



Study on Energy System Configuration of Wireless In-Wheel Motor with Supercapacitor

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**June 21th 4D – Electric Drive Vehicle Technology
EVS29**

- Introduction
- The First Trial Unit of Wireless In-Wheel Motor
- The Second Trial Unit of W-IWM (W-IWM2)
- Power-flow Control
- Simulations
- Experiments
- Conclusion

□ 1. Introduction

□ In-Wheel Motor

Independent wheel torque control

Weight reduction and high responsivity

Interior space saving

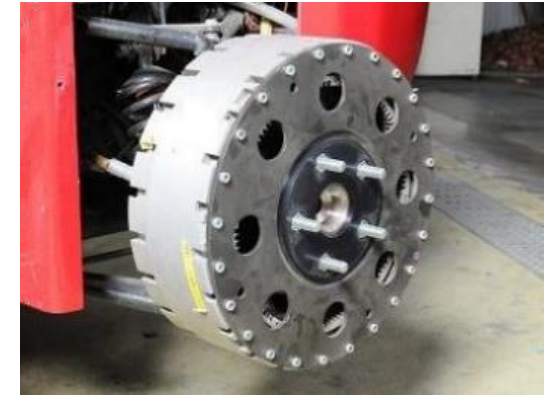
□ Problems

Power lines disconnection

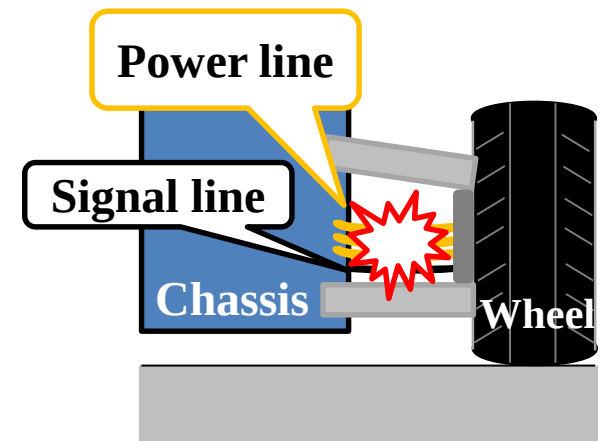
Vibration and impact caused by relative displacement

Continuous bending caused by steering

Power lines freezing in cold region



In-Wheel Motor of 「FPEV2-Kanon」



Radical solution using Wireless Power Transfer

□ 1. Introduction

□ Wireless Power Transfer

Magnetic Resonant coupling

Add resonant capacitors

⇒ Power Factor compensation S-S
S-P etc.



WPT using Magnetic Resonance Coupling

Resonant frequency	Distance	Efficiency	Power
kHz – MHz	0.1 – 1 m	Coil to Coil Over 90 %	0 – 100 kW

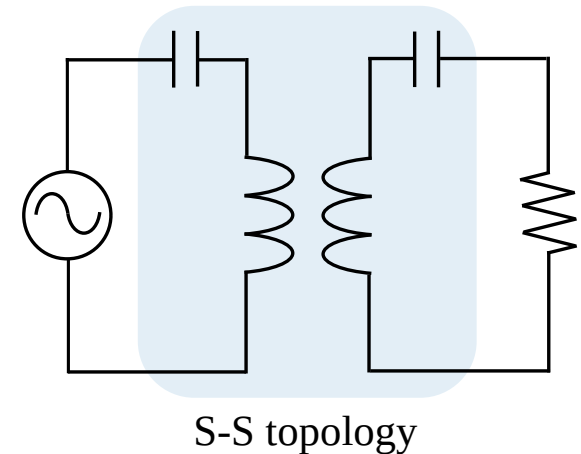
Series-Series topology

Insert an resonant capacitor to coil in series

Good for bidirectional power transfer

Suitable for Electrical Vehicle application

⇒ **Resonant frequency 85 kHz**
Transmitting distance 0.1 – 1 m
Transmitting power over kW



□ Introduction

□ The First Trial Unit of Wireless In-Wheel Motor

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□ Power-flow Control

□ Simulations

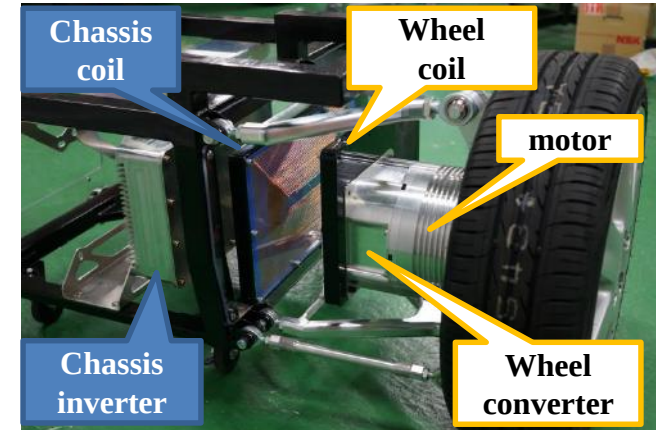
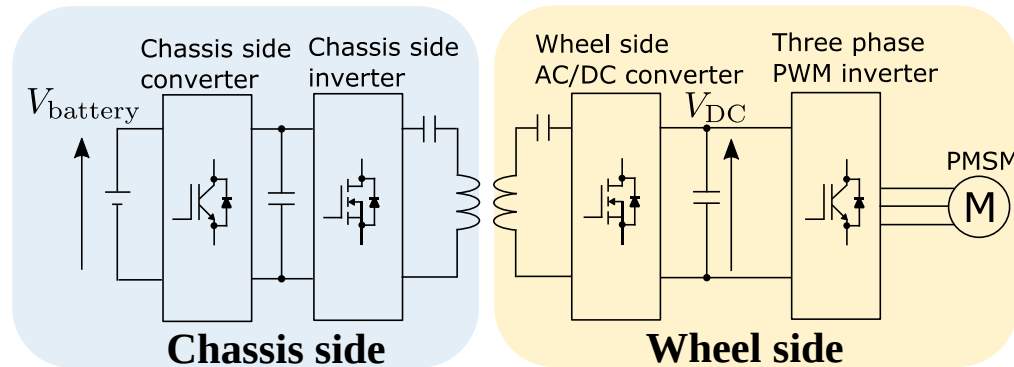
□ Experiments

□ Conclusion

□ 2. The First Trial Unit of W-IWM

□ Wireless In-Wheel Motor

The world first In-Wheel Motor driven by WPT
 Radical solution for power lines disconnection
 Transmit **3.3 kW** at the efficiency about **89%**



The first trial unit of W-IWM



Experimental vehicle with W-IWM

Improve practicability of IWM drastically

□2.The First Trial Unit of W-IWM

□Real car driving



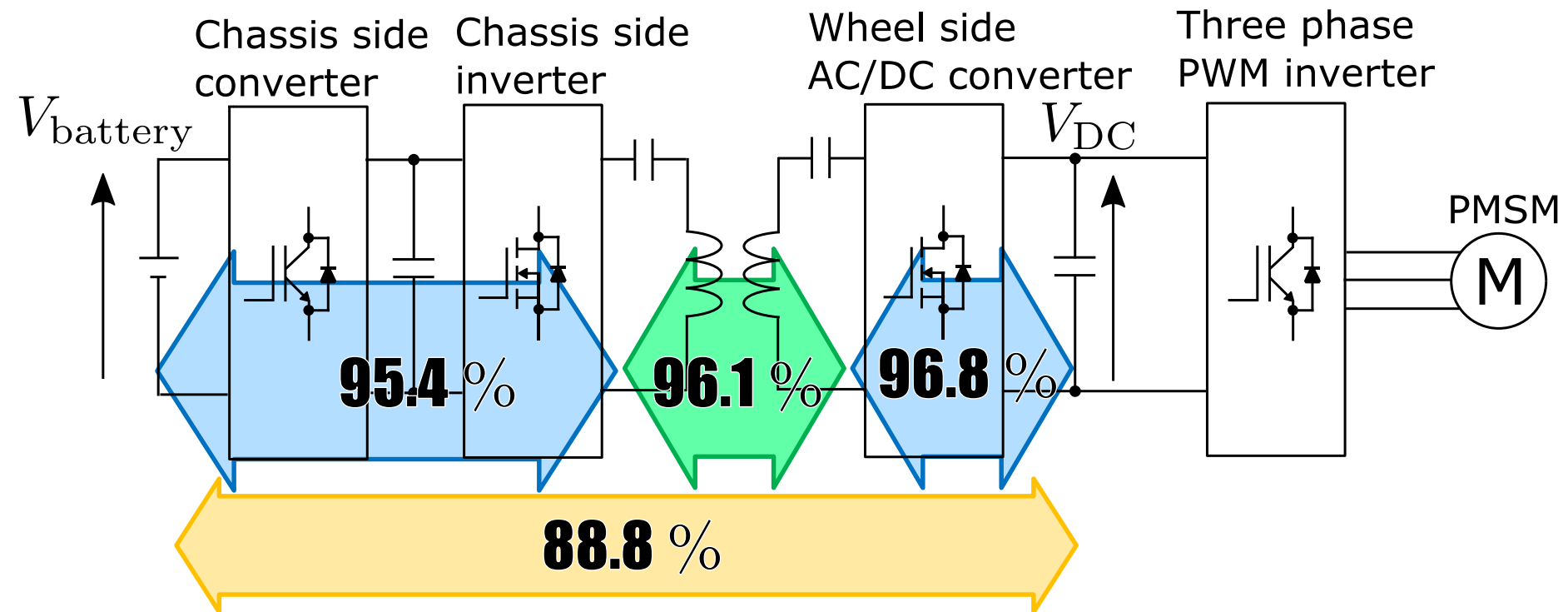
Kashiwa Campus, The University of Tokyo

□ 2. The First Trial Unit of W-IWM

□ Efficiency

Efficiency between chassis battery and wheel side DC-link

Transmit **3.3 kW** from the chassis battery to the wheel side DC-link



DC to DC efficiency is about 89 %

□ 2. The First Trial Unit of W-IWM

□ Dynamic-Wireless Power Transfer

Transmit power from road side transmitter

Charge EVs while driving from infrastructure



Range extension

Battery capacity reduction

Battery charging time saving



UK plan for Wireless re-charging lane

<https://www.gov.uk/government/organisations/highways-england>

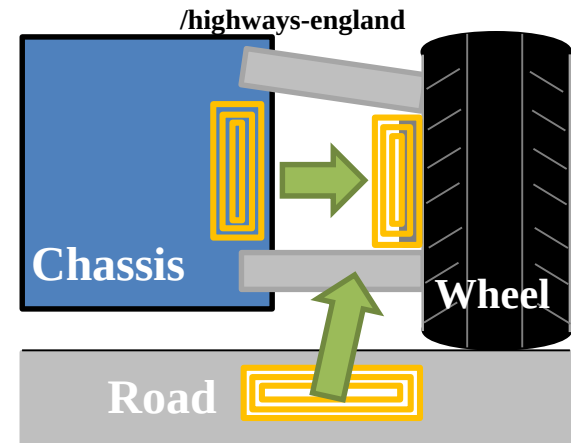
D-WPT for Wireless In-Wheel Motor

Drive the motor via WPT from road side



High efficiency

WPT power go through less converters



Further improvement on practicability is promising

□2.The First Trial Unit of W-IWM

□ Advanced control of electric vehicles and development of wireless in-wheel motors

Plenary Lecture on IEEE International Conference on
Advanced Intelligent Mechatronics 2016 July 12-15 Banff, Canada



Hiroshi FUJIMOTO

Advanced motion control and autonomous driving of EVs

Enhance safety, driving comfort, and cruising range by IWM

Wireless In-Wheel Motors

Overview and design method of W-IWM

Effectiveness verification by real car driving test

□ Index

□ Introduction

□ The First Trial Unit of Wireless In-Wheel Motor

□ The Second Trial Unit of W-IWM (W-IWM2)

□ Power-flow Control

□ Simulations

□ Experiments

□ Conclusion

□3. The Second Trial Unit (W-IWM2)

