

Dynamic Wireless Power Transfer System for Electric Vehicles to Simplify Ground Facilities

- Real-time Power Control and Efficiency Maximization -

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Outline

1. Introduction
2. System structure of DWPT for EVs
3. Control strategy with proposed method
4. Real-time estimation and controller design
5. Simulation and experiment
6. Conclusion

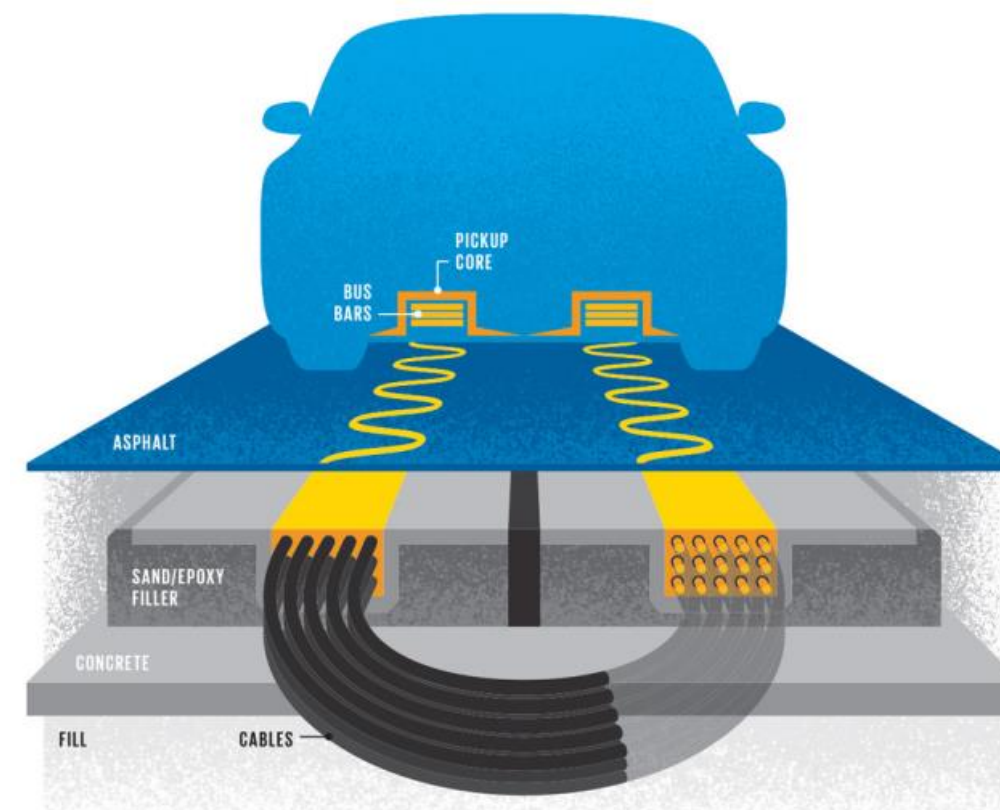
1.1. Background

Wireless Power Transfer (WPT) to EV applications



- Frequent charging and **Dynamic charging** are acceptable.
- The mileage per charge of EVs can be extended.
- The size of the energy storage system can be reduced.

➔ EV becomes cheaper and more useful !



Nissan "LEAF"
(from Nissan HP)

[“British Highway Will Recharge Your Batteries as You Drive”, *IEEE SPECTRUM*, 14 Aug 2015
<http://spectrum.ieee.org/cars-that-think/transportation/advanced-cars/british-highwaywill-recharge-your-batteries-as-you-drive>]

1.2. Dynamic charging for EVs

A dynamic WPT system can provide electricity to moving EVs.

Challenges

- **Stable supply of energy**
- **Highly efficient mid-range transmission**
- **Simplification of ground facilities**



When being applied to rugged roadways over long distances, it is important to simplify ground facilities as much as possible.



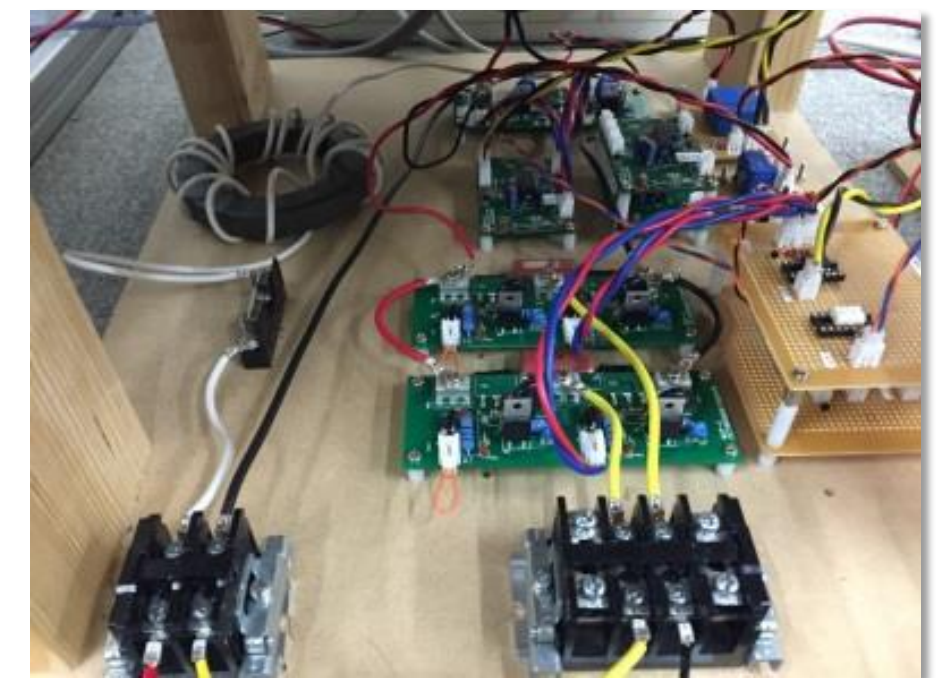
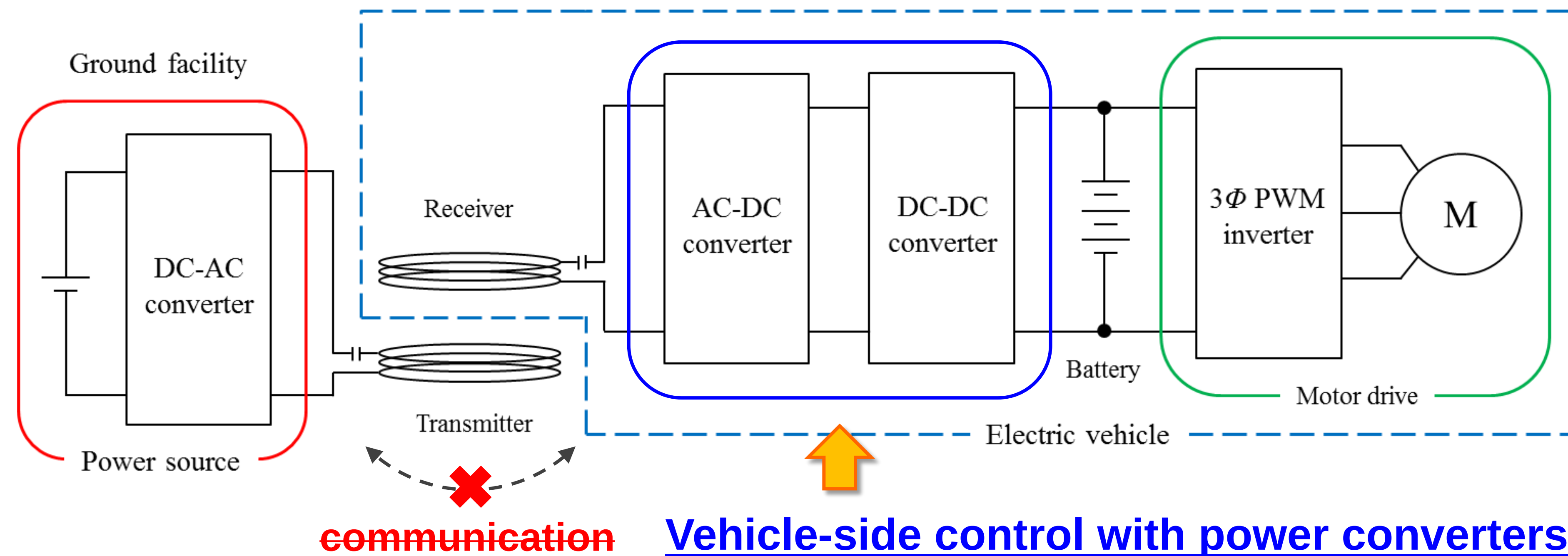
Controls should be achieved on the vehicle side.

1.3. Vehicle-side control for DWPT

Previous research: Efficiency and Power control on the vehicle side (**Static WPT**)

[G. Lovison et al., IECON(2015), K. Hata et al., APEC(2016)]

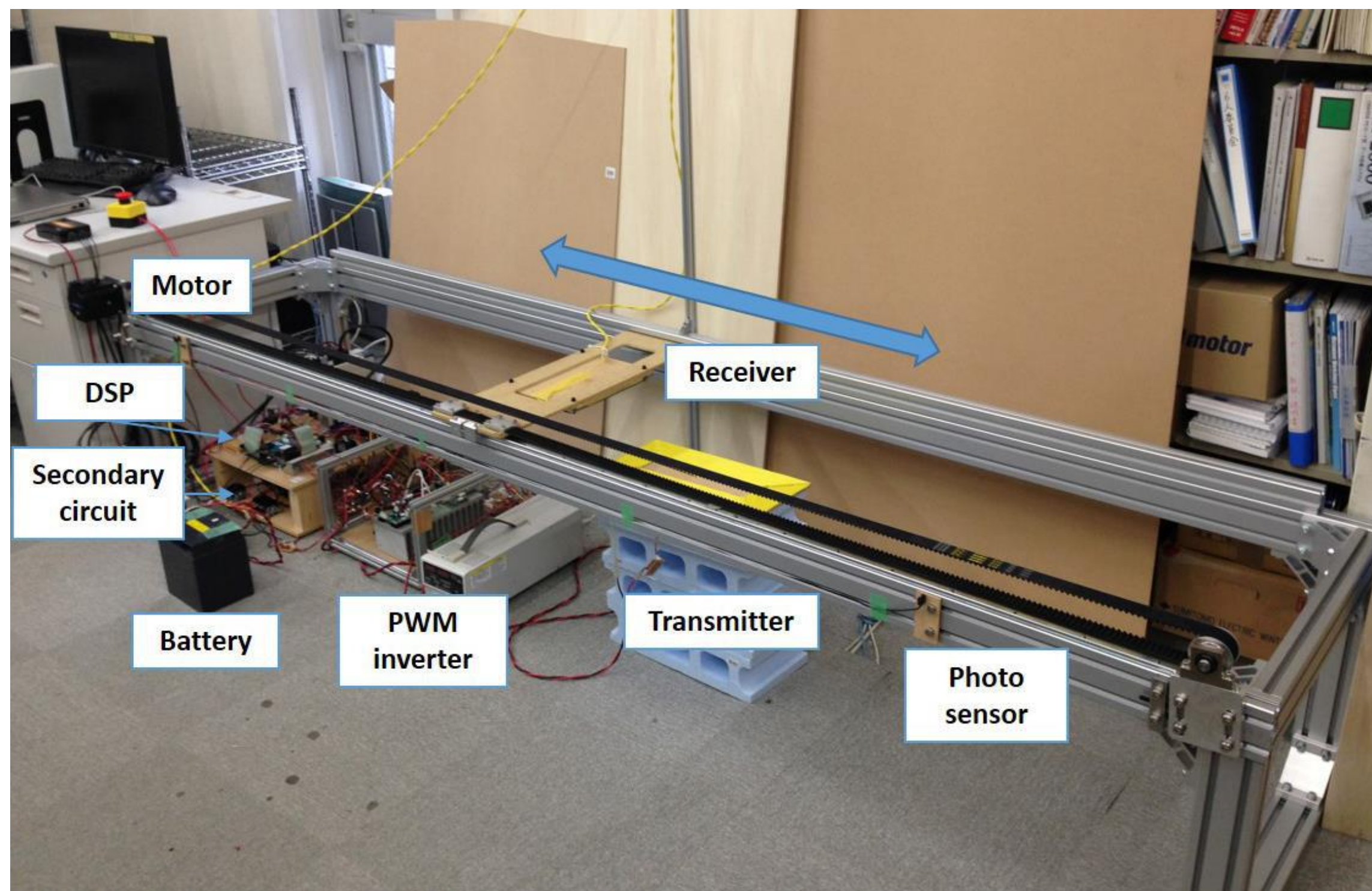
➡ **Apply to Dynamic WPT system** (Real-time estimation and control)



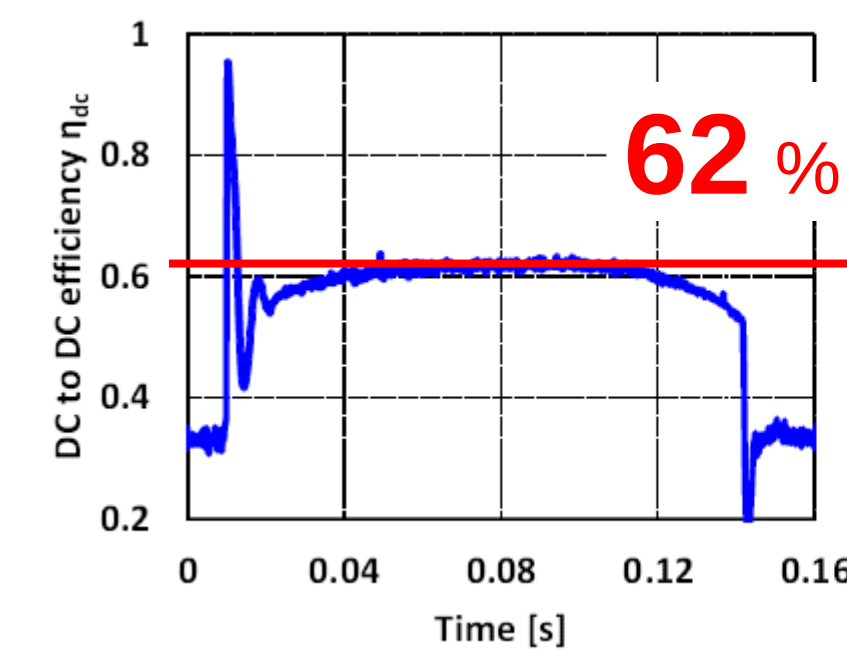
1.4. Results of proposed control method

Real-time vehicle-side power control and efficiency maximization

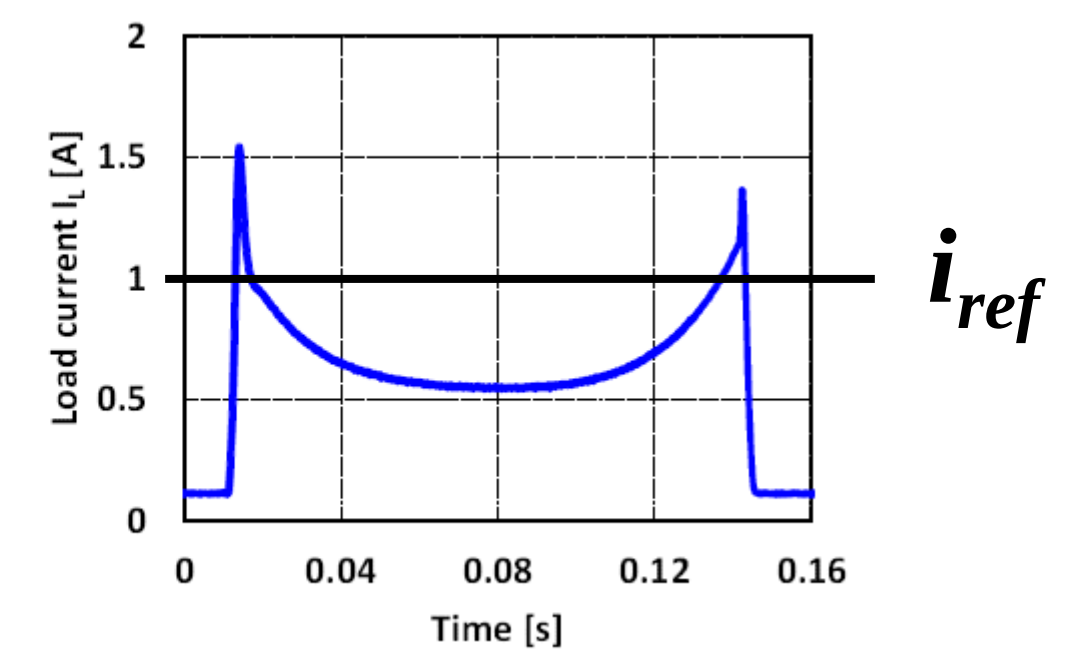
Experimental setup



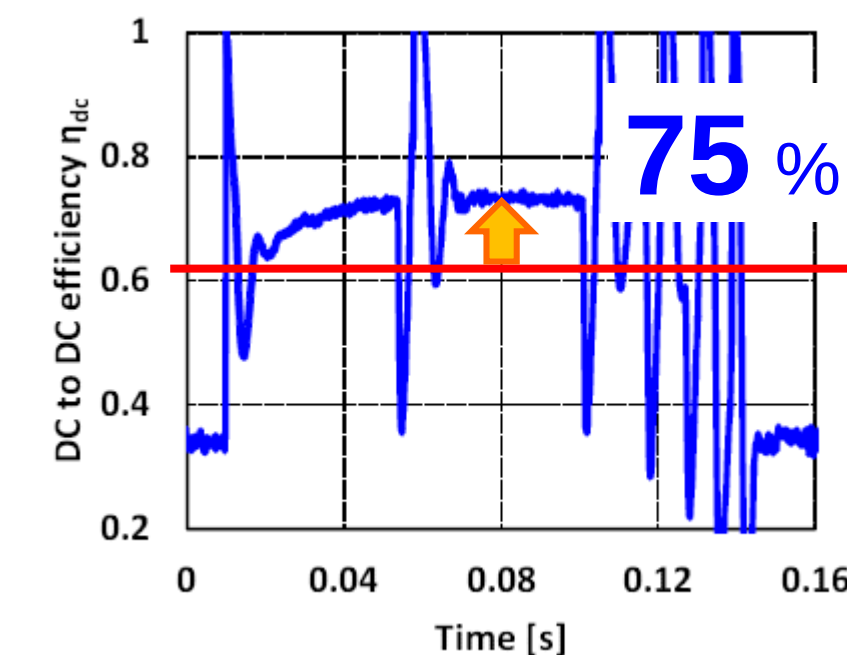
w/o control



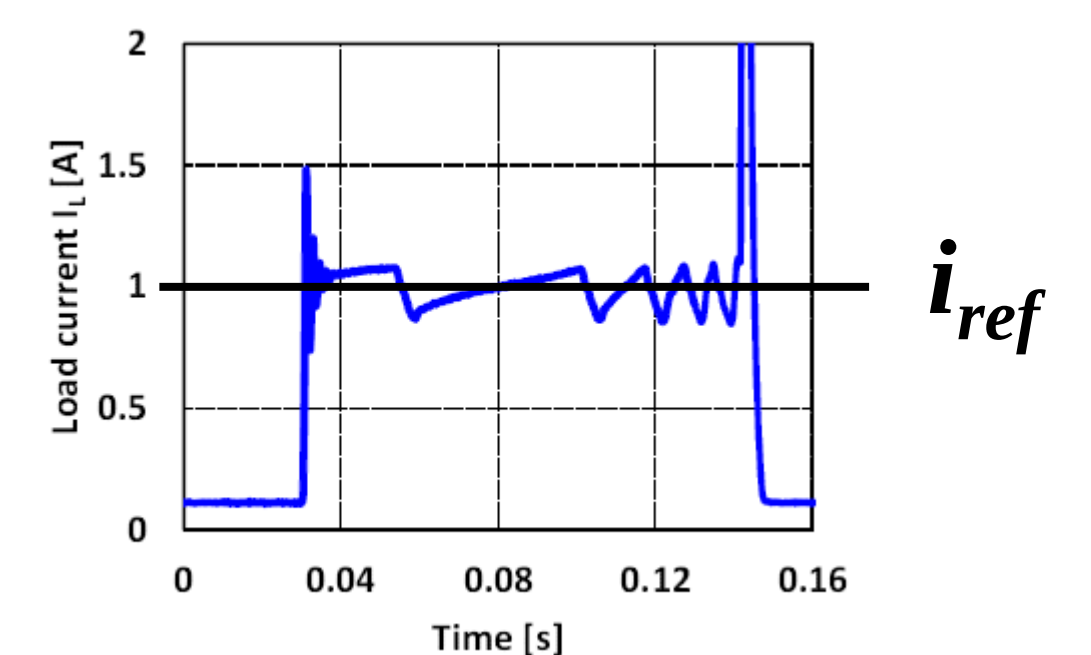
Uncontrollable



w/ control



Controllable



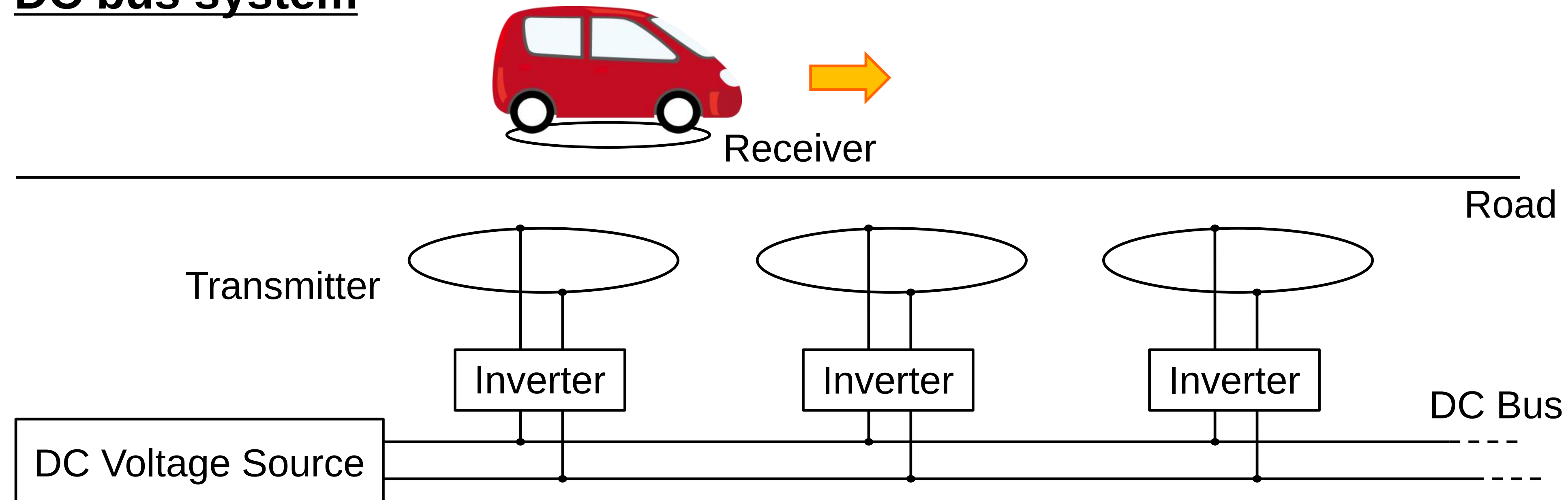


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2.1. Road-side system (Ground facilities)

DC bus system

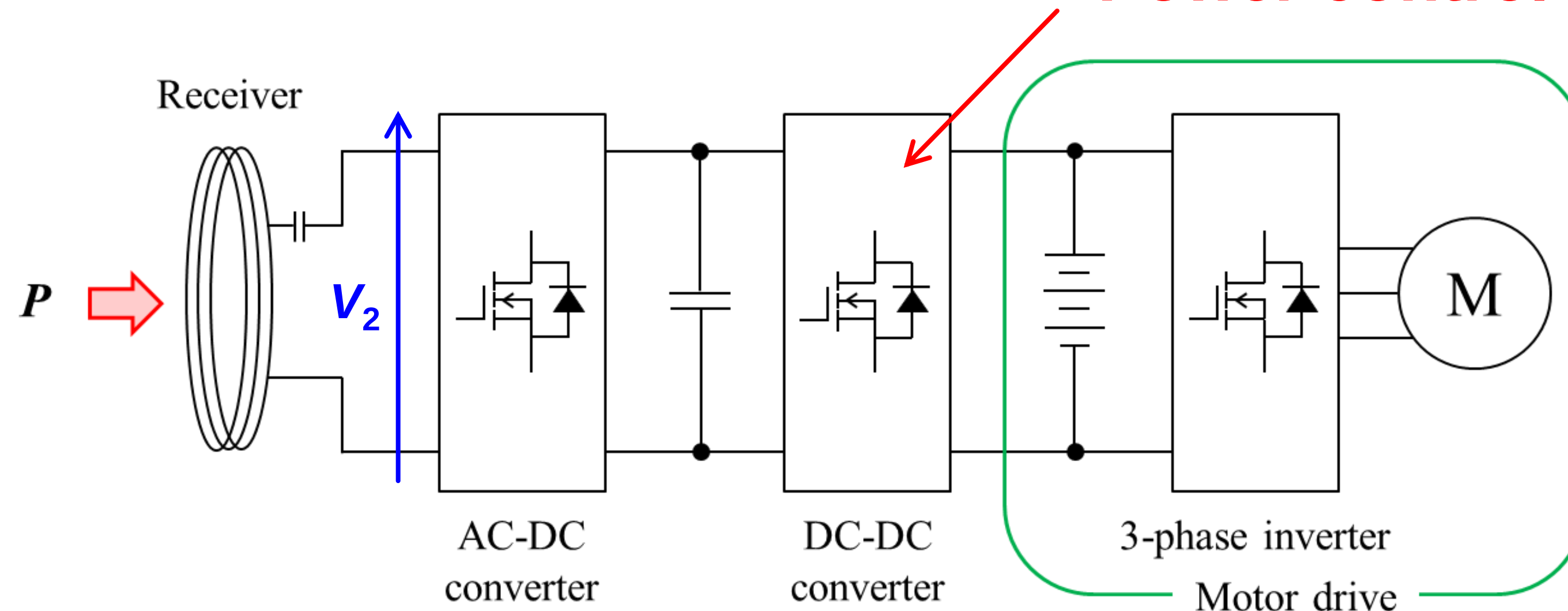


- ✓ **Simple structure** reduces cost and maintenance work.
- ✓ **High power transfer** is possible with one inverter for each transmitter.
- ✓ DC bus system has **less EMI** than high-frequency AC bus system.

