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Requirements Engineering and Morphological Analysis of Adaptive Control Strategies for Flywheel Energy Storage Systems in Industrial Applications

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Outline

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Introduction – Motivation and background

- Industrial sector is responsible for 44 % of the German electricity consumption

- Industrial grids and applications are characterized by

  - a high load density
  - short distances between individual stations
  - mainly inductive motor loads
  - dynamic, short-term loads
  - small average load

- Braking energy is either fed back into the AC grid or converted into heat by a chopper (braking resistor)

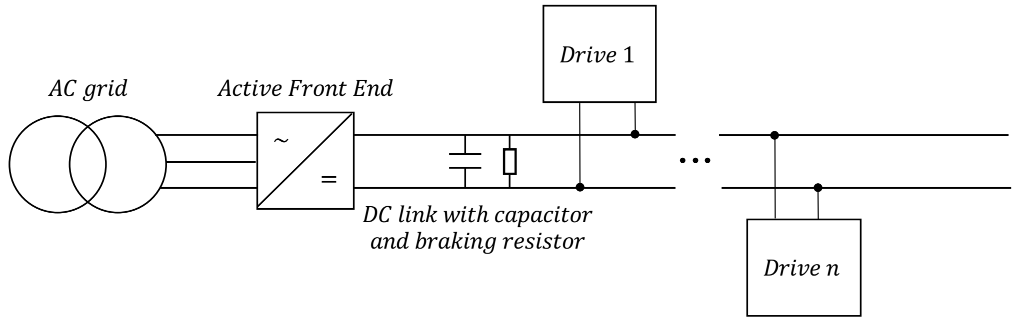

Fig. 1: Topology of a drive system.

Introduction – Flywheel energy storage system (FESS)

- FESS can charge using the braking energy
- FESS can decrease the peak loads drawn from the AC grid
- FESS can achieve millions of cycles and do not use rare materials, e. g. lithium
- FESS are characterized by high discharge rates
- FESS need to be designed safely
- FESS require peripheral devices (vacuum pump and cooling system)

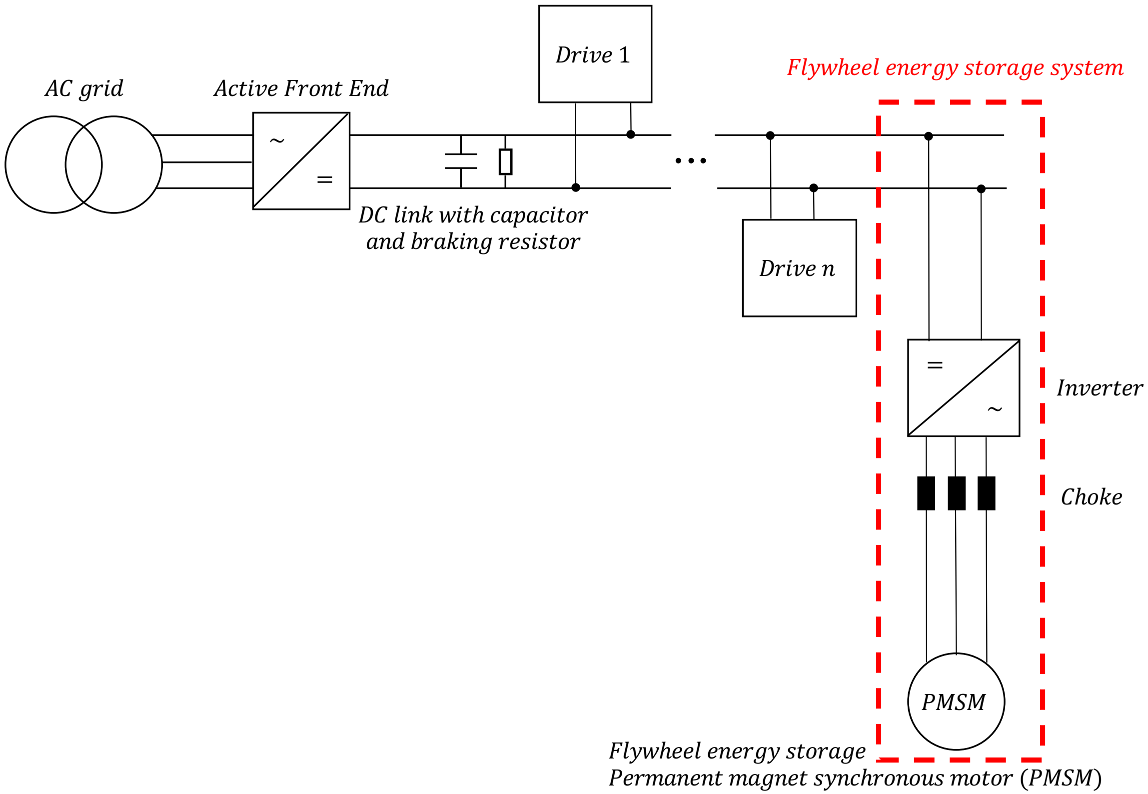

Fig. 2: Topology of a drive system with an integrated flywheel energy storage system.

