TECHNISCHE
UNIVERSITÄT
DARMSTADT

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Automation Architecture for Demand Response on Aqueous Parts Cleaning Machines

Schriftenreihe des PTW
„Innovation Fertigungstechnik“

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Produktionsmanagement,
Technologie und
Werkzeugmaschinen

Automation Architecture for Demand Response on Aqueous Parts Cleaning Machines

Vom Fachbereich Maschinenbau
an der Technischen Universität Darmstadt
zur
Erlangung des Grades eines Doktor-Ingenieurs (Dr.-Ing.)
genehmigte

DISSERTATION

vorgelegt von

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aus Frankfurt am Main

Berichterstatter:	Prof. Dr.-Ing. Matthias Weigold
Mitberichterstatter:	Prof. Dr.-Ing. Reiner Anderl
Tag der Einreichung:	18.04.2023
Tag der mündlichen Prüfung:	20.06.2023

Darmstadt 2023

D17

Schriftenreihe des PTW: "Innovation Fertigungstechnik"

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D 17 (Diss. TU Darmstadt)

Shaker Verlag
Düren 2024

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Darmstadt, Techn. Univ., Diss., 2023

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Printed in Germany.

ISBN 978-3-8440-9450-3
ISSN 1864-2179

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Foreword of the Editor

To reduce greenhouse gas emissions, the share of renewable energies in electricity production is increasing worldwide. However, renewable energy generation fluctuates as it depends on the weather. At the same time, the industrial sector has a large share of the total electrical energy consumption and current research shows that it is possible to adapt this energy consumption to the fluctuating renewable energy generation by means of demand response. Production equipment such as aqueous parts cleaning machines contain untapped potential for energy flexibilisation and thus for supporting demand response. The use of demand response in the industrial sector is made possible by the transformation of industrial automation from hierarchically structured to service-oriented architectures.

This thesis uses these new structures and develops an automation architecture to implement demand response on aqueous parts cleaning machines. The first part is a demand response potential analysis for aqueous parts cleaning machines that determines the potential of the machines. Then, an automation architecture is developed that enables the execution of demand response. This consists of an object-oriented automation programme and a data model for the data exchange between the machine control level and the IT level. Finally, a demand response control algorithm is presented that executes demand response measures and is integrated into an IT framework.

Previous research is mostly limited to the development and simulative validation of demand response algorithms. Only few approaches show the implementation of demand response on real production plants, but then do not describe in a structured way how the plants were adapted to enable the execution of the algorithms. The demand response automation architecture developed in this thesis fills this research gap by describing how the automation of production plants must be designed to enable demand response in industry. Thus, it is transferable and scalable to be used on different machines of different sizes.

In this thesis, the method is applied to a real aqueous parts cleaning machine and not only validated theoretically or in simulation. The application consists of the object-oriented demand response automation program implemented on the machine's PLC and the demand response data model in the form of an OPC UA data model. The implemented demand response automation architecture is validated in a field test.

Darmstadt, July 2023 Prof. Dr.-Ing. Matthias Weigold

Acknowledgements

This thesis was developed in the Energy Technologies and Applications in Production (ETA) research group which is part of the institute of Production Management, Technology and Machine Tools (PTW) at the Technical University of Darmstadt. I would like to extend special thanks to Prof. Dr.-Ing. Matthias Weigold, head of the PTW, for the trusting cooperation and support during my research work as well as the feedback on my research. I would also like to thank Prof. Dr.-Ing. Reiner Anderl for taking on the role of the co-lecturer.

The research of this work was carried out as part of the German research projects PHI-Factory, Synergie and KI4ETA, funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the Federal Ministry of Education and Research (BMBF). I would like to thank all research and industry partners with whom I have worked in these projects for the discussions and their input to this thesis.