□ W-IWM2

Power up

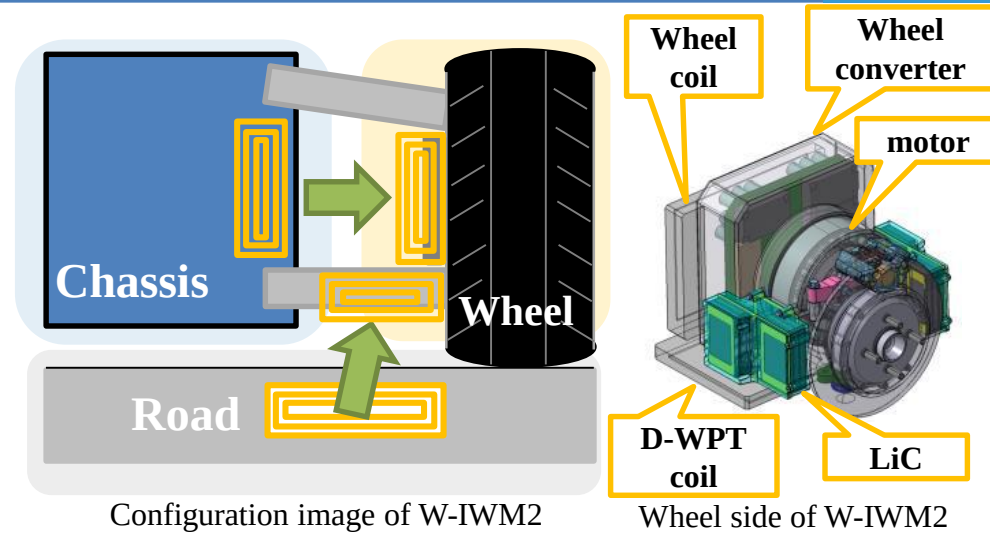
3.3 kW/Wheel → 12 kW/Wheel

Further efficiency improvement

Regeneration efficiency improvement

Dynamic-WPT

Further driving range extension



□ Proposed method

Lithium-ion Capacitor on the wheel side

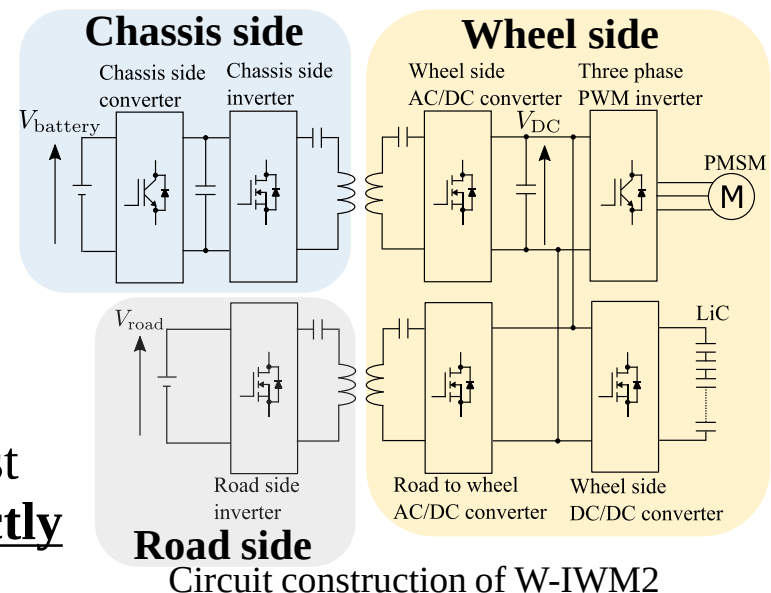
Regenerate wheel power within wheel side

Regeneration efficiency improvement

Additional circuit for Dynamic-WPT

Receiving coil for D-WPT can be placed lowest

Drive the motor via D-WPT from road directly



□3. The Second Trial Unit (W-IWM2)

□ Efficient regeneration

Conventional

Efficiency of regeneration via WPT **89 %**

Proposed

Regenerate wheel power to LiC **96 %**

Regenerate and power via WPT **79%**

Regenerate and power via LiC **92%**

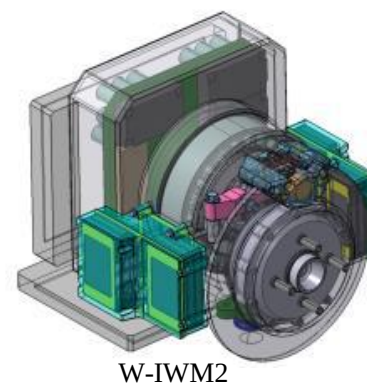
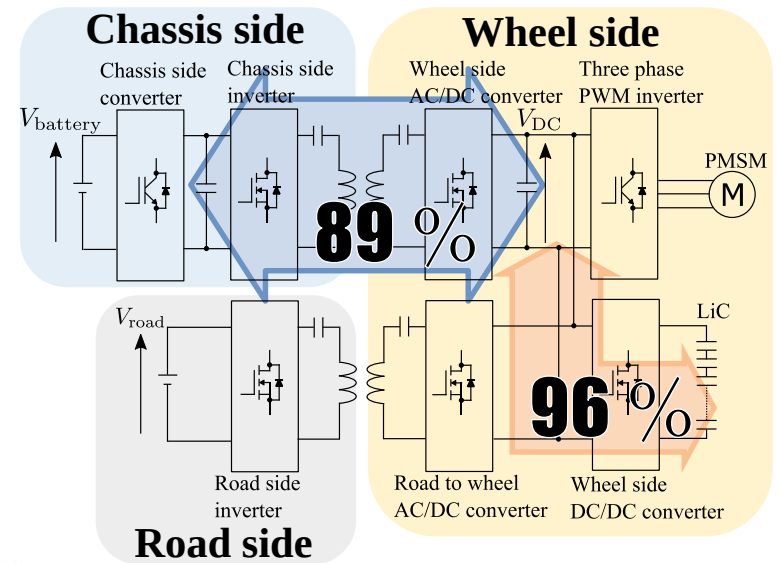
Regenerative power should go through LiC

□ Dynamic-WPT

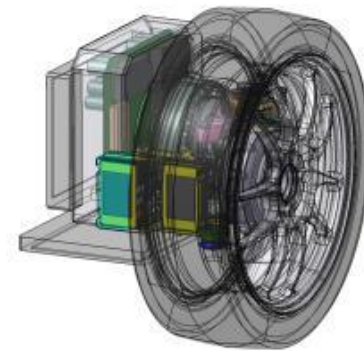
Additional circuit for D-WPT

Drive the motor via D-WPT from road directly

Power-flow should be controlled



W-IWM2



W-IWM2 w/ wheel

Power-flow control for efficient operation

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□4.Power-Flow Control

□ Control method for W-IWM2

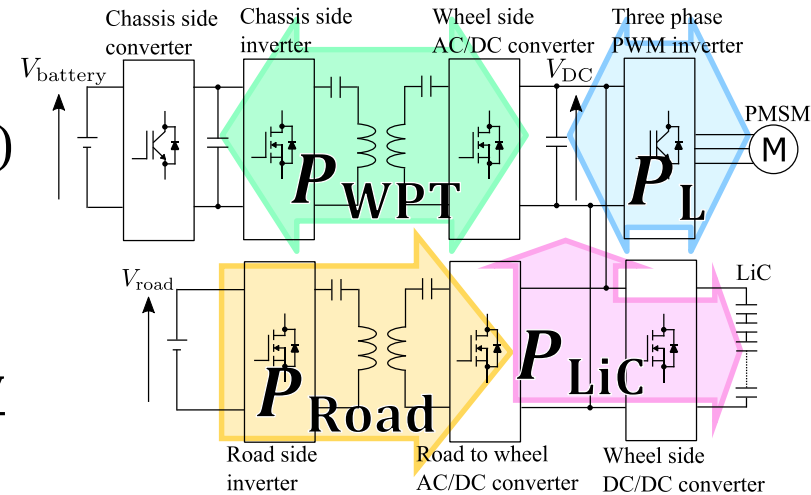
Multiple power sources

AC/DC converter (WPT from the chassis side)

AC/DC converter (D-WPT from a road side)

DC/DC converter (LiC)

Power should be controlled properly



Voltage feedback control of the wheel side DC/DC converter

LiC powers or regenerates according to a power-flow change

$$P_L = P_{WPT} + P_{LiC} + P_{Road}$$

Power control of the wheel side AC/DC converter

P_{WPT} can be controlled

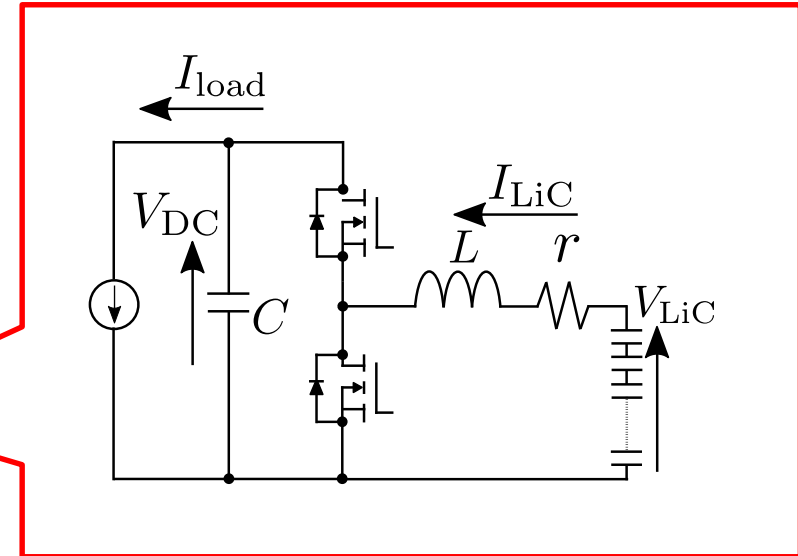
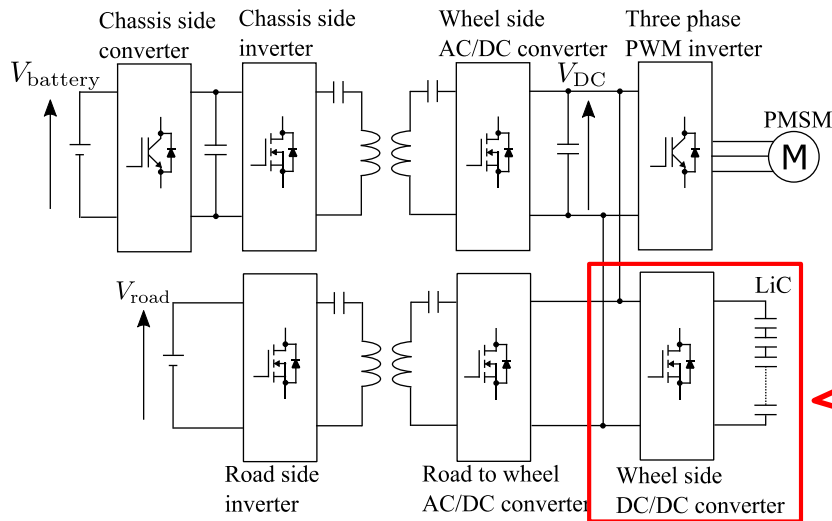


P_{LiC} and SOC of LiC can be controlled

Power-flow control of multiple power sources

□4.Power-Flow Control

□Load voltage V_{DC} control by wheel side DC/DC converter



Linearization using State-Space Averaging method

Steady state

$$D' = \frac{V_{LiC} + \sqrt{V_{LiC}^2 - 4rV_{DC}I_{load}}}{2V_{DC}} \quad I_{LiC} = \frac{I_{load}}{D'}$$

Minute fluctuation

$$\frac{dv_{DC}}{dt} = \frac{D'}{C} i_{LiC} + \frac{I_{LiC}}{C} d' - \frac{1}{C} i_{load}$$

