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Monitoring of Robust Power System Security
-
Computation of Feasibility Margin of Power System Operation against Uncertainties

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Security Issues for Future Power Systems

Backgraund

- Increase in renewable energy (RE) generations.
- Degradation of power system security due to uncertainties.

Objectives

- Proposal of an effective method to deal with uncertainties.
- Effective index to measure degree of system security w.r.t. uncertainties.

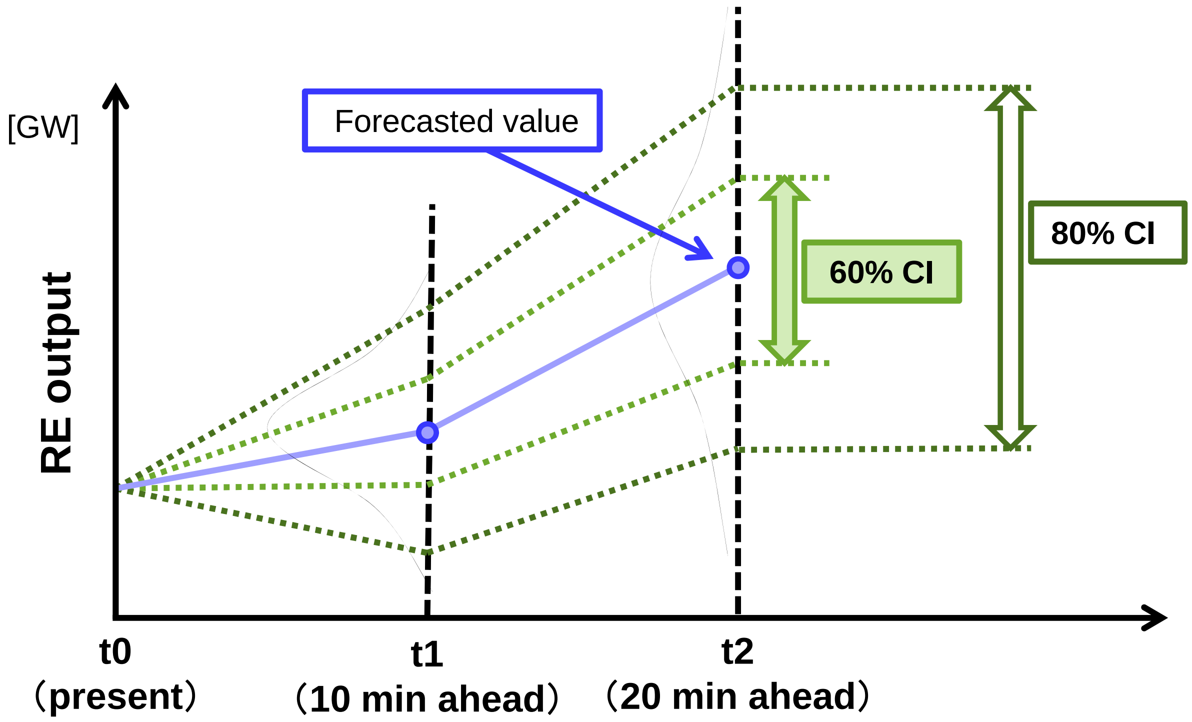
(key Issue)

- Concept of Robust Power System Security (RS)
- A new problem formulation for monitoring RS
- Combination of deterministic RS approach and probabilistic approach.

PV in 2030 in Japan：53GW (Peak load:170GW)

Uncertainty Modeling for Robust Security Analysis

Confidence Interval (CI) of important uncertain parameter is defined based on confidence level .



Uncertainties increase for more future forecast

Approach to treat uncertainties

Analysis of Uncertainties

- Load & RE Forecast
- Cumulants, Cov
- Confidence interval (CI)

CI

Deterministic method
Robust Security Approach

Secure Operation in CI

- Robust Security Analysis with CI
- Monitoring of RS Region

Covariance matrix for Probabilistic constraints

RS region for DELD

Power System Operation and Control (Real-Time Dynamic ELD)

- Robust security for important event, constraints
- Stochastic security for less important constraints such as overloading

Measure of Static Security Region (SS)

SS Region: **Region of operating points satisfying all security constraints for all contingencies n=1….N**

Index α to Measure SS Region

$\alpha = c^T u$, c: **Specified vector**

Objective function

Upper bound $\overline{\alpha}_{SS} = \max_u c^T u$

Lower bound $\underline{\alpha}_{SS} = \min_u c^T u$

Constraints of SS (Case for OPF)

No Uncertainty Case

- ✓ Power Flow Equations $F^{(n)}(u)=0$
- ✓ Constraints $G^{(n)}(u) \leq 0, \quad n = 0,1,\cdots,N$
- ✓ Control Variables $\underline{u} \leq u \leq \overline{u}$