I would like to thank my colleagues at the PTW and especially the members of the ETA research group for their contribution to the success of this work through the intensive discussions, motivating words and above all, for supporting me over the last few months such that I could devote myself on the completion of this thesis. In particular, I would like to thank Niklas Panten, Philipp Schraml and Nina Raue (née Strobel) who's research inspired me for this thesis. Furthermore, I want to thank Fabian Borst, Lukas Theisinger and Heiko Ranzau for the valuable discussions on automation systems and optimisation and Jonathan Magin for his input on aqueous parts cleaning machines. Special thanks also go to my student assistant Florian Körner for his support regarding Tikz graphics.

I owe special thanks to Ghada Elserafi and Martin Lindner for the cooperation and intensive research exchange in the last years and especially their constructive feedback on this thesis, which contributed greatly to this work's quality. Moreover, I would like to thank Nicholas Mackinnon for his spelling and grammar correction.

My special gratitude goes to the Diss Booster Team. I would like to thank Thomas Kohne for motivating me in the final phase of the thesis and for fertile discussions on research concept and thesis structure. I would like to thank Benedikt Grosch for the close collaboration in the past years, for many inspiring discussions on our research and for helping finding all the errors in my code until it finally worked. I would like to thank you both for being there for me in difficult situations and for all the fun we had together.

I would like to express my heartfelt thanks to my family on whose help and support I can always rely. I would especially like to thank my parents, who taught me that I can achieve anything and who always believe in me.

Finally, I want to thank my wife Mona for valuable discussions, constructive and extensive feedback on this thesis and unconditional and endless support during the last years. I could have not done this without you.

Darmstadt, July 2023 Daniel Fuhrländer-Völker

Abstract

The share of fluctuating renewable energy in the electricity grid is increasing strongly, primarily in industrialised countries. The industrial sector accounts for a large share of the total electrical energy consumption and current research shows that it is possible to adapt this energy consumption to the fluctuating renewable energy generation using demand response (DR). Especially aqueous parts cleaning machines have a high DR potential. However, only a few approaches exist that show how DR measures can be implemented on real production machines.

This work develops a method that enables the execution of DR measures on aqueous parts cleaning machines. The so-called demand response automation architecture design (DRAAD) method consists of a DR potential analysis, a DR automation architecture including a DR automation program and a DR data model, as well as a DR control algorithm.

The DR potential analysis analyses the technical DR potential of the machine components for the DR method *store energy inherently* and of the cleaning process for the DR method *interrupt process*. The DR potential analysis uses only the machine documentation and simple calculations, such that it can be carried out by employees of the machine manufacturer.

The framework for the DR automation architecture is a cyber-physical production system. This consists of the physical aqueous parts cleaning machine, its digital twin, external elements such as the energy market and a cyber-physical interface representing the communication in the cyber-physical production system. The digital twin includes the DR automation program, the DR data model and the DR process model, which is used by the DR control algorithm, in the digital master. The digital twin also includes a digital shadow and digital services.

The object-oriented DR automation program implements sensor, actuator, and system objects as well as functions that enable the execution of the DR methods *store energy inherently* and *interrupt process*. In addition to DR functions, functional safety functions are included. The communication between DR automation program and DR control algorithm is modelled in the DR data model. This includes all data points needed for the calculation (observing) and execution (controlling) of the two DR actions.

The DR control algorithm, a model predictive control algorithm, minimises the energy cost of the aqueous parts cleaning machine based on varying energy prices. Both DR measures are implemented and the approach is scalable and transferable to different aqueous parts cleaning machines.

The DRAAD method is applied and validated on the aqueous parts cleaning machine MAFAC KEA in the ETA research factory. The DR potential analysis of the machine results in a DR power potential of 87 % of the machine's rated power for *store energy inherently* and a DR energy power potential of 99 % of the energy consumption of the reference cleaning process for *interrupt process*. In the field test, a power change of 49 % and an energy shift of 82 % can be retrieved.