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Adaptive control – MIAC vs. MRAC

- Adaption of the desired state of charge (rotational speed) **and** maximum current led by the inverter

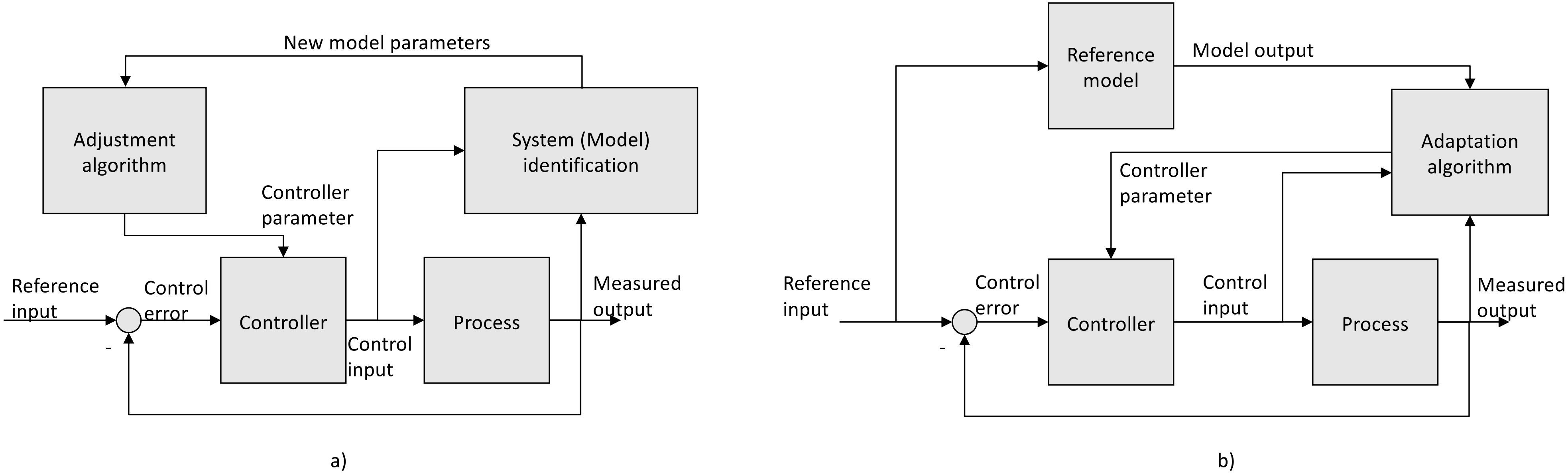

Figure 3. Topology of the a) model identification adaptive control (MIAC) and the b) model reference adaptive control (MRAC).

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Efficiency evaluation

- The active front end shall cover the average load and the FESS shall cover the positive and negative peak loads

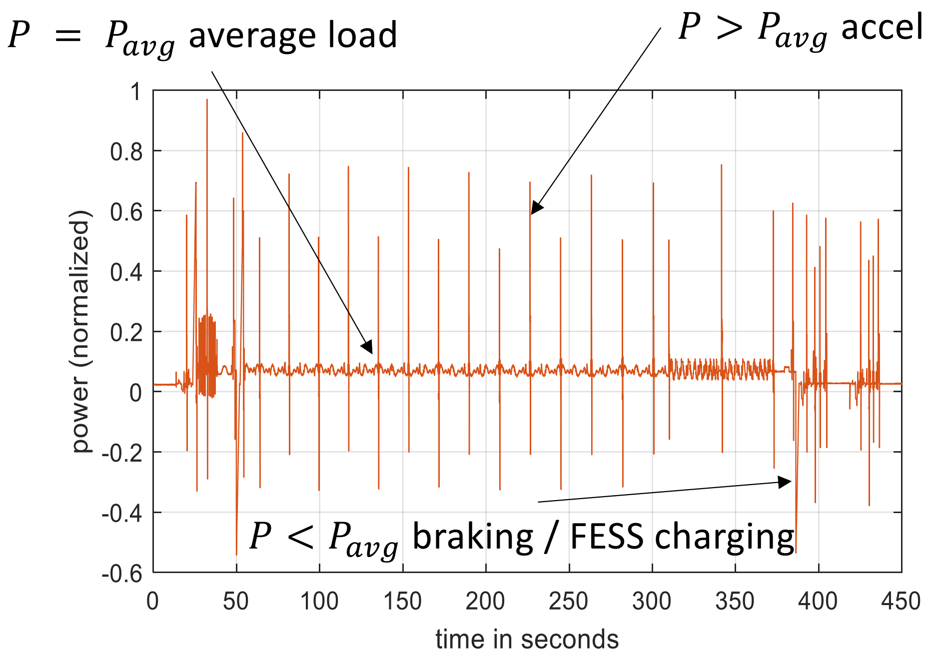

Fig. 4: Normalized AC power on the grid side of machine A1.