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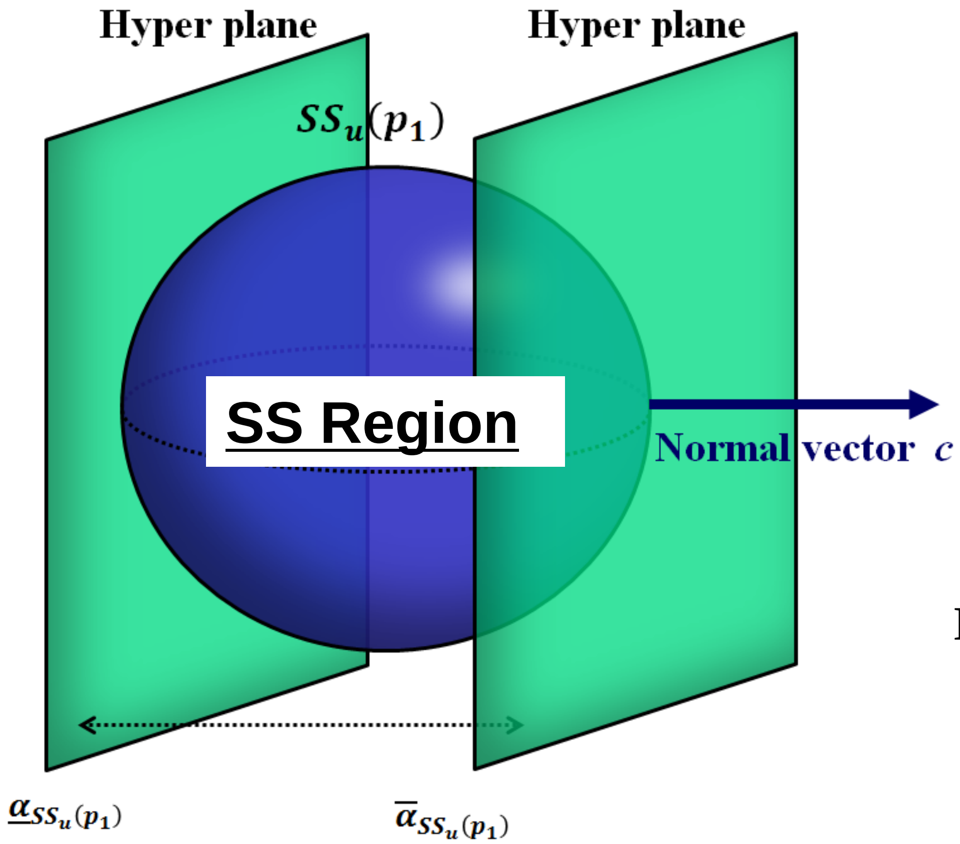
Meaning of Proposed Measure



Hyper-plane

$$c^T u = \alpha$$

c: normal vector

Hyper-plane and SS intersect if

$$\underline{\alpha}_{SS} \leq \alpha \leq \overline{\alpha}_{SS}$$

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Robust Static Security Region (RSS)