2.2. Vehicle-side system

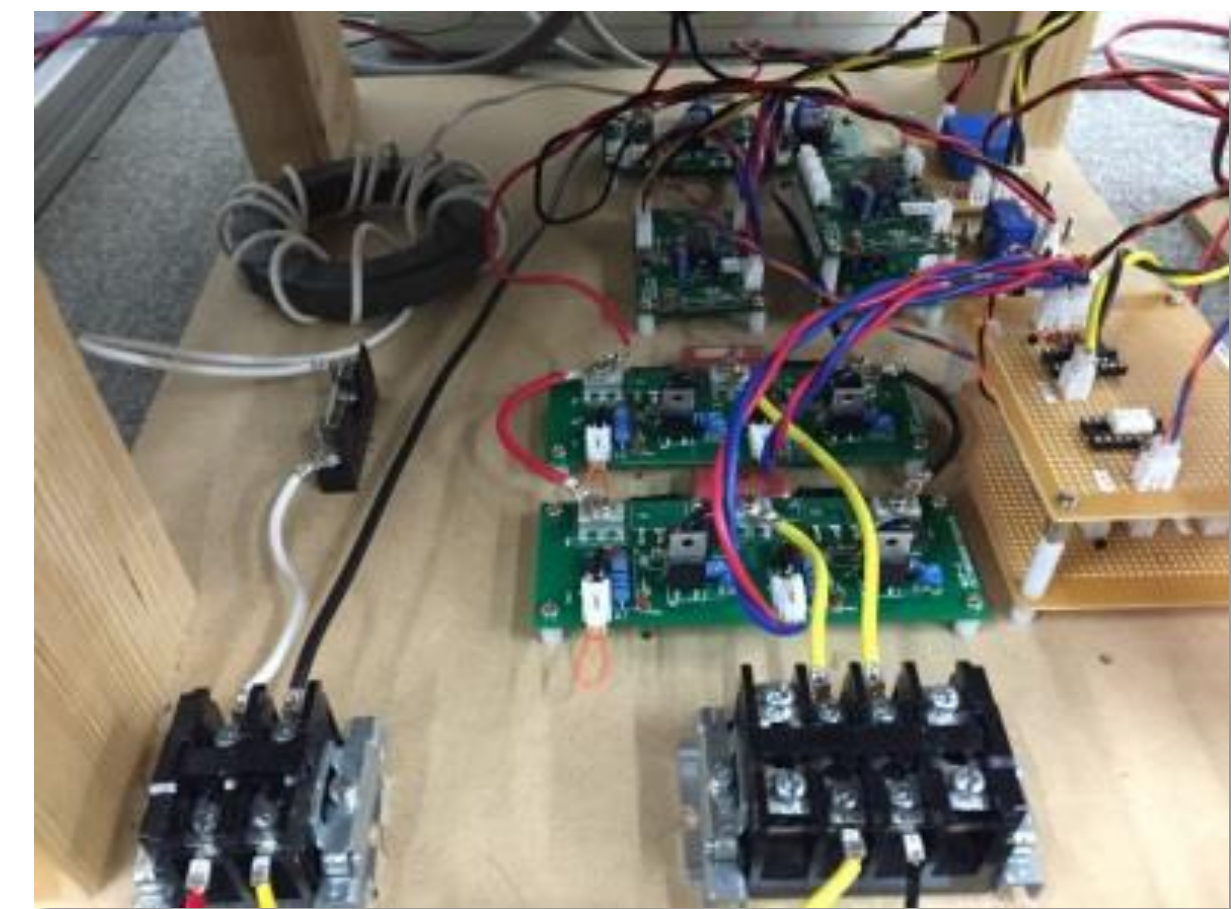
Vehicle-side control with power converters

Power control for battery charging and motor drive



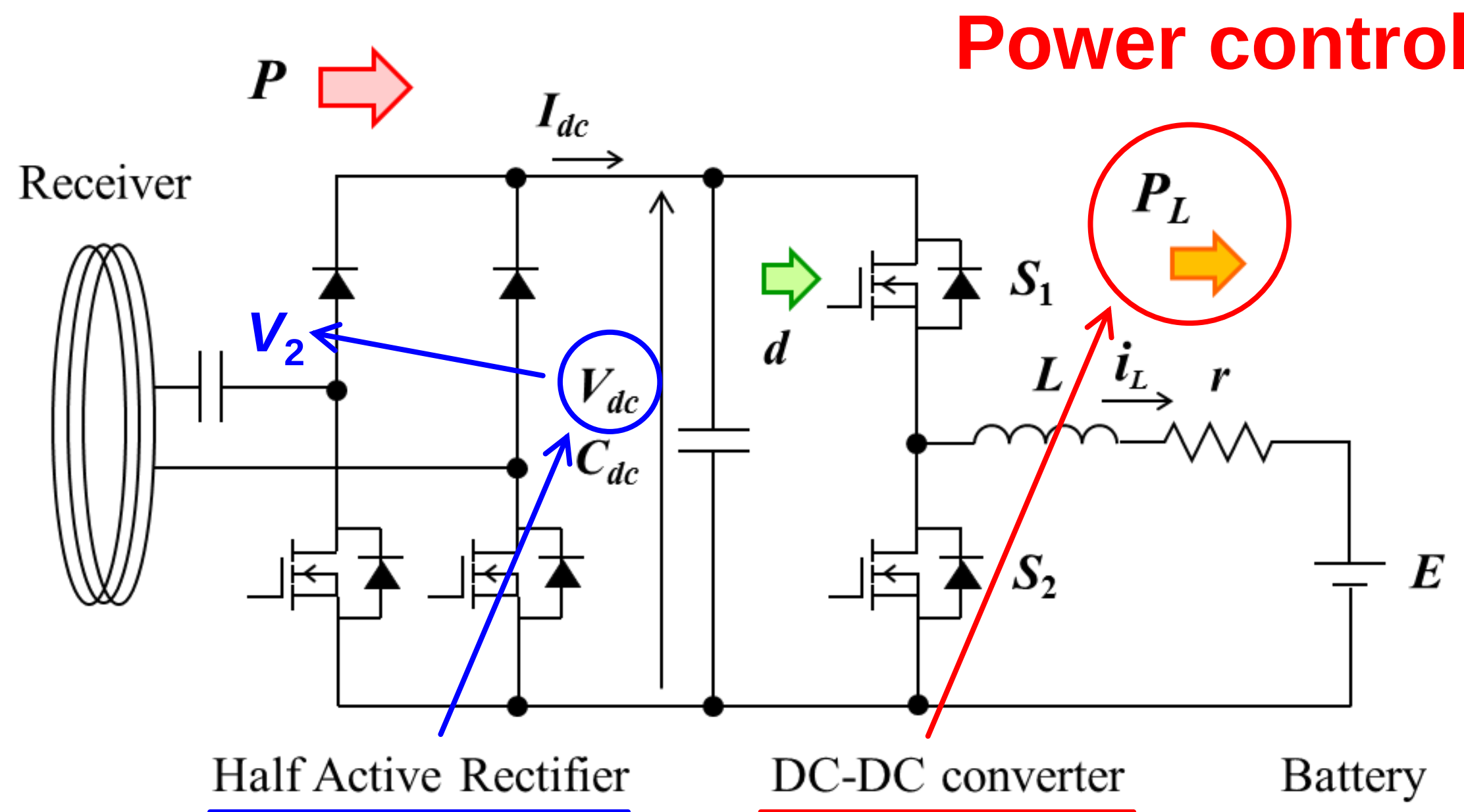
V_2 control for efficiency maximization
by Half Active Rectifier (HAR)

Power converters



2.3. Circuit configuration on the vehicle

Circuit configuration (Motor drive system is neglected.)



Half Active Rectifier (HAR):

Hysteresis control

DC-DC converter:

Model-based FF and FB control

Half Active Rectifier controls V_{dc} (V_2) for efficiency maximization

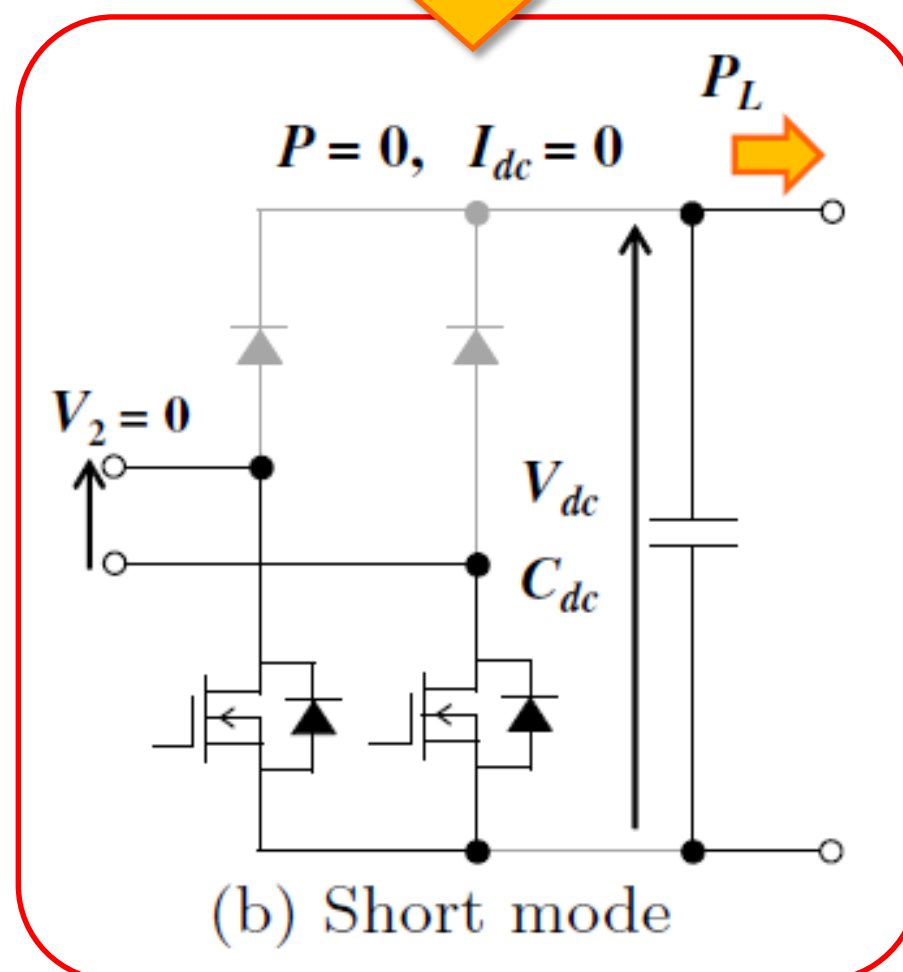
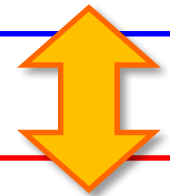
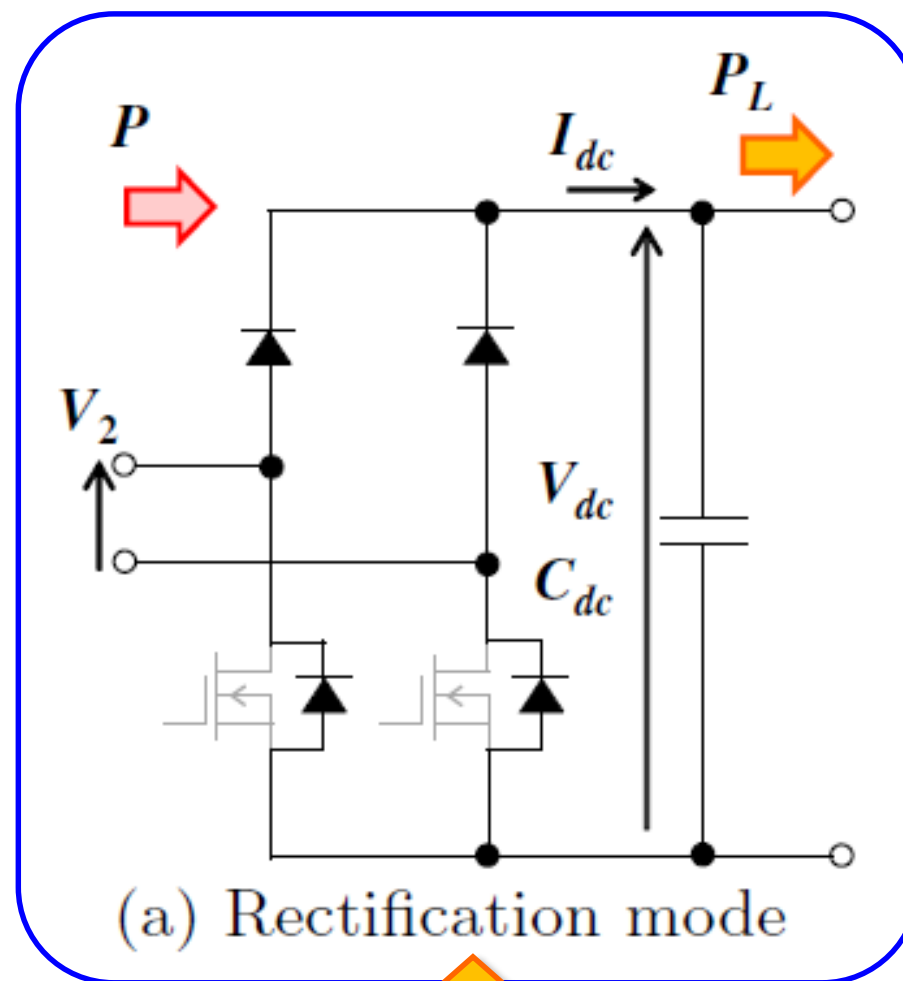
by rectifying and cutting-off the transmitting power P .



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3.1. Half Active Rectifier (HAR)



Rectification mode

- **Diode rectifier circuit**
- Turning OFF lower arm MOSFETs
- Transmitting power P flows into the DC link.

Short mode

- **Short circuit**
- Turning ON lower arm MOSFETs
- Transmitting power P is cut-off.

3.2. Efficiency maximization by HAR

Reference voltage for efficiency maximization

[Kato, Imura, Hori, EVS27 (2013)]

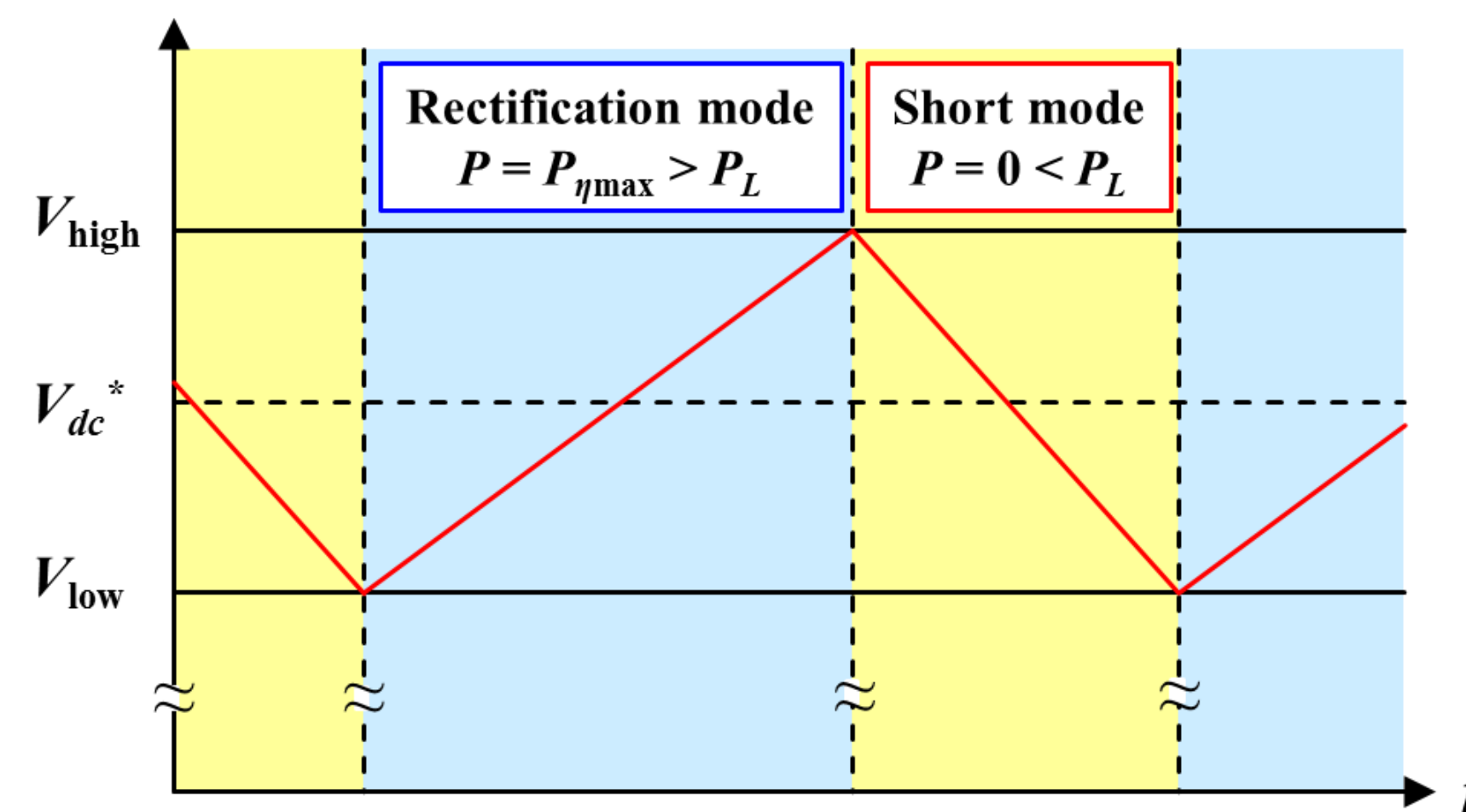
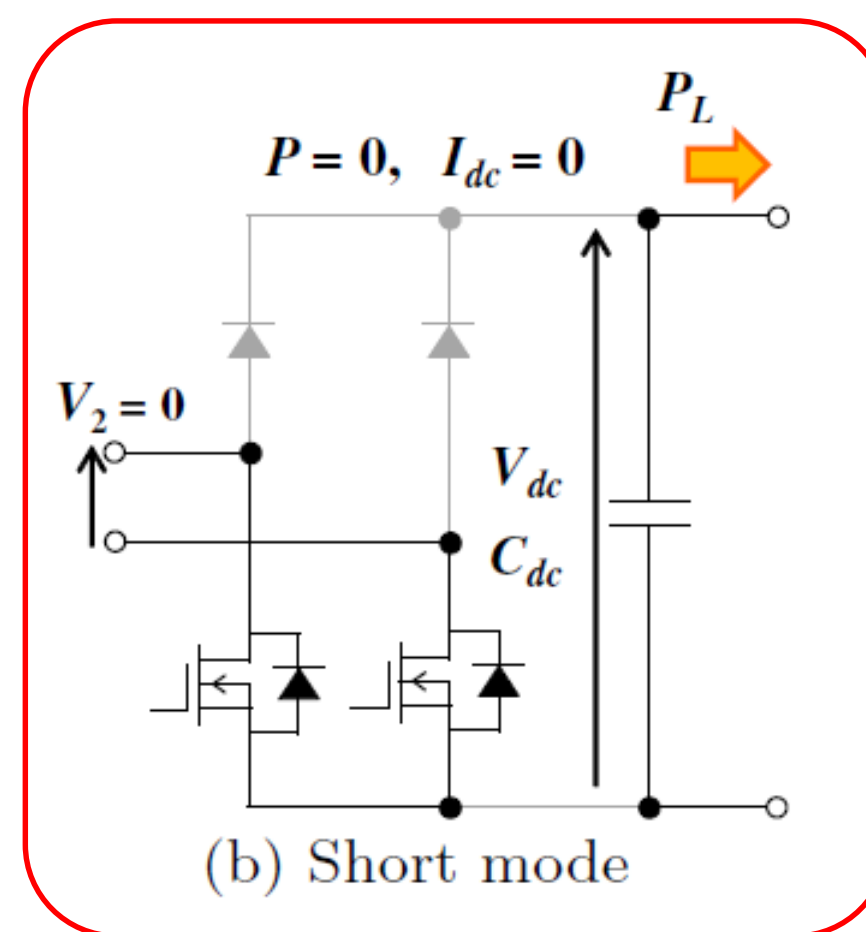
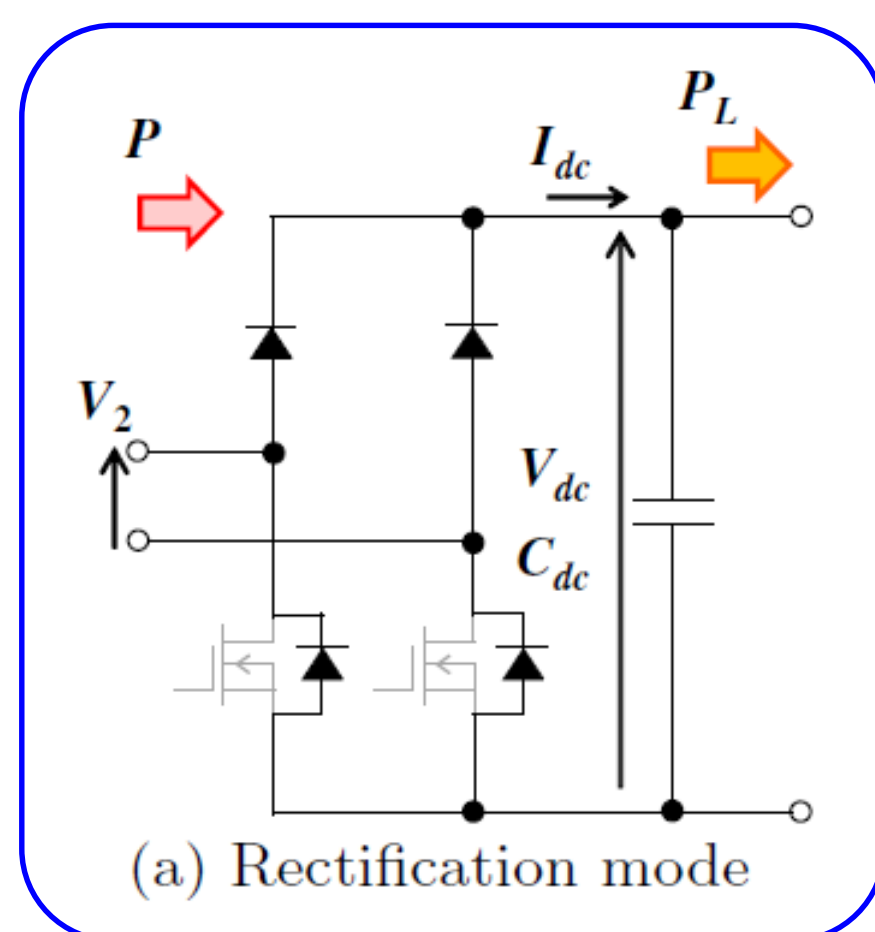
$$V_{dc\eta\max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 L_m}{\sqrt{R_1 R_2 + (\omega_0 L_m)^2} + \sqrt{R_1 R_2}} V_S \quad \Rightarrow \quad \text{Maximum efficiency}$$

DC link voltage control by Half Active Rectifier

(Rectification mode) If P is larger than P_L , V_{dc} is increased.

(Short mode) P_L is supplied by the DC link. V_{dc} is decreased.

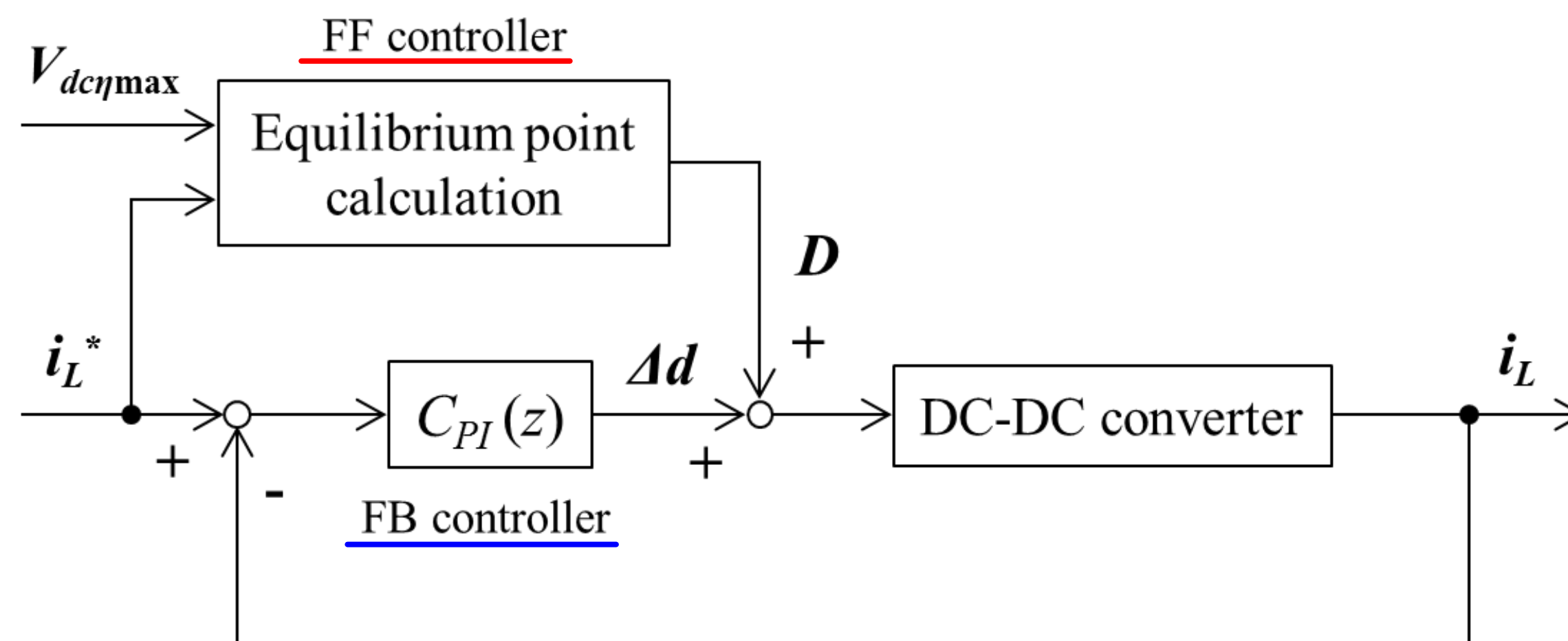
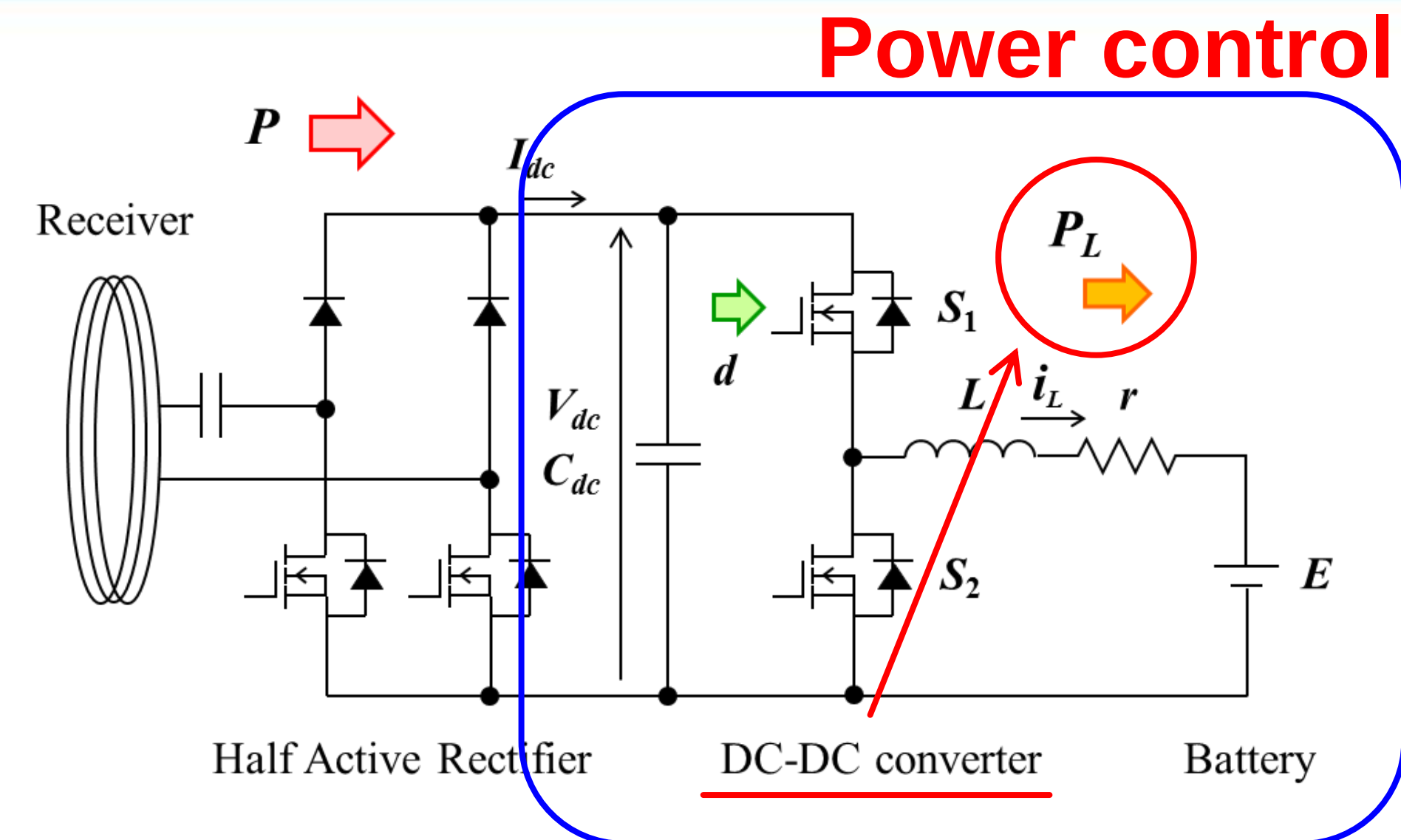
V_{dc} is controllable.



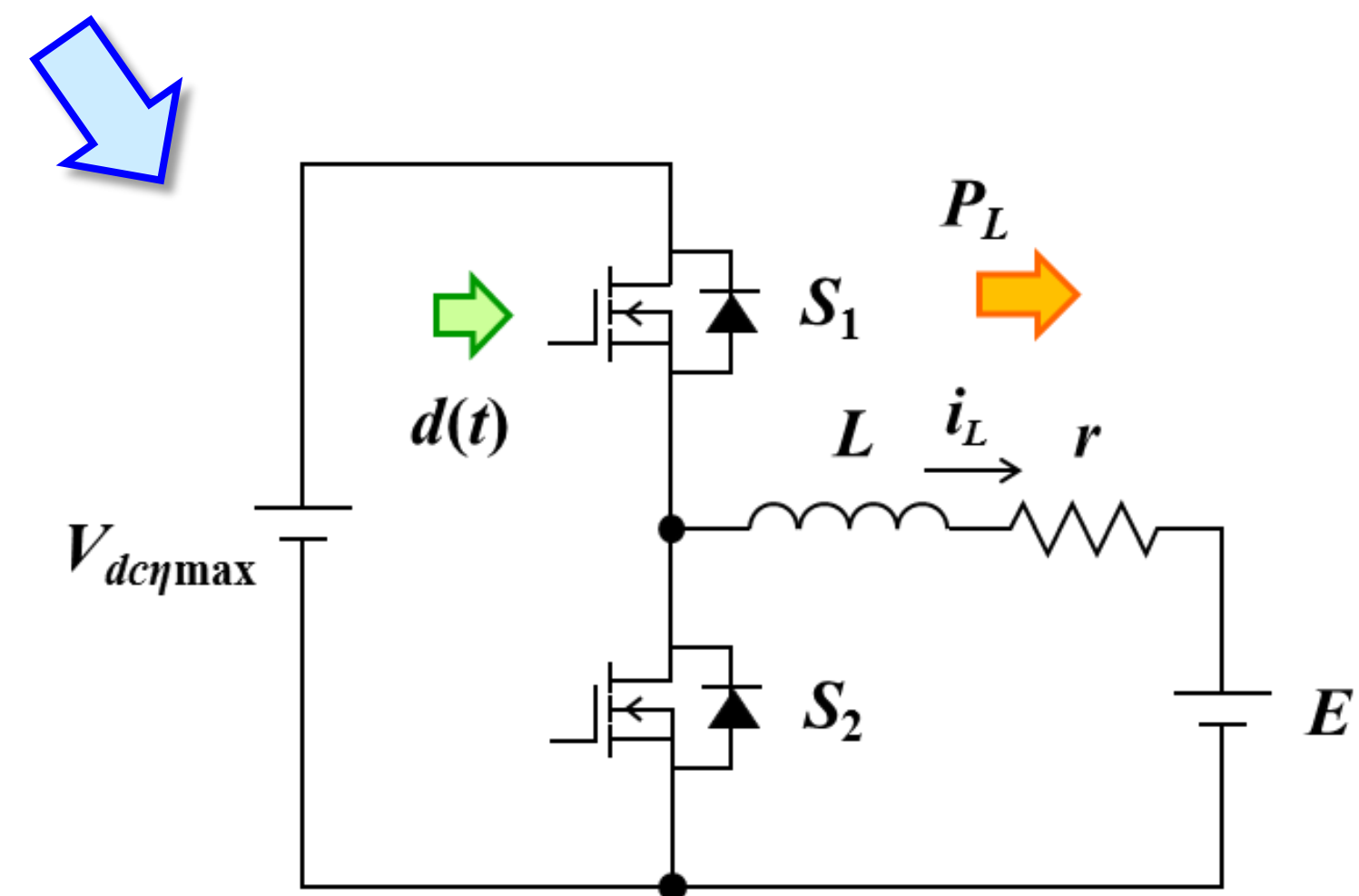
3.3. Power control by DC-DC converter

Model-based controller design

- V_{dc} is controlled by Half Active Rectifier.
- The DC-DC converter model is simplified.
- **Feedforward** and **Feedback** controllers are designed based on the DC-DC converter model.