Keywords: Cyber-physical production system, digital twin, data model, energy-flexibility, model predictive control

Zusammenfassung

Weltweit steigt der Anteil erneuerbarer Energien im Stromnetz stark an. Die Erzeugung erneuerbarer Energien schwankt, da sie vom Wetter abhängig ist. Der industrielle Sektor hat einen großen Anteil am gesamten elektrischen Energieverbrauch und aktuelle Forschung zeigt, dass es möglich ist, diesen Energieverbrauch mittels Demand Response (DR) an die schwankende erneuerbare Energieerzeugung anzupassen. Vor allem wässrige Bauteilreinigungsanlagen besitzen ein hohes DR Potential, da ihr Reinigungstank als Energiespeicher genutzt und der Reinigungsprozess unterbrochen werden kann. Allerdings existieren nur wenige Ansätze, die zeigen, wie DR Maßnahmen an realen Produktionsanlagen implementiert werden können.

In dieser Arbeit wird eine Methode entwickelt, die die Ausführung von DR Maßnahmen auf wässrigen Bauteilreinigungsanlagen ermöglicht. Die sogenannten Demand Response Automationsarchitektur Design (DRAAD) Methode umfasst eine DR Potentialanalyse, eine DR Automationsarchitektur, bestehend aus einem DR Automationsprogramm und einem DR Datenmodell, sowie einen DR Regelungsalgorithmus.

In der DR Potentialanalyse wird das technische DR Potential der Maschinenkomponenten für die DR Maßnahme *Energie inhärent speichern* sowie des Reinigungsprozesses für die DR Maßnahme *Prozess unterbrechen* ermittelt. Die DR Potentialanalyse nutzt nur die Maschinendokumentation und einfache Rechnungen, sodass eine Durchführung durch Mitarbeitende des Maschinenbauunternehmens ermöglicht wird.

Der Rahmen für die DR Automationsarchitektur ist ein cyber-physisches Produktionssystem, bestehend aus der physischen wässrigen Bauteilreinigungsanlage, ihrem digitalen Zwilling, der einen digitalen Master, digitalen Schatten und digitale Services umfasst, externen Elementen wie dem Energiemarkt sowie einem cyber-physischen Interface, dass die Kommunikation im cyber-physischen Produktionssystem repräsentiert. Der Digitale Master beinhaltet das DR Automationsprogramm, das DR Datenmodell sowie das DR Optimierungsmodell, welches durch den DR Regelungsalgorithmus genutzt wird.

Das objekt-orientierte DR Automationsprogramm enthält Sensor-, Aktor-, und Systemobjekte sowie Funktionen, die die Speicherung der Energie in Maschinenkomponenten mit einem hohen DR Potential sowie das Unterbrechen des Reinigungsprozesses ermöglichen. Neben DR Funktionen sind Funktionen für funktionale Sicherheit integriert.

Die Kommunikation zwischen DR Automationsprogramm und DR Regelungsalgorithmus wird im DR Datenmodell modelliert. Dies beinhaltet alle Datenpunkte, die für die Berechnung (beobachtend) und Ausführung (steuernd) beider DR Maßnahmen benötigt werden. Der DR Regelungsalgorithmus, ein Model Predictive Control Algorithmus, minimiert die Energiekosten der wässrigen Bauteilreinigungsanlage basierend auf variierenden Energiepreisen.

Die DRAAD Methode wird auf die wässrige Bauteilreinigungsanlage MAFAC KEA in der ETA-Fabrik angewandt und validiert. Die DR Potentialanalyse resultiert in einem Potential zur Leistungsänderung von 87 % der Anschlussleistung und einem Potential zur Verschiebung des Energieverbrauchs von 99 %. Im Feldversuch kann eine Leistungsänderung von 49 % und eine Energieverschiebung von 82 % abgerufen werden.