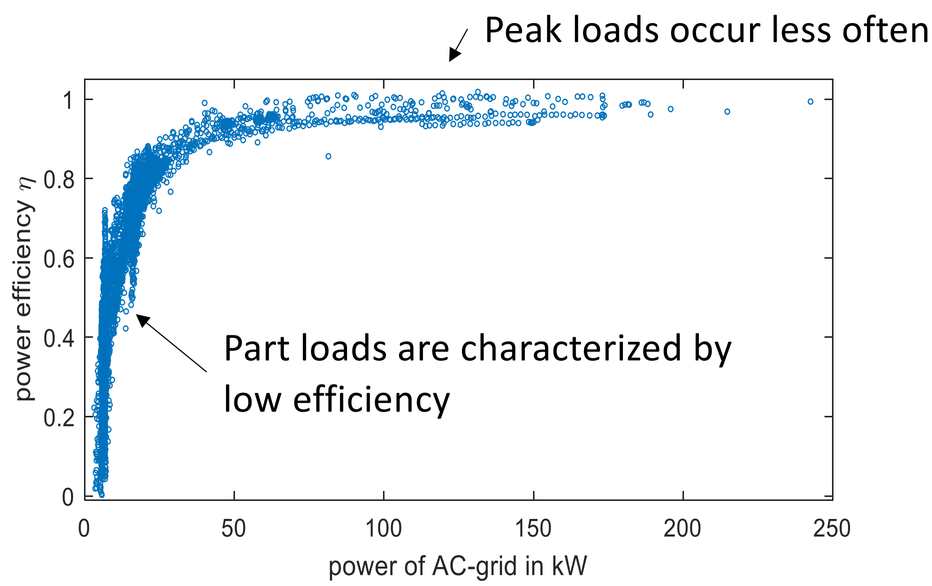

Fig. 5: Conversion efficiencies of the active front end of machine A1 for a power flow from the AC-grid to the DC link.

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Requirements engineering – Methodology

3 workshops with 3 developers and 3 users on benefits, drawbacks and plug ‘n‘ play characteristics led to

- ➢ 74 requirements for the adaptive control algorithm and the system integration
- ➢ 8 dimensions of fulfilment (A-H)

Code	Description	Quantity
A	Maintenance and availability	5
B	Design of peripheral devices	7
C	Sparse communication between machine and FESS	6
D	Required control intelligence	13
E	Reduced complexity of control software integration	4
F	Reduced complexity of hardware integration	9
G	**Economic business case and efficiency**	**19**
H	Regulatory constraints	11

Requirements engineering – Most important findings

- A short installation time and high transferability of the FESS algorithm is a major challenge in the research project.
- The use of braking energy is seen as the main advantage.
- Stand-by losses are a crucial aspect for the users.
- The voltage band used by the FESS, active front end and consumer drives needs to be adjustable.
- Electromagnetic compatibility has to be proven.
- The machine status has to be known at any time.

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Morphological analysis of adaptive control strategies

Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
State detection	DC link voltage	Load current	Rotational speed of the consumer	Induced voltage of the motor	Temperature
Recuperation	DC link voltage	Load current	Rot. speed of the consumer	Induced voltage of the motor	Sound pressure level/ frequency
Load prediction	Day type method	Machine learning approaches	Statistical methods	Expert systems (rule-based)	Fuzzy control
Dynamic load sharing	Droop control	Filter	…	…	…
Load characteristics	Descriptive statistics	Pattern recognition	Machine learning models	Clustering (unsupervised)	…
Control architecture	PID control	MRAC	MIAC	Gain scheduling	Dead-beat control
Teaching	Offline training	Online training		…	…
Energy management	1^{st} order low-pass filter	Adaptive droop control	Droop control with hysteresis	…	…

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Conclusion

- We carried out measurements, workshops and literature research in order to find requirements and solution approaches for the adaptive control and integration of flywheel energy storage systems into industrial applications.

- Two solution paths seem to be promising:

  - Droop control using a characteristic curve, also known as virtual impedance, that measures the DC voltage and decides on the inverter‘s output current
  - Direct measurement of the total consumer current

- Both paths could be combined.

- The MIAC approach seems to be suitable as the algorithm shall work on several different machines without creating individual, theoretical models. Identification and load prediction are realized using machine learning tools.

- The next steps are system modelling and testing in a laboratory as well as in real applications.

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Thank you very much!

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