Simplified



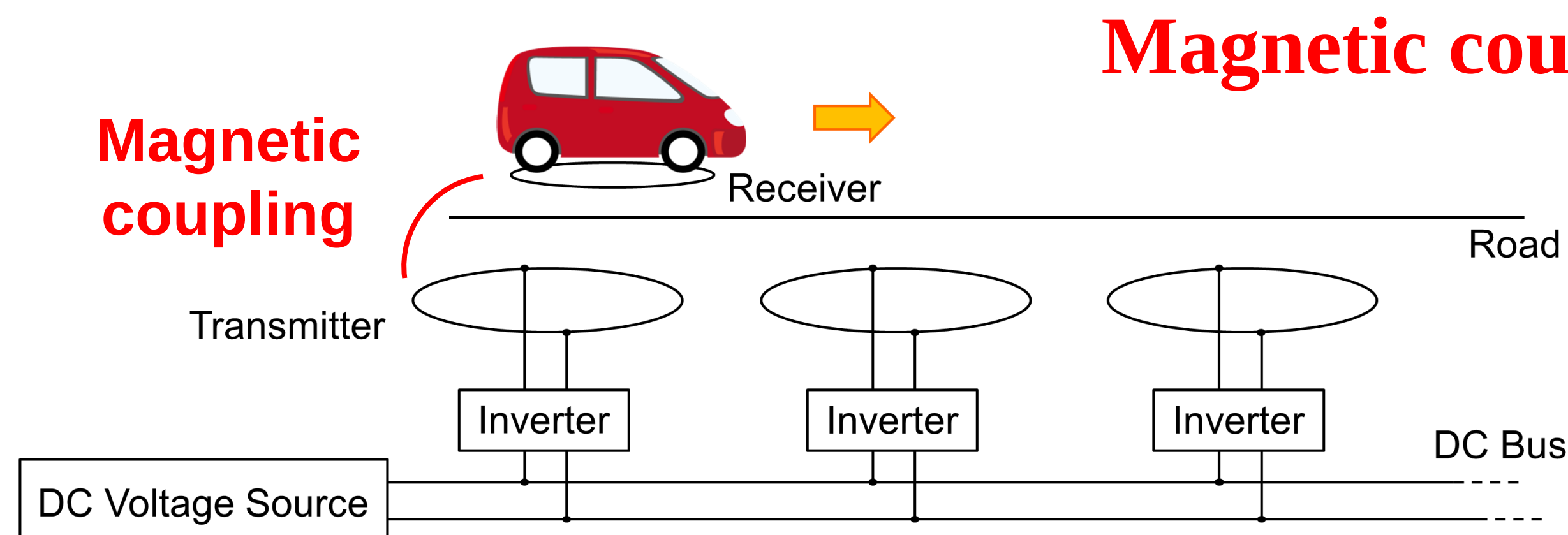


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4.1. Real-time estimation for DWPT

DC bus system



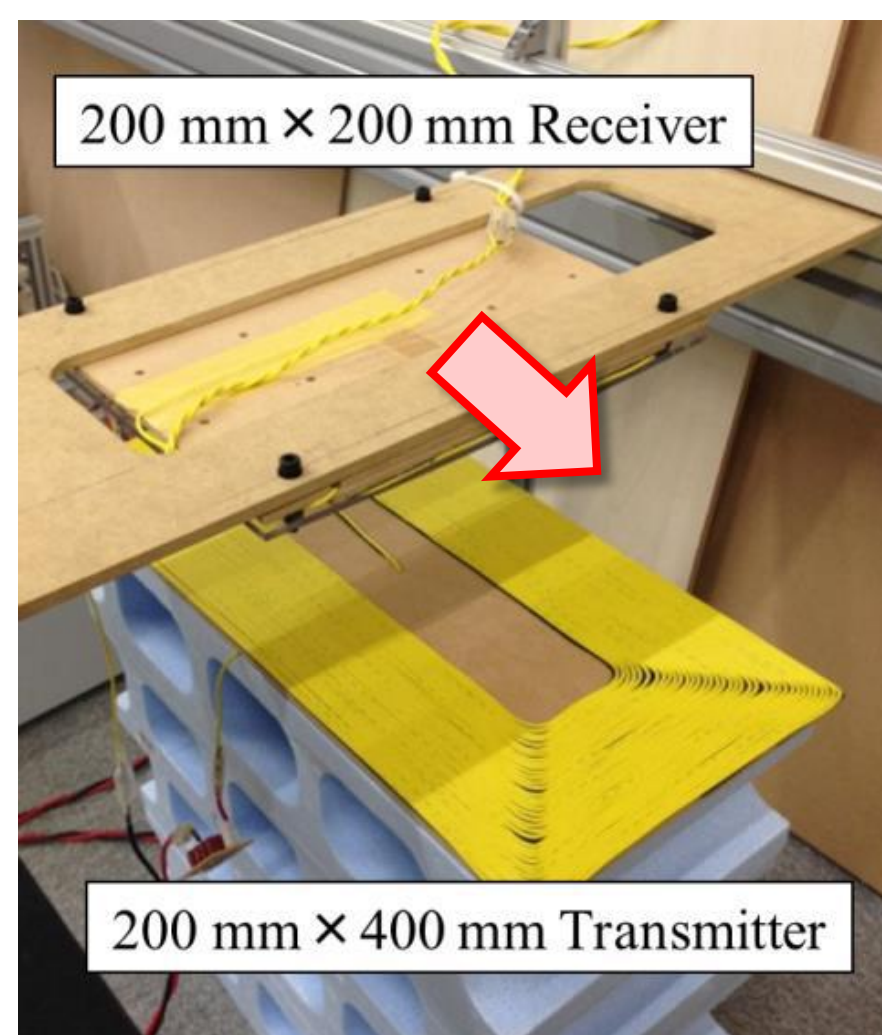
Magnetic coupling changes according to vehicle motion.

Reference voltage for efficiency maximization

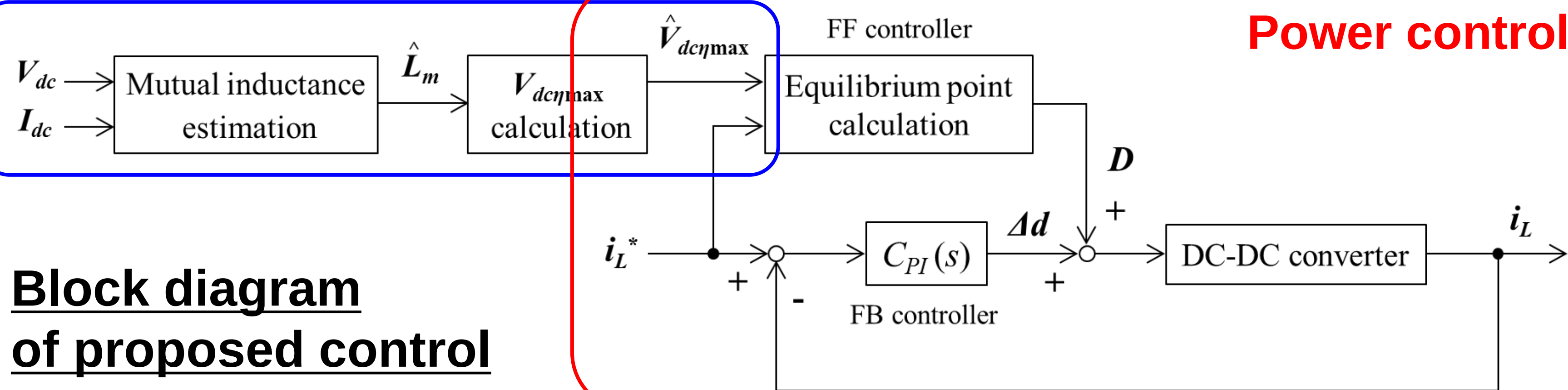
[Kato, Imura, Hori, EVS27 (2013)]

$$V_{dc\eta\max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 L_m}{\sqrt{R_1 R_2 + (\omega_0 L_m)^2} + \sqrt{R_1 R_2}} V_S$$

➔ **Mutual inductance** has to be estimated !



Efficiency maximization

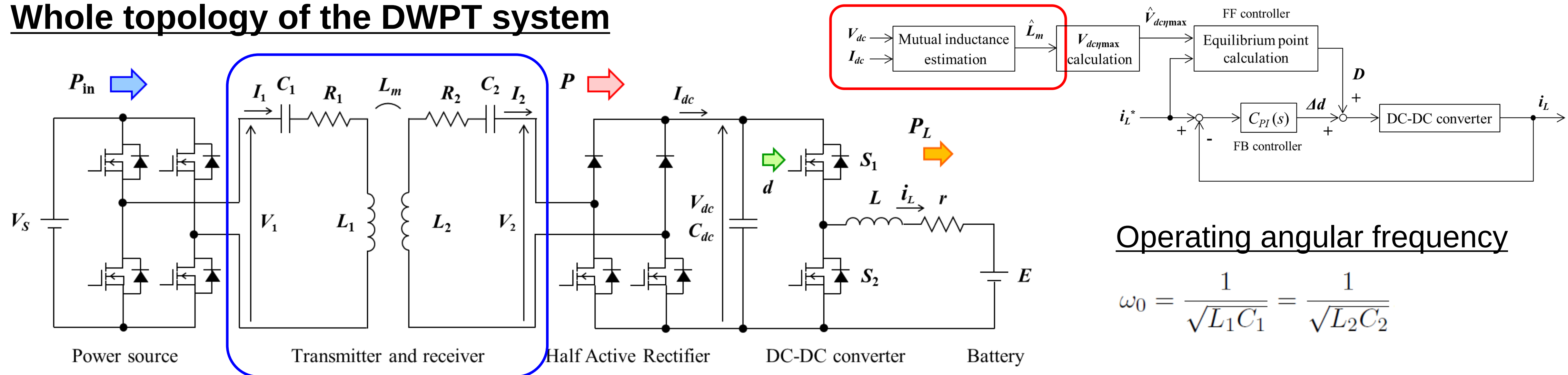


Block diagram of proposed control

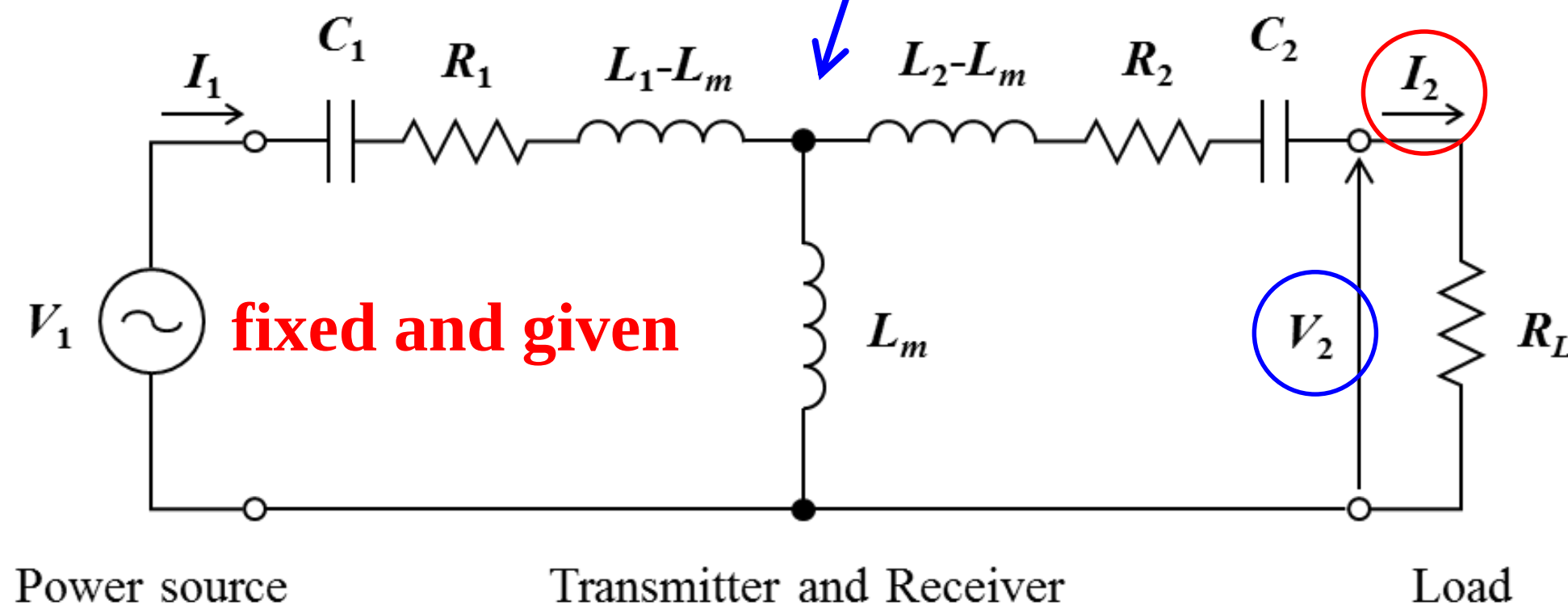
Power control

4.2. Mutual inductance estimation

Whole topology of the DWPT system



Equivalent circuit



From circuit equations,

Estimation equation

[Kobayashi, Imura, Hori, WoW (2015)]

* Recursive Least Square (RLS) filter is used for noise reduction.

$$I_2 \approx \frac{\omega_0 L_m V_1 - R_1 V_2}{R_1 R_2 + (\omega_0 L_m)^2}$$

$$\hat{L}_m = \frac{V_1 \pm \sqrt{V_1^2 - 4R_1 I_2 (V_2 + R_2 I_2)}}{2I_2 \omega_0}$$

Operating angular frequency

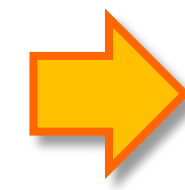
$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}$$

4.3. Efficiency maximization by HAR

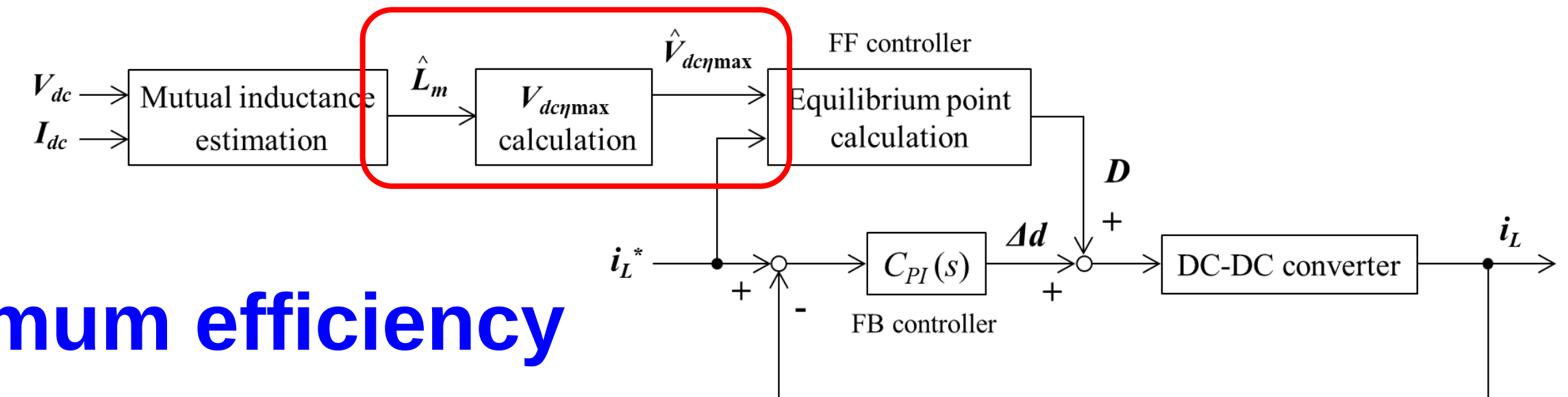
Reference voltage for efficiency maximization

[Kato, Imura, Hori, EVS27 (2013)]

$$V_{dc\eta\max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 L_m}{\sqrt{R_1 R_2 + (\omega_0 L_m)^2} + \sqrt{R_1 R_2}} V_S$$



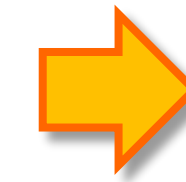
Maximum efficiency



DC link voltage control with hysteresis comparator

[Gunji, Imura, Fujimoto, ICM (2015)]

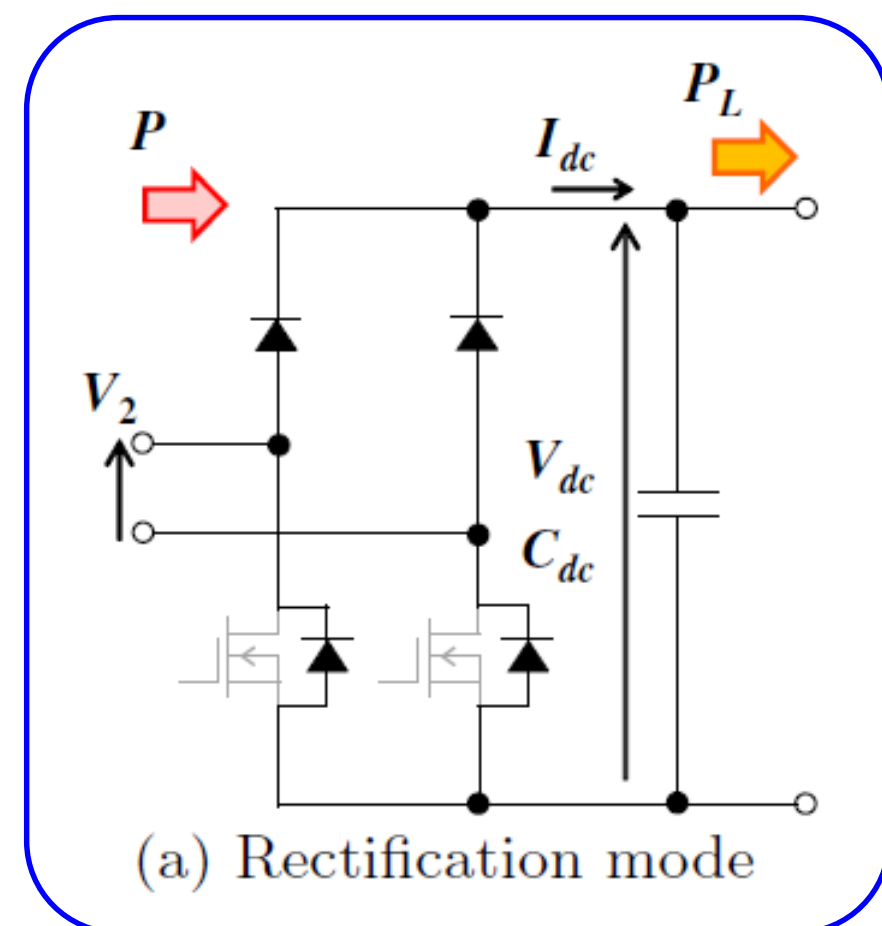
The upper bound V_{high} and the lower bound V_{low} are defined using the reference voltage V_{dc}^* and the hysteresis band ΔV .



$$V_{\text{high}} = V_{dc}^* + \Delta V$$

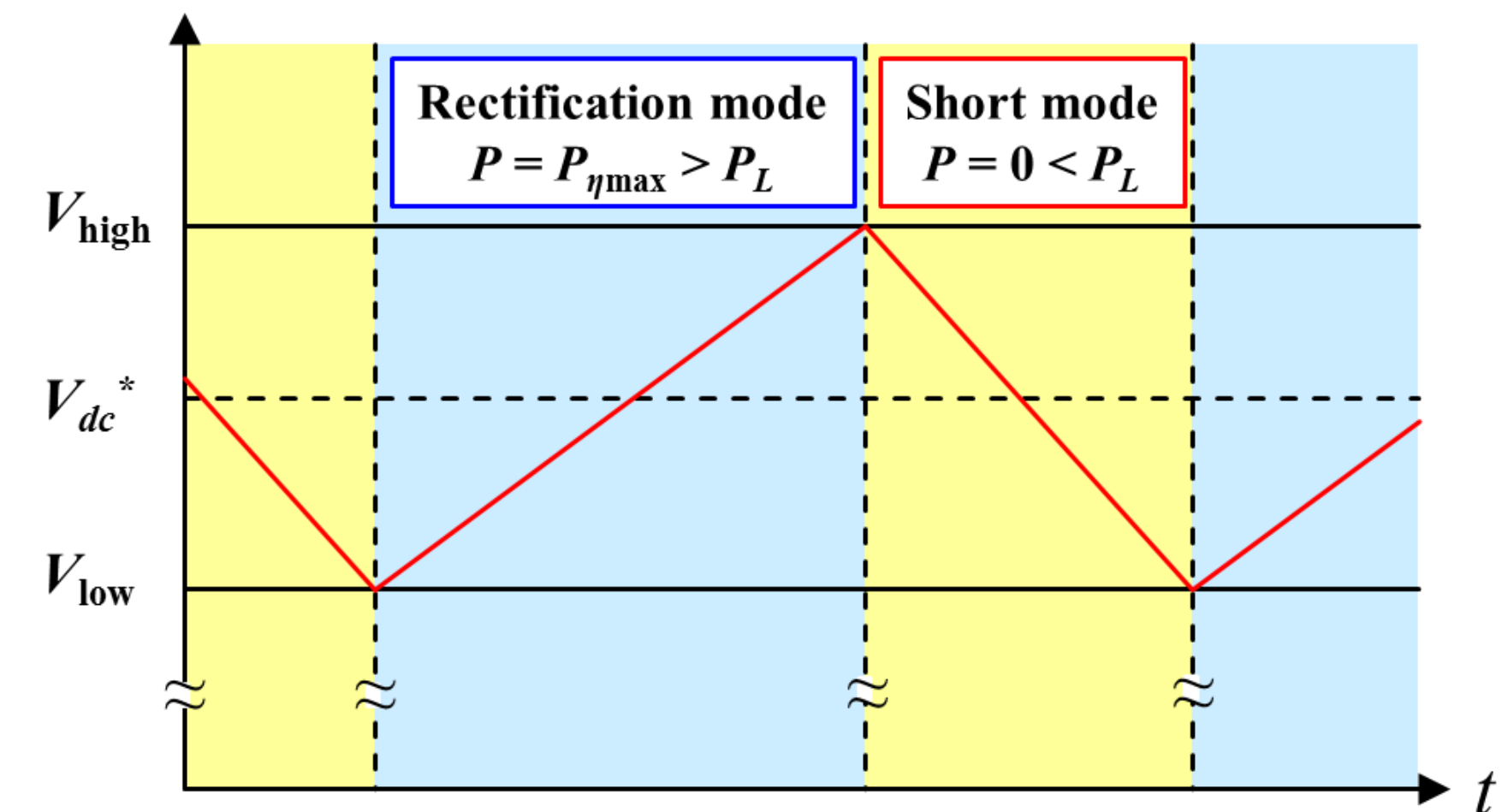
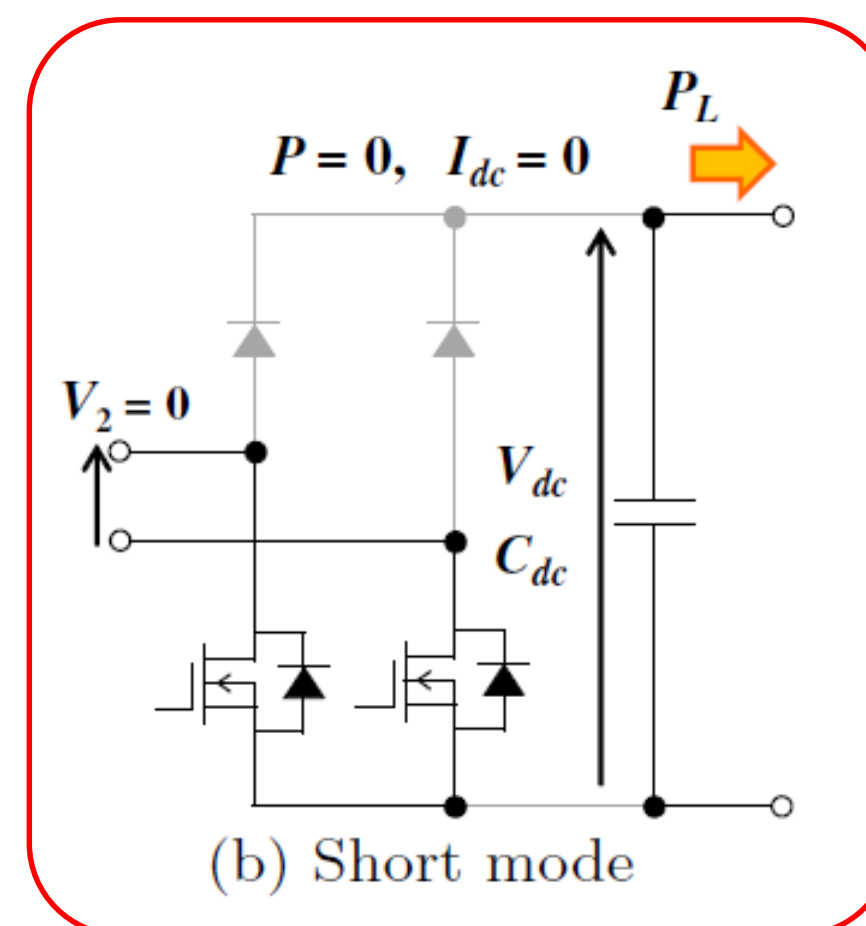
$$V_{\text{low}} = V_{dc}^* - \Delta V$$

Hysteresis control



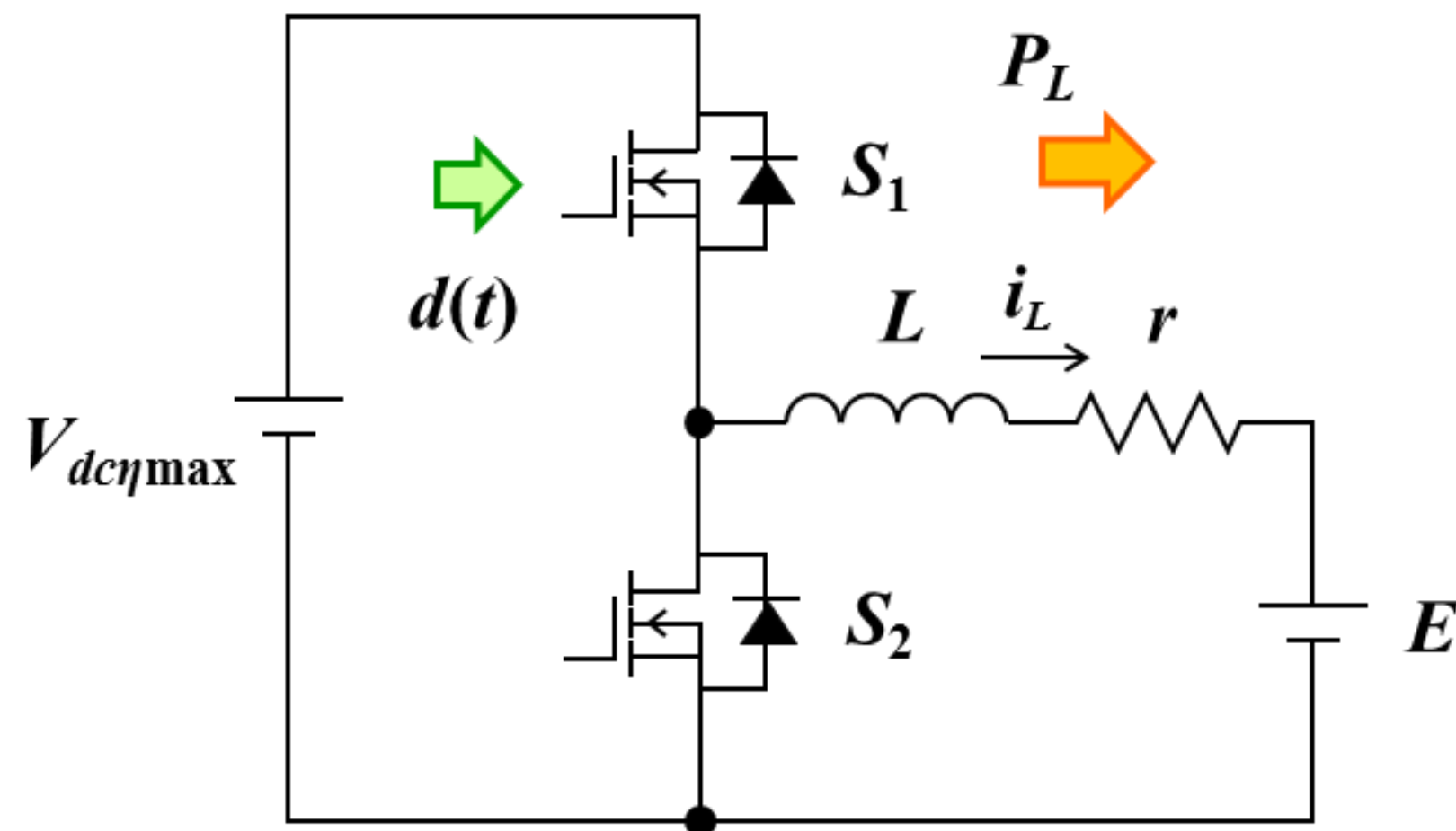
$$V_{dc} > V_{\text{high}}$$

$$V_{\text{low}} > V_{dc}$$



4.4. Power control by DC-DC converter

Simplified DC-DC converter model



State space averaging model

$$\frac{d}{dt}i_L(t) = -\frac{r}{L}i_L(t) - \frac{1}{L}E + \frac{d(t)}{L}V_{dc\eta\max}$$