V_{LiC} : Voltage of LiC

V_{DC} : Load voltage

I_{LiC} : Current of LiC

I_{load} : Load Current

r : ESR of LiC and Inductor

D' : Duty ratio of upper switch

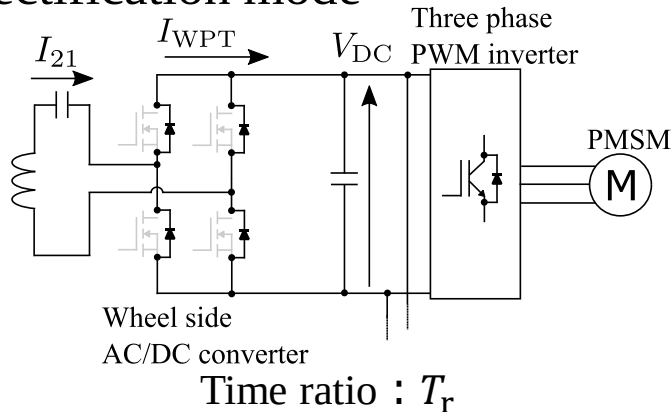
Control on power-flow of the wheel side

□4.Power-Flow Control

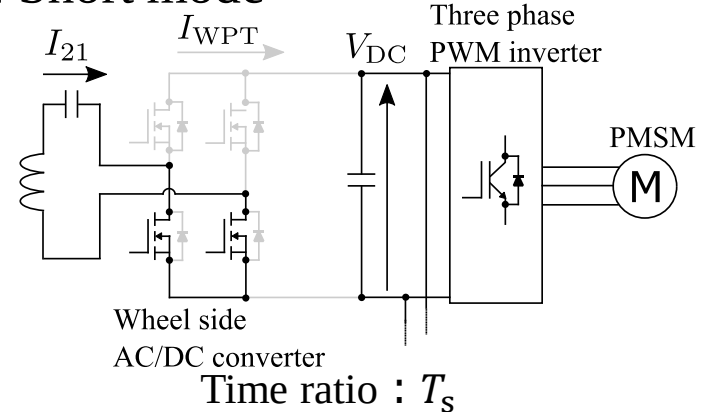
□Power control by wheel side AC/DC converter

Two-mode control

□ Rectification mode



□ Short mode



Average output current of the wheel side AC/DC converter by switching two modes of wheel side AC/DC converter

$$\text{Duty ratio : } \alpha = \frac{T_r}{T_r + T_s}$$

$$\bar{I}_{dc} = \frac{2\sqrt{2}}{\pi} \alpha \bar{I}_{21} \left(\omega_0 L_m V_{11} \gg \frac{2\sqrt{2}}{\pi} R_1 V_{DC} \right)$$

ω_0 : Resonance frequency

L_m : Mutual inductance

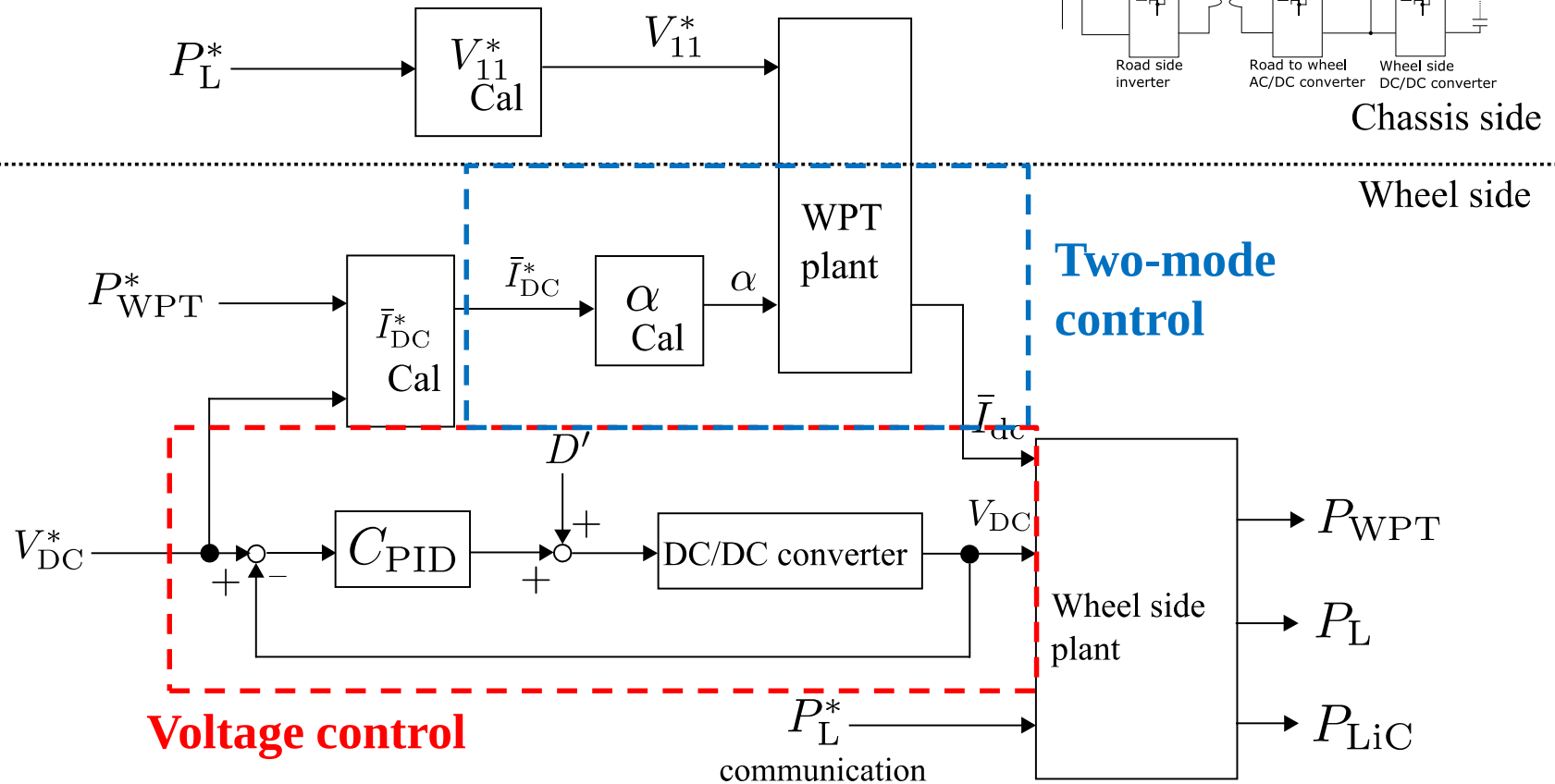
R_1 : Chassis side coil resistance

V_{11} : Effective voltage of chassis side coil

Transmitting power control via chassis to wheel

□ 4. Power-Flow Control

□ Block diagram

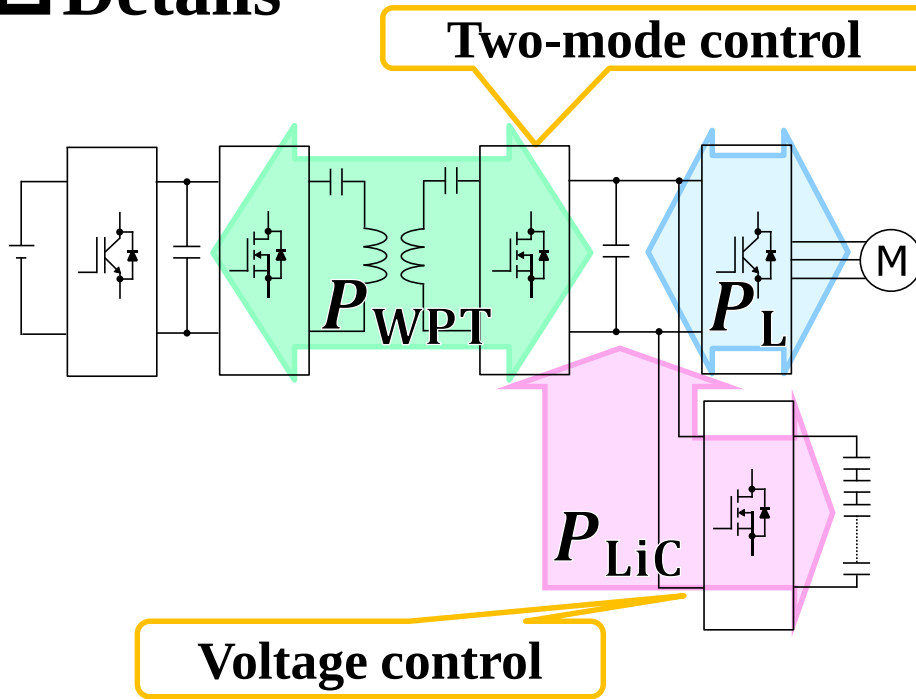


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□ 5. Simulations

□ Details



Resonance frequency	85 kHz
Inductance of coil on chassis side L_1	270 μ H
Inductance of coil on wheel side L_2	250 μ H
Mutual inductance L_m	25.0 μ H
Capacitance of smoothing capacitance C	2200 μ F
Inductance of DC/DC converter L	60.8 μ H
ESR of DC/DC converter and LiC	31.4 m Ω
Switching frequency of DC/DC converter	40 kHz
Pole placement of PID controller for DC/DC converter	-1000 rad/s
Switching frequency of two-mode control	500 Hz

Power-flow fluctuations with load change

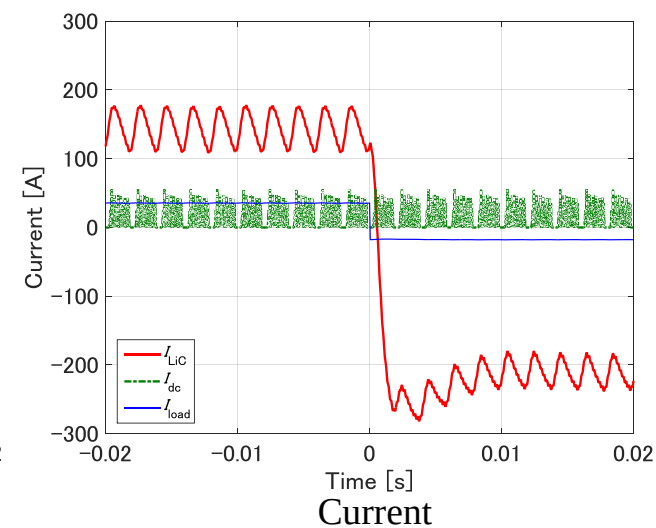
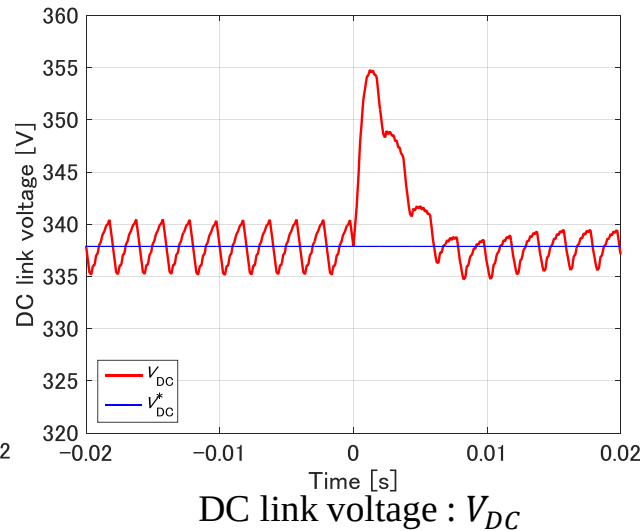
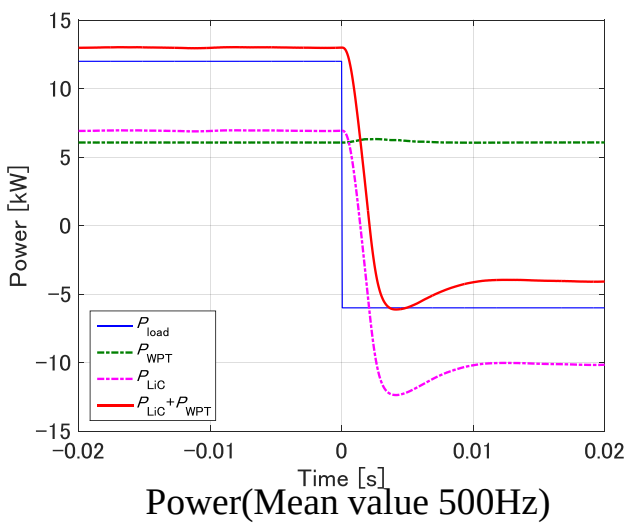
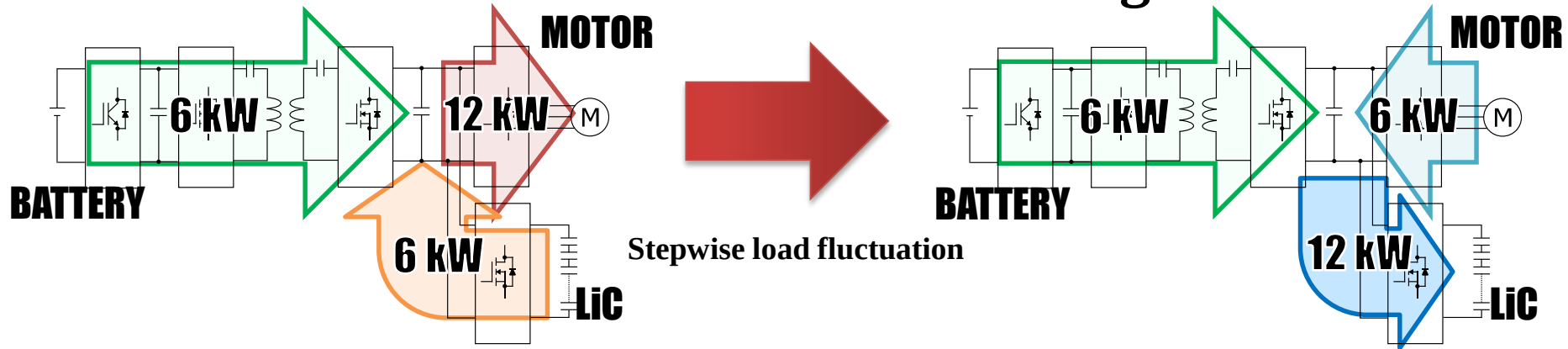
Power-flow control achievable by only voltage control of DC/DC converter