RSS Region: The Worst Case SS Region with Uncertainties

Measure of RSS Region

Objective function

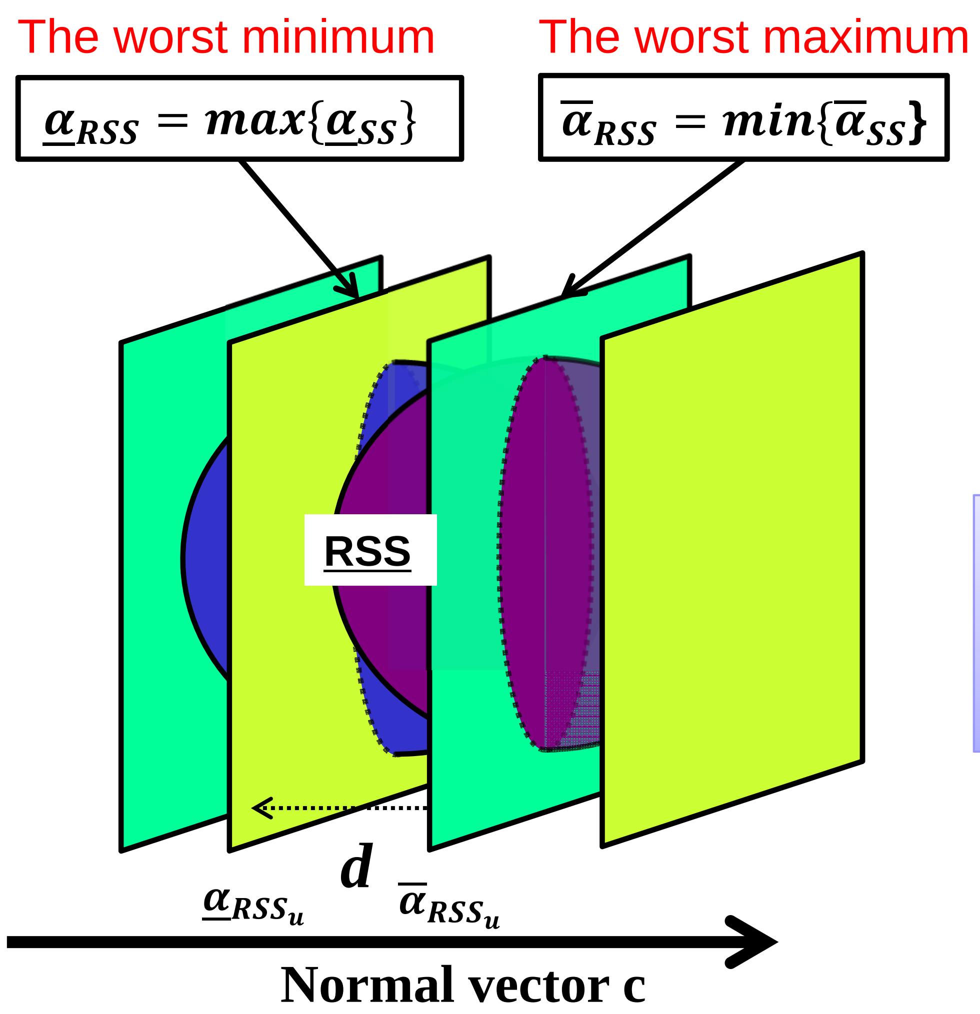
Upper bound $\overline{\alpha}_{RSS} = \min_{u,p} \{\max_{u} c^T u\}$

Lower bound $\underline{\alpha}_{RSS} = \max_{u,p} \{\min_{u} c^T u\}$

Constraints

- ✓ Power Flow Equations $F^{(n)}(u,p)=0$
- ✓ Constraints $G^{(n)}(u,p) \leq 0, \quad n = 0,1,\cdots,N$
- ✓ Control Variables $\underline{u} \leq u \leq \overline{u}$
- ✓ Uncertainties in CI $\underline{p} \leq p \leq \overline{p}$

Robust Static Security Region (RSS)



RSS Region exists if

$$\underline{\alpha}_{RSS} \leq \alpha \leq \overline{\alpha}_{RSS}$$

Measure of RSS

$$d = \frac{1}{\|c\|}\left(\overline{\alpha}_{\mathrm{RSS}} - \underline{\alpha}_{\mathrm{RSS}}\right)$$

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Bilevel Optimization Problem

General NL Problem

$$\overline{\alpha}_{RSS} = \min_{\boldsymbol{u},\boldsymbol{p}} \{ \boldsymbol{c}^T \boldsymbol{u} \}$$

s.t.

$$H(p,u) \le 0$$

$$u \in \arg\max_{\boldsymbol{u}} \{ \boldsymbol{c}^T \boldsymbol{u} \}$$

s.t.

$$H(p,u) \le 0$$

Linear Problem

$$\overline{\alpha}_{RSS} = \min_{\boldsymbol{u},\boldsymbol{p}} \{ \boldsymbol{c}^T \boldsymbol{u} \}$$

s.t.

$$Ap + Bu \le b$$

$$u \in \arg\max_{\boldsymbol{u}} \{ \boldsymbol{c}^T \boldsymbol{u} \}$$

s.t.