Linearized transfer function model (transient)

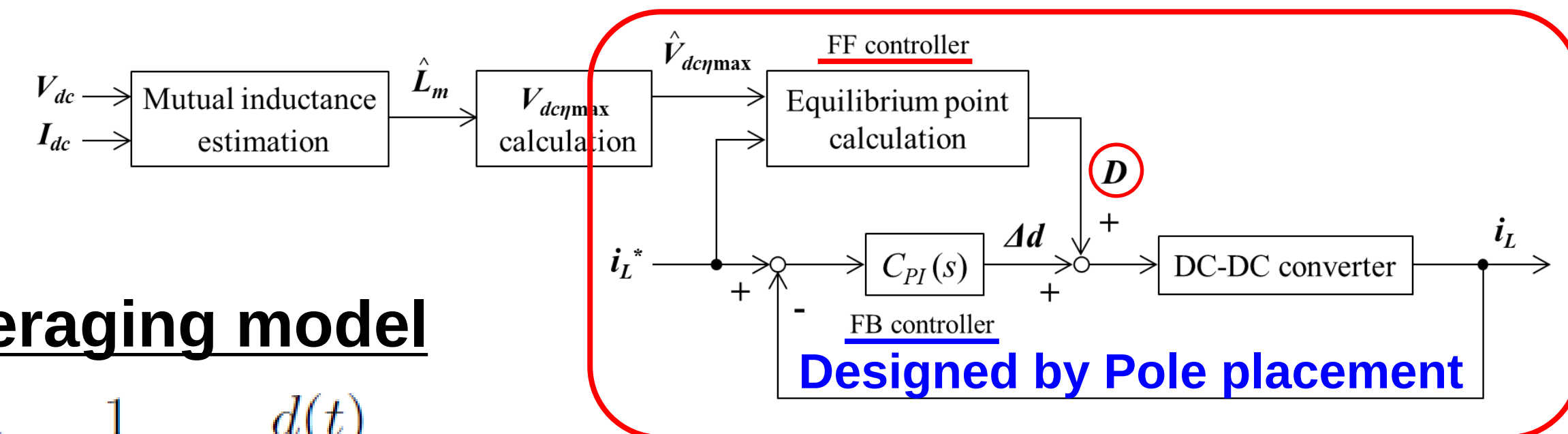
$$\Delta P_i(s) = \frac{\Delta i_L(s)}{\Delta d(s)} = \frac{V_{dc\eta\max}}{Ls + r} \quad 1^{\text{st}} \text{ order system} \rightarrow \text{PI controller}$$

Equilibrium point (steady state)

$$I_L = i_L^* \quad \text{Reference current}$$

$$D = \frac{E + ri_L^*}{V_{dc\eta\max}}$$

FF controller



PI controller gains are designed by pole placement.

$$C_{PI}(s) = \frac{sK_P + K_I}{s} \quad K_P = \frac{2L\omega_c - r}{V_{dc\eta\max}} \quad K_I = \frac{L\omega_c^2}{V_{dc\eta\max}}$$

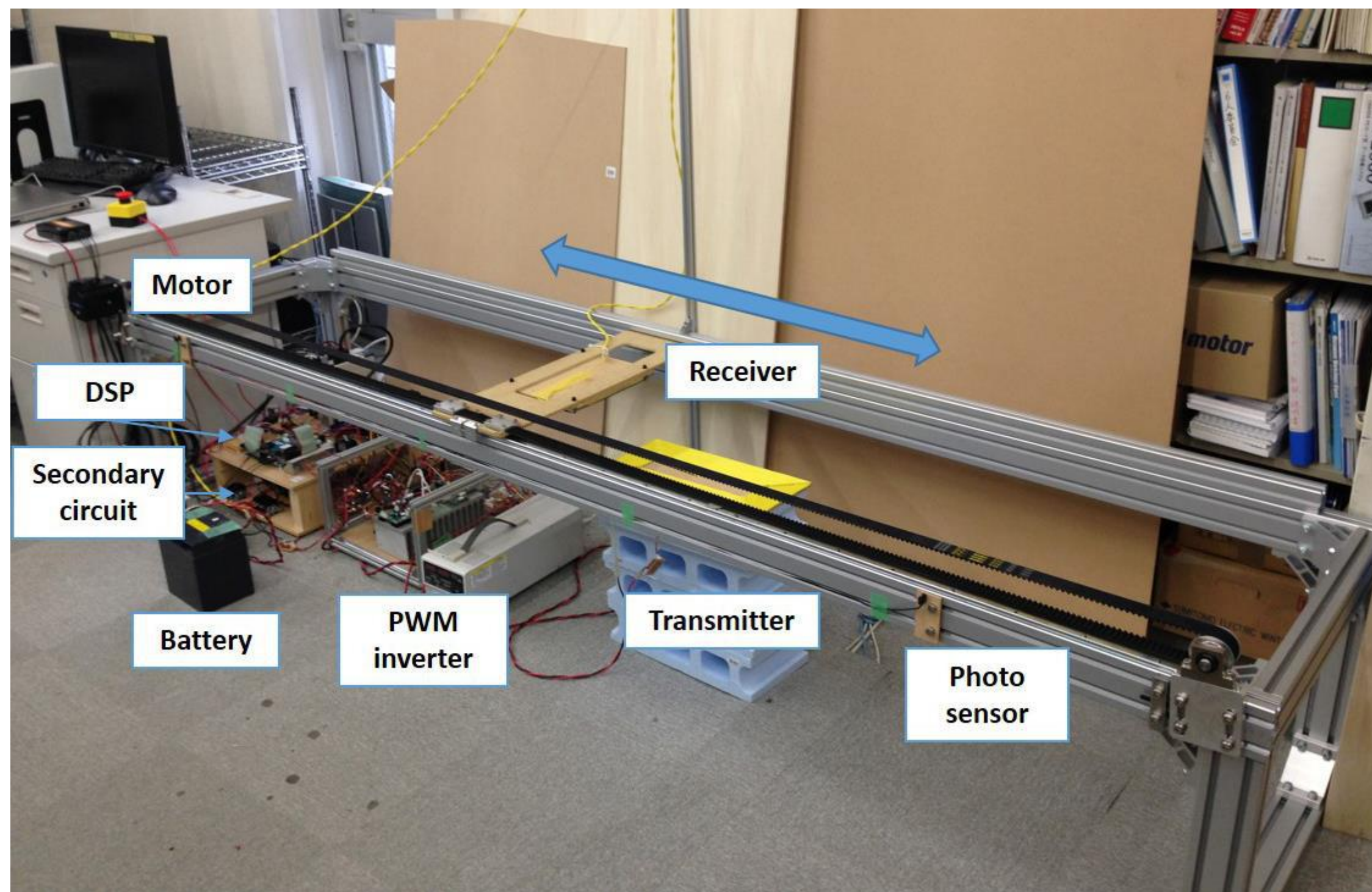
*** FB controller is discretized by Tustin transform**



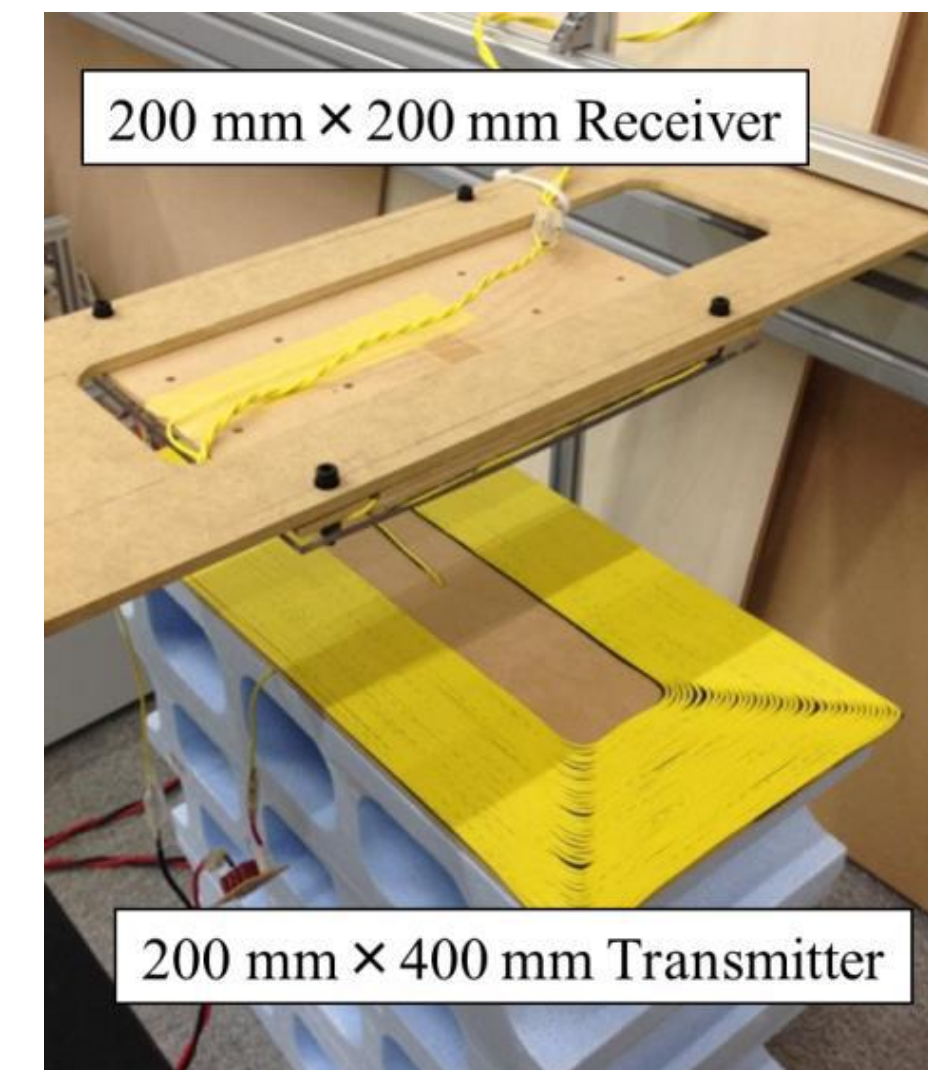
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5.1. Experimental setup (1/2)

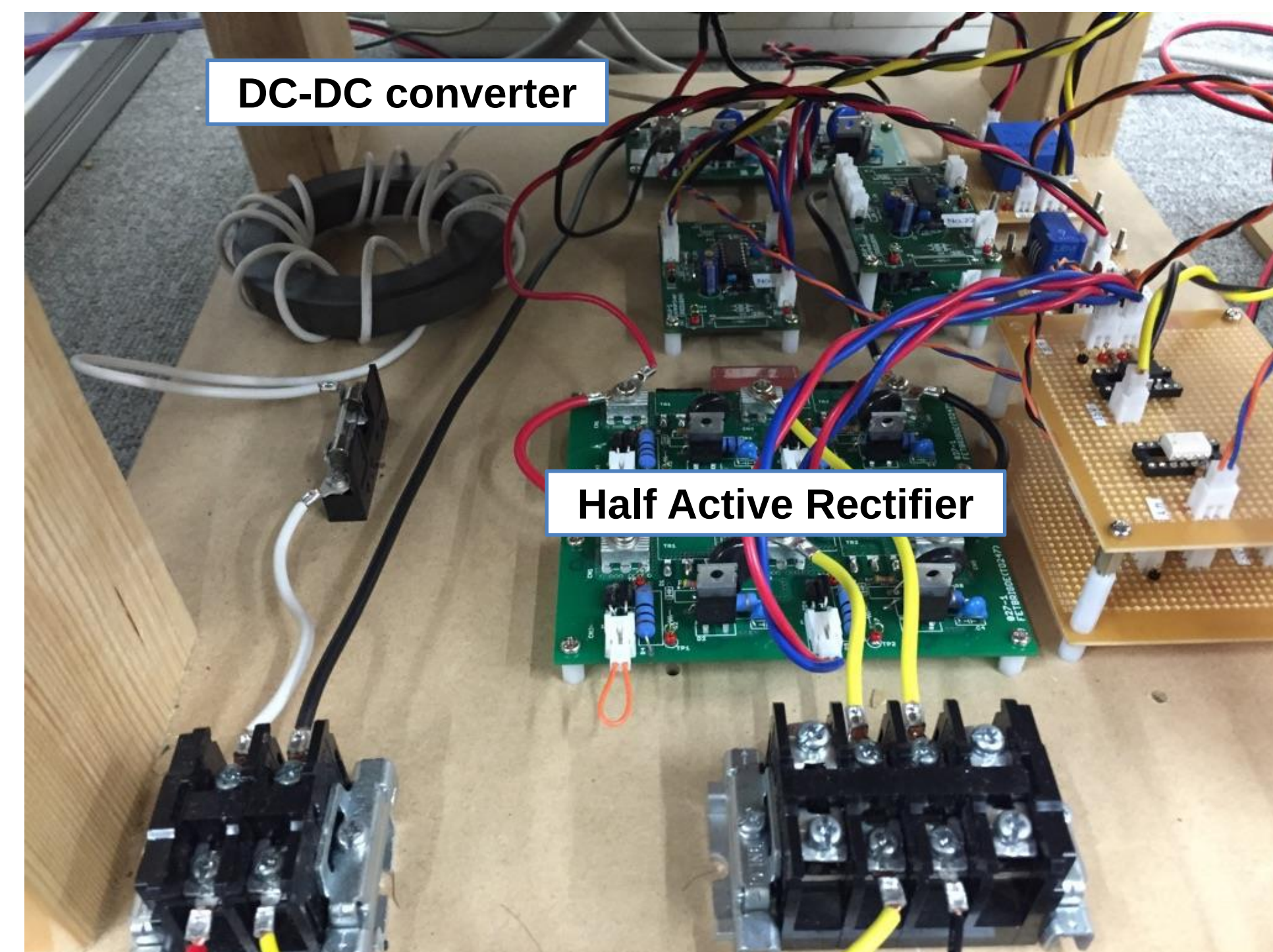
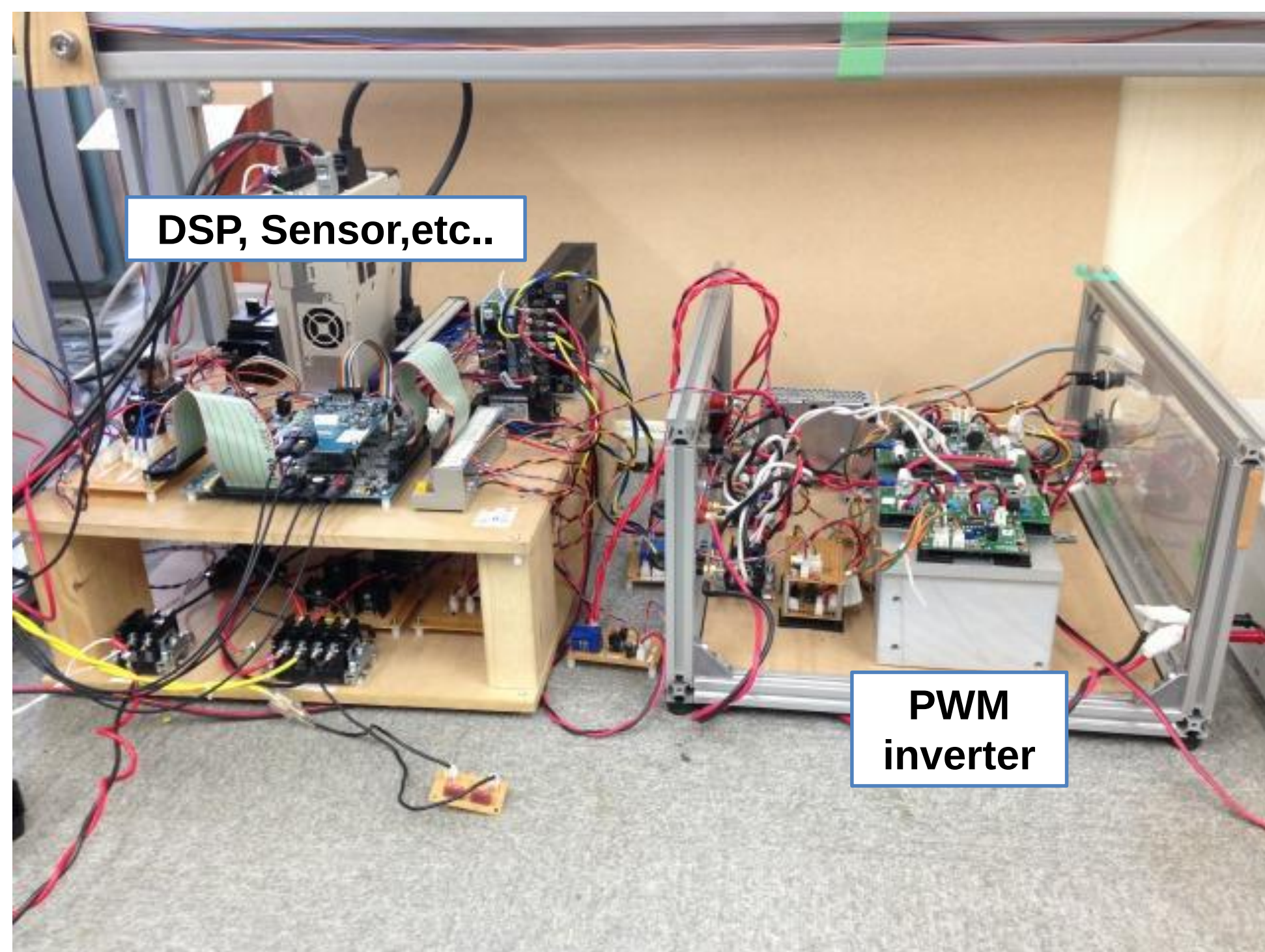


Parameter	Value	Parameter	Value
Power source voltage V_S	18 V	Battery voltage E	6 V
Operating frequency f_0	100 kHz	Reactor resistance r	0.3 Ω
Hysteresis band ΔV	0.5 V	Reactor inductance L	1000 μH
Carrier frequency f_c	20 kHz	DC link capacitance C_{dc}	2000 μF

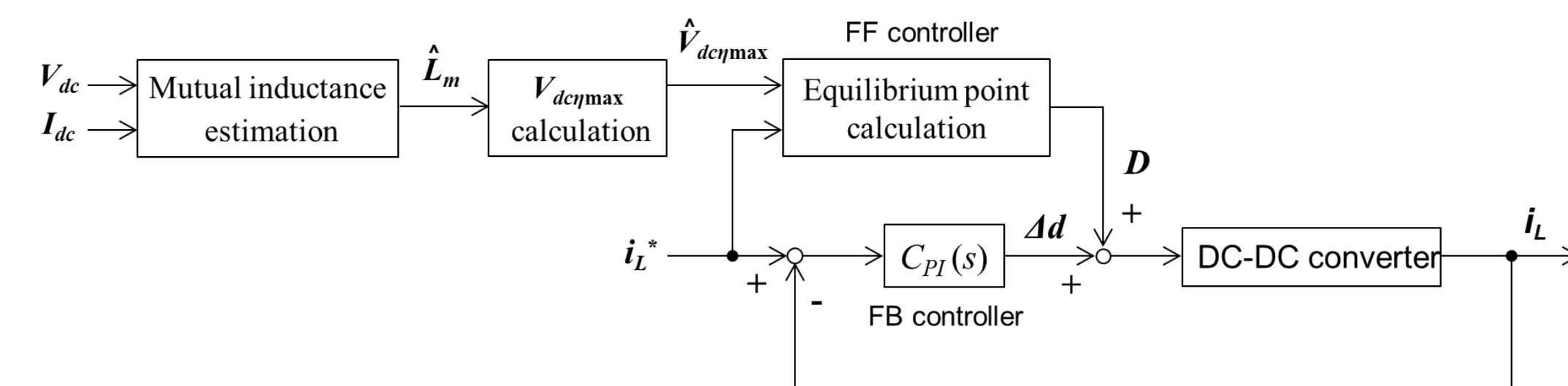


	Transmitter	Receiver
Resistance R_1, R_2	1.95 Ω	1.60 Ω
Inductance L_1, L_2	417.1 μH	210.6 μH
Capacitance C_1, C_2	6030 pF	12110 pF
Resonant frequency f_1, f_2	100.4 kHz	99.7 kHz
Coil gap	100 mm	
Mutual inductance L_m	36.3 μH (no misalignment)	
Coupling coefficient k	0.122 (no misalignment)	

5.1. Experimental setup (2/2)

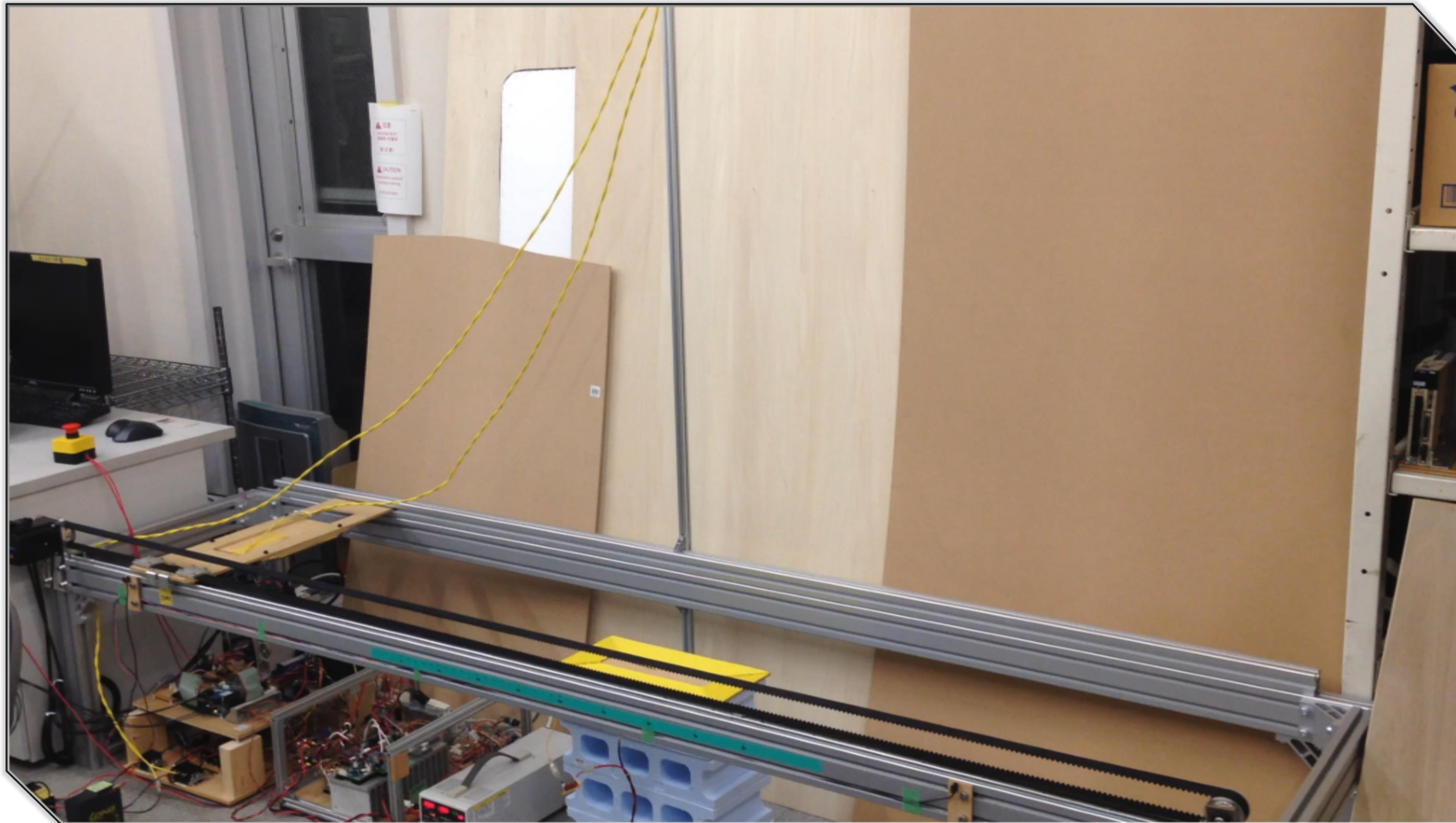


Parameter	Value	Parameter	Value
Power source voltage V_S	18 V	Battery voltage E	6 V
Operating frequency f_0	100 kHz	Reactor resistance r	0.3 Ω
Hysteresis band ΔV	0.5 V	Reactor inductance L	1000 μH
Carrier frequency f_c	20 kHz	DC link capacitance C_{dc}	2000 μF



5.2. Experimental movie

1/3 scale DWPT simulation setup (10km/h)



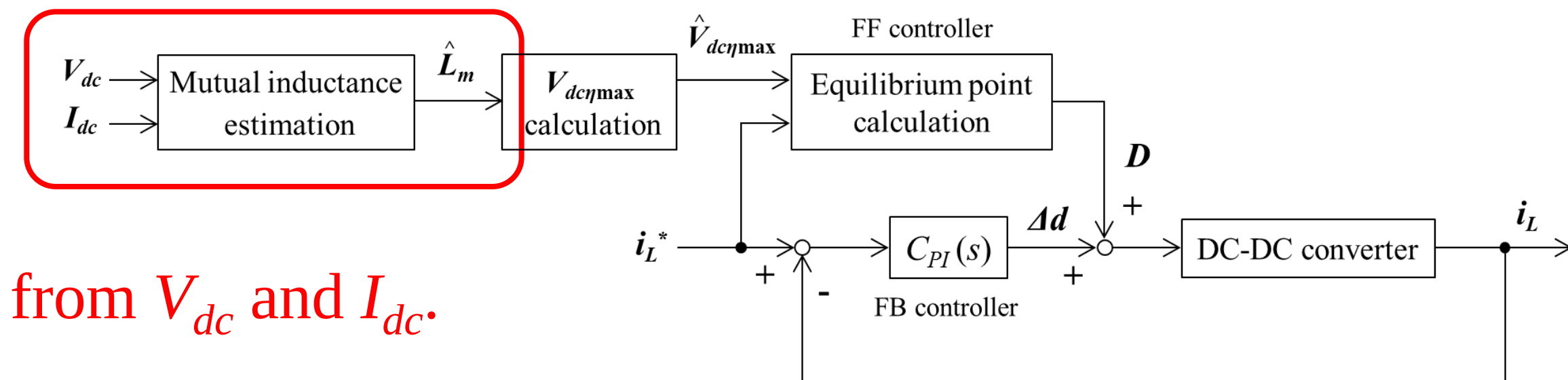
5.3. Mutual inductance estimation

Estimation equation of mutual inductance

[Kobayashi, Imura, Hori, WoW (2015)]

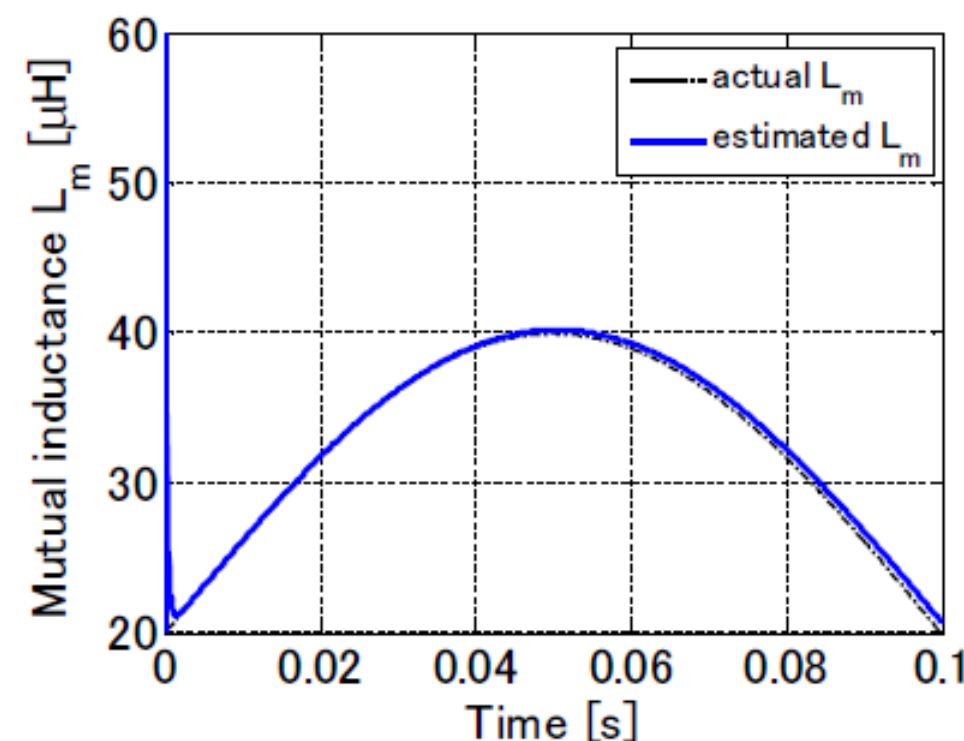
$$\hat{L}_m = \frac{V_1 \pm \sqrt{V_1^2 - 4R_1 I_2 (V_2 + R_2 I_2)}}{2I_2 \omega_0}$$

V_2 and I_2 are calculated from V_{dc} and I_{dc} .