Power-flow fluctuations with P_{WPT} change

P_{LiC} or SOC of LiC are controllable with two-mode control

5. Simulations

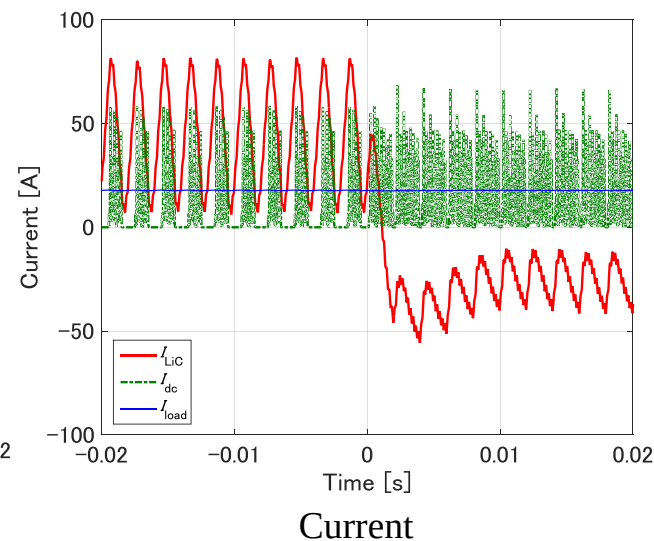
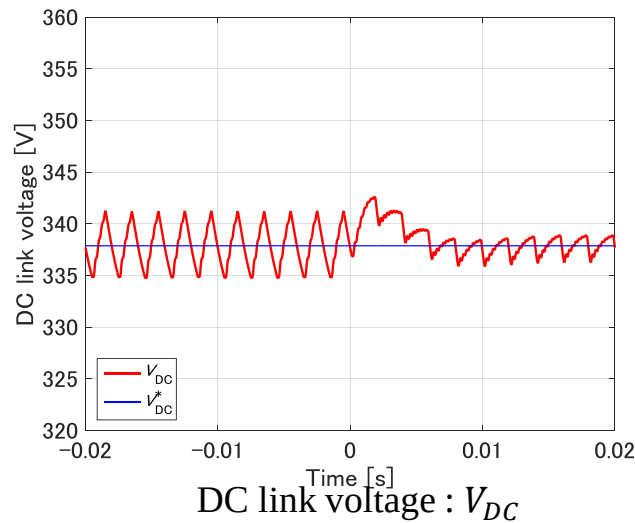
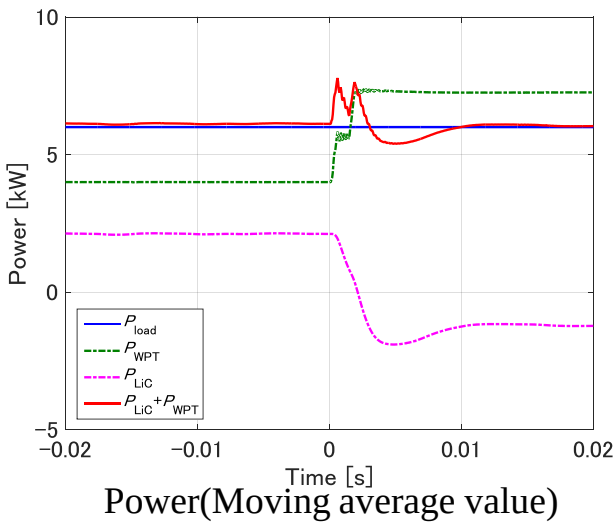
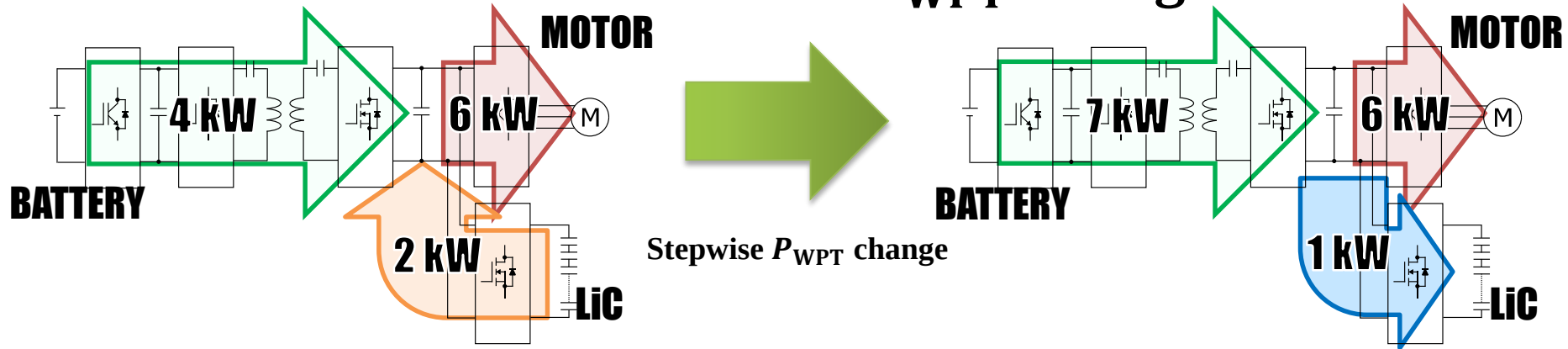
Power-flow fluctuation with load change



Power-flow control achievable by only voltage control of DC/DC converter

5. Simulations

Power-flow fluctuation with P_{WPT} change



P_{LiC} or SOC of LiC controllable by two-mode control

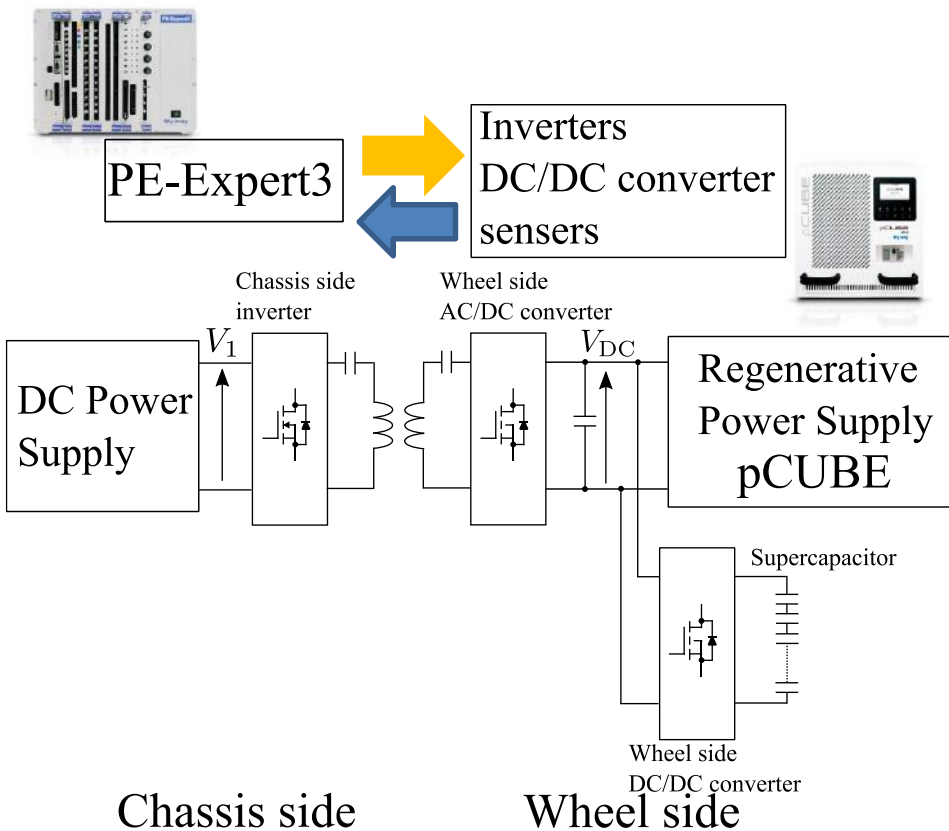
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□ 6. Experiments

□ Experimental setup

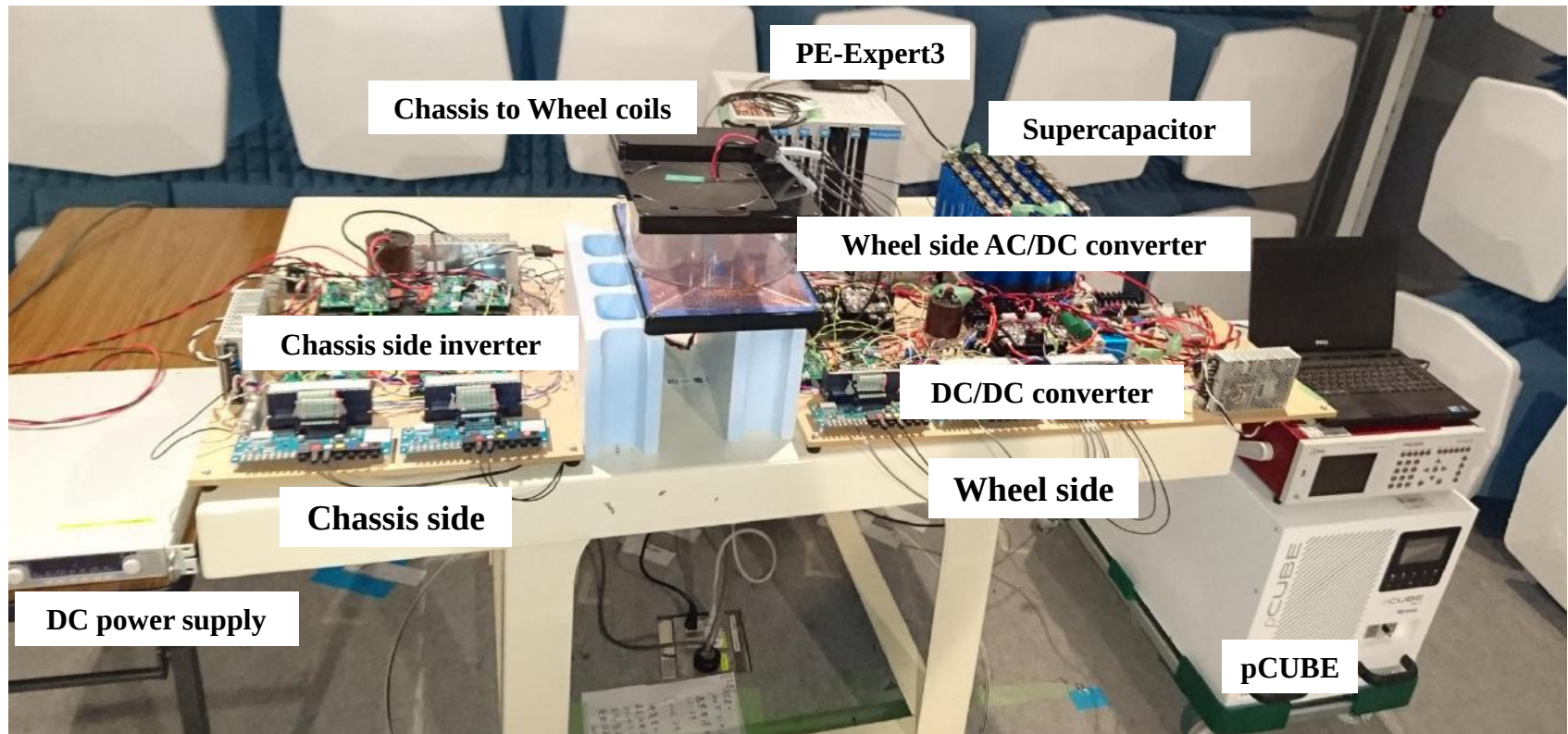
Small power model



Resonance frequency	85 kHz
Inductance of coil on vehicle side L_1	269.63 μ H
Resistance of coil on vehicle side R_1	558.09 m Ω
Inductance of coil on wheel side L_2	224.51 μ H
Resistance of coil on wheel side R_2	361.81 m Ω
Gap between coils	100 mm
Mutual inductance L_m	25.78 μ H
Capacitance of smoothing capacitor C	2145 μ F
Inductance of wheel side DC/DC converter L	60.8 μ H
ESR of DC/DC converter and SC	41.0 m Ω
Switching frequency of wheel side DC/DC converter	40 kHz
Pole placement of PID controller for DC/DC converter	-1000 rad/s
Pole placement of PID controller for AC/DC converter	-6.81 rad/s
Switching frequency of two-mode control	500 Hz
Load voltage V_{DC}	200 V
Voltage of SC V_{LiC}	50 V
Maximum output	1.2 kW