Stichwörter: Cyber-physisches Produktionssystem, Digitaler Zwilling, Datenmodell, Energieflexibilität, Model Predictive Control

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Abbreviations

AI	artificial intelligence.
AMQP	Advanced Message Queuing Protocol.
APCM	aqueous parts cleaning machine.
API	application programming interface.
CIRP	The International Academy for Production Engineering.
DDS	Data Distribution Service.
DR	demand response.
DRAAD	demand response automation architecture design.
EPEX	European Power Exchange.
ERP	enterprise resource planning.
ETA	Energy Technologies and Applications in Production.
EU	European Union.
FMU	Functional Mock-up Unit.
HMI	human machine interface.
HTTPS	Hypertext Transfer Protocol Secure.
HVAC	heating, ventilation, and air conditioning.
IEC	International Electrotechnical Commission.
IEEE	Institute of Electrical and Electronics Engineers.
IFAC	International Federation of Automatic Control.
IIC	Industry Internet of Things Consortium.
IoT	Internet of Things.
IP	Internet Protocol.
IPC	industrial personal computer.
IT	information technology.
JSON	JavaScript Object Notation.
MES	manufacturing execution system.
MILP	mixed integer linear programming.
MPC	model predictive control.
MQTT	Message Queuing Telemetry Transport.
OPC UA	Open Platform Communications Unified Architecture.
OPC UA FX	OPC UA Field eXchange.
OT	operating technology.

PID	proportional–integral–derivative.
PLC	programmable logic controller.
PTW	Production Management, Technology and Machine Tools.
RAMI4.0	Reference Architecture Model Industrie 4.0.
REST	Representational State Transfer.
ROS	Robot Operating System.
SCADA	supervisory control and data acquisition.
TCP/IP	Transmission Control Protocol/Internet Protocol.
UML	Unified Modeling Language.
US	United States of America.
VDI	Association of German Engineers e.V..
XML	Extensible Markup Language.
XMPP	Extensible Messaging and Presence Protocol.
YAML	YAML Ain’t Markup Language.

Symbols

Symbol	Description
$a_{n,k}$	binary variable, one during process step n at time step k
$\tilde{a}_{n,k}$	binary variable, one during and before process step n at time step k
$\mathbf{A}$	matrix containing all binary variables $a_{n,k}$
$\tilde{\mathbf{A}}$	matrix containing all binary variables $\tilde{a}_{n,k}$
$\mathcal{A}_g$	set of machine modules active in the process step g
b_n	binary help variable
$\mathcal{B}_n$	set of machine modules active in the process event n
C_k	electricity price at time step k
c_{p}	specific heat capacity of a material
$c_{\mathrm{p,fluid}}$	specific heat capacity of cleaning fluid
$c_{\mathrm{p,parts}}$	specific heat capacity of parts
d_f	duration machine module f is active during complete cleaning process
$d_{f,g}$	duration f-th machine module is switched on during process step g
$d_{f,j}$	duration a part traverses process chamber j of machine module f
d_g	duration of process step g
d_n	duration of cleaning process event n
$\mathbf{d}$	durations of all cleaning process events
d_{clean}	duration of cleaning
d_{dry}	duration of drying
d_{event}	fixed duration of an event
d_{load}	duration of loading
d_{meas}	measured activation duration
d_{start}	remaining duration of active event
E	total energy of a system
f	index of machine module
F	total number of machine modules
$\mathcal{F}$	set of machine modules rated green or yellow in the DR potential analysis
g	index of process step
G	total number of process steps
$\mathcal{G}$	set of process steps rated green or yellow in the DR potential analysis
h_k	binary setpoint of tank heater at time step k
$h_{l,k}$	setpoint of machine module l at time step k
$\mathbf{h}$	setpoints of tank heater at all time steps