$$Ap + Bu \le b$$

↓

Transformation into MILP problem

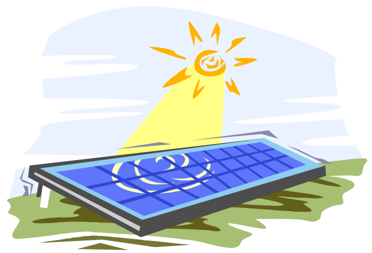
Robust Static Analysis Example

Controllable parameter

- Conventional generator outputs **u=[G1, G2, G3]'**

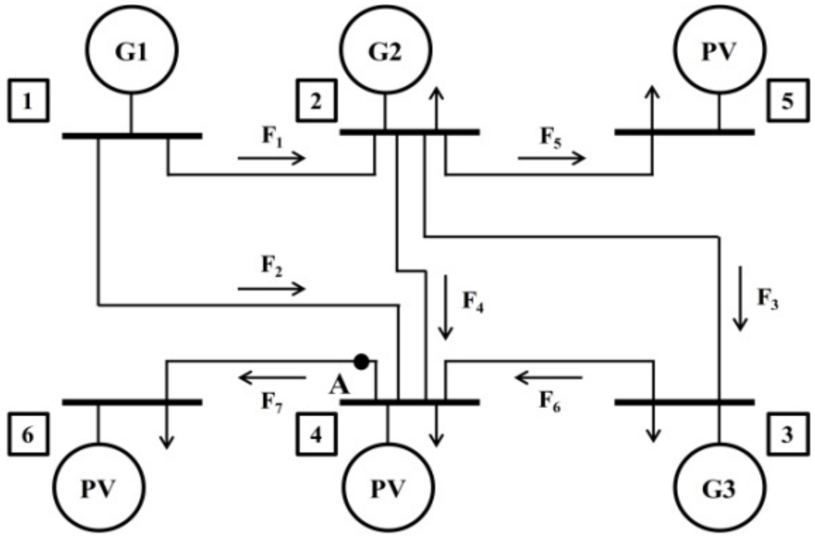
Uncertainties for RSS

- PV generations at 3 nodes **p=[PV1, PV2, PV3]'**



Constraints for RSS : Linear

- Demand and supply balance
- Generator output limits
- Power flow equation (DC power flow)
- Security limits of line flows



Contingency

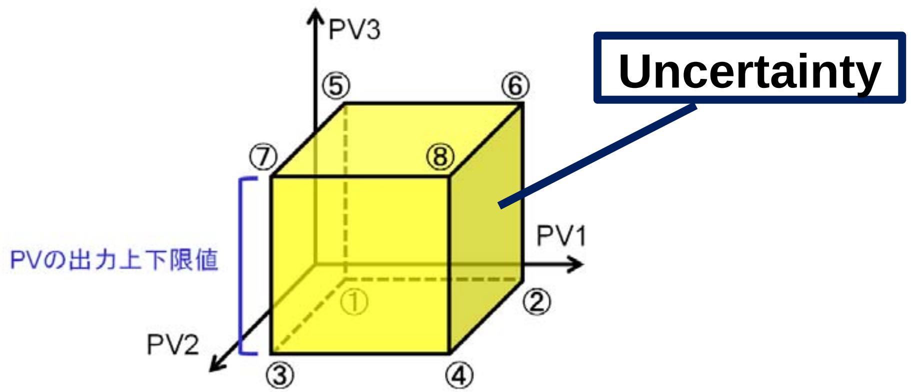
- 1 of 2 Lines Trip at A

Uncertainties in PV generations

Max and Min of PV Output Predictions

[kW]

	PV1		PV2		PV3		
	Max	MIn	Max	MIn	Max	Min	
Case1	250	250	250	250	250	250	- No Uncertainties
Case2	200	300	200	300	200	300	- Small
Case3	50	450	50	450	50	450	- Large



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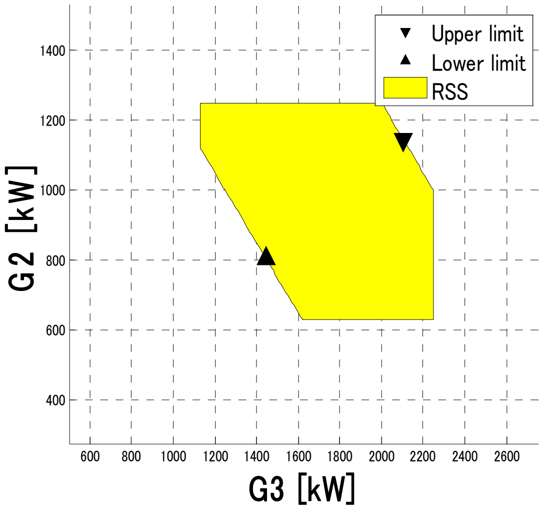
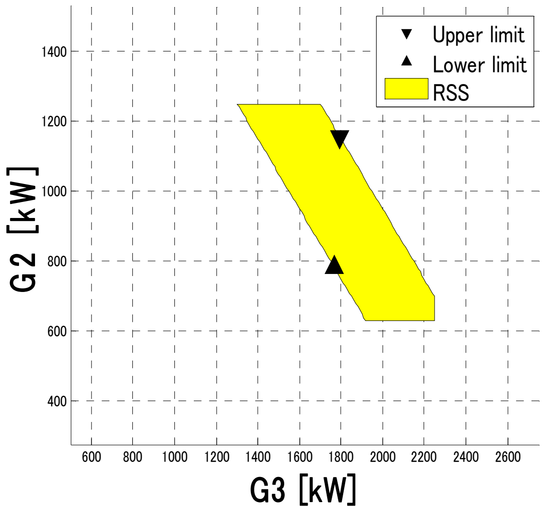
Result of RSS Region Analysis