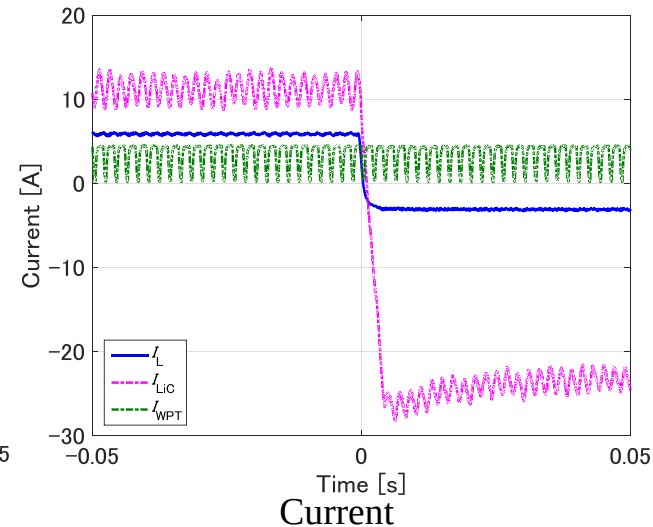
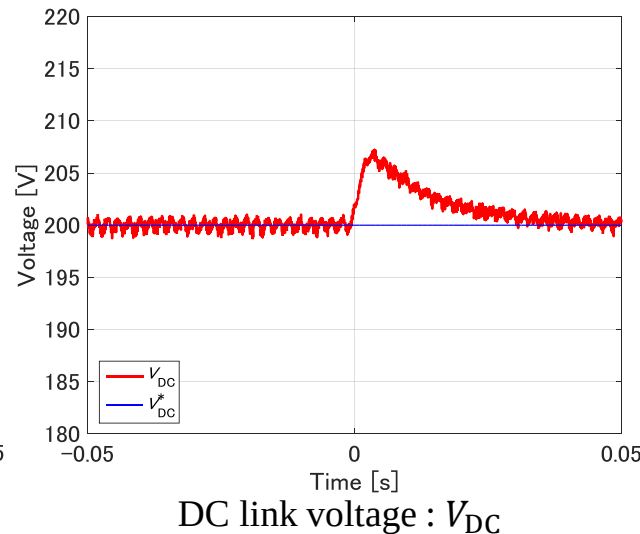
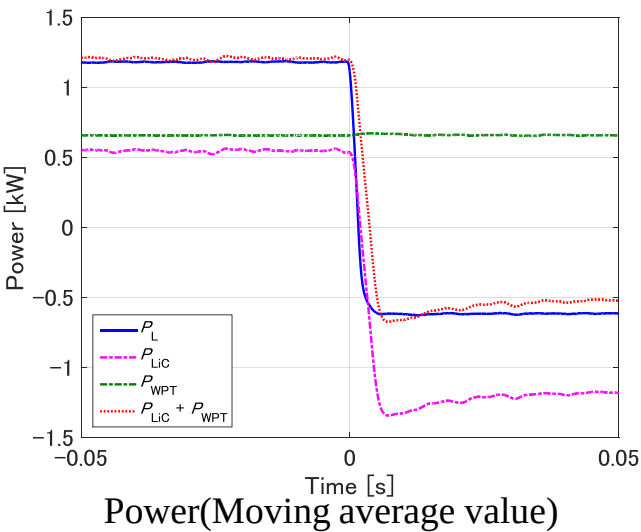
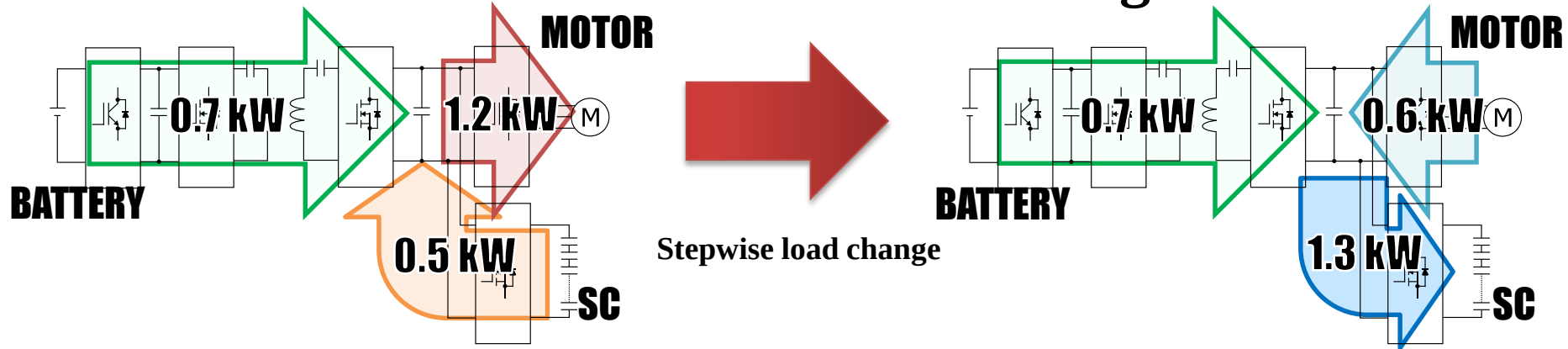
□ 6. Experiments

□ Outline of experimental setup



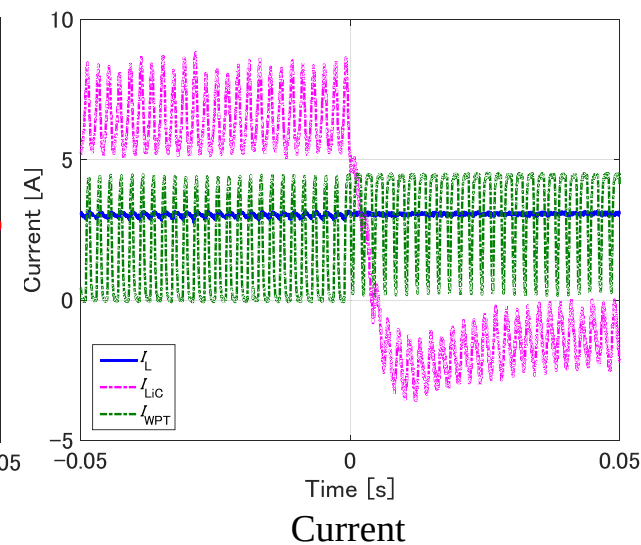
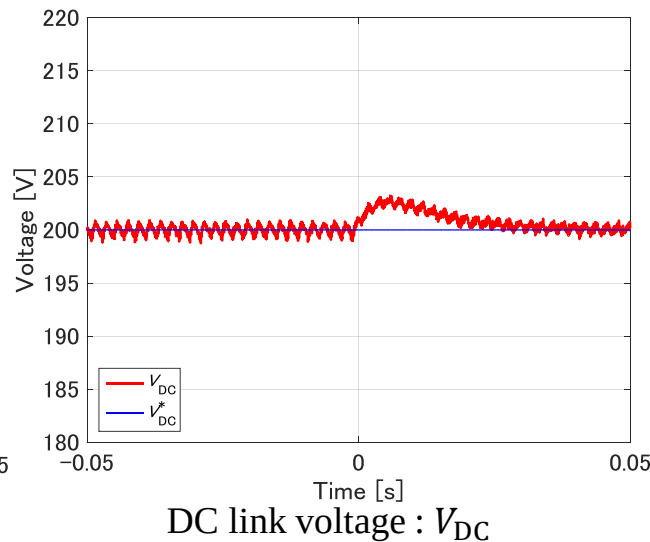
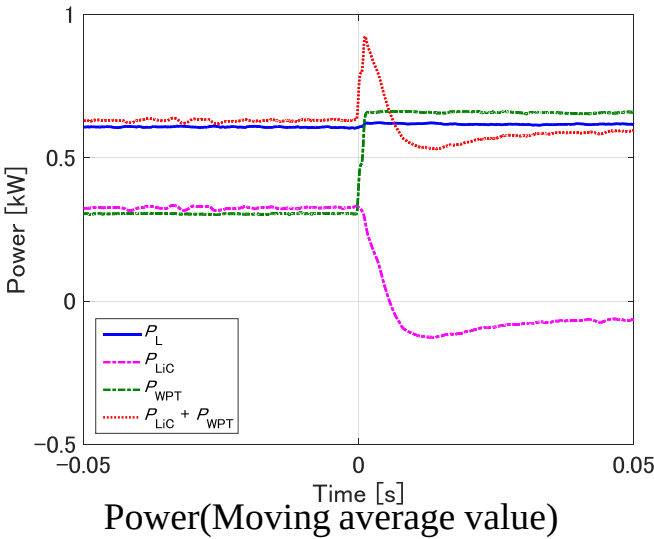
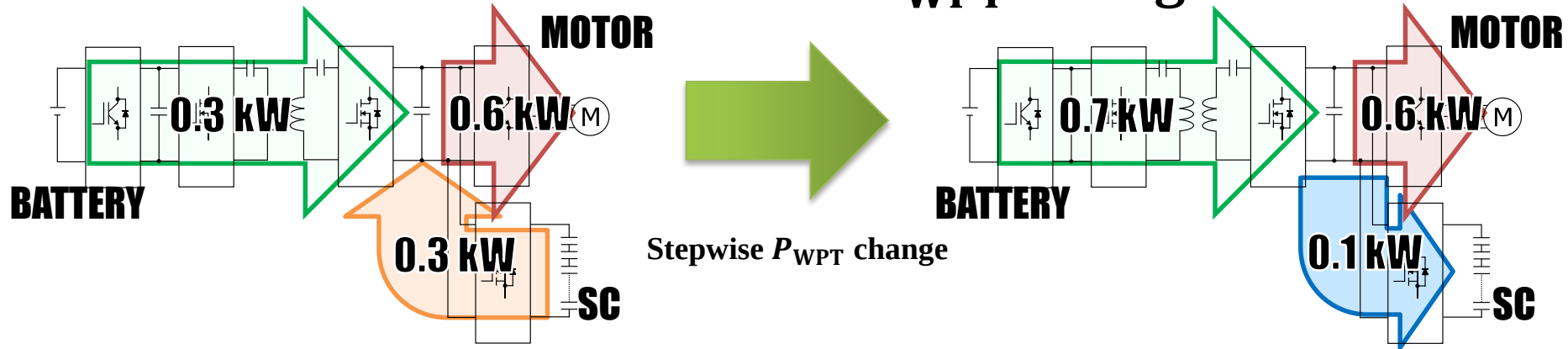
6. Experiments

