechanisms to determine design robustness (qualitative) or data analysis and screening (quantitative) uncovering patterns through determination of age and reliability relationship function. See summary of both methods in Table 3.1.

Table 3.1

Summary of Qualitative and Quantitative Testing Methods

Qualitative testing	Quantitative testing
Understanding reasons and causes	Numerical data, statistics, failure rates
Developing ideas, failure modes	Formulates facts, uncovers patterns
Focus on failure modes not stress	Predict life at normal use conditions
Might be misleading due to crossover effect	Obtain expected life data in shorter time
Less useful for predicting service life	Accelerated usage rate
Destructive (foolish failure) limit	Not reaching destruct limit
Design robustness determination	Age and reliability relationship function
Highly accelerated life testing	Stress applied at carefully increased levels
Few days	Few weeks
Engineering experience	Analytical models, Weibull, Arrhenius
Detailed product knowledge	

Failures revealed during stress testing of printed circuit board assembly include but are not limited to: 1) damage during the fabrication process; 2) overheating due to manufacturing mistakes [28]; 3) component package defects (such as inductor ferrite cracking); 4) oxidation visual defects, related poor solder joint quality, ionic contamination [29]; 5) other solder defects – voiding, not enough solder, incorrect solder paste stencil openings; 6) assembly errors of the case or cabling – not installed properly or damaged [30].

3.4. Burn-in as a Reliability Improvement Tool

Marginal products are revealed during power on, function test, burn-in or run-in, environmental stress screening, highly accelerated stress screening or audit. Burn-in (see Fig. 3.6) confirms that the operation of assembled units is within specification limits.

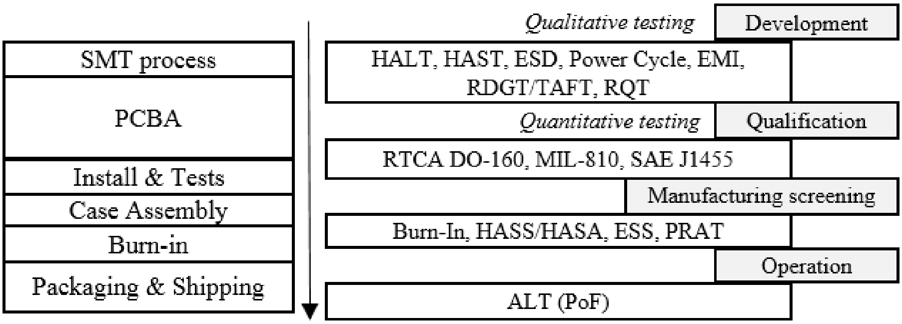


Fig. 3.6. Burn-in testing in mass production of electronic devices.

During the service life, the initial failure rate decreases the overall reliability for the first years due to various assembly or manufacturing defects [29]. The concept of stress screening is to simulate 2 years of field operation through reduction of service life and early reveal of field failures (see Fig. 3.7).

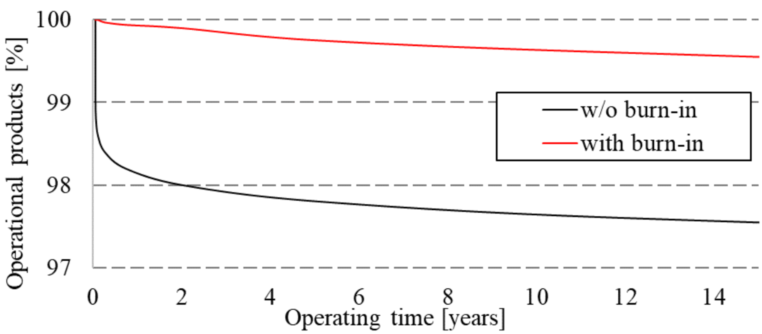


Fig. 3.7. Operational products with and without stress test (burn-in).

Burn-in after assembly and delivery to customers is one of the stress testing options, for example, robot motor drive inverter burn-in while performing the robot specific program. The developed thermo-electrical and lifetime consumption model of inverter IGBT module allows estimating the damage of hardware through one cycle of operation. Multiple repetitive cycles of the specific robot program are scheduled and simulated.

Acceleration of 6 degrees of freedom industrial robot welding program wear of drive inverter IGBT module through repetitive program application is simulated from 1 hour to 72 hours. Damage accumulation for Axes 1–3 inverter IGBT and anti-parallel diode after 1 hour, 24 hours and 72 hours of accelerated testing is shown in Fig. 3.8. Testing profile does include a delay of 5 seconds after each cycle but does not include a realistic schedule such as technical break, changing of workshop shifts, lunch break, or other operation interruptions.