Case1



Index $\boldsymbol{d}$ = 707

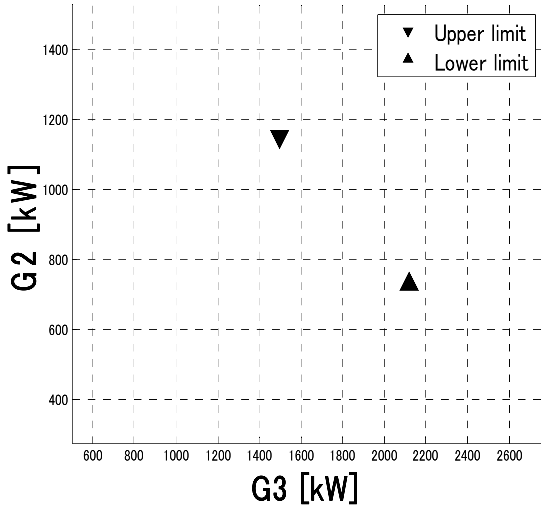
Case2



Region shrinks

Index $\boldsymbol{d}$ = 283

Case3



Region disappears

Index $\boldsymbol{d}$ = -141

Measure of RSS

$$\boldsymbol{d} = \frac{1}{\|\boldsymbol{c}\|}\left(\overline{\boldsymbol{\alpha}}_{\mathrm{RSS}} - \underline{\boldsymbol{\alpha}}_{\mathrm{RSS}}\right)$$