Power-flow fluctuation with load change



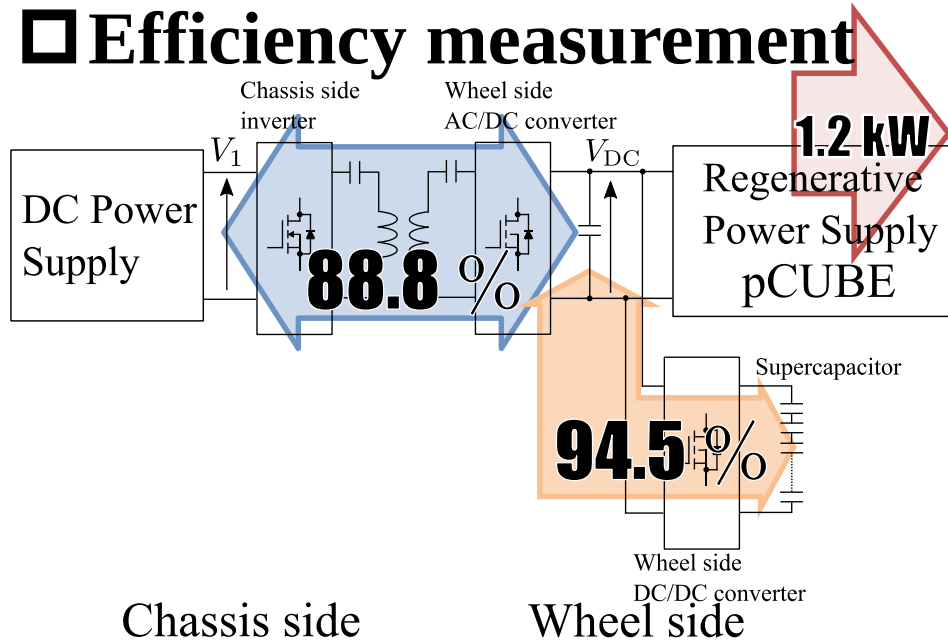
□ 6. Experiments

□ Power-flow fluctuation with P_{WPT} change



6. Experiments

Efficiency measurement



Capacitance of smooting capacitor C	1328 μF
Inductance of wheel side DC/DC converter L	60.8 μH
ESR of inductor	12.0 $\text{m}\Omega$
SiC on- resistance (BSM120D12P2C005:ROAM)	13.0 $\text{m}\Omega$
Pole placement of PID controller for DC/DC converter	-1000 rad/s
DC-link voltage V_{DC}	200 V
Voltage of Supercapacitor V_{LiC}	50 V
Inductor current I_{LiC}	25 - 26 Adc
Load output	1.2 kW

Efficiency of DC/DC converter on different switching frequency

20 kHz	30 kHz	40 kHz	50 kHz	60 kHz	85 kHz
93.6 %	94.1 %	94.5 %	92.0 %	92.8 %	90.8 %

High frequency – Switching loss

Low frequency – Hysteresis loss

$$P_h = k_h f B_m^{1.6}$$

$$B_m = k \frac{E}{fA}$$

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□ 7. Conclusion

□ Study on Energy System Configuration of Wireless In-Wheel Motor with Supercapacitor

W-IWM

Radical solution for power line disconnection



Improves practicality of IWM

W-IWM2

Equips LiC on wheel side

Circuit for Dynamic-Wireless Power Transfer



**Efficiency improvement
D-WPT applicable**

Power-flow control

Voltage control of wheel side DC/DC converter

Power control of wheel side AC/DC converter



**Achieves power-flow control
 P_{LiC} and SOC of LiC controllable**

Future works

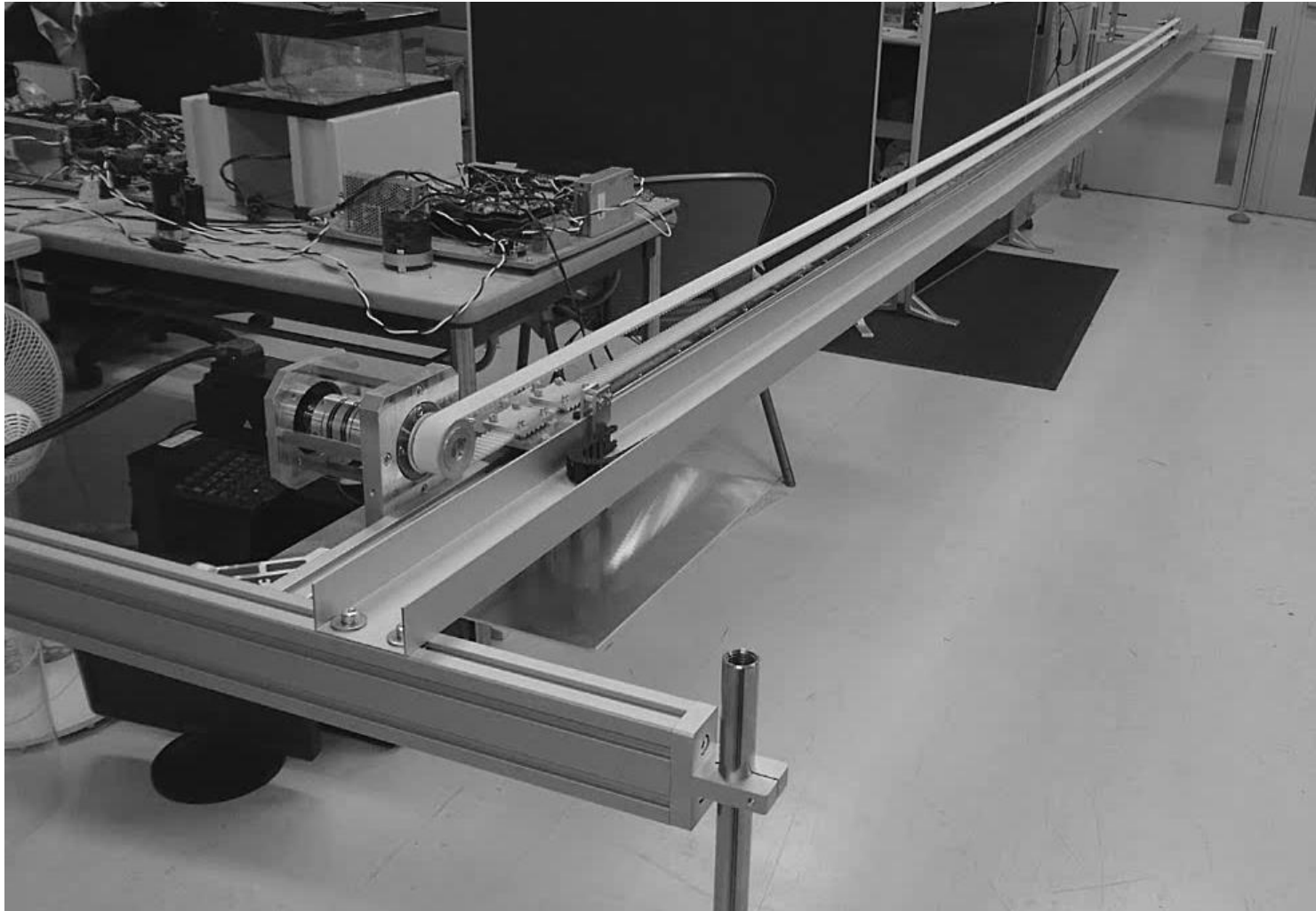
Real machine of W-IWM2 construction

Experiment using small power model

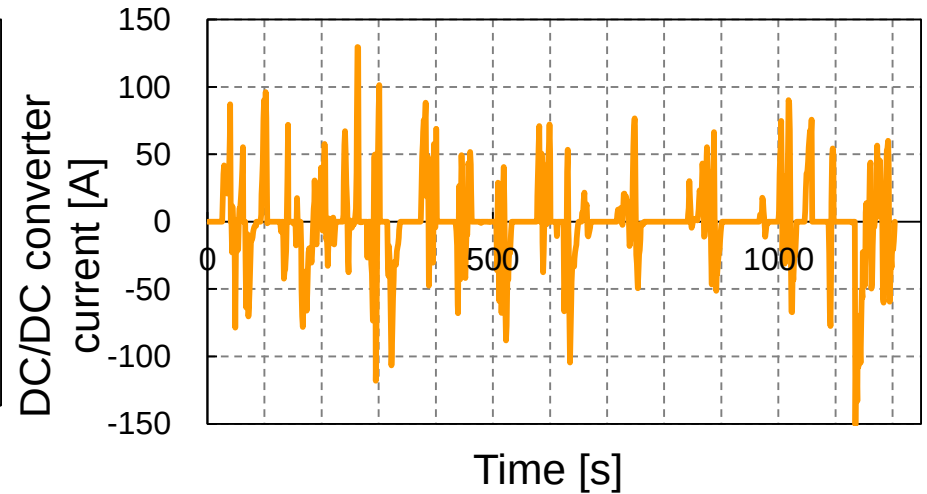
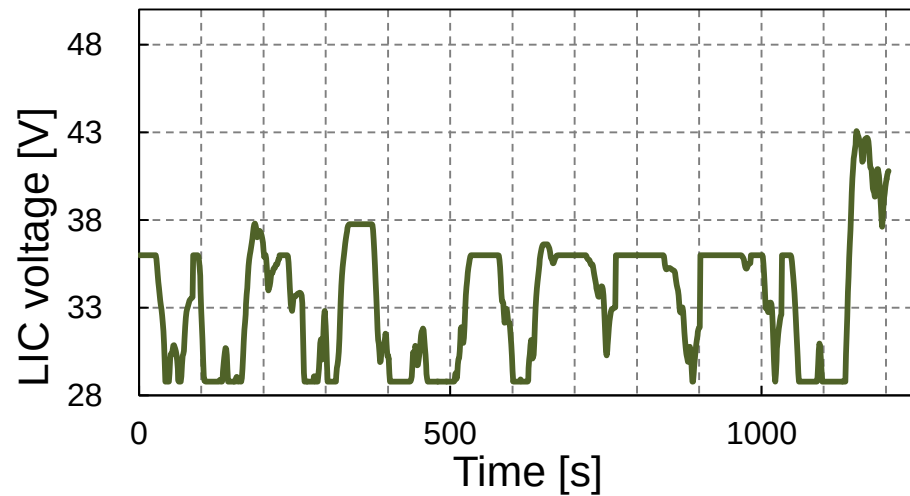
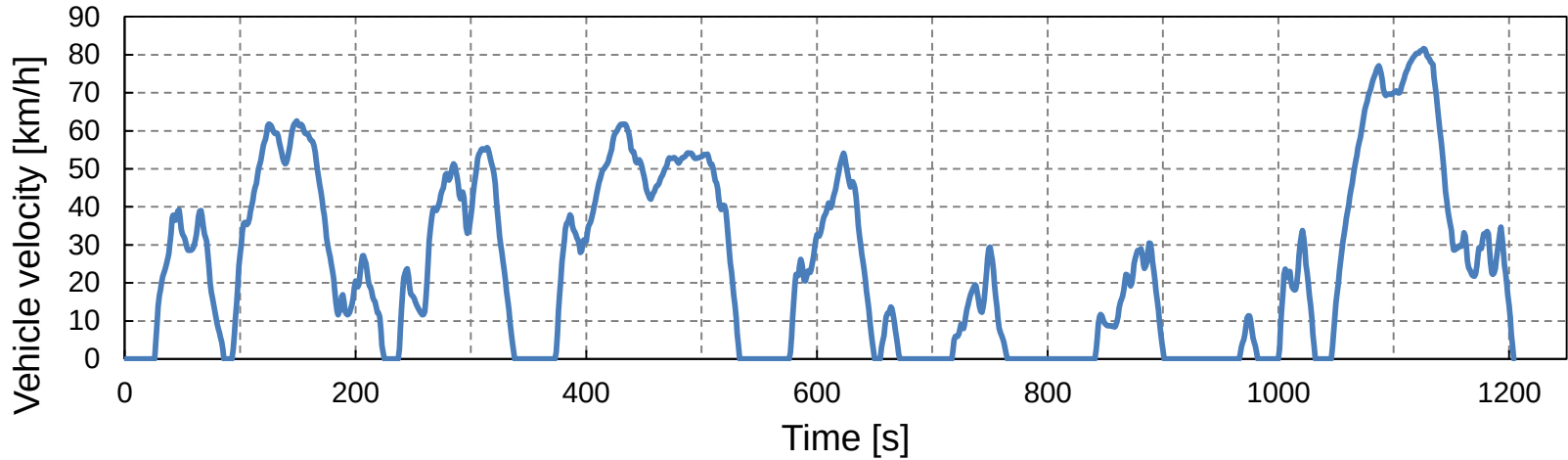