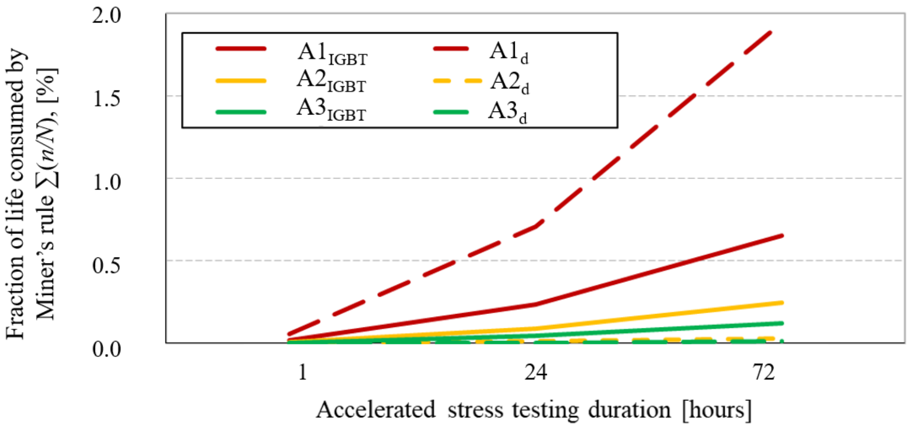


Fig. 3.8. Accumulation of lifetime consumption and cycling of welding program.

Simulation results reveal that if a sample lifetime consumption value of 0.002 is selected as a threshold, testing times to reach this threshold are significantly different for each robot axis. While for Axis 1, 24-hour testing is sufficient, wear of the other axis is below the target value, which is not acceptable, as the objective is to achieve equal lifetime consumption for all of the 6-robot axis inverter hardware.

The number of cycles during normal wear is decreased compared to accelerated wear (see Fig. 3.9), as it includes an estimated coefficient to consider longer delays, realistic operation schedules such as technical breaks, changing of workshop shifts, lunch breaks and other operation interruptions.

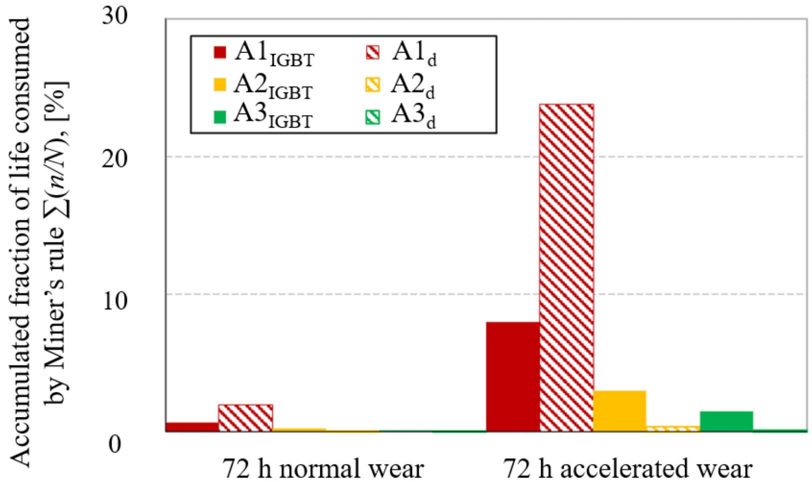


Fig. 3.9. Normal and accelerated robot welding program cycling.

Power consumption and mission profile for each robot program are different, transferred to different lifetime consumption values. Stress testing of other robot programs such as adhesive bonding, handling or clinching were simulated (see Fig. 3.10), where lower values of lifetime consumption were revealed; uneven loading was evident for other robot programs as well.

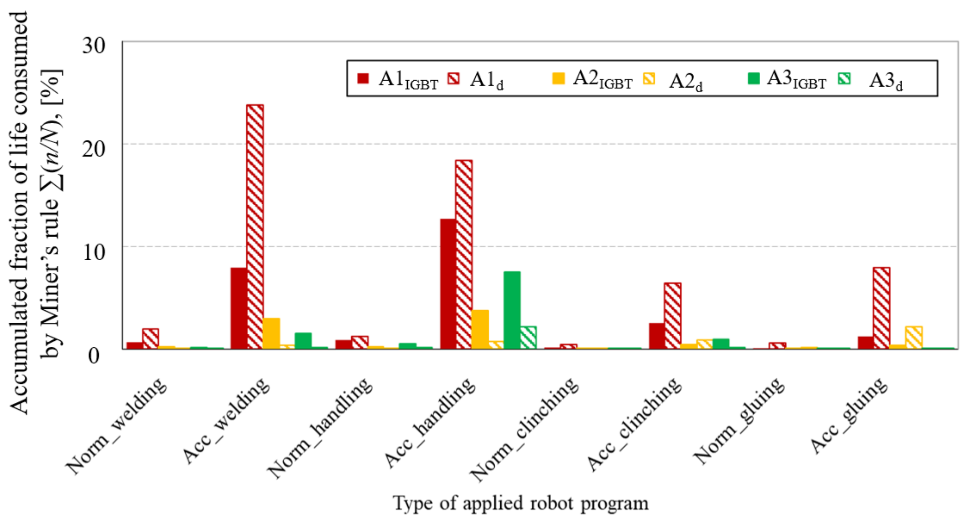


Fig. 3.10. Normal and accelerated robot program 72-h cycling – welding, handling, clinching, adhesive bonding programs.