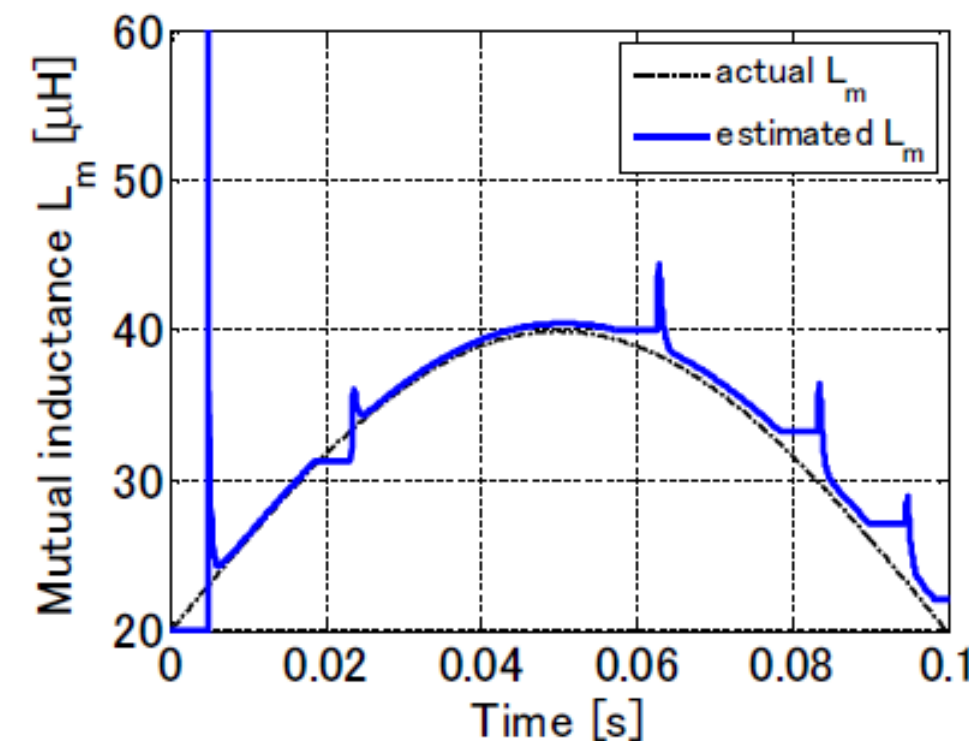


Simulation

w/o control

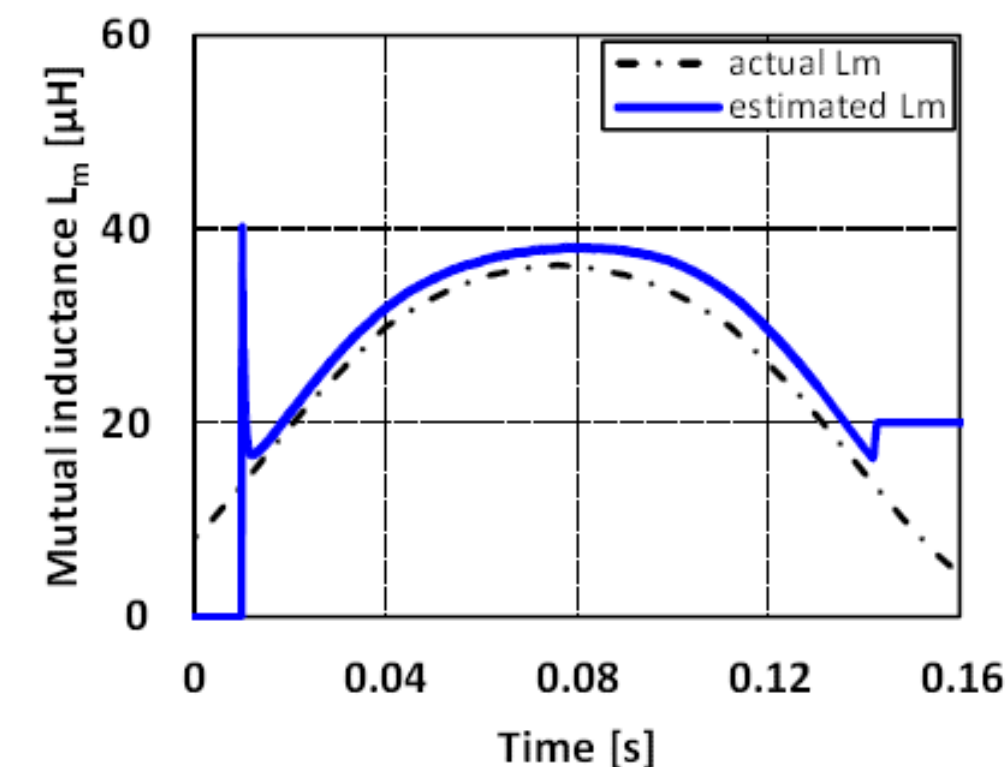


w/ control

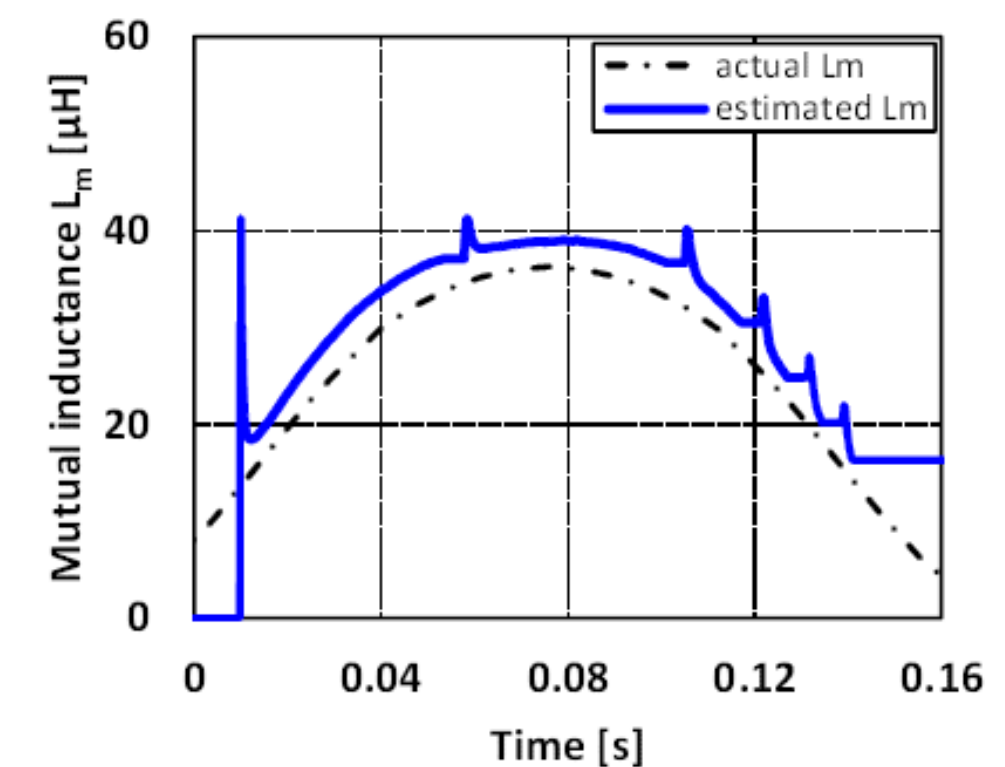


Experiment

w/o control



w/ control



- (w/ control) $\hat{L}_m$ was updated only during the rectification mode of HAR.

- **No time delay on the estimation**



The proposed estimation is working.

5.4. DC link voltage control

Reference voltage for efficiency maximization

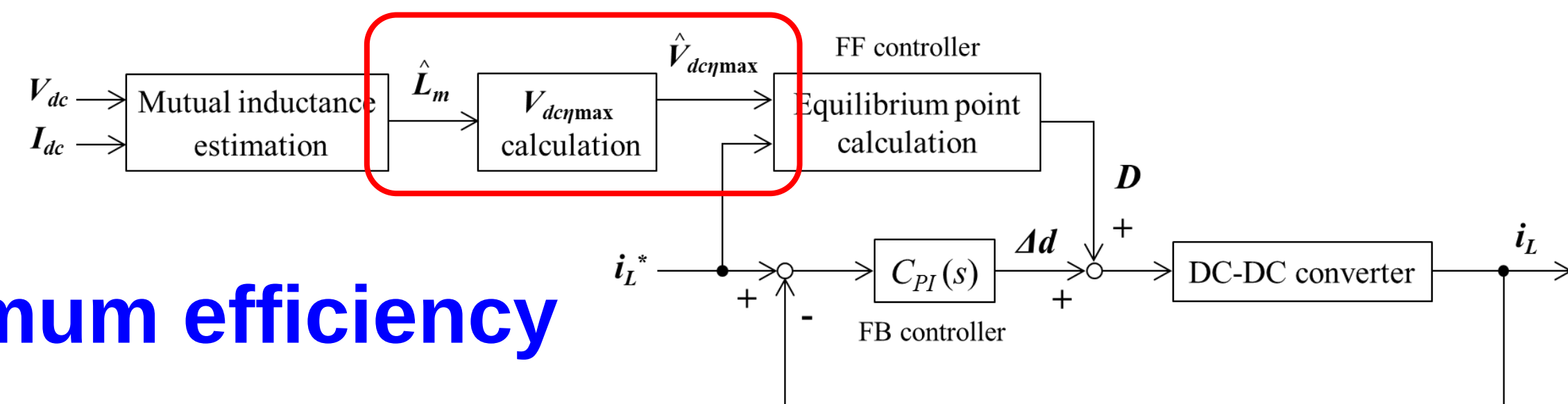
[Kato, Imura, Hori, EVS27 (2013)]

$$V_{dc\eta\max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 \hat{L}_m}{\sqrt{R_1 R_2 + (\omega_0 \hat{L}_m)^2} + \sqrt{R_1 R_2}} V_S$$

$\hat{L}_m$ is used for the calculation.

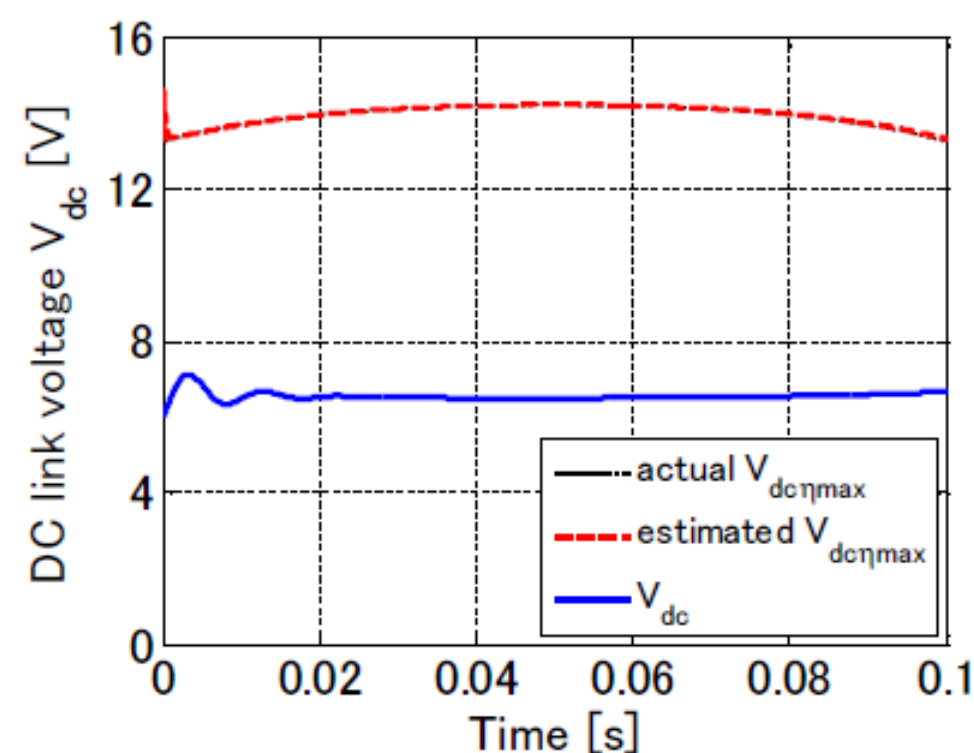


Maximum efficiency

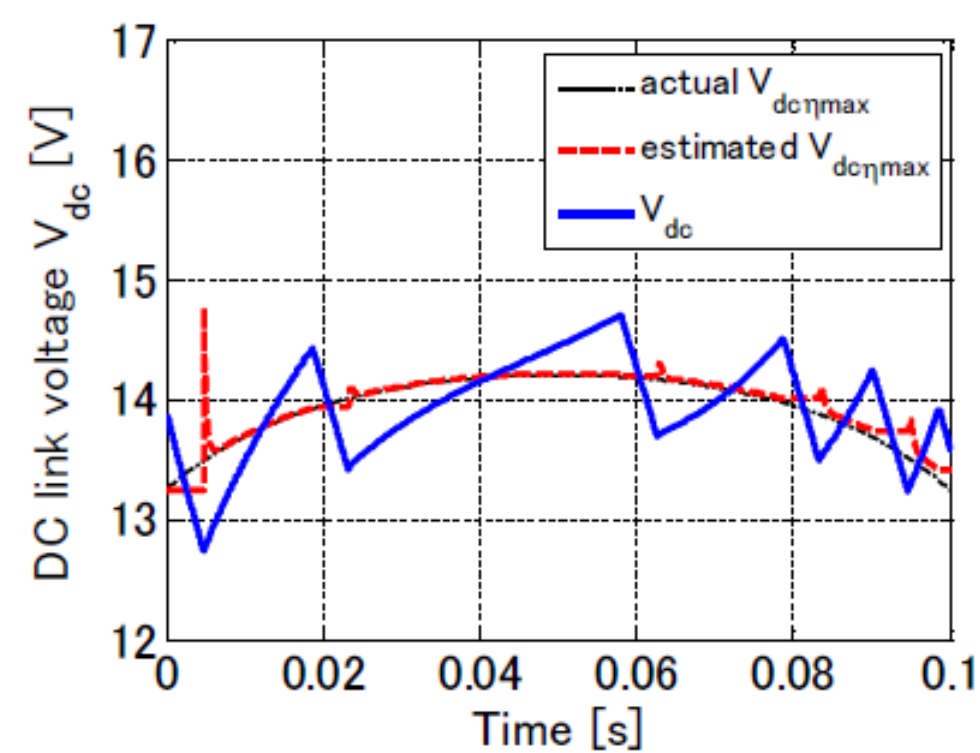


Simulation

w/o control

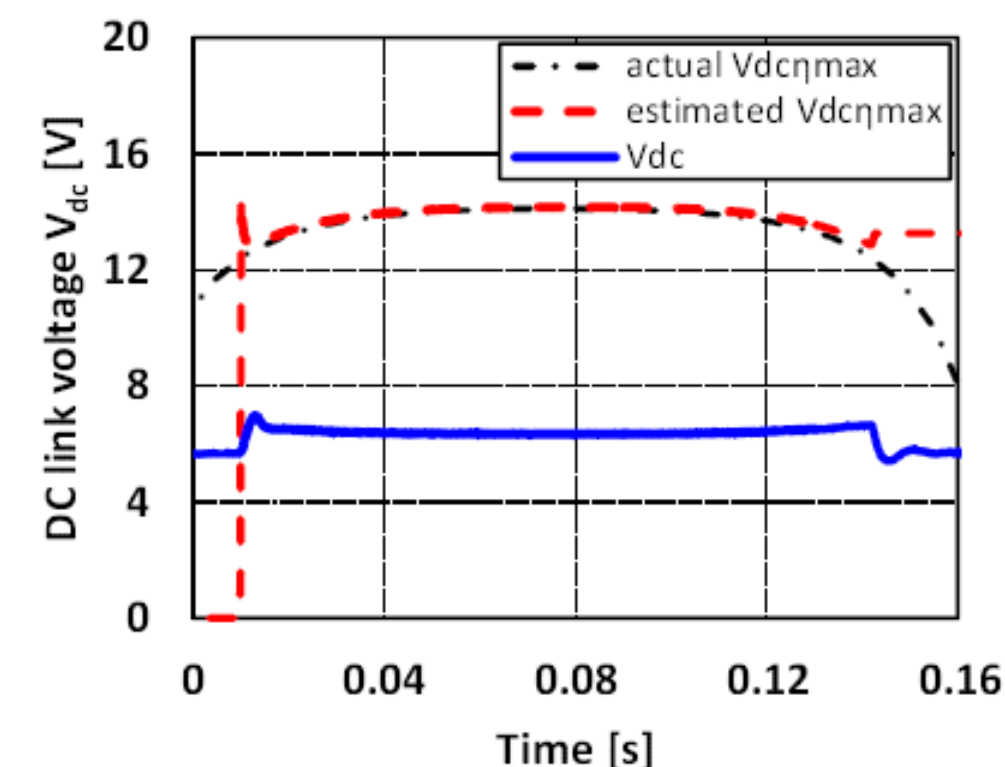


w/ control

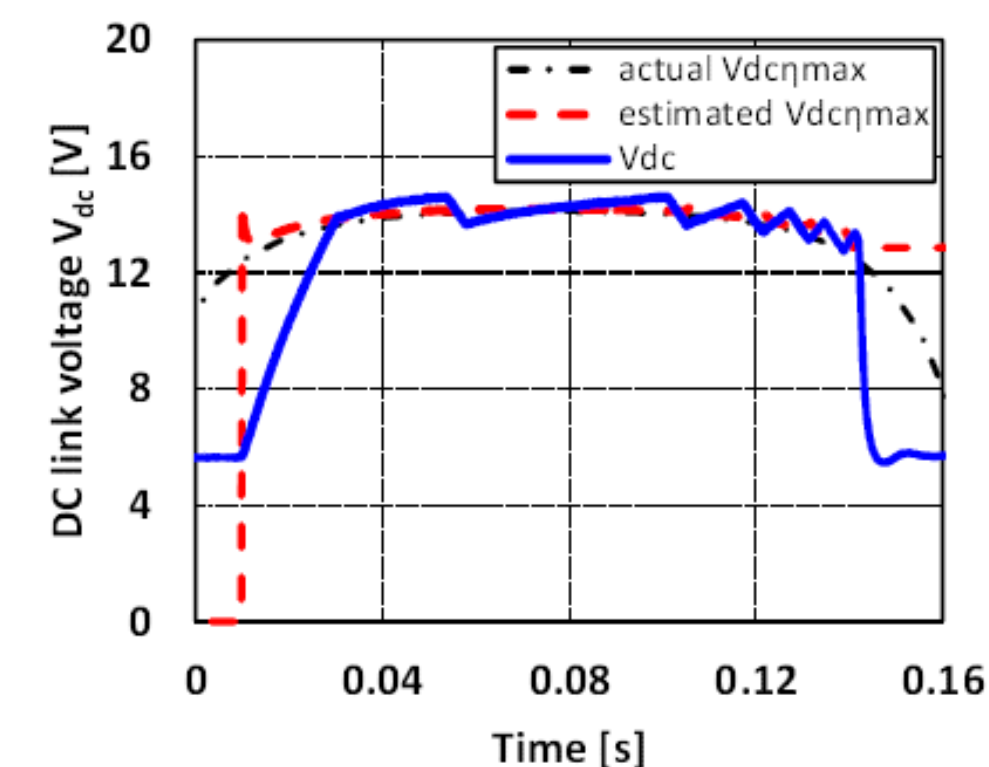


Experiment

w/o control



w/ control



- (w/o control) V_{dc} depends on the battery voltage and the charging current.
- (w/ control) **V_{dc} can be controlled around $V_{dc\eta\max}$ using Half Active Rectifier.**

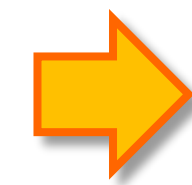
5.5. Efficiency maximization

Reference voltage for efficiency maximization

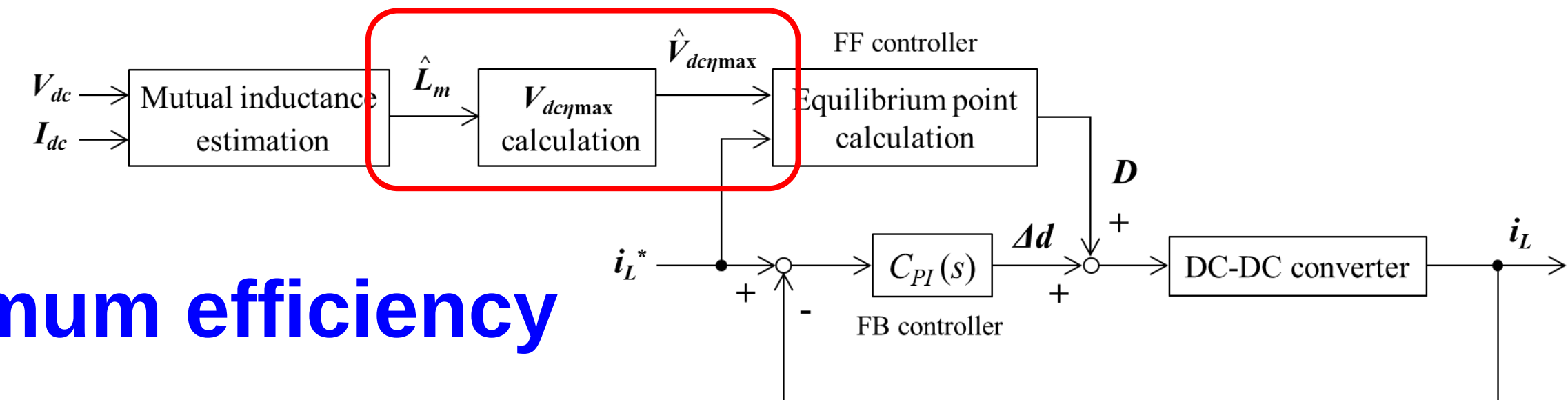
[Kato, Imura, Hori, EVS27 (2013)]

$$V_{dc\eta\max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 \hat{L}_m}{\sqrt{R_1 R_2 + (\omega_0 \hat{L}_m)^2} + \sqrt{R_1 R_2}} V_S$$

$\hat{L}_m$ is used for the calculation.

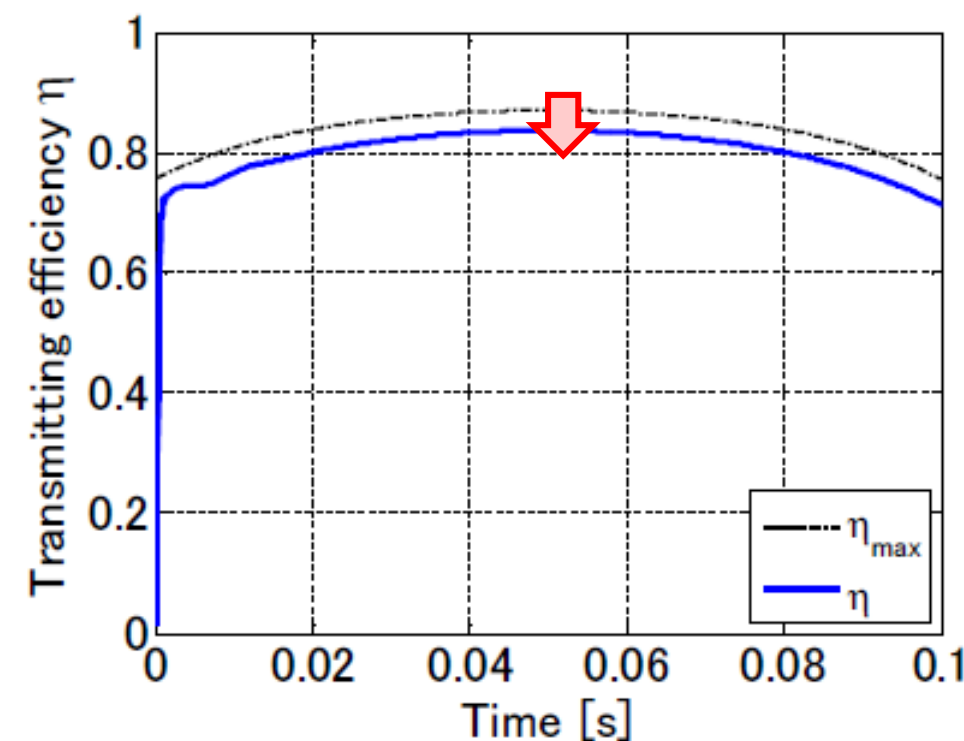


Maximum efficiency

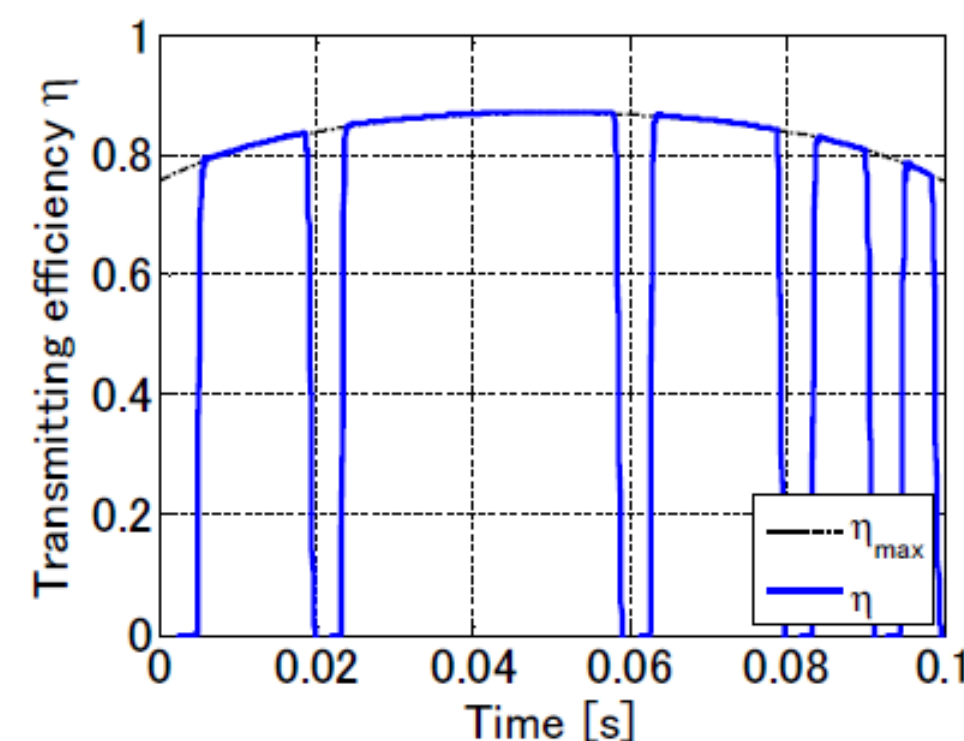


Simulation (AC to AC)

w/o control

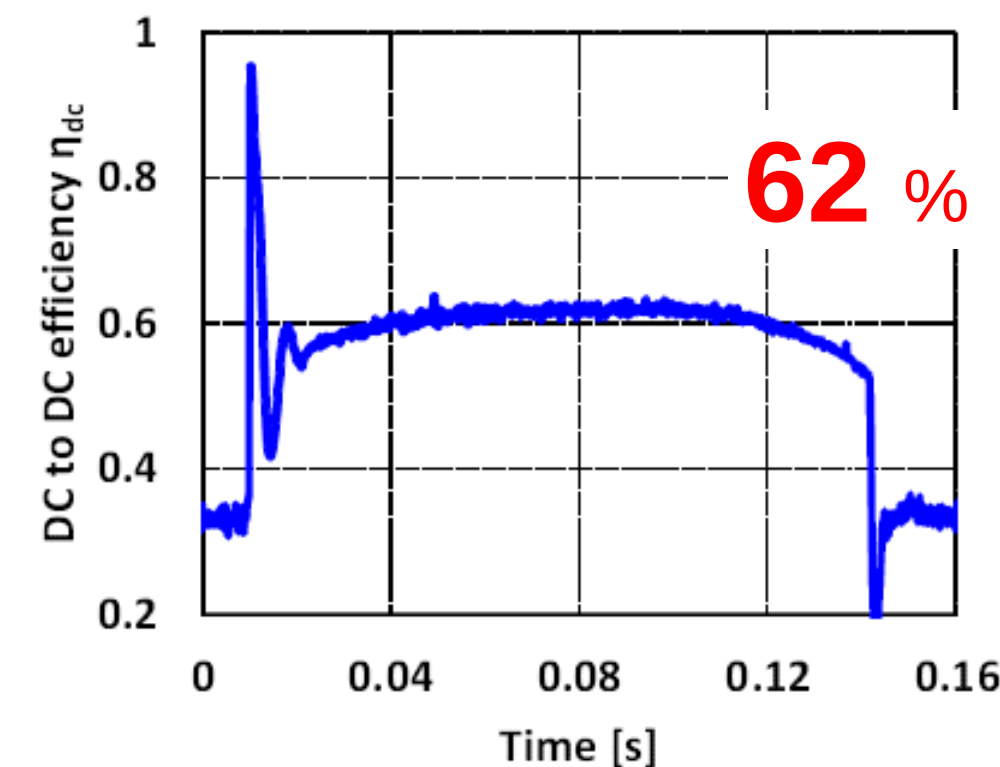


w/ control

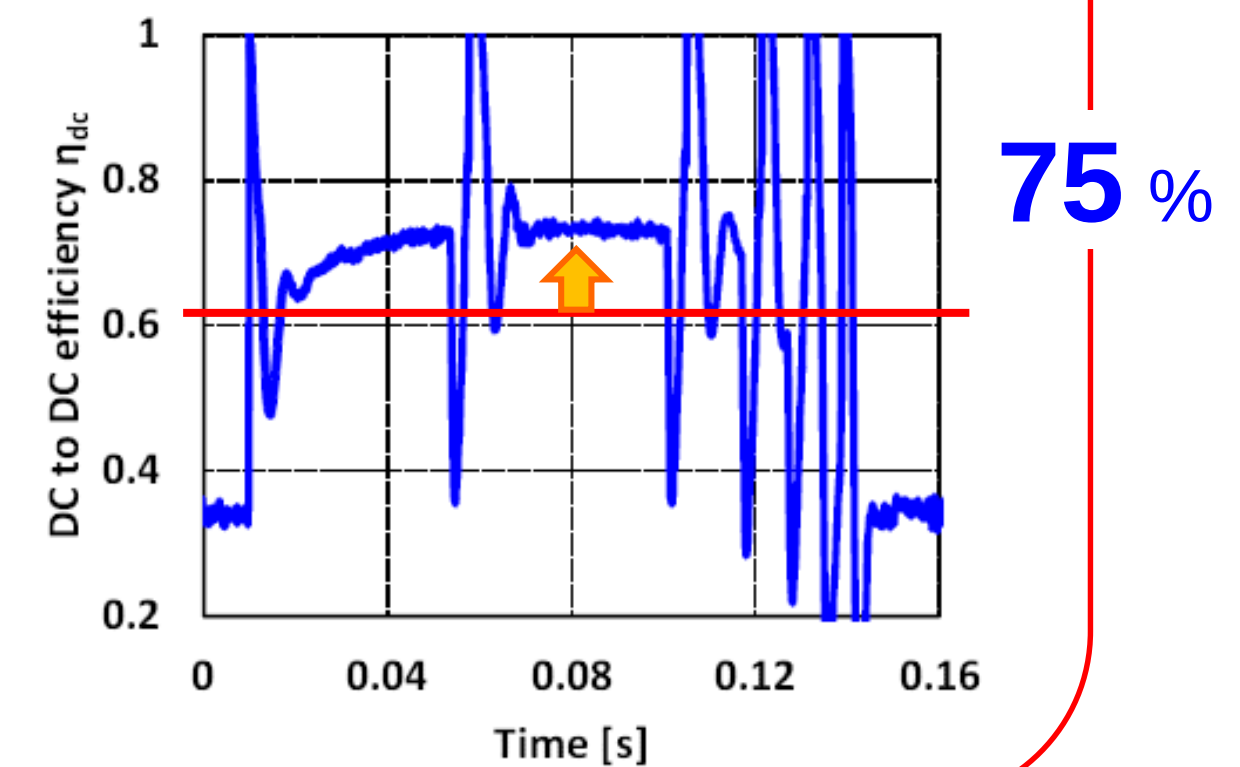


Experiment (DC to DC)

w/o control



w/ control

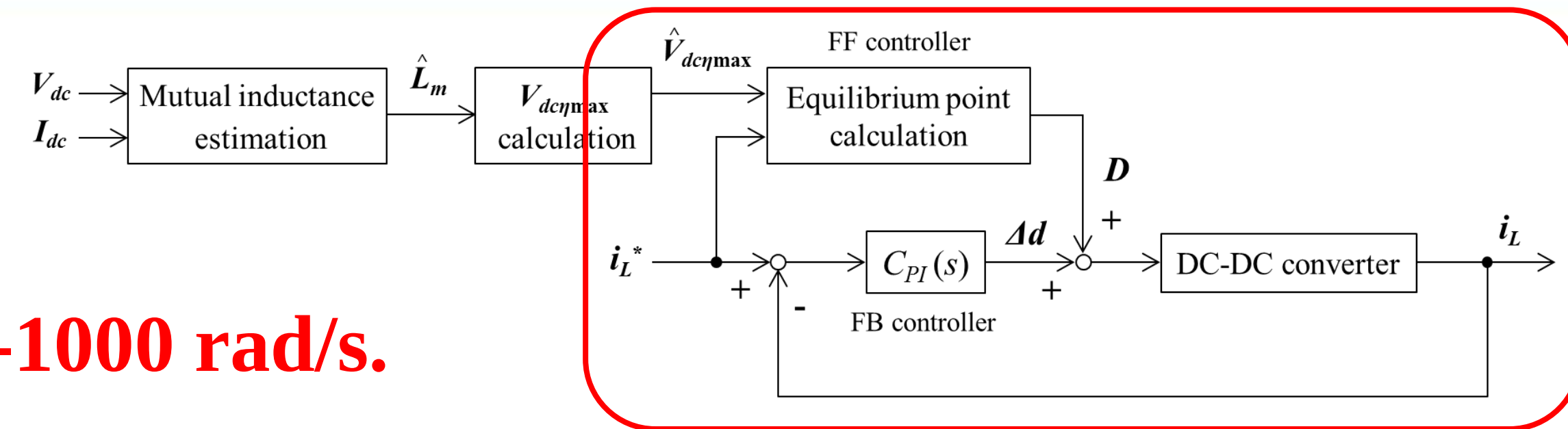


- (w/o control) $\eta_{\max}$ cannot be achieved because V_{dc} is not optimized.
- (w/ control) **η can be maximized by V_{dc} control using Half Active Rectifier.**