**Experiment using real car
Power management
considering D-WPT**

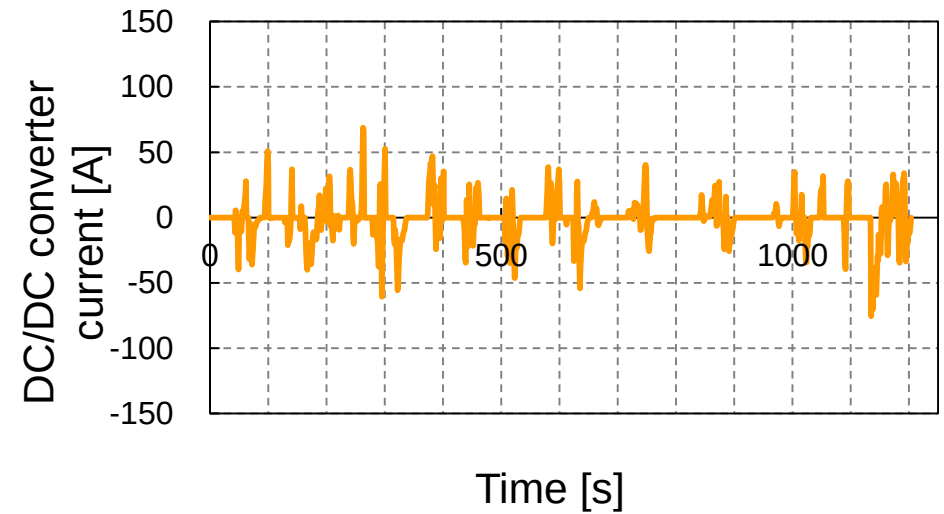
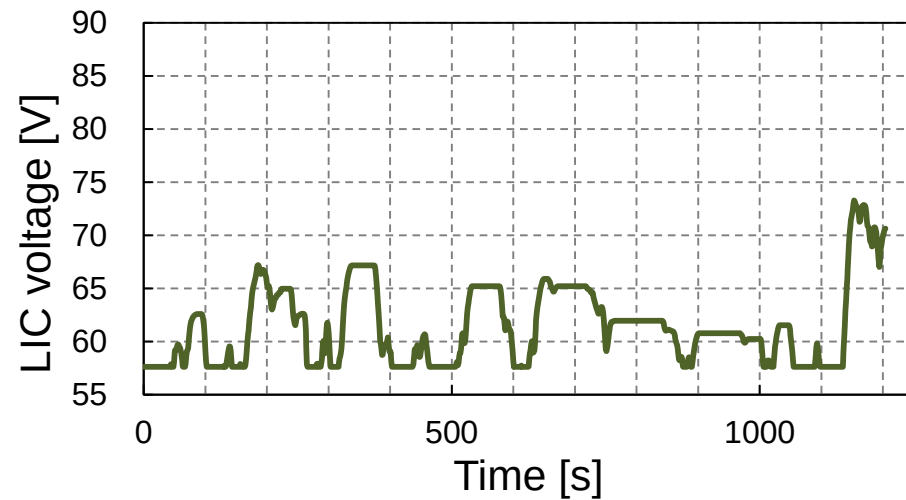
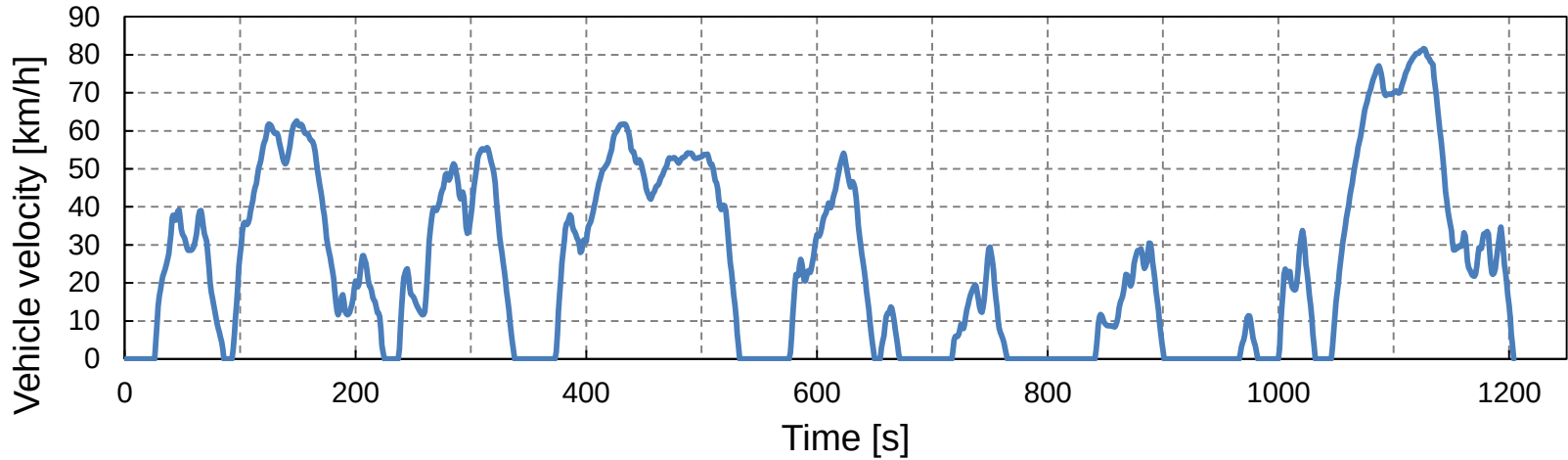
□ Experimental setup for Dynamic-WPT



LiC 12series (JC08)

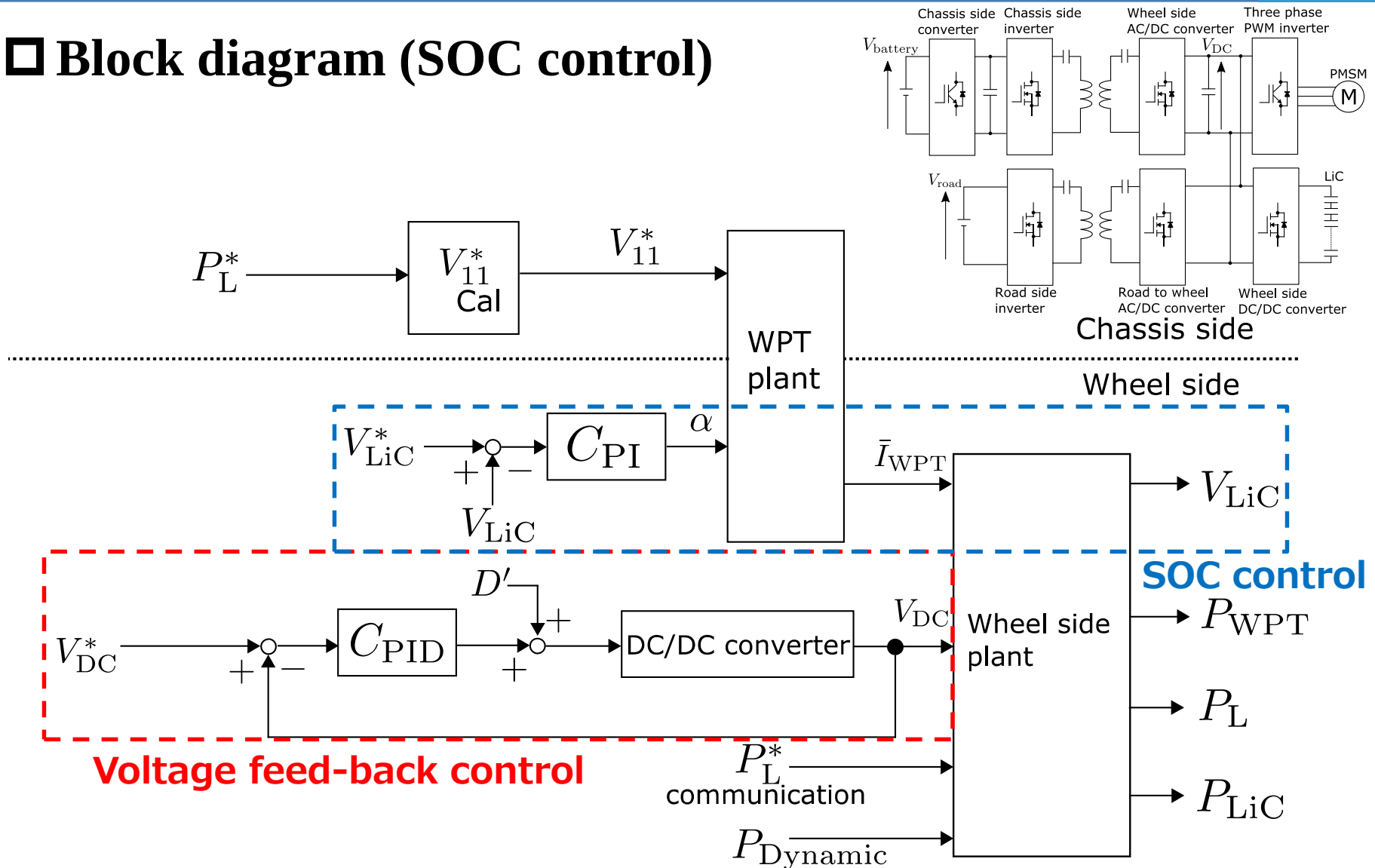


LiC 24series (JC08)



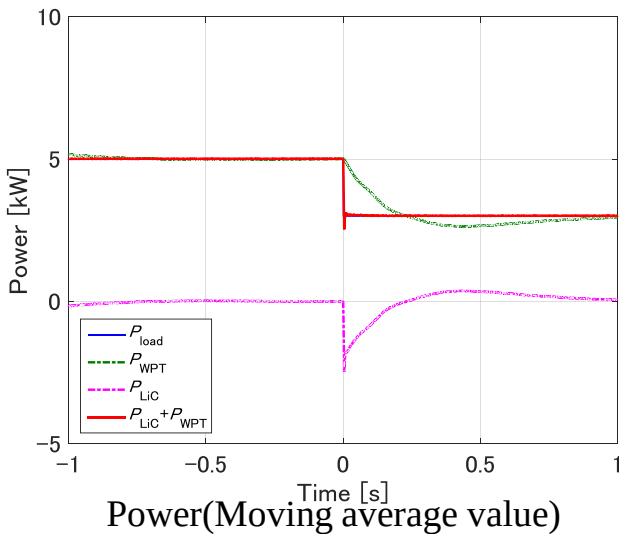
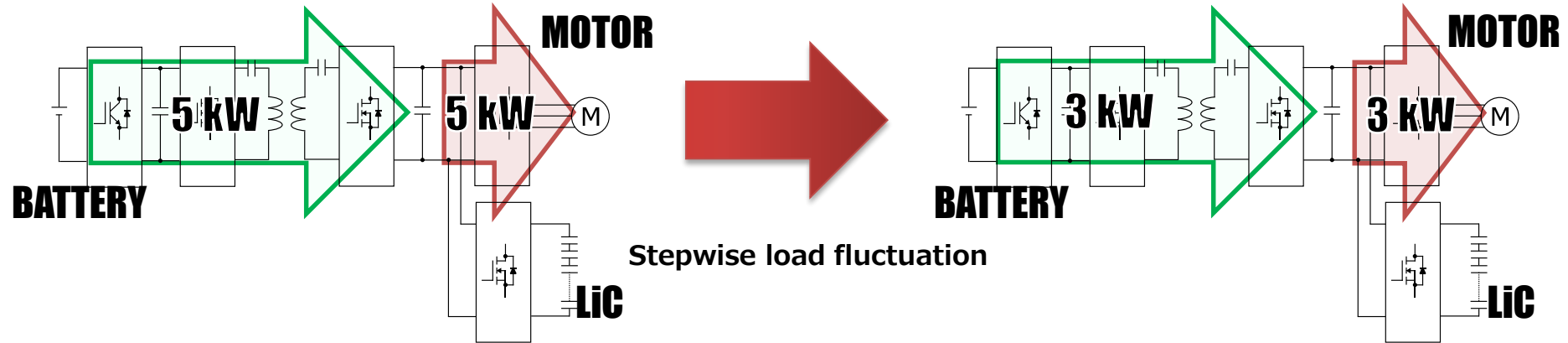
APPENDIX

Block diagram (SOC control)