A more efficient alternative to burn-in with robot program profile is burn-in testing at the drive inverter printed circuit board assembly site. In the controlled environment, it is possible to achieve equal degradation of axis hardware through a stable process with electric load.

3.5. Conclusions

Burn-in is one of the stress screening options. Target costs including warranty returns and test duration, as well as reliability are considered. Major challenges are capital costs of the setup, reduction of pass yield and increase in overall production costs, while benefits include decreased risk of early failures and higher customer satisfaction.

A lifetime model of 6 degrees of freedom industrial robot drive inverter IGBT modules was simulated to evaluate the accumulation of lifetime consumption through normal and accelerated cycling of the 4 robot program types. Results revealed that the wear of electronics is program dependent and that robot axis hardware wears out unevenly due to differences in an applied stress profile. Suitability to local stress screening of robot hardware after assembly at the manufacturing site is low since equal lifetime consumption is not achieved. Burn-in during manufacturing of inverter is recommended, as a specific application designed for stress testing is expected to achieve the objective more efficiently.

CONCLUSIONS

1. While the number of industrial robots and DC system applications is increasing, maintaining of the initial functionality of industrial hardware is required to provide sustainability and continuity for the manufacturing processes, creating a demand for reliability data of the DC microgrid solutions.
2. Robot tool weight has a direct impact on motor drive inverter IGBT lifetime, increasing motor current and thermal swing. Studied application of robot program repetition with 0 kg and 125 kg tool revealed an increase in the estimated fraction of consumed lifetime for power electronics components between 29–249 % per cycle.
3. Analysis method of robot motor drive inverter IGBT with anti-parallel diode junction temperatures and estimated consumed fraction of lifetime allow to identify and evaluate the contribution of robot load weight, application type and layout type to temperature changes within the hardware of robotized equipment. High peak temperatures of less dynamic (adhesive bonding) programs are up to 25 % lower compared to sample spot welding or handling programs.
4. Various robot programs have differences up to 10 times in cumulative lifetime consumption values per cycle, comparing dynamic (welding, handling) and less dynamic (adhesive bonding) robot programs, with the anti-parallel diode of Axis 1 having the highest fraction of consumed lifetime.
5. Energy consumption model with a robot program code input is verified on the industrial robot, therefore, introduced thermal and lifetime computations are expected to align with the realistic field data, with the accuracy losses introducing predicted misalignment. The model provides an opportunity to test various remaining lifetime improvement concepts quickly and highlight impact factors – tool mass, stop to standstill cycles, program velocity, average current consumption, and others.
6. Focus of previous studies has been on DC microgrid layout energy efficiency improvements, therefore, analysis and comparison of suggested and not yet reviewed robotized manufacturing system layout and control improvements considering reliability is a valued addition to previous work.
7. Addition of an optimal capacitance capacitor (7.3 mF) to the state-of-the-art single robot hardware layout has the highest probability of implementation, as it reduces the computed fraction of life consumed by Miner's rule by 12.73 % for IGBT and 14.67 % for the anti-parallel diode in the robot motor drive inverter power electronics circuit.
8. Peak value of current consumption from the AC grid in a multiple robot-single supply layout can be decreased from 43 A to 30 A (30.2 % decrease) for the same combination of two robot programs by changing the starting time for each program.
9. In a multiple robot-single supply layout, less likely to be implemented due to higher initial development costs and some technology not being transferred to a production environment, two studied robot program alignment options revealed a decrease in the

computed fraction of life consumed – 10.21 % in IGBT and 45.58 % in the anti-parallel diode of the studied axis drive inverter power electronics switch components.

10. Development methods to supply highly reliable robotized manufacturing hardware capable to operate for as long as possible have been reviewed and presented, including the deployment of a reliability program to improve through the elimination of failure modes and early failures.
11. Stress testing reduces the reliability of an individual unit, as its useful lifetime is consumed, but the reliability of the batch is increased after the elimination of marginal products. Duration of burn-in stress testing considers the reduction of pass yield, warranty returns and other costs, while benefits include reduced risk of early failures.
12. To achieve a minimum of 0.2 % fraction of lifetime consumption (robot axis drive inverter IGBT) during burn-in testing of sample welding program field operation, test duration varies from 24 hours (Axis 1) to 100 hours (Axis 3).
13. Inverter IGBT modules wear out unevenly between robot axes, depending on the stress profile of the robot program, therefore, burn-in of the inverter is recommended at the supplier site with equal and controlled lifetime consumption.
14. Mission profile analysis provides data for on-site adjustment of predictive maintenance schedule depending on the robot program type, tool weight, and other impact factors.

Future Vision

Further development options include a possible increase of available inverter options by manufacturer reducing costs and increasing market share with lower cost and reduced lifetime versions. Equipment with low lifetime consumption value has an indicator of impractical use of resources, as equipment cost can be reduced by reducing overrating of components.

A further extended digital model of production at virtual commissioning software with the developed innovative energy consumption, junction temperature and long-waited lifetime consumption module provides application-specific data for predictive maintenance and other research purposes. The developed model supports further integration in virtual commissioning software.

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See the complete bibliography with 170 titles in the full Thesis.

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