5.6. Power control (Charging current control)

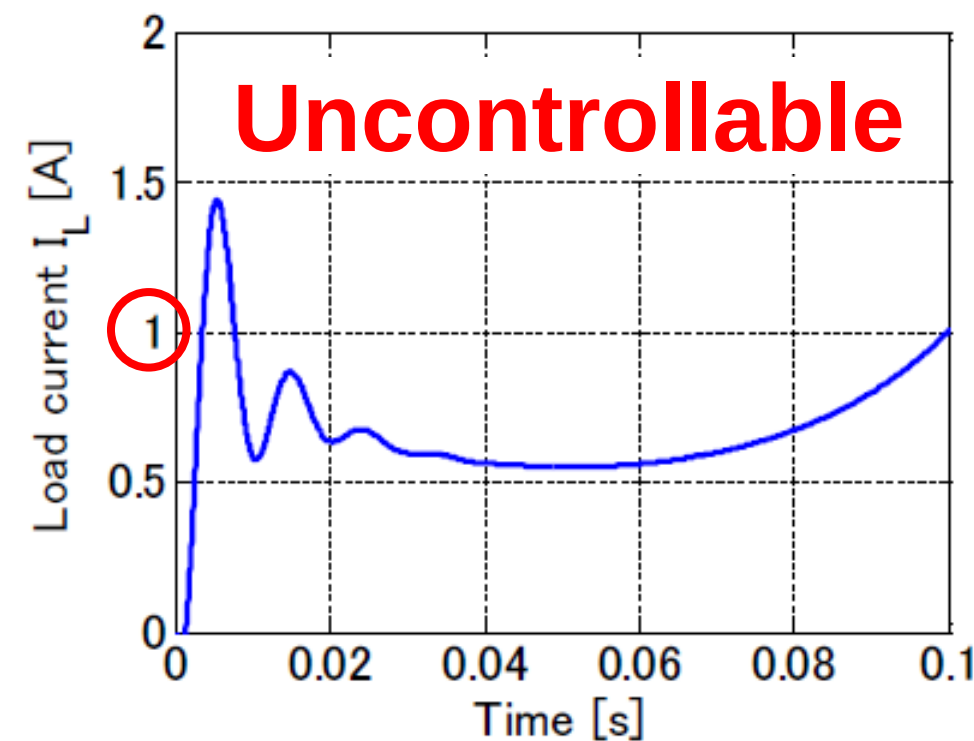
Reference current and FB controller design

- Reference current i_L^* was set to 1 A.
- Closed loop poles ω_{cl} were placed at **-2000 rad/s** or **-1000 rad/s**.

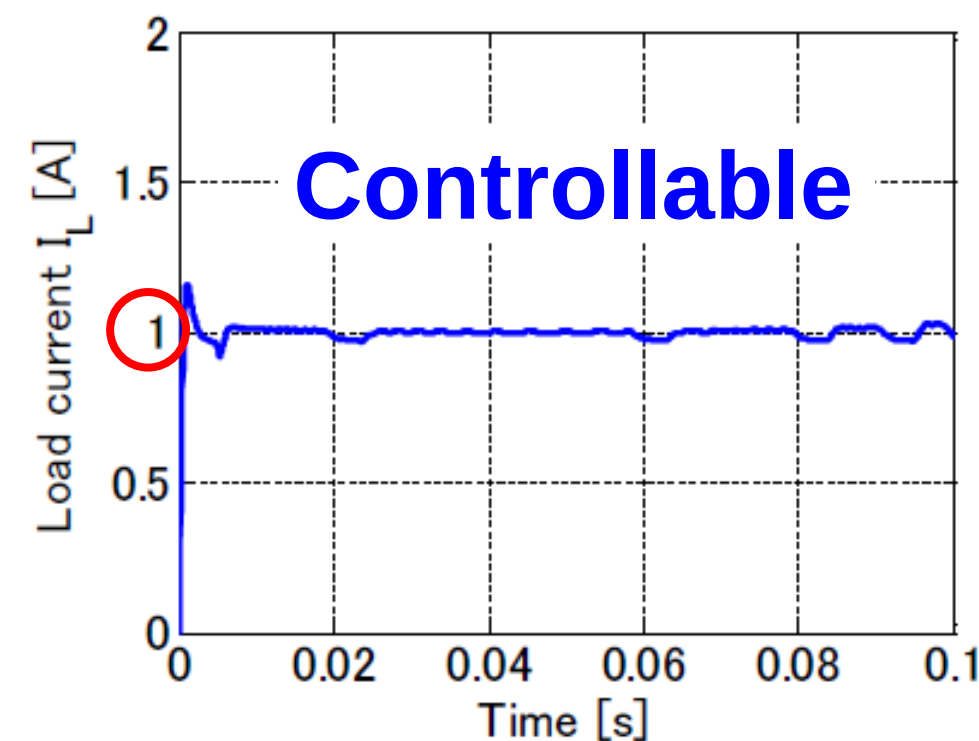


Simulation ($\omega_{cl} = -2000 \text{ rad/s}$)

w/o control

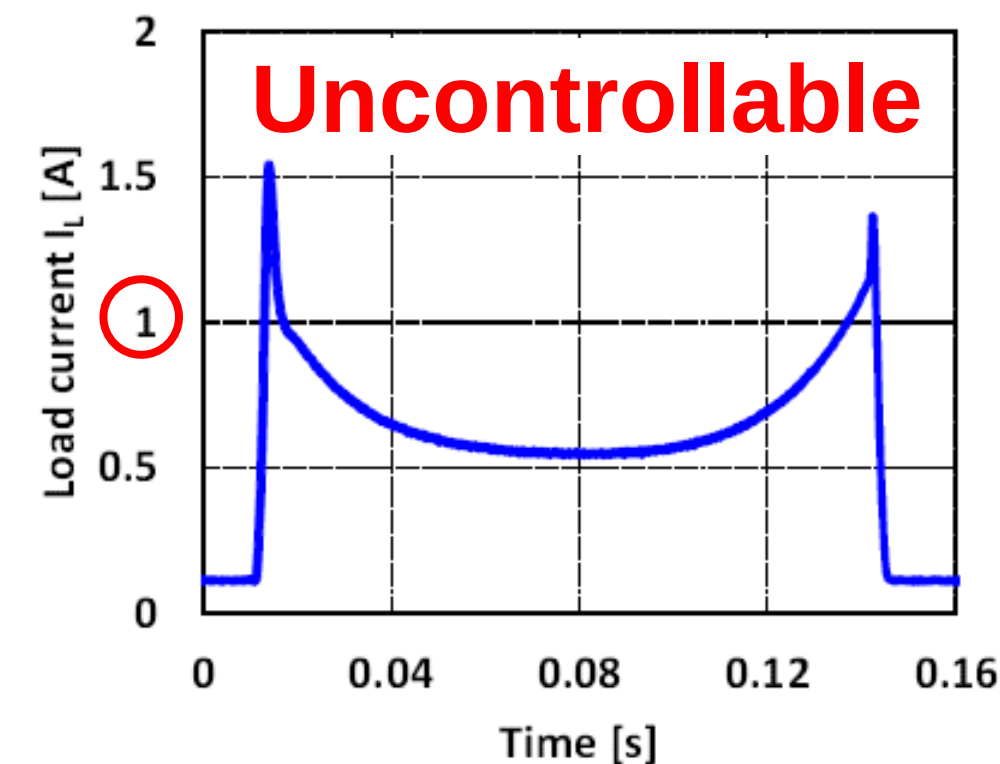


w/ control

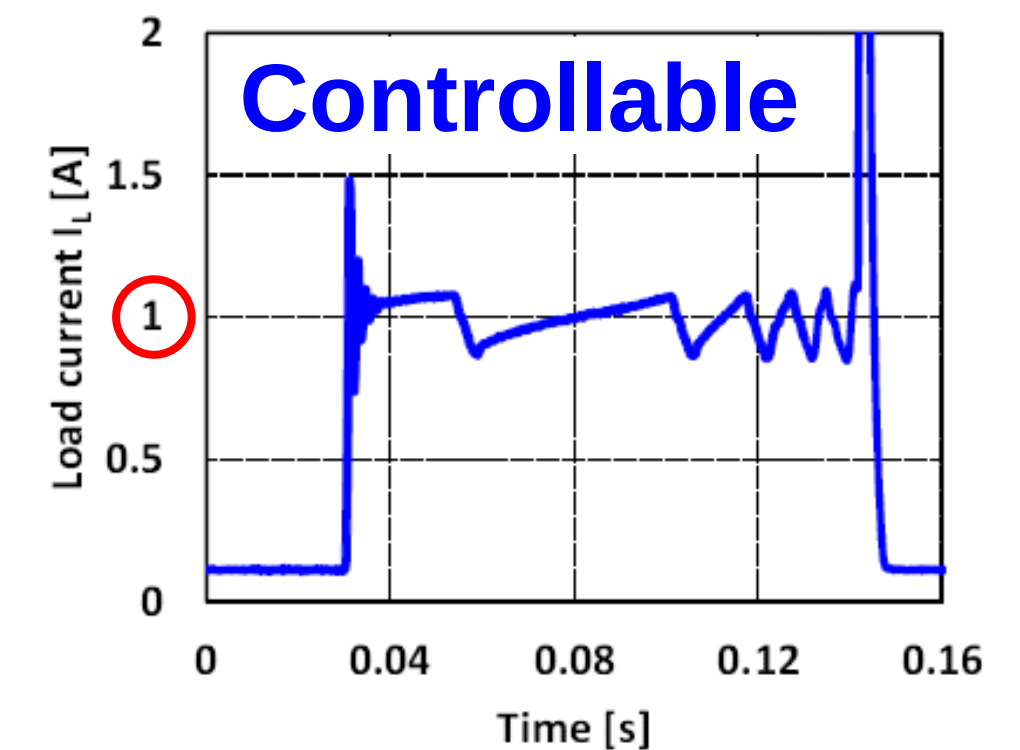


Experiment ($\omega_{cl} = -1000 \text{ rad/s}$)

w/o control



w/ control



- (w/ control) **The desired charging current can be achieved by the proposed control**
- Feedback control of DC/DC converter will improve the response speed.



Outline

1. Introduction
2. System structure of DWPT for EVs
3. Control strategy with proposed method
4. Real-time estimation and controller design
5. Simulation and experiment
6. Conclusion

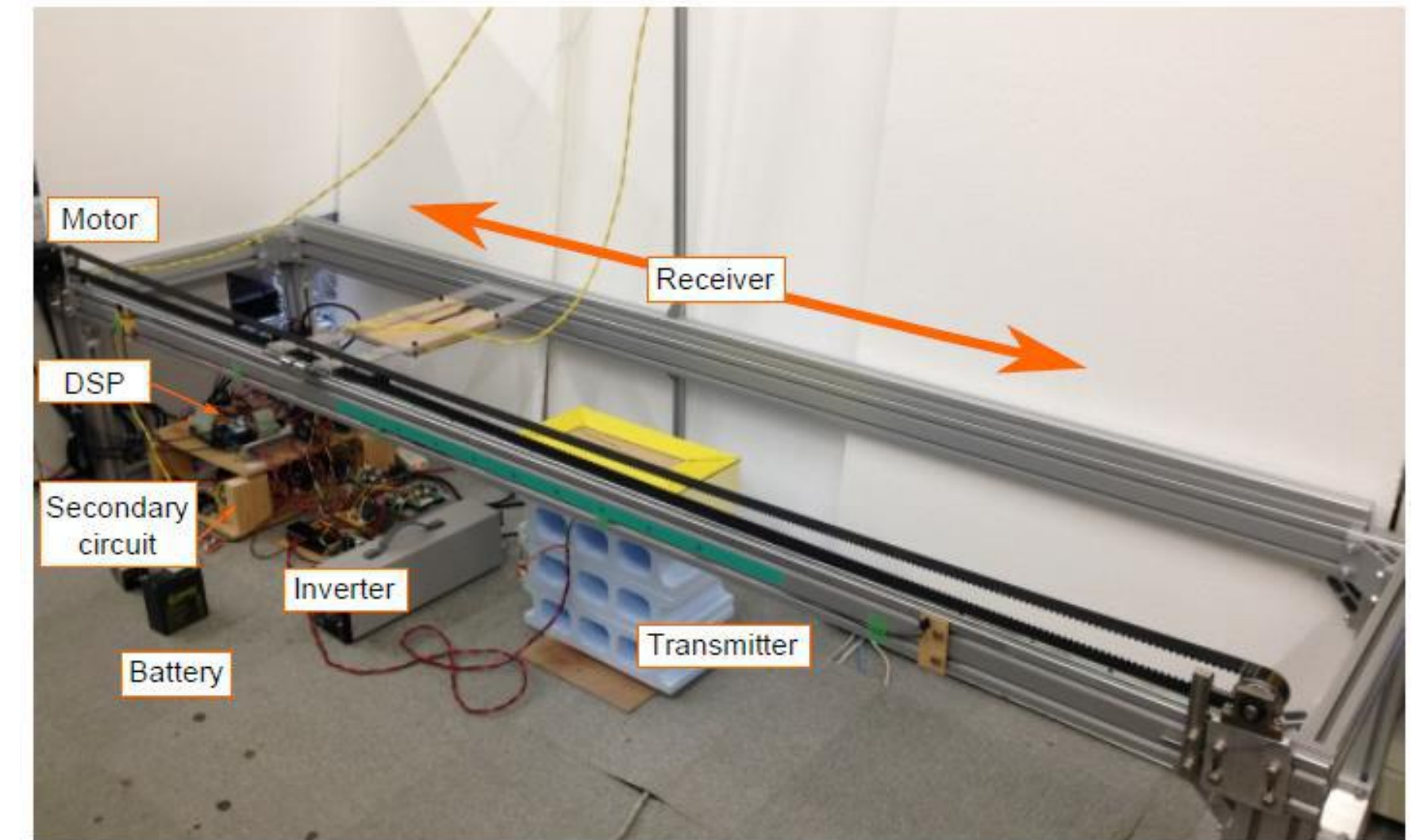
6. Conclusion

Summary

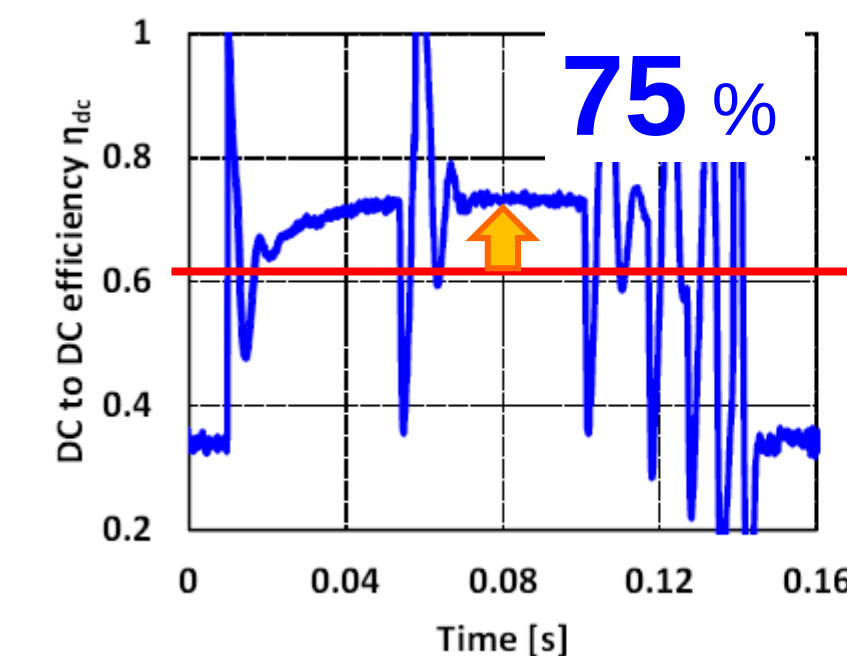
- Power control and efficiency maximization should be achieved on the vehicle side in dynamic charging.
- **Real-time estimation and control were proposed.**
- The effectiveness of the proposed method was verified by the simulations and the experiments.

Future work

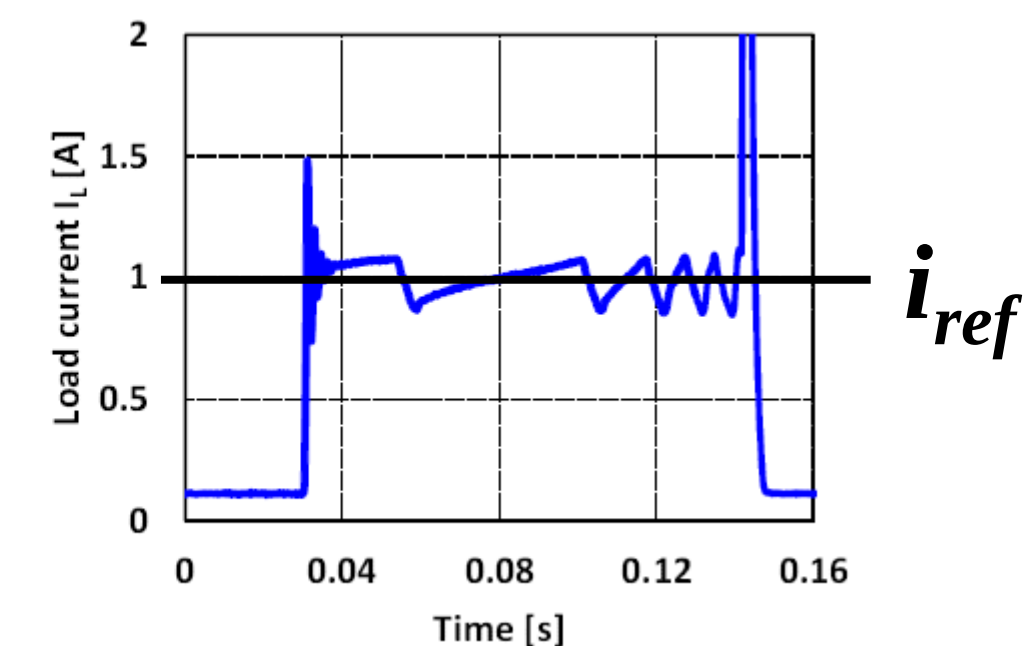
- Experimental verification of the proposed method **using the trial unit on the experimental vehicle**



w/ control



Controllable





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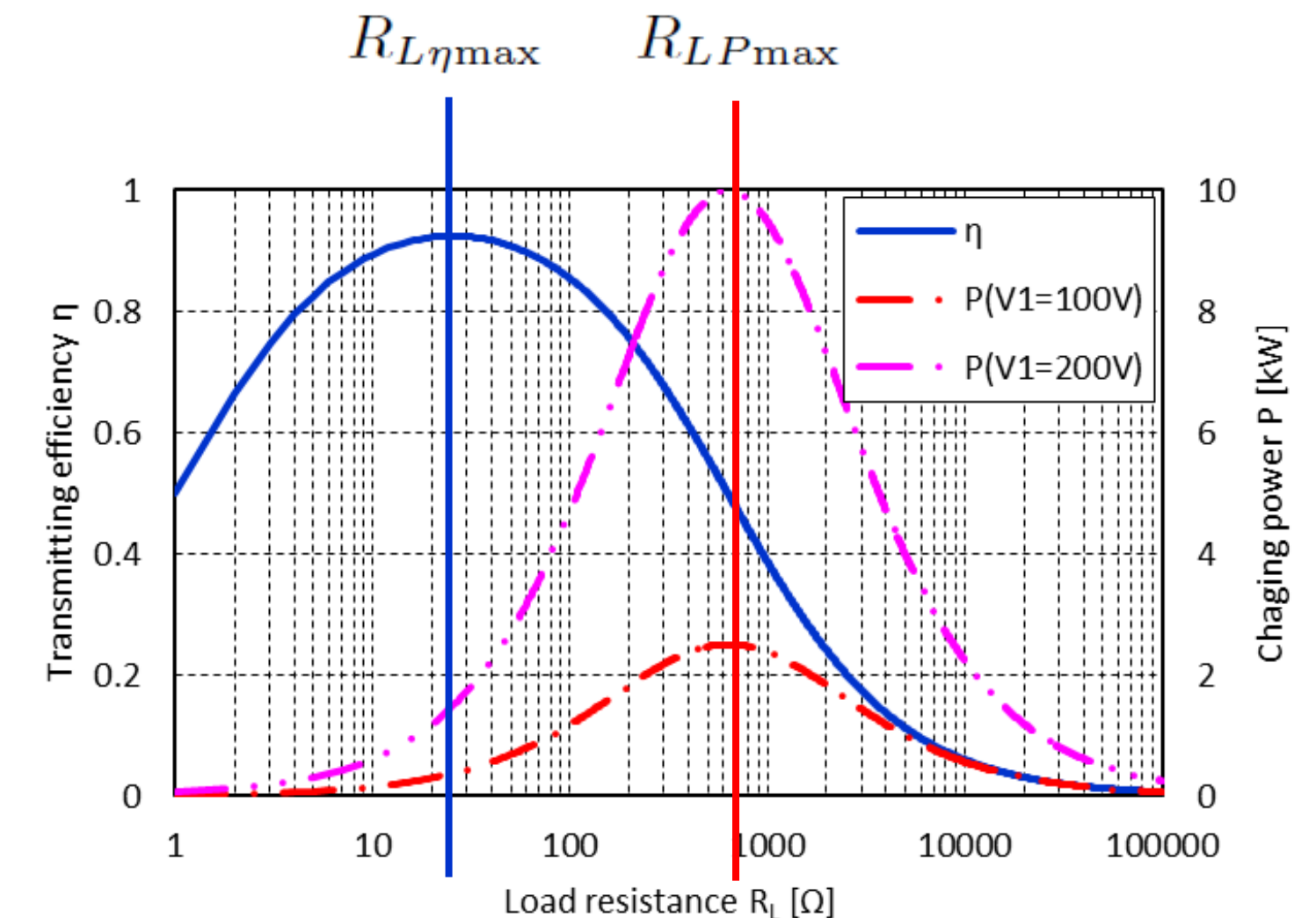
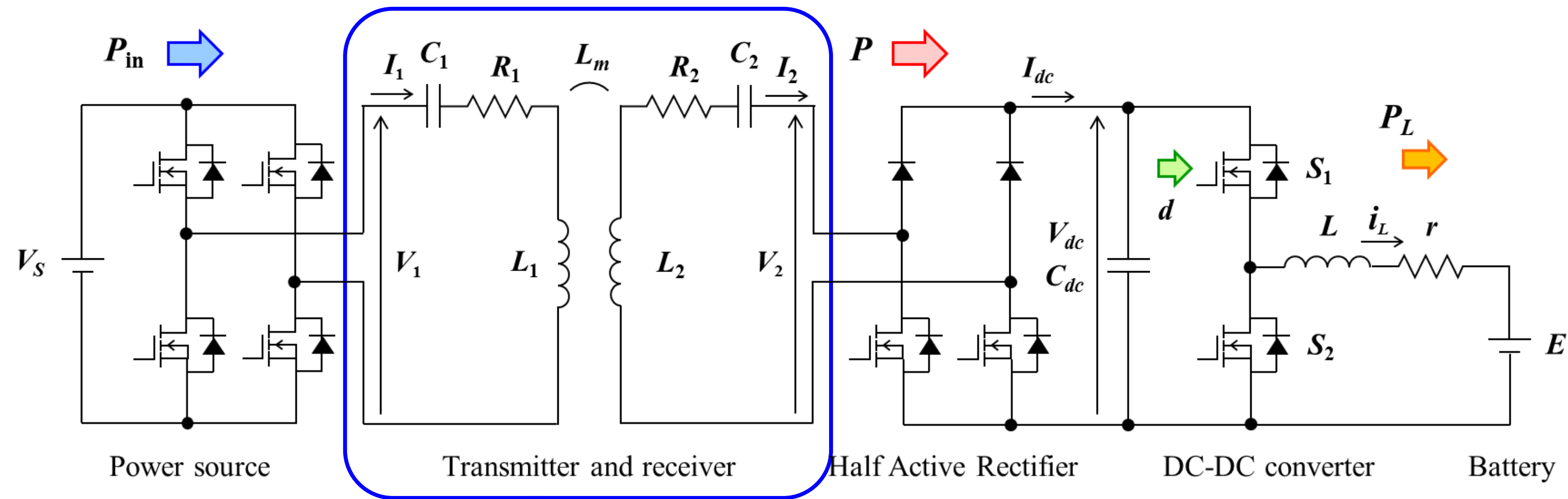