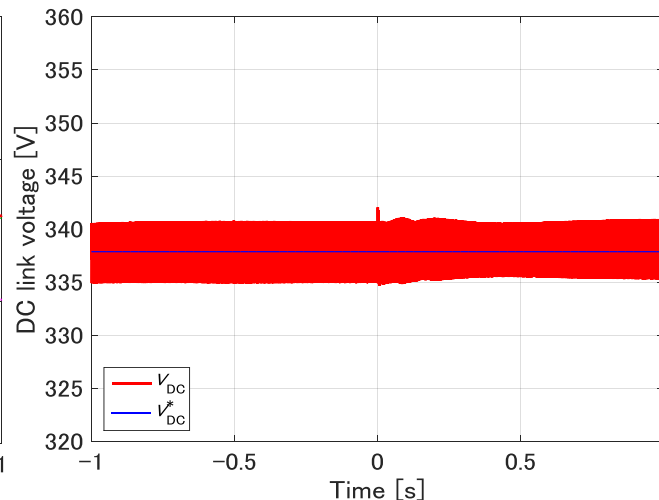
APPENDIX

Stepwise load decrement (5 kW → 3 kW)



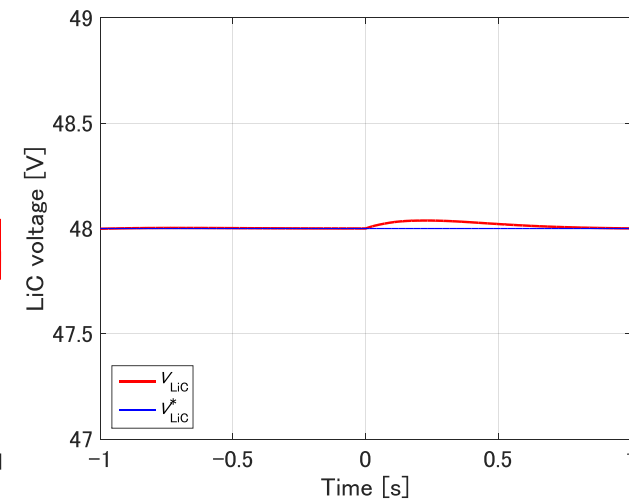
Power(Moving average value)

Load decrement



DC link voltage : V_{DC}

SOC increases

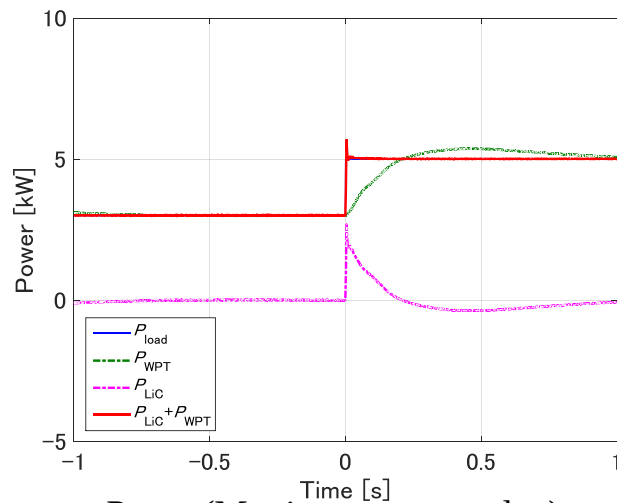
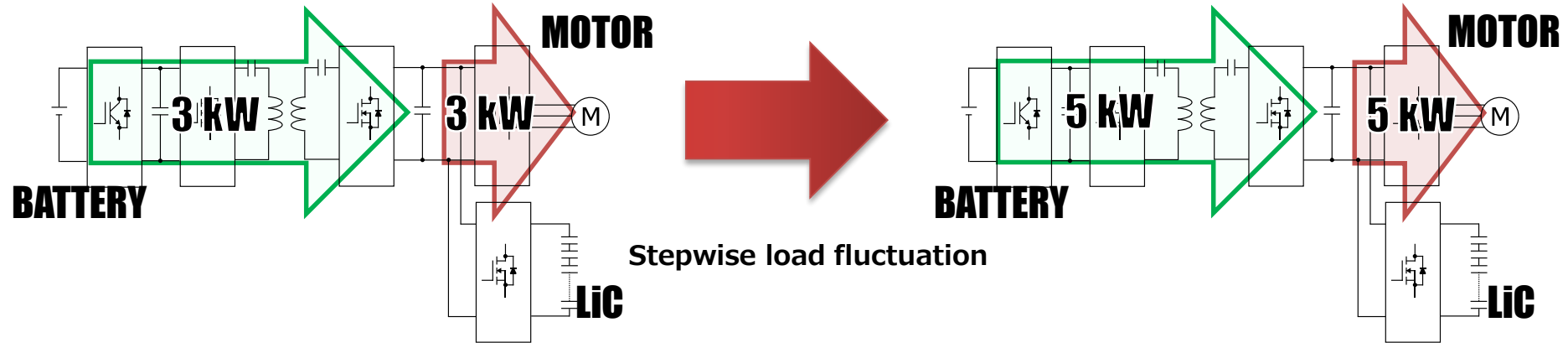


LiC voltage : V_{LiC}

P_{WPT} decreases

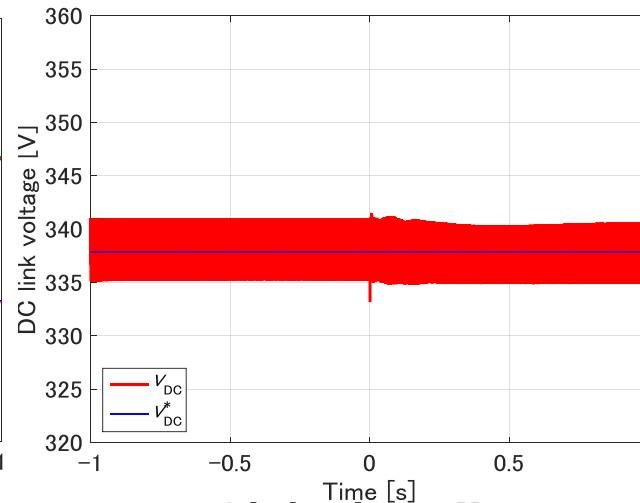
APPENDIX

Stepwise load increment (3 kW → 5 kW)



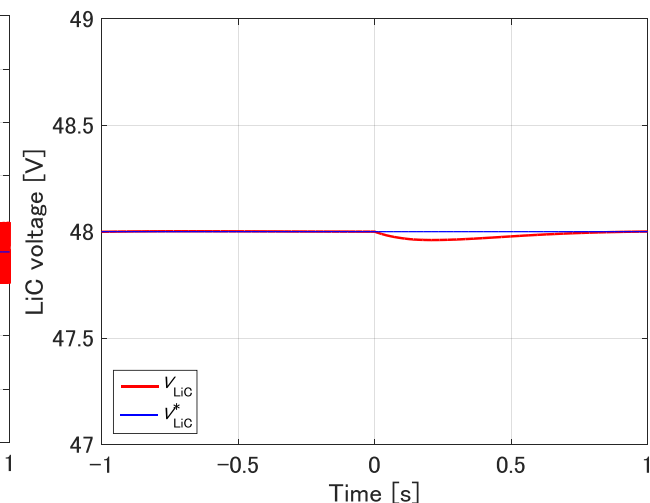
Power(Moving average value)

Load increment



DC link voltage : V_{DC}

SOC decreases

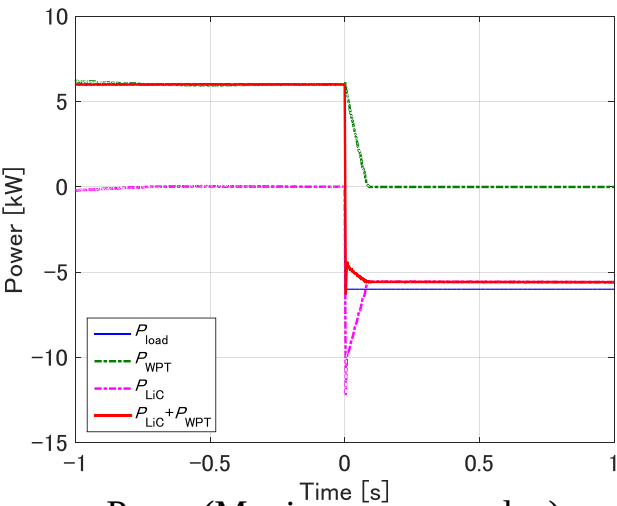
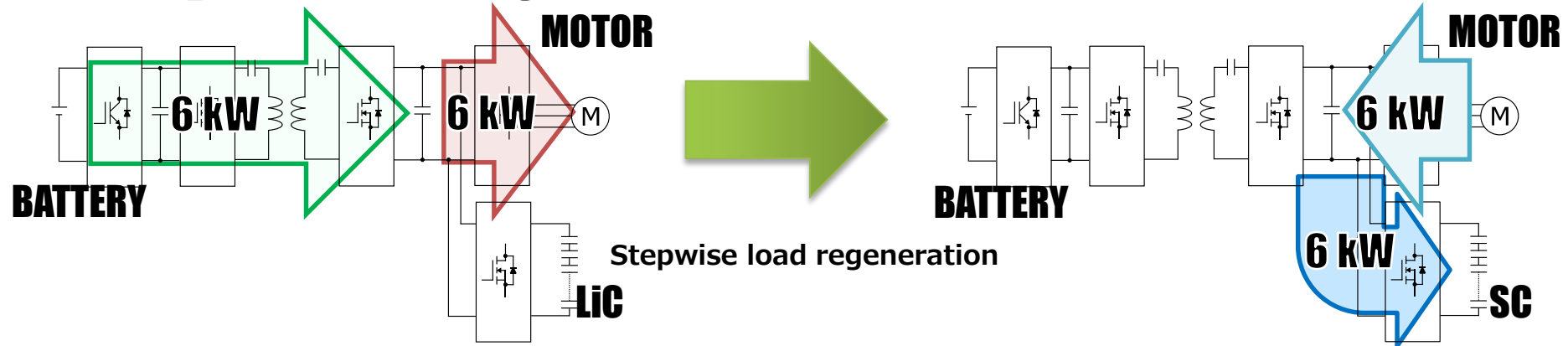


LiC voltage : V_{LiC}

P_{WPT} increases

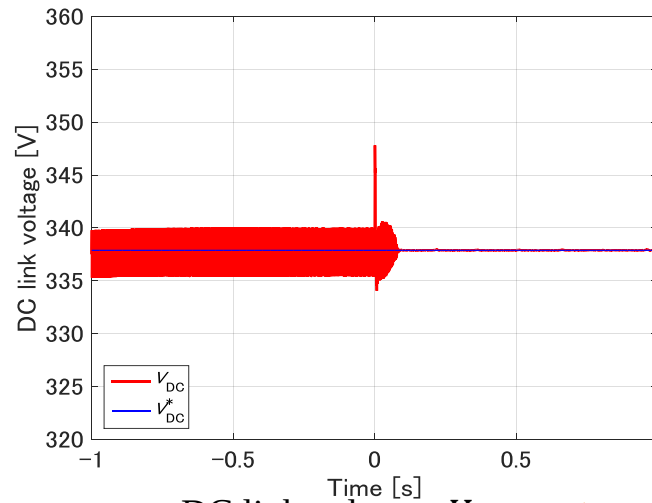
APPENDIX

Stepwise load regeneration (6 kw→-6 kW)



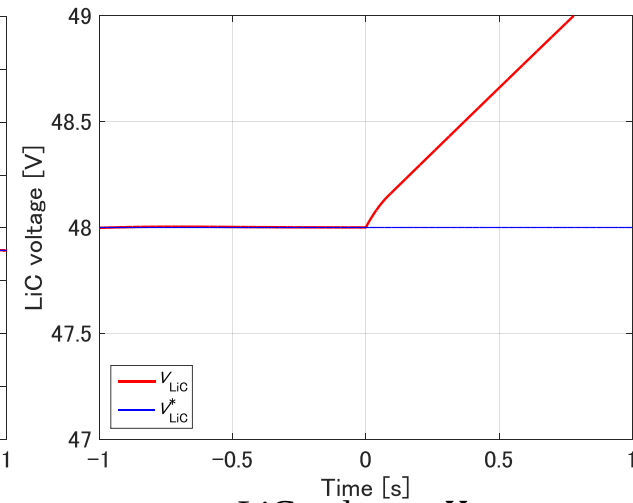
Power(Moving average value)

Load regeneration



DC link voltage : V_{DC}

SOC increases



LiC voltage : V_{LiC}

Stop WPT from chassis