Confirmation of Exact Detection of RSS

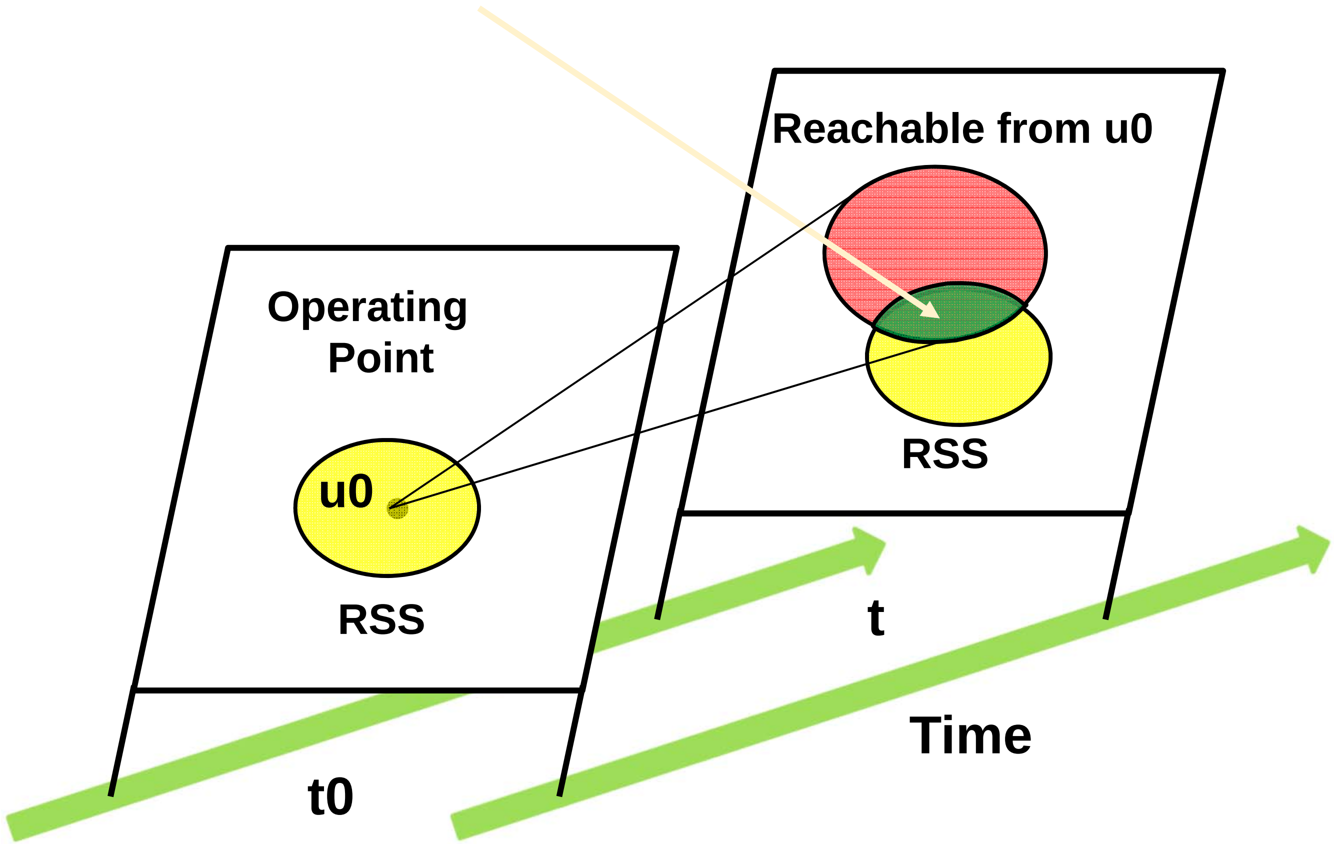
$c^T = [\,0\ 1\ 1\,]$

$c^T u = u_2 + u_3$

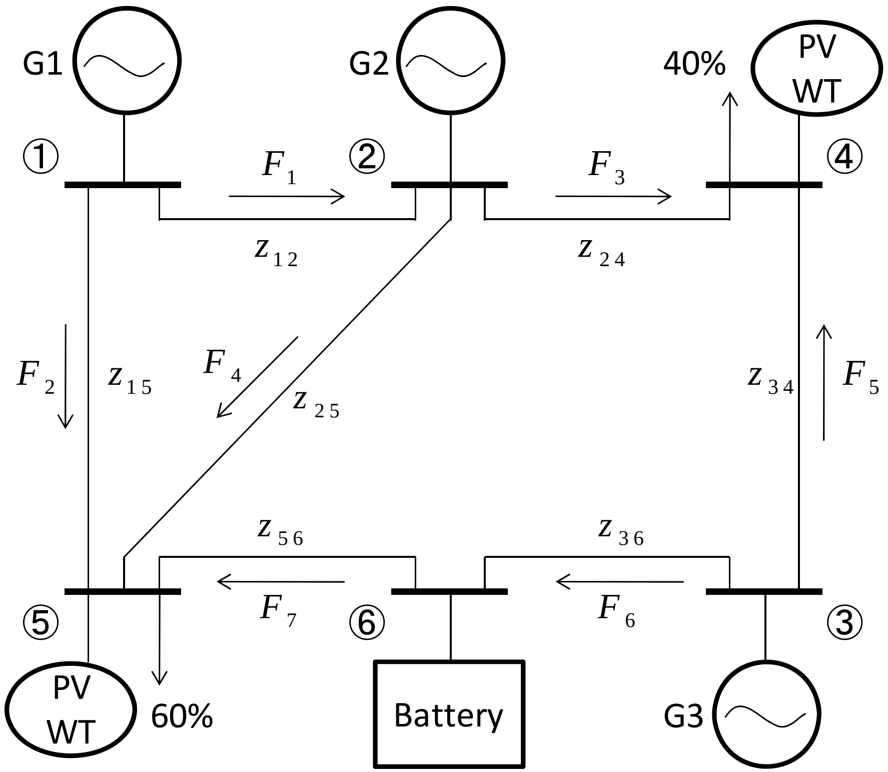
Definition of Robust Security Region

Robust Static Security region (RSS)

Robust Dynamically Reachable Security region (RRS)
RRS : (RSS) + (Ramp Rate Constraints of u)



Test System



Test System

- Generator Conditions:
  Small Grid (island system)
- Installed Capacity 5.5 GW
- Peak loading 5.1 GW
- PV 1 GW
- WT 1 GW
- BT (NaS) 400kW (2.4GWh)

Battery Data

	Upper Limit [kW]	Battery capacity [kWh]	Efficiency [%]
BT	400	2,400	90

Generator Specifications (Diesel Generators)

	Capacity [kW]	Upper/Lower Limit[kW]	Ramp Rate [kW/min]	Start-up Cost	Coefficients of the Generation Cost		
					a	b	c
G1	2,000	1,000～2,000	66.67	4,000	0.0011	16.416	4,320.00
G2	1,250	625～1,250	41.67	2,500	0.0021	17.41	3,677.50
G3	2,250	1,125～2,250	75	4,500	0.0002	20.178	3,933.70

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Robust Dynamic Analysis Example

Controllable parameter

- Generator outputs **u=[G1, G2, G3]'**

Uncertainties

- RE generations **p=[RE1, RE2]'**

Constraints for RRS : Linear

- Demand and supply balance
- Generator output limits
- Power flow equation (DC power flow)
- Security limits of line flows
- Generator Ramp Rate Constraints
- Initial Operating Point at t=t0