DRIVE ELECTRIC INNOVATION
PROPULSER L'INNOVATION EN MOBILITÉ ÉLECTRIQUE

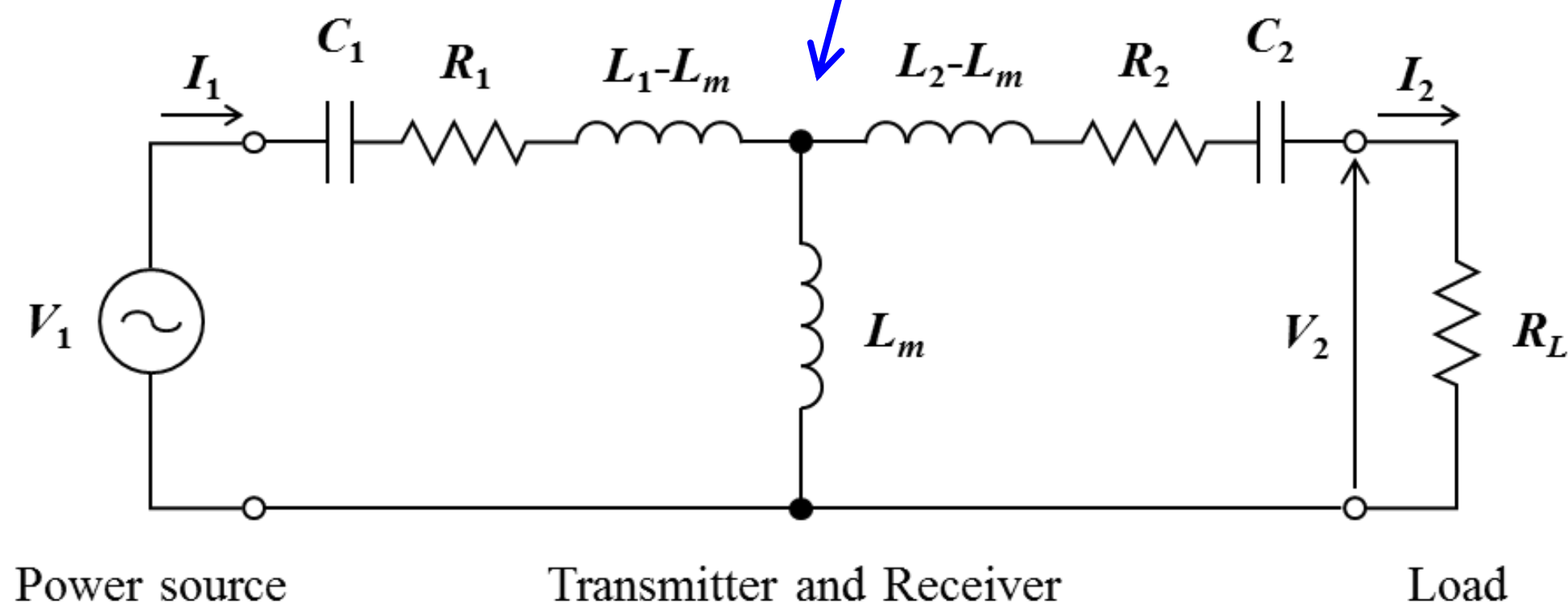
EVS29.ORG

Appendix: Circuit analysis

Whole topology of the DWPT system



Equivalent circuit



Operating angular frequency

Transmitting efficiency

$$\eta = \frac{(\omega_0 L_m)^2 R_L}{(R_2 + R_L) \{R_1 R_2 + R_1 R_L + (\omega_0 L_m)^2\}}$$

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}$$

Transmitting power

$$P = \frac{(\omega_0 L_m)^2 R_L}{\{R_1 R_2 + R_1 R_L + (\omega_0 L_m)^2\}^2} V_1^2$$

Appendix: Transmitting efficiency and power

Transmitting efficiency

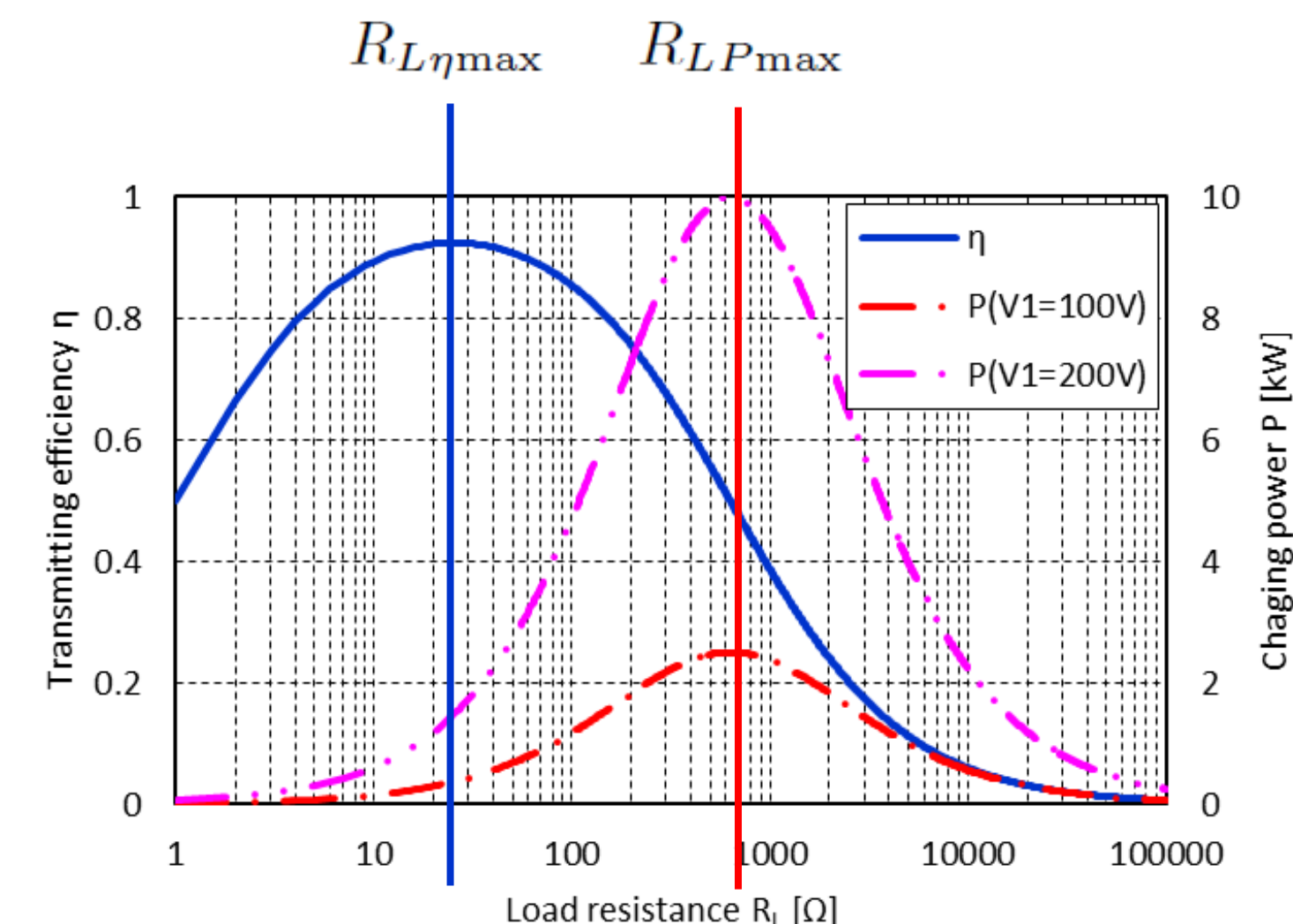
$$\eta = \frac{(\omega_0 L_m)^2 R_L}{(R_2 + R_L)\{R_1 R_2 + R_1 R_L + (\omega_0 L_m)^2\}}$$

η and P are determined by R_L .  **Vehicle-Side Control**

(R_L control only)

Transmitting power

$$P = \frac{(\omega_0 L_m)^2 R_L}{\{R_1 R_2 + R_1 R_L + (\omega_0 L_m)^2\}^2} V_1^2$$



Maximum efficiency and desired power CANNOT be achieved simultaneously.

For maximum efficiency

$$R_{L\eta\max} = \sqrt{R_2 \left\{ \frac{(\omega_0 L_m)^2}{R_1} + R_2 \right\}}$$

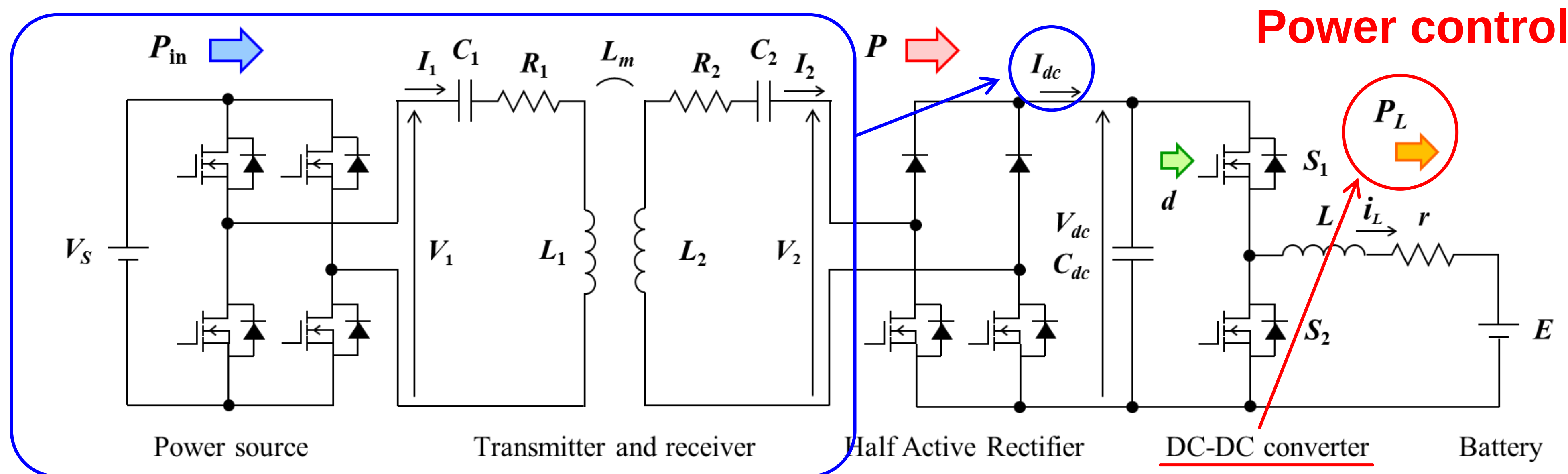
≠

For maximum power

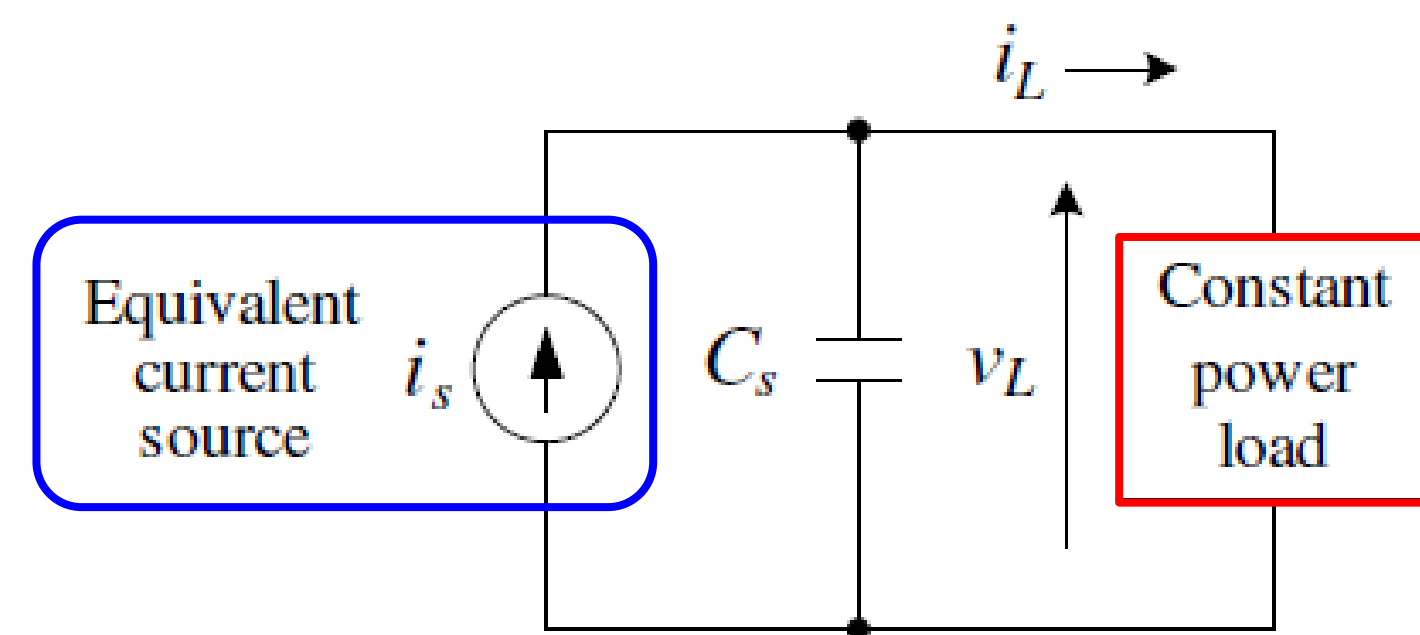
$$R_{LP\max} = \frac{(\omega_0 L_m)^2}{R_1} + R_2$$

Appendix: Stability analysis of DC link voltage

Whole topology of the DWPT system



Equivalent current source [Irie, Tahara, IEEJ Trans. IA (2009)]



Simplified circuit model [Gunji, Imura, Fujimoto, IEEE ICPE-ECCE Asia (2015)]

$$P_{\Delta}(s) = \frac{\Delta v_L(s)}{\Delta i_s(s)} = \frac{1}{C_s \left(s - \frac{p_L}{C_s V_L^2} \right)}$$

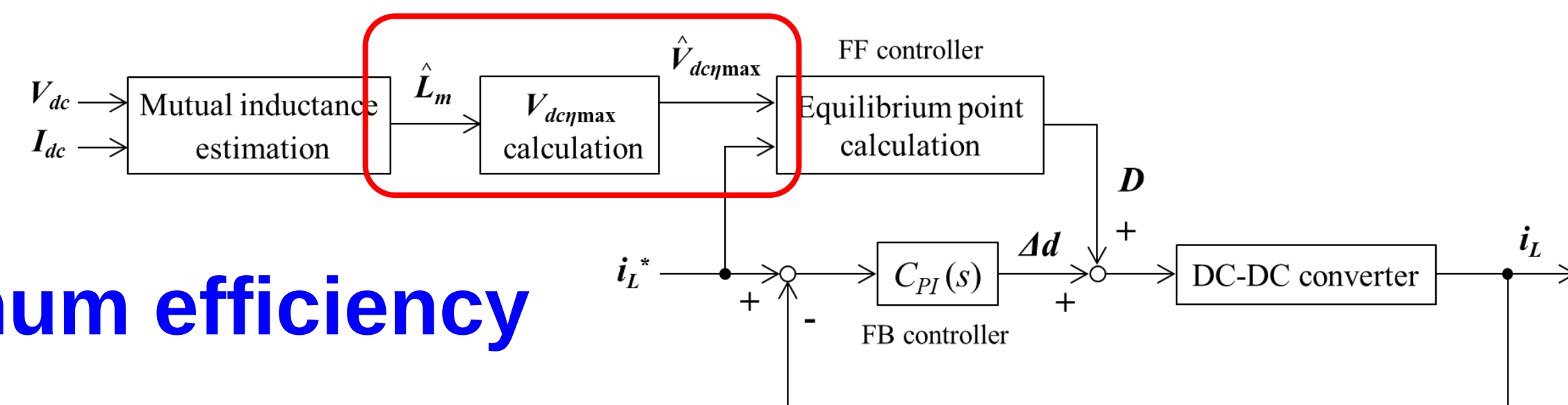
Unstable pole

Appendix: Efficiency maximization by HAR

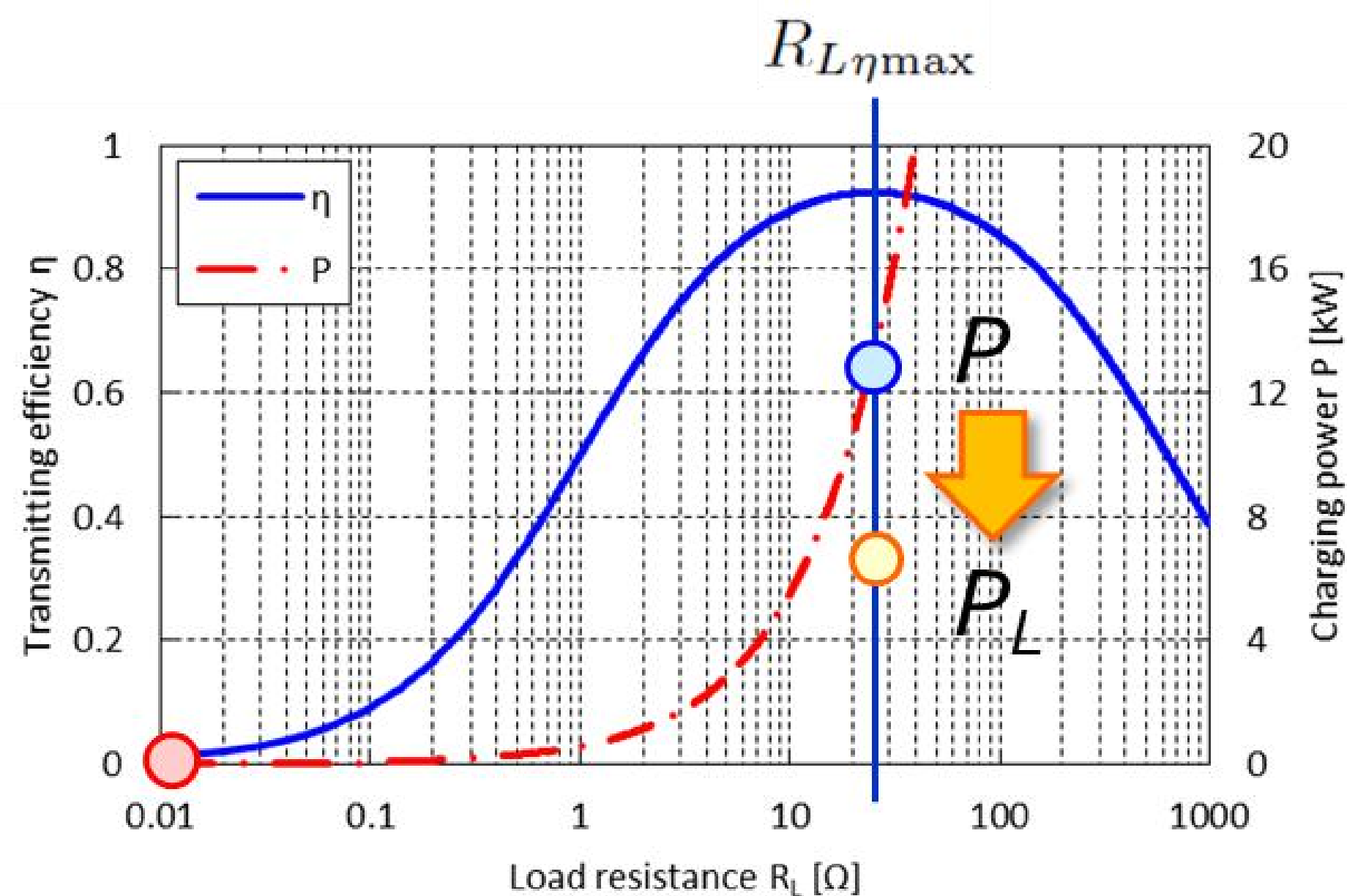
Reference voltage for efficiency maximization

[Kato, Imura, Hori, EVS27 (2013)]

$$V_{dc\eta\max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 L_m}{\sqrt{R_1 R_2 + (\omega_0 L_m)^2} + \sqrt{R_1 R_2}} V_S \quad \Rightarrow \quad \text{Maximum efficiency}$$



Operating point in each modes of Half Active Rectifier



(Rectification mode) R_L is optimized.

⇒ **Transmitting efficiency is maximized.**

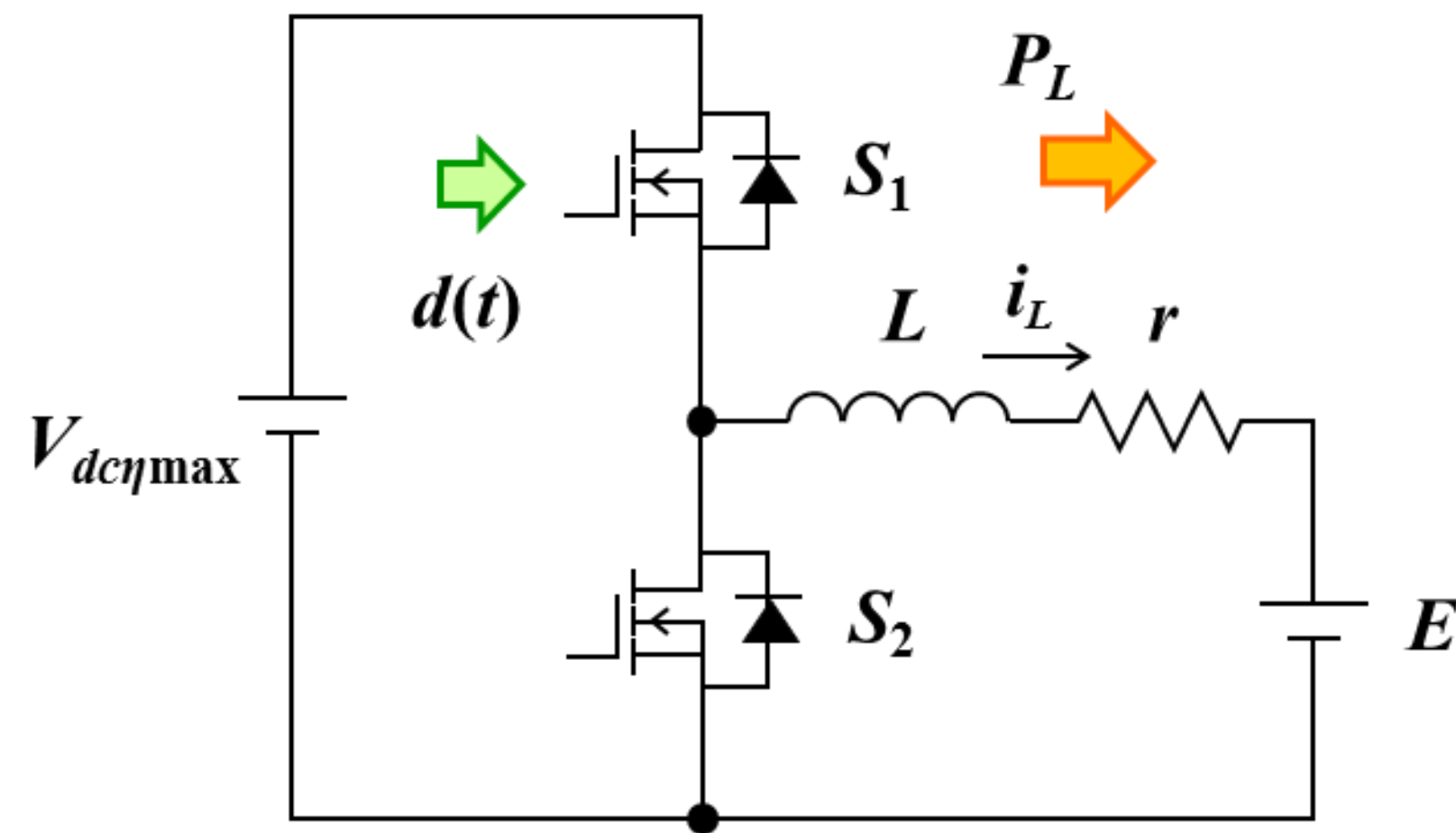
(Short mode) R_L is minimized.

⇒ Transmitting power is drastically decreased.

⇒ **Losses during the short mode can be neglected.**

Appendix: Modeling of DC-DC converter

Simplified DC-DC converter model



State space averaging model

$$\frac{d}{dt}i_L(t) = -\frac{r}{L}i_L(t) - \frac{1}{L}E + \frac{d(t)}{L}V_{dc\eta\max}$$

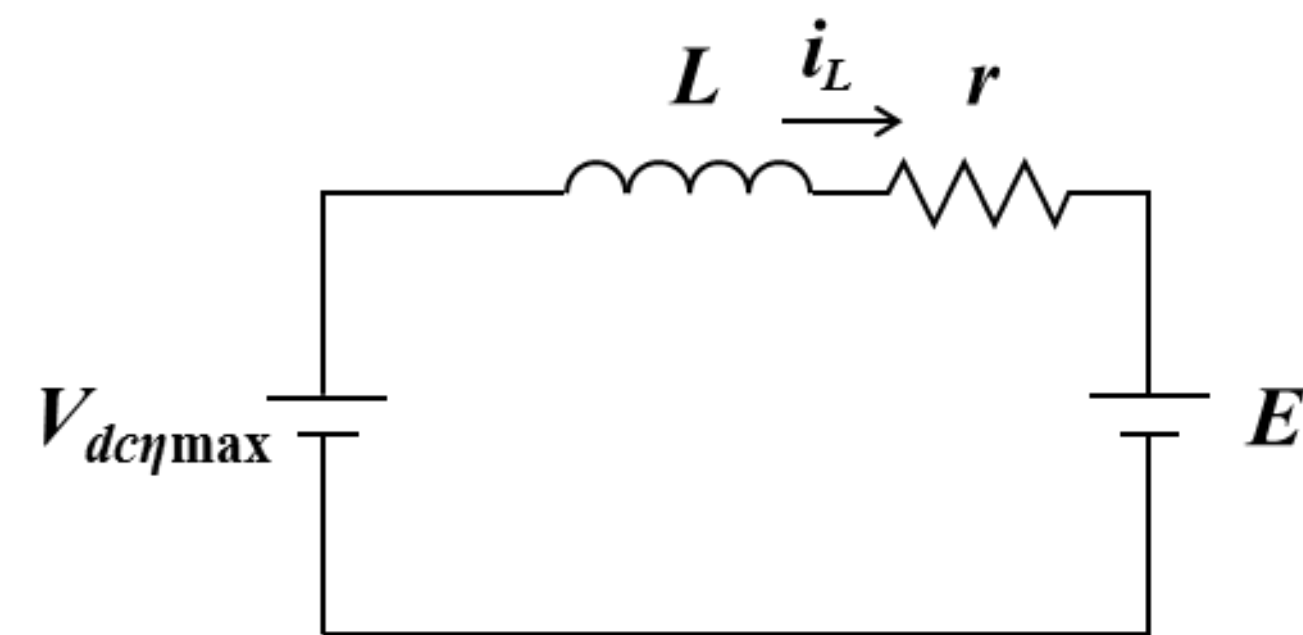
Linearized model

$$\frac{d}{dt}\Delta i_L(t) = -\frac{r}{L}\Delta i_L(t) + \frac{V_{dc\eta\max}}{L}\Delta d(t)$$

State equation of each operation modes

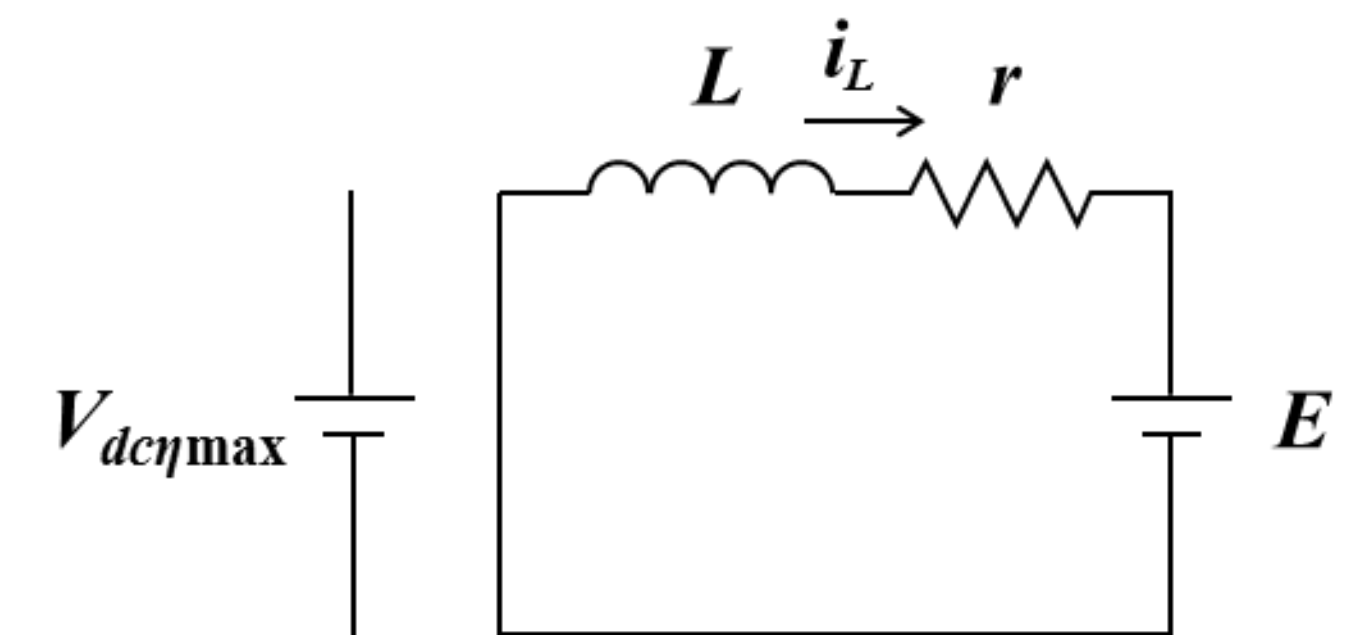
(Continuous current mode only)

(S_1 : ON, S_2 : OFF)



$$\frac{d}{dt}i_L(t) = -\frac{r}{L}i_L(t) - \frac{1}{L}E + \frac{1}{L}V_{dc\eta\max}$$

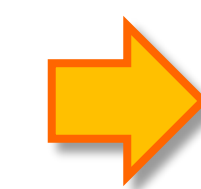
(S_1 : OFF, S_2 : ON)



$$\frac{d}{dt}i_L(t) = -\frac{r}{L}i_L(t) - \frac{1}{L}E$$

Transfer function model

$$\Delta P_i(s) = \frac{\Delta i_L(s)}{\Delta d(s)} = \frac{V_{dc\eta\max}}{Ls + r}$$



Controller design

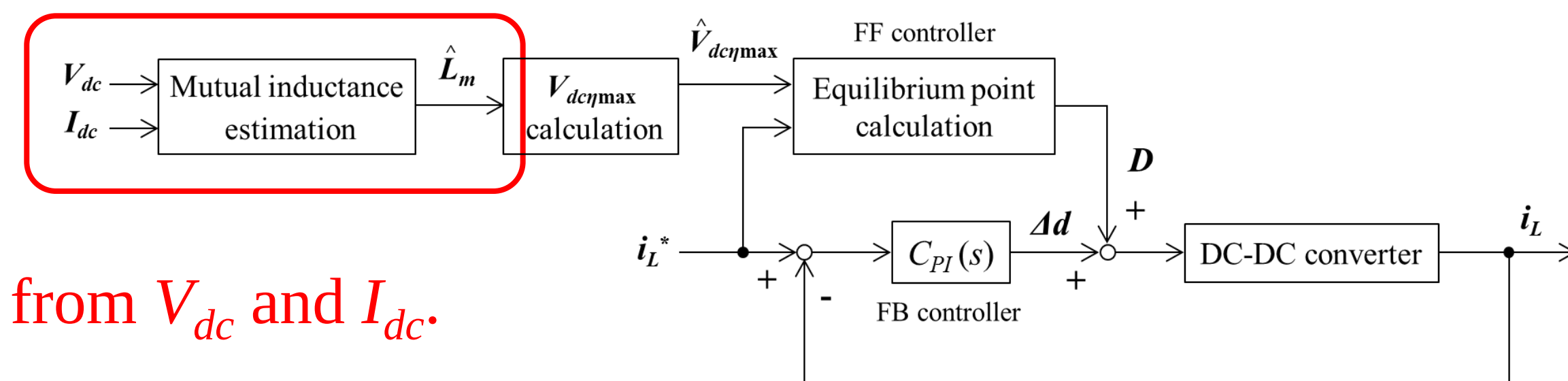
Appendix: Conditional updating of estimation

Estimation equation of mutual inductance

[Kobayashi, Imura, Hori, WoW (2015)]

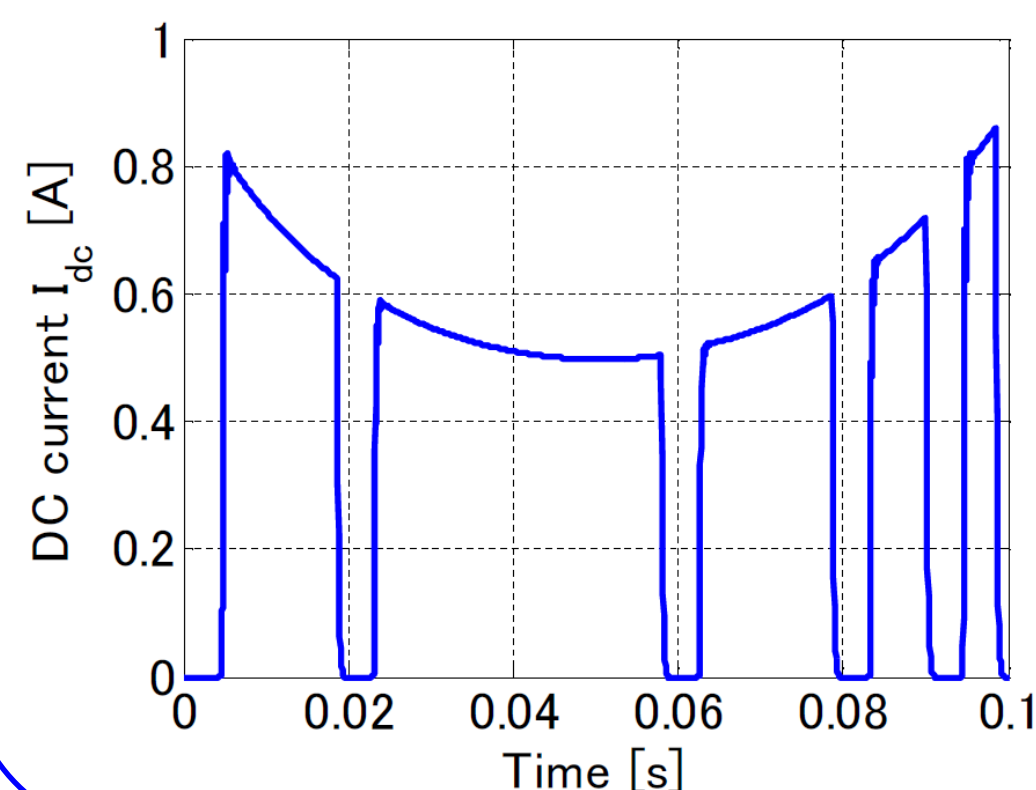
$$\hat{L}_m = \frac{V_1 \pm \sqrt{V_1^2 - 4R_1 I_2 (V_2 + R_2 I_2)}}{2I_2 \omega_0}$$

V_2 and I_2 are calculated from V_{dc} and I_{dc} .

