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DC Microgrid for Robotic Manufacturing – field demonstration and laboratory experience.

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***Abstract*—Paper present real manufacturing application based approach to DC based power supply and infrastructure verification. Alternative solutions for improved management of power flows and integration of renewable energy sources has become an interesting topic and discussions of alternative DC related power infrastructure with respect to existing technology. Since modern manufacturing solutions implement industrial robot manipulators more detailed evaluation of possible opportunities regarding DC based supply has been introduced. Typical distribution of units and respective electrical power flows present need for power measurement equipment with multipoint functionality experiments. Obtained practical measurement results enable evaluation of DC based energy distribution system potential compared to existing solution and future operation scenarios including energy storage and buffering approaches. Implementation of single AC/DC converter unit has been evaluated in laboratory conditions with respect to power quality within DC distribution link.**

Keywords: «DC power supply», «Active frontend», «Microgrid», «Power Supply»

I. INTRODUCTION

Continuous needs for energy efficiency and productivity within manufacturing industries has driven efficient use of energy resources and materials and requirements of various legal policies. Intensively automated industries with industrial robotic units in Europe is related to automotive manufacturing particularly body shop and novel DC based power supply system application has been discussed in this research article. Major efficiency targets for automotive industry has been set by [1] EU Directive 2020 of 20% energy efficiency target of full product life cycles by 2020. Increasing costs for energy sources as well as various national initiatives for renewable energy share increase or replacement of conventional sources energy mix as Energiewende policy initiated in Germany present opportunities for novel power electronic intensive infrastructure solutions as discussed by [2]. Existing AC based power distribution infrastructure has standardization basis opposed to novel DC based solutions excluding applications as railway transportation but general application DC standardization initiatives has been presented [3]. DC type application examples developed within ship propulsion [4] and aircraft [5] modifications and commercial premises [6] support idea of DC related industrial manufacturing power supply infrastructure. Modification of AC based tools and related equipment for DC supply with identical system functionality is presented in this paper. Research activities are divided in full scale factory production infrastructure conversion along with laboratory scale system development located in university.

II. INDUSTRIAL ROBOTIC APPLICATIONS WITH DC SUPPLY.

Multirobot applications with high degree of automation such as automotive production has been discussed by [7] and present idea of electrical energy efficiency as optimization goal like typical parameters of production cycle. Small scale robotic installation recuperative braking energy utilization has been proposed by [8] based on interconnection of single unit DC voltage buses. Following Fig.1 represent identical motion trajectory performed by industrial robot based on manufacturing process and electrical power flow with AC and DC based units. Analysis reveal average 10% share of consumed energy as potential for reuse during braking motion and it is dependent on robot task.

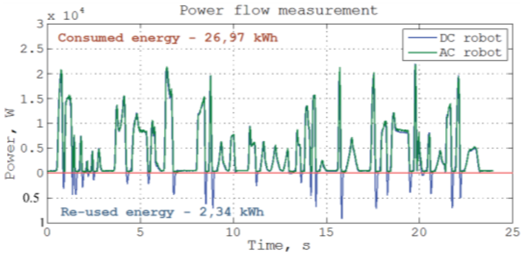

Figure 1 Example of identical motion task for industrial robot for AC and DC supply

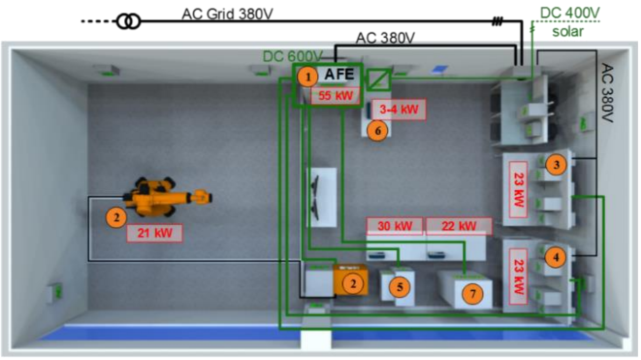

Figure 2 Laboratory scale industrial DC supply grid testing layout.