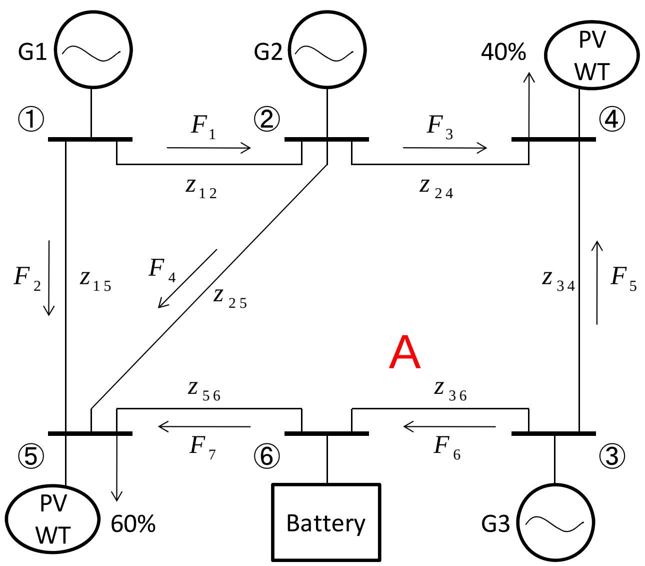
Contingency

- 1 of 2 Lines Trip at A

Objective function

$$\boldsymbol{\alpha} = \mathbf{c}^{\mathrm{T}}\mathbf{u} = \textbf{Total Generation}$$

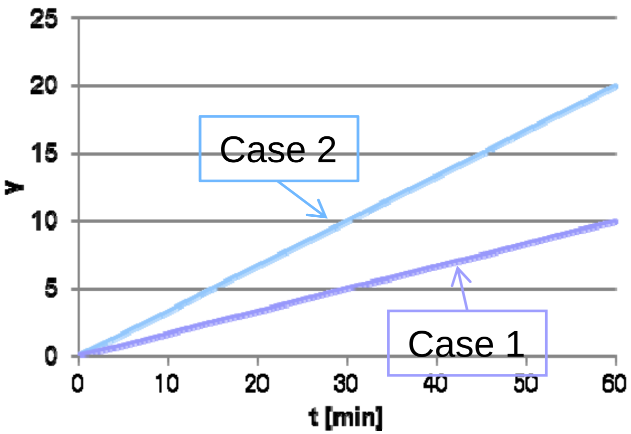
$$\mathbf{c}^{\mathrm{T}} = [\mathbf{1}\ \ \mathbf{1}\ \ \mathbf{1}]$$



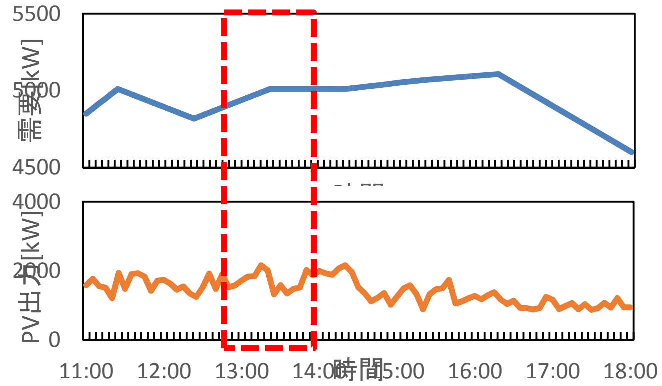
Test System

Setting of CI for Prediction Errors

CI for Future Predictions



Predictions of Load and PV Generation



Case 1 : small prediction error (20% Error at 1 hour ahead)

$$CI = [\hat{p}(t) - \sigma(t), \quad \hat{p}(t) + \sigma(t)]^T$$

Case 2 : large prediction error (40%Error at 1 hour ahead)

$$CI = [\hat{p}(t) - 2\sigma(t), \ \hat{p}(t) + 2\sigma(t)]^T$$

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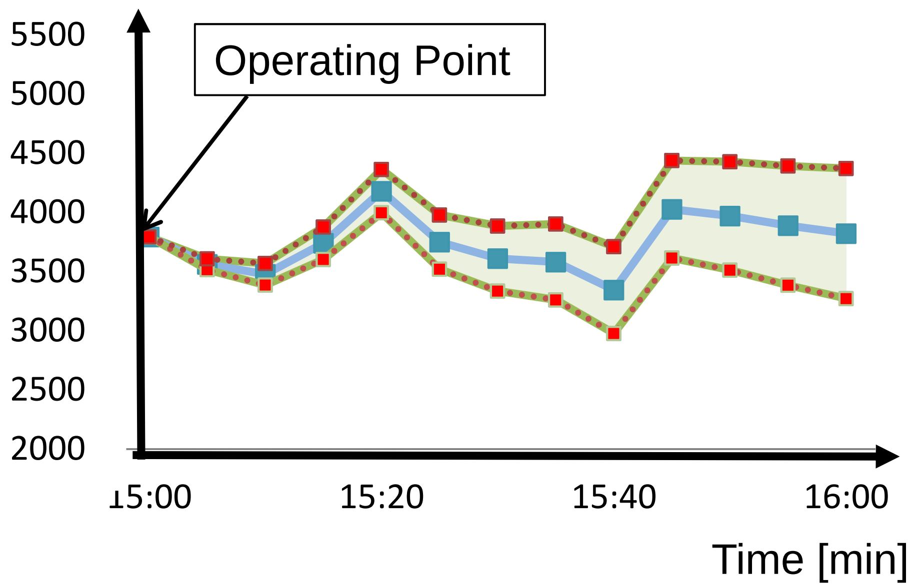
Results of RRS Evaluations