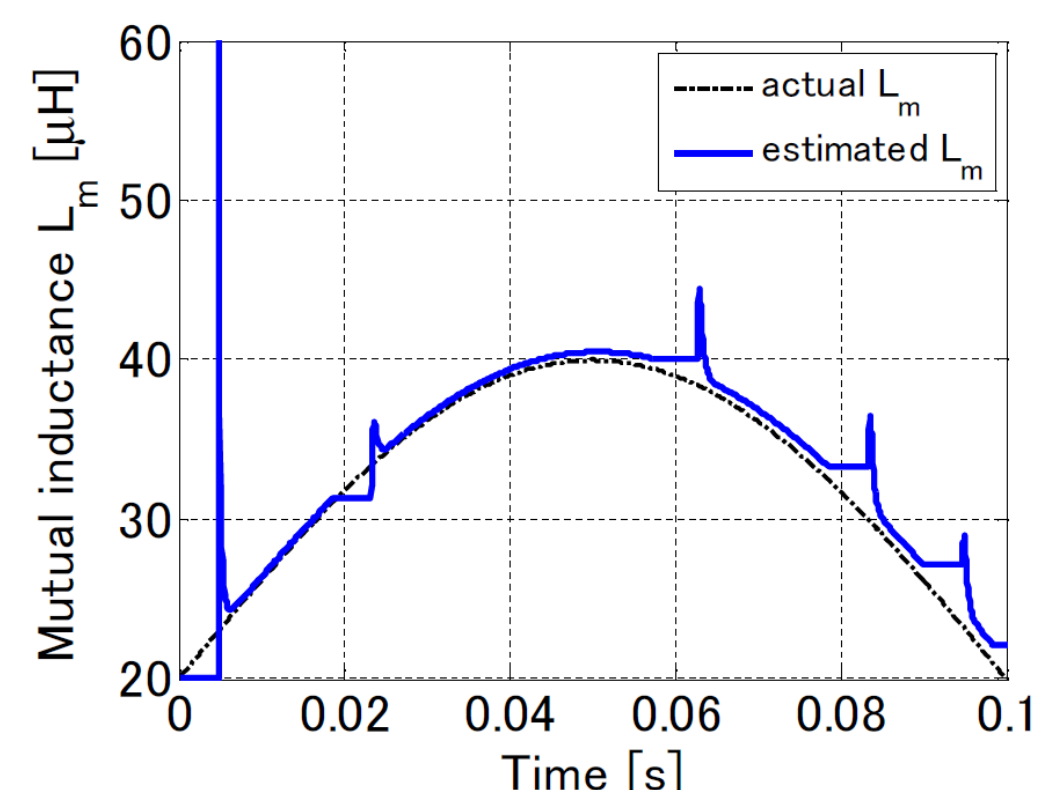


Simulation

DC current

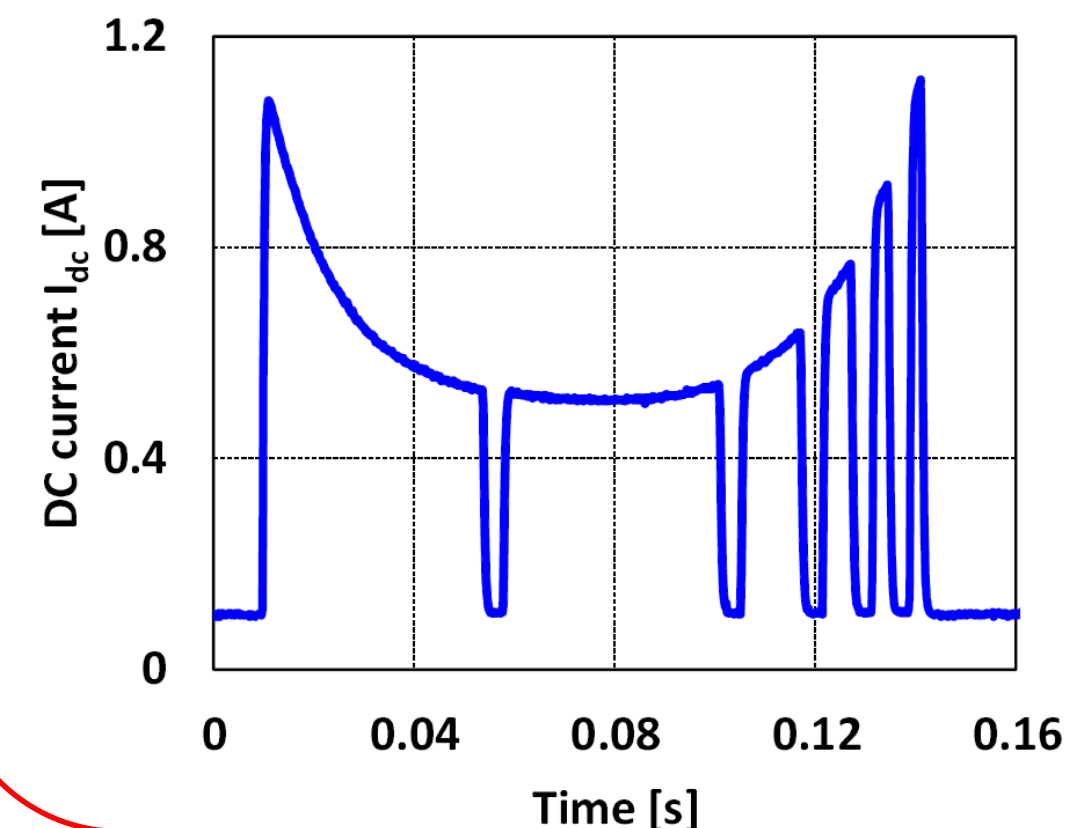


Mutual inductance

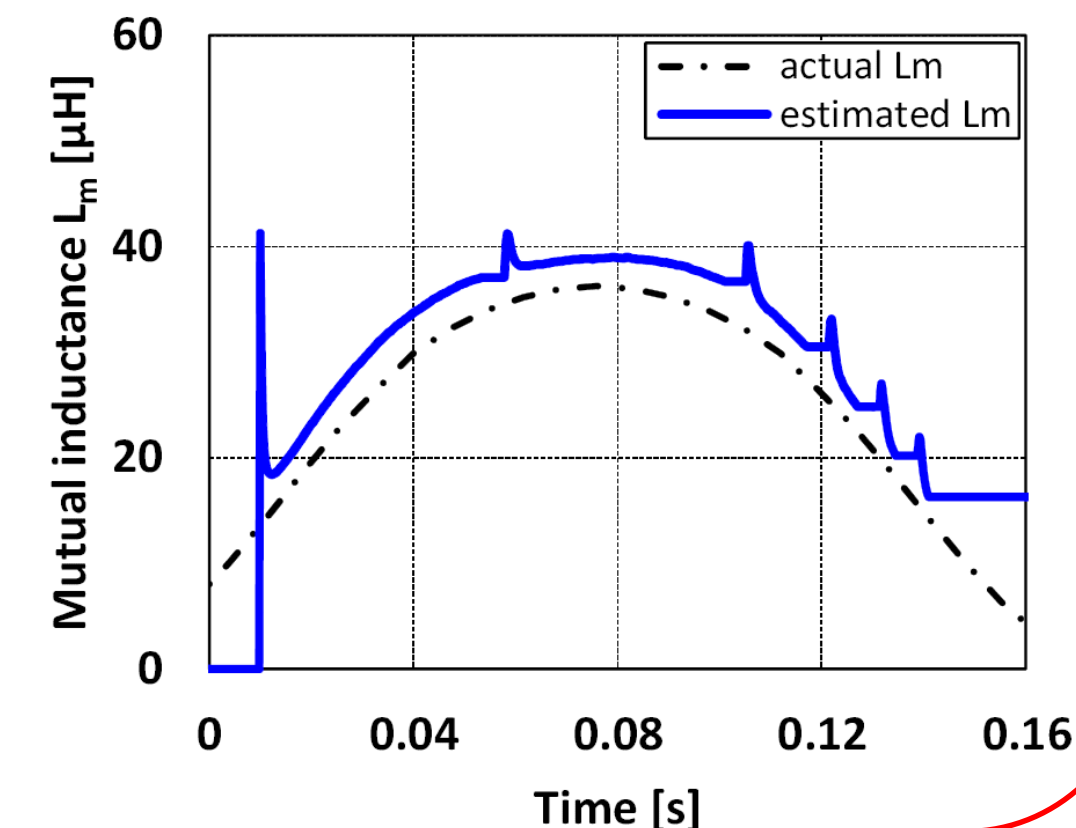


Experiment

DC current



Mutual inductance



- During short mode, the calculated L_m is not correct because I_{dc} becomes 0.
- The estimated value should be updated during the rectification mode.

Appendix: Recursive Least Square (RLS) filter

Output $y[i]$ and regressor $\varphi[i]$ are determined as follows:

$$y[i] = V_1 + \sqrt{V_1^2 - 4R_1I_2[i](V_2[i] + R_2I_2[i])}$$

$$\varphi[i] = 2I_2[i]\omega_0.$$

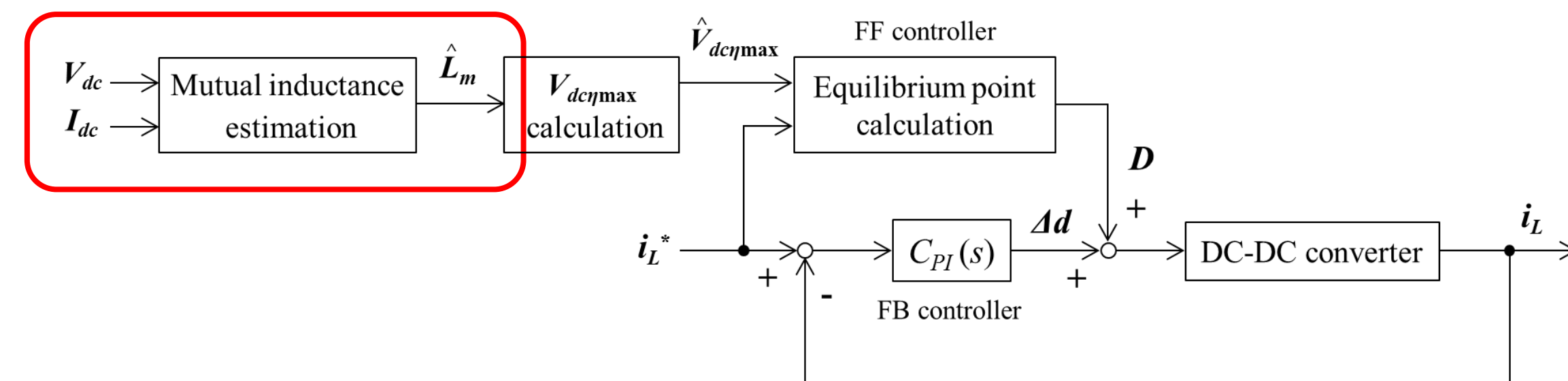
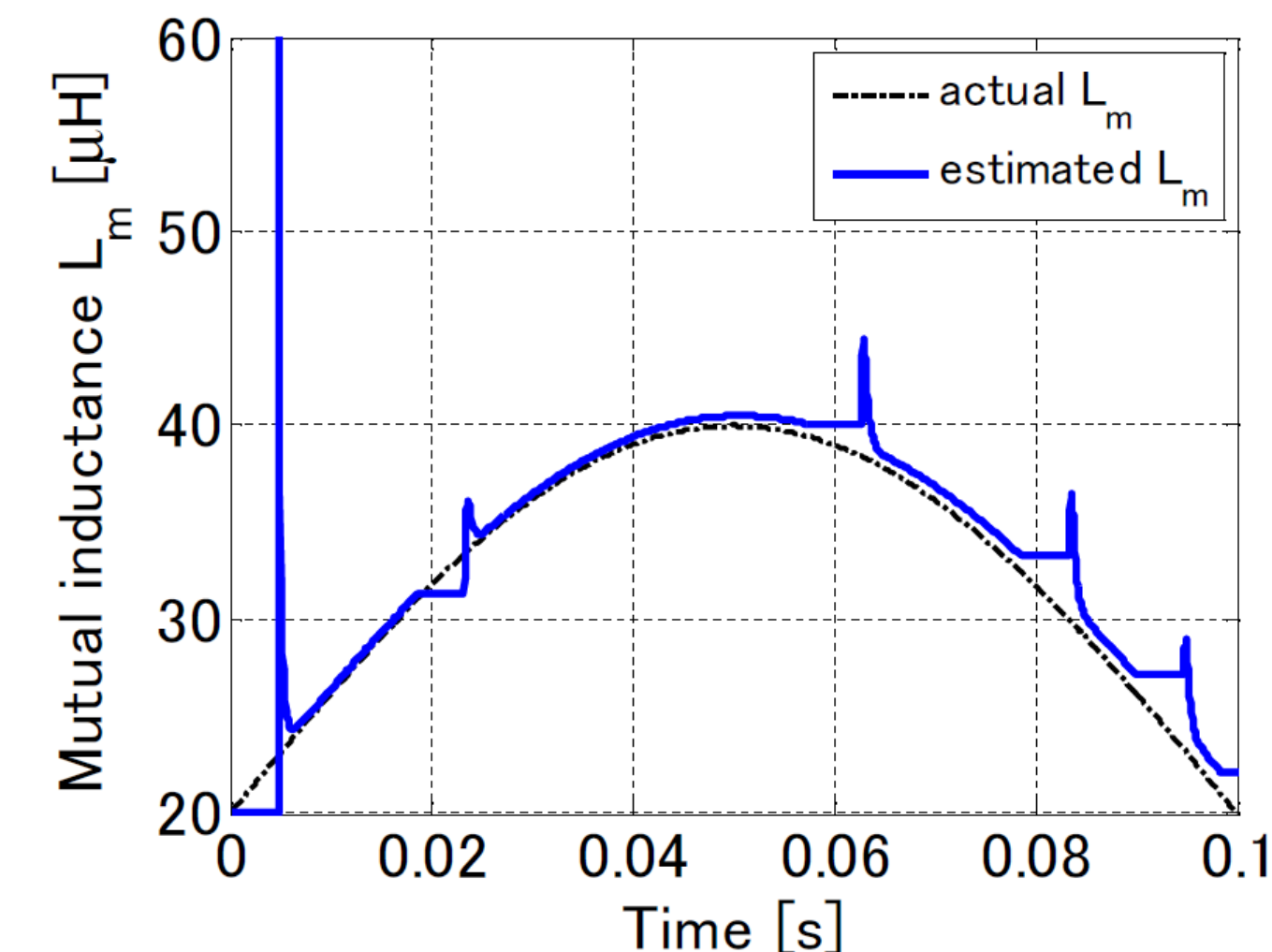
RLS filter is used to estimate L_m statistically by updating $\hat{L}_m[i]$, $y[i]$ and $\varphi[i]$ with following equations.

$$\hat{L}_m[i] = \hat{L}_m[i-1] + \frac{\varphi[i]P[i-1]}{\lambda + \varphi[i]^2P[i-1]}\epsilon[i]$$

$$\epsilon[i] = y[i] - \varphi[i]\hat{L}_m[i-1]$$

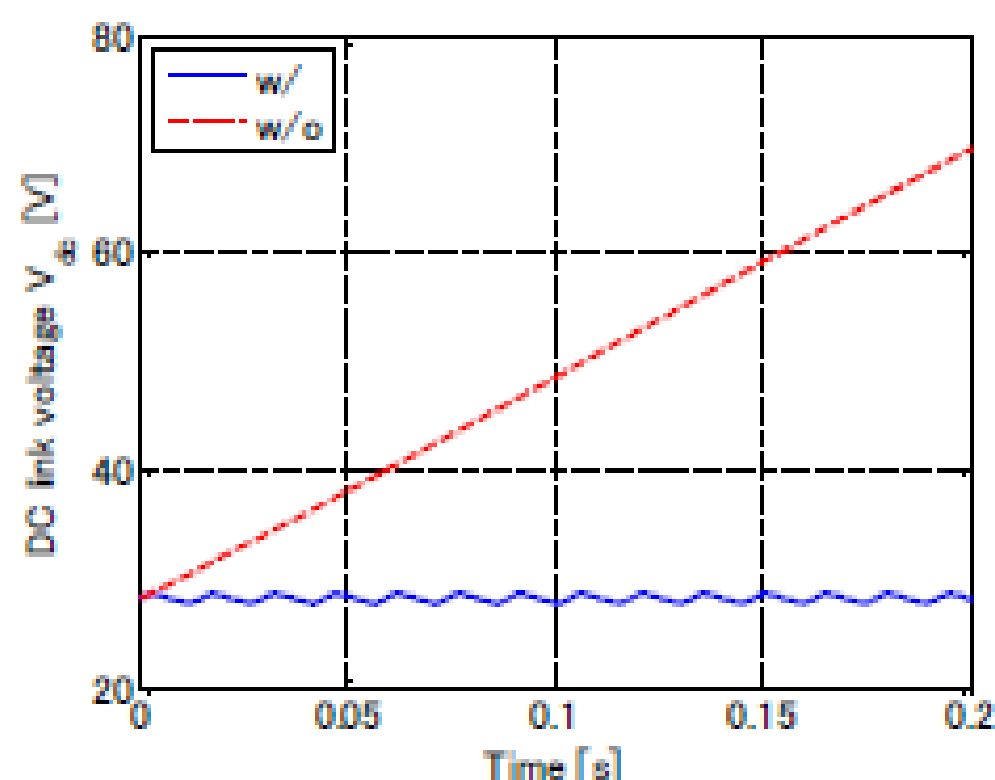
$$P[i] = \frac{1}{\lambda} \left\{ P[i-1] - \frac{\varphi[i]^2P[i-1]^2}{\lambda + \varphi[i]^2P[i-1]} \right\}$$

Simulation result

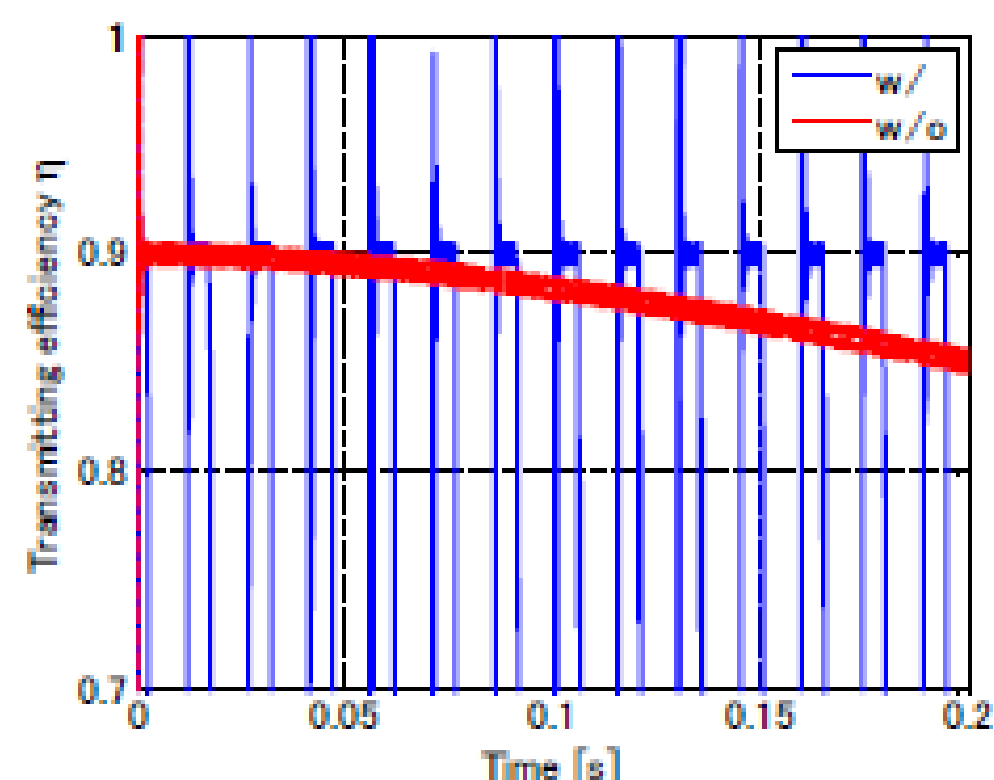


Appendix: Results of efficiency maximization

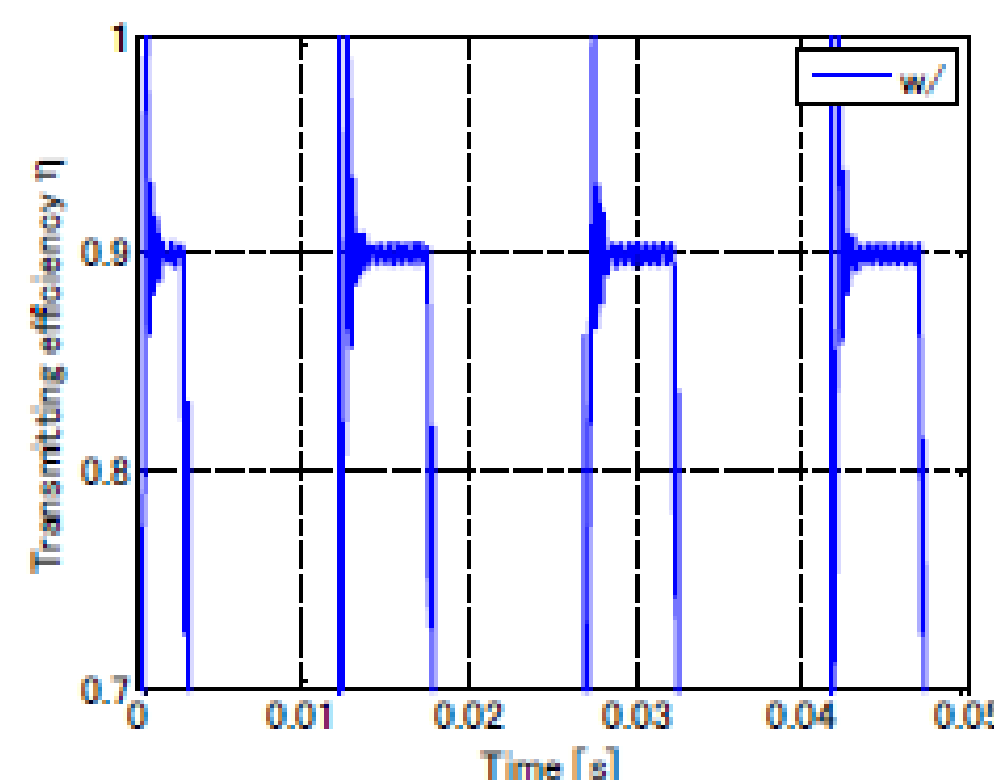
Simulation results of efficiency maximization using Half Active Rectifier



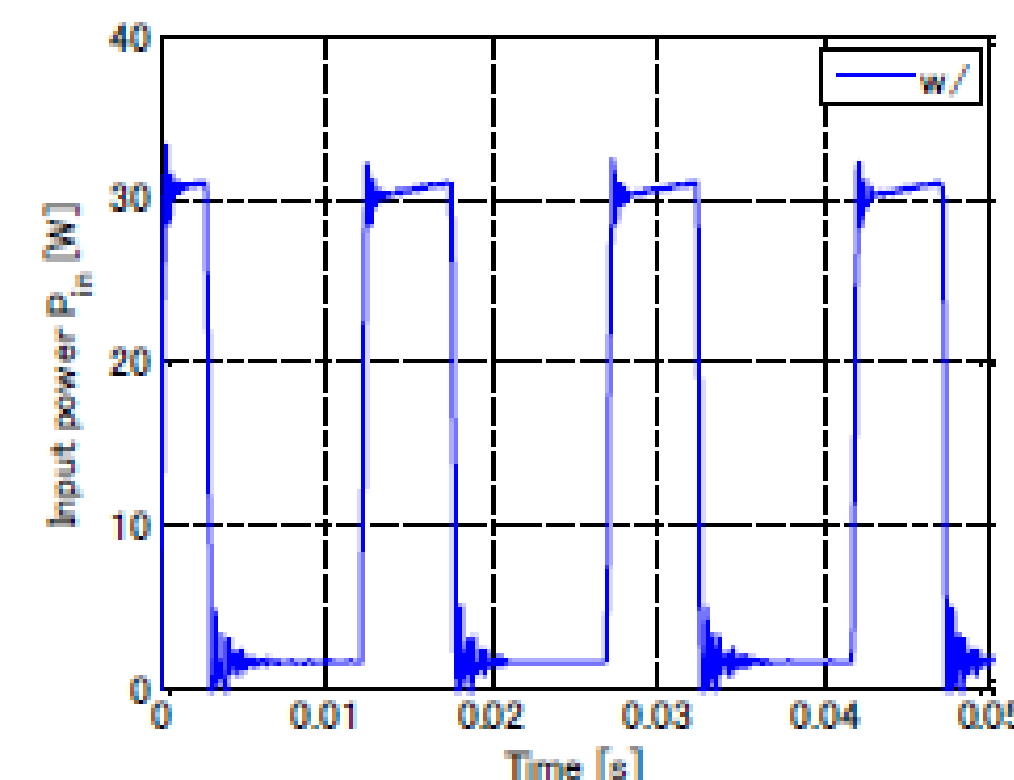
(a) DC link voltage V_{dc}



(b) Transmitting efficiency η



(c) Transmitting efficiency η
(zoom)



(d) Input power P_{in}

(w/o control)

V_{dc} is unstable and η is decreased.

(w/ control)

V_{dc} is stabilized around $V_{dc\eta\max}$.

(Rect. mode)

Transmitting efficiency η is maximized.

(Short mode)

Input power P_{in} is drastically decreased.