III. ENVIRONMENTS FOR DC TYPE SUPPLY TESTING.

A. University laboratory based DC supply system

Selected number of industrial components have been arranged within university laboratory forming reduced scale system for DC power distribution verification including industrial robot manipulator and related systems for energy storage and renewable energy source integration as in following Fig.2. The reduced industrial DC system is formed by (1) single active frontend unit AC/DC bidirectional converter of 55kW rated power and 600V DC voltage. Group of industrial robot (2) along with two motor-generator units (3,4) for power flow formation replicating industrial robot. Relevant units as lithium ion based storage (7) and supercapacitor module (5) along with photovoltaic panel integration and DC/DC converter (6) have been included for extended functionality verification. Reduced scale industrial DC grid laboratory allow real manufacturing process based operations and evaluate performance of electrical units designed for fully converted and DC supplied factory installation along with simulation [9] and verification.

B. Demonstration facility of DC based robotic manufacturing.

In order to demonstrate and examine new functionality of DC power distribution within manufacturing with industrial robot manipulators and related tools prototype production cell has been designed by Daimler AG located Germany according to microgrid structure in Fig. 3 within project activities [10].

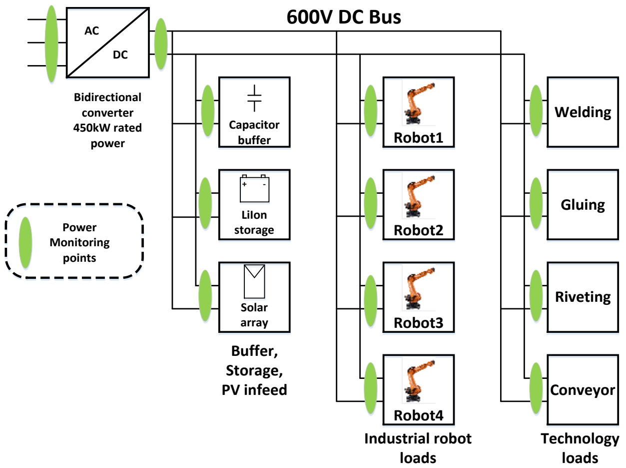

Figure 3 Demonstration prototype of DC microgrid for manufacturing application.

Figure 4 Demonstration manufacturing unit as DC microgrid for experimental analysis.

Single bidirectional AC/DC of 450 kW power rating serve as main interface to existing AC infrastructure. Group of 4 industrial robots are forming load combined with relevant manufacturing technologies such as spot welding, rivet joining, glue application and positioning of workpieces. Main electrical power distribution system is extended by connection of capacitor based directly connected DC buffer storage and photovoltaic panel integration as well as LiIon based battery storage with DC/DC converters respectively.

IV. DEVELOPMENT OF POWER METERING FOR MULTIPOINT APPLICATION.

Implementation of demonstrator manufacturing cell with DC has been realized in 10 by 10 meter area and task of synchronous multipoint measurements of electrical power flow of several connections along common ring type DC rail structure. Measurement solution has been elaborated based on custom made system for 13 measurement locations of electrical power flow with voltage to frequency measurement of voltage combined with hall effect sensors of current and synchronization of common sampling time as presented in [11]. Transmission of data has been implemented by fiber optic interconnection and collection within single text file with 2.8 kHz sampling frequency and averaged 20 millisecond values of voltage and current for further analysis along 50 Hz AC measurement data. Presented experimental setup has led to 110 second long cycle of industrial manufacturing operation data representing DC power flow within DC microgrid incorporating production tools and loads. 13 measurements with shared time axis grouped by similar magnitudes of power flow are represented in following Fig. 5. Analytical results of reuse potential for regenerative energy at industrial robot application by braking energy yield from 1.2% to 10.6% depending on trajectory as summarized in Table 1. Production technology loads modified for DC type supply represent 1% average reverse power flow. Influence of buffer unit based on typical electrolytic capacitor bank with 66% share of regenerative energy show capacitor optimization potential since significant share of energy is related to internal losses of functional capacitor unit. Evaluation of load group by 4 industrial robots, technology tools and capacitor buffer within single production cycle present 13.2% reused power flow with respect to average cycle power consumption.