Symbol	Description
$\mathbf{H}$	setpoints of all machine modules at all time steps
i_k	binary variable, is one if an interruption is set at time step k
j	index of cleaning chamber
J	total number of cleaning chambers
k	time step
K	optimization horizon
l	index of machine modules selected for *store energy inherently*
L	total number of machine modules selected for *store energy inherently*
m	mass of a material
m_{fluid}	mass of cleaning fluid
m_{parts}	mass of a part
n	index of cleaning process events
n_{start}	currently activated cleaning process event
N	total number of cleaning process events
$\mathcal{N}_{\text{parts}}$	total number of parts in one cleaning tray
Q	energy supplied to a system as heat
$\dot{Q}$	heat flow
$\dot{Q}_{\text{env}}$	heat flow from the cleaning liquid to the environment
$\dot{Q}_{\text{parts}}$	heat flow from the cleaning liquid to the parts
$\dot{Q}_{\text{spray}}$	heat flow from the cleaning liquid to the aqueous parts cleaning machine
P_f	rated power of machine module f
P_g	cumulated rated power of machine modules active in process step g
P_l	rated power of machine module l selected for *store energy inherently*
P_n	cumulated rated power of machine modules active in process element n
P_{clean}	cumulated rated power of machine modules active in process step cleaning
P_{dry}	cumulated rated power of machine modules active in process step drying
P_{flex}	absolute achievable energy-flexible power demand
P_{heat}	rated power of tank heater
P_{int}	cumulated rated power of machine modules active in process step interruption
P_{meas}	average measured power
P_{module}	cumulated rated power of machine modules selected for *store energy inherently*
P_{total}	rated power of the aqueous parts cleaning machine
R	thermal resistance
R_{env}	thermal resistance between liquid and production hall
R_{spray}	thermal resistance between liquid and aqueous parts cleaning machine

Symbol	Description
s_n	start of cleaning process element n
S	fixed end time step of cleaning process
t	time
Δt	time interval
T	temperature
T_k	tank temperature at time step k
T_{env}	temperature of the production hall (environment)
T_{f1}	temperature of the first fluid during heat exchange
T_{f2}	temperature of the second fluid during heat exchange
T_{lb}	lower limit for tank temperature
T_{ub}	upper limit for tank temperature
T_{parts}	temperature of the parts before loading
T_{start}	tank temperature for $k = 0$
ΔT	temperature difference
ΔT_k^+	tank temperature increased by tank heater at time step k
ΔT_k^-	tank temperature decrease at time step k
$\Delta T_{\mathrm{clean},k}^-$	heat loss during spray cleaning at time step k
$\Delta T_{\mathrm{env},k}^-$	heat loss to environment during spray cleaning at time step k
$\Delta T_{\mathrm{parts},k}^-$	heat loss to parts during spray cleaning at time step k
$\Delta T_{\mathrm{spray},k}^-$	heat loss to aqueous parts cleaning machine during spray cleaning at time step k
U	inner energy of a system
ΔU	change of inner energy of a system
$\Delta U_{\mathrm{env},k}$	change of inner energy of a system caused by the temperature loss to the environment
$\Delta U_{\mathrm{parts},k}$	change of inner energy of a system caused by the temperature loss to the environment
$v_{l,k}$	process value of system l at time step k
$\Delta v_{l,k}$	change of process value of system l at time step k
$v_{\mathrm{lb},l}$	lower bound of process value of system l
$v_{\mathrm{ub},l}$	upper bound of process value of system l
$v_{l,\mathrm{start}}$	start process value of system l for $k = 0$
V_{tank}	tank volume
W	work done to a system by its surroundings
W_f	energy demand of machine module f
W_g	energy demand of process step g
W_{flex}	absolute energy DR potential
W_{meas}	measured energy consumption
W_{total}	total energy demand of aqueous parts cleaning machine for one cleaning process
x	setpoint of actuator or system

Symbol	**Description**
x_{lb}	lower bound of setpoint
x_{ub}	upper bound of setpoint
$z_{n,k}$	variable used for linearisation
α	heat transfer coefficient
β_{env}	regression factor for temperature loss to environment
β_{parts}	regression factor for temperature loss to parts
β_{spray}	regression factor for temperature loss to aqueous parts cleaning machine
δ	duration of a time step k
ρ_{fluid}	density of cleaning fluid
$\tau_{l,k}$	disturbance on system l at time step k
φ_f	share of energy demand of machine module f
φ_g	share of energy demand of process step g
Φ_{P}	power ratio, technical DR potential for *store energy inherently*
$\Phi_{\mathrm{P,meas}}$	power ratio of measured power change
Φ_{W}	energy ratio, technical DR potential for *interrupt process*
$\Phi_{\mathrm{W,meas}}$	energy ratio of measured energy shift