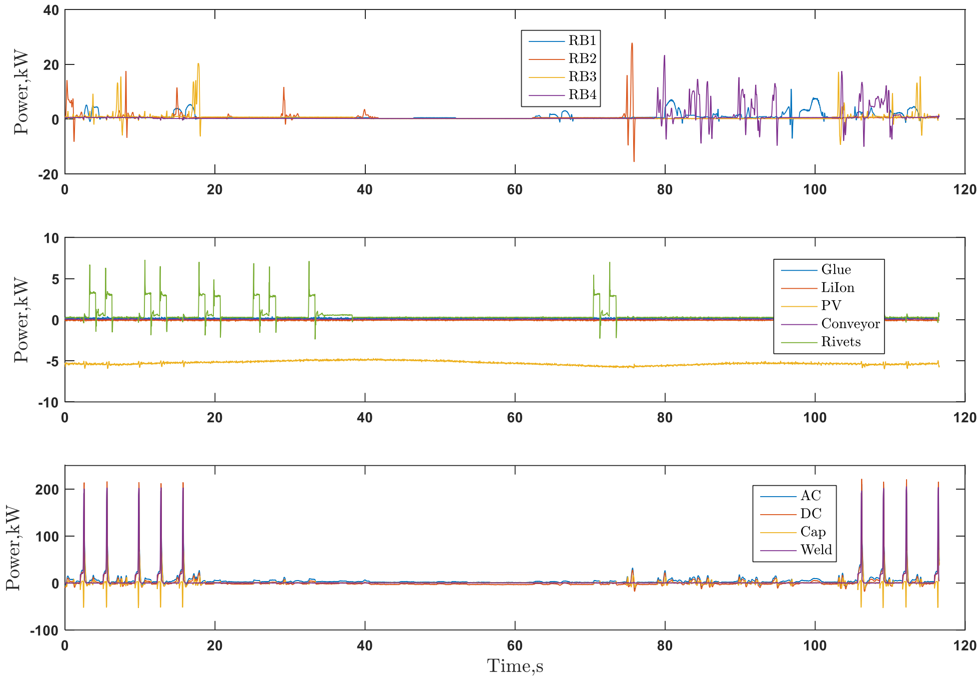

Figure 5. Synchronized power flow measurement data representation of 13 units: 4 industrial robots (top), technology tools, PV injection and LiIon storage (middle), AC, DC, Buffer capacitor and spot welding (bottom)

TABLE I. SINGLE PRODUCTION CYCLE (110 SECONDS) AVERAGED POWER FLOW RESULTS

	P_{pos}, kW	P_{neg}, kW	P_{neg}/P_{pos}, %
Load group (4 robots, capacitor buffer, tools)	8.01	1.06	13.23
Robot 1	0.99	0.012	1.21
Robot 2	0.94	0.1	10.64
Robot 3	0.68	0.04	5.9
Robot 4	0.64	0.04	6.25
Production tools (4 units)	3.51	0.04	1
Buffer capacitor unit	1.25	0.82	66

HARMONIC CONTENT AND DC LINK POWER QUALITY

Utilization of actively commutated converters interfaced with microgrid DC link also present effects of higher frequency content within DC power flow. In order to obtain data for electrical system modelling voltage and current data has been obtained with frequency of 41 kHz thus presenting frequency related analysis within range up to 20 kHz. Such frequency range is considered sufficient for electrical mode iteration since it provide insight of fundamental switching frequency of AC/DC converter being 8kHz and its second harmonic. The following pictures represent obtained experimental measurement data of DC link voltage being controlled according to setpoint value of 600V by active frontend converter under several steady load conditions. Four operation conditions have been depicted: simple AC/DC converter operation without DC link (AFE only), operation with load emulators switched on at no load, load of 44kW being consumed from DC microgrid and recuperation of 33kW via active frontend to AC mains. Fig.6 and Fig.7 represent voltage and current waveforms at selected conditions at AC/DC converter DC terminals.

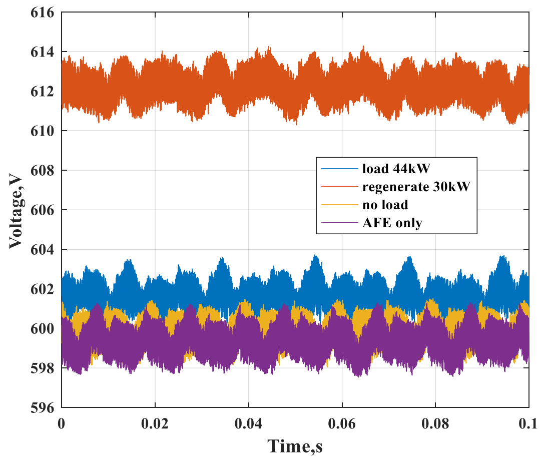

Figure 6. DC voltage waveforms at various load conditions

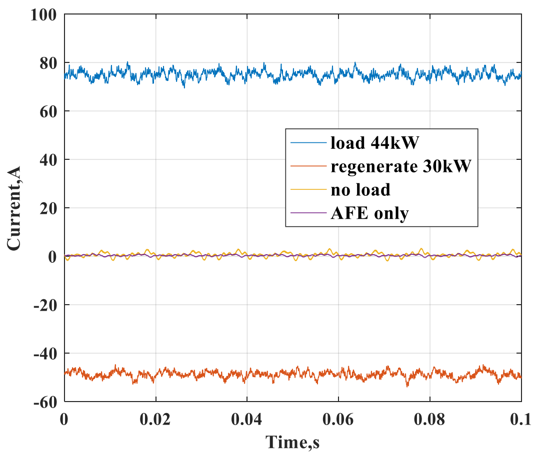

Figure 7. DC current waveforms at various load conditions

By means of frequency content analysis significant frequencies and relative variation under changing load conditions has been obtained as shown in Fig.8 and Fig.9.

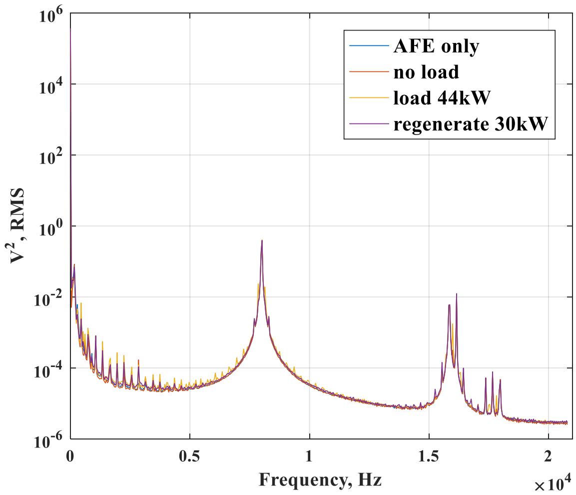

Figure 8. Frequency content analytical results of DC terminal voltage at various load states.

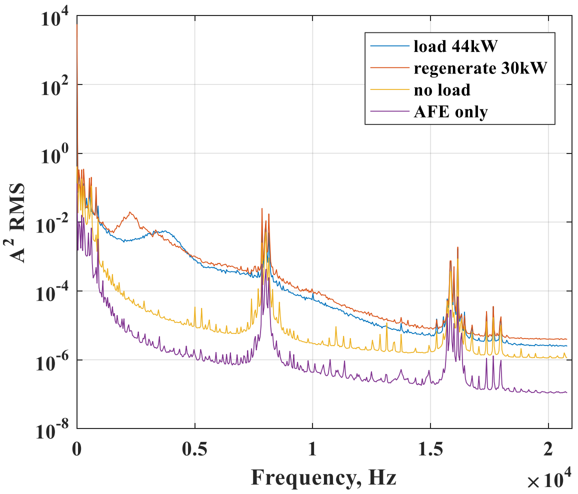

Figure 9. Frequency content analytical results of DC terminal current at various load states.

Obtained results represent influence of higher load currents on frequency content spreading and should be taken into account by individual load unit selection and respective parametrization for distributed electrical measurement systems within common microgrid.

Conclusions

Implementation of laboratory scale DC grid and factory level industrial DC demonstration production cell infrastructure along with novel power measurement equipment has provided basis of real manufacturing based investigation of energy efficiency improvement along with new functionality regarding industrial robot based production. Effective utilization of motion related recuperative energy has been obtained based on DC infrastructure for efficiency improvement. Observation of typical robot trajectory related energy flow present up to 10% reusable energy share by single robots. Along with internal electrical energy reuse functionality new advantages for energy storage and pulsed load support are identified with potential applications for stable energy supply and backup functionalities. Presence of internal energy storage allow extended operation for controlled shut down instances during main power outages as well as peak power reduction for pulsed load types. New extended functions require further research for system scaling and dimensioning for both industry and household related applications. Industrial DC power equipment based microgrid power quality parameters and performance evaluation in typical operation has been presented by experimental measurements.

Acknowledgments

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