RRS analysis at 15:00 for 1 hour ahead

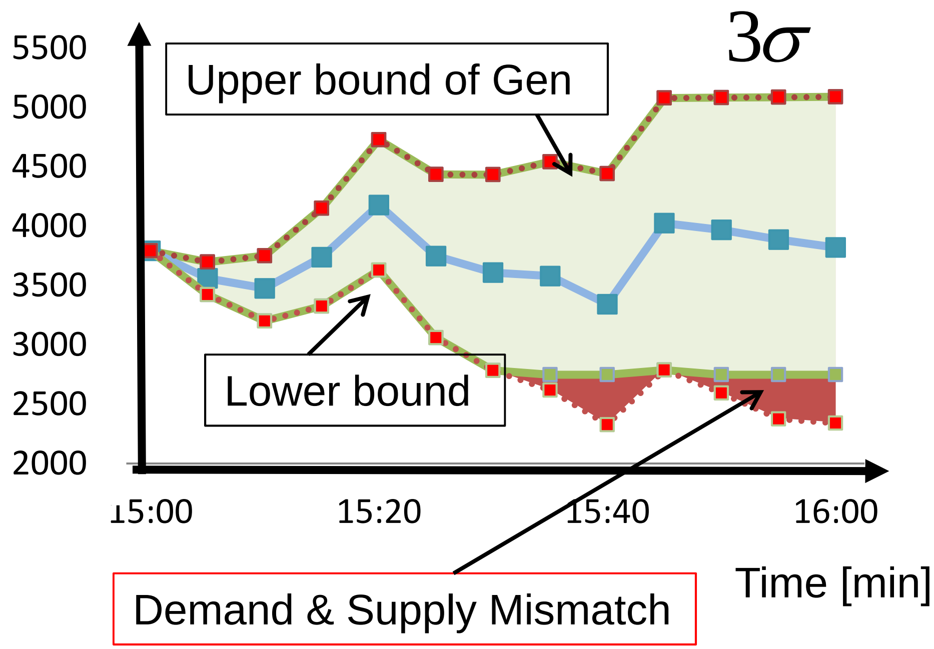
$c^T = [\,1\ 1\ \ldots 1]$
$c^T u$ = *Total Generation*

Total Thermal Generation



Case 1

Total Thermal Generation



Case 2

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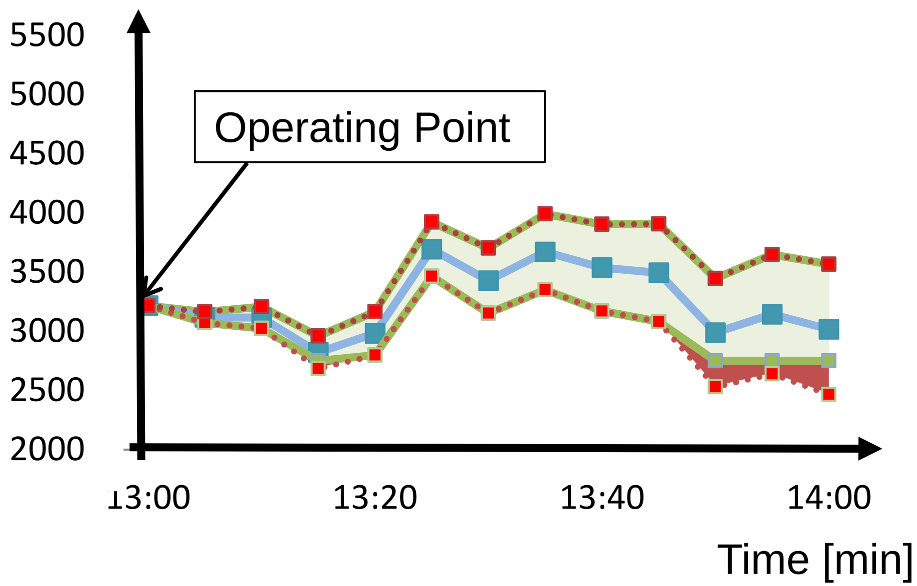
Results of RRS Evaluations

RRS analysis at 13:00 for 1 hour ahead

$c^T = [\ 1\ 1\ \ldots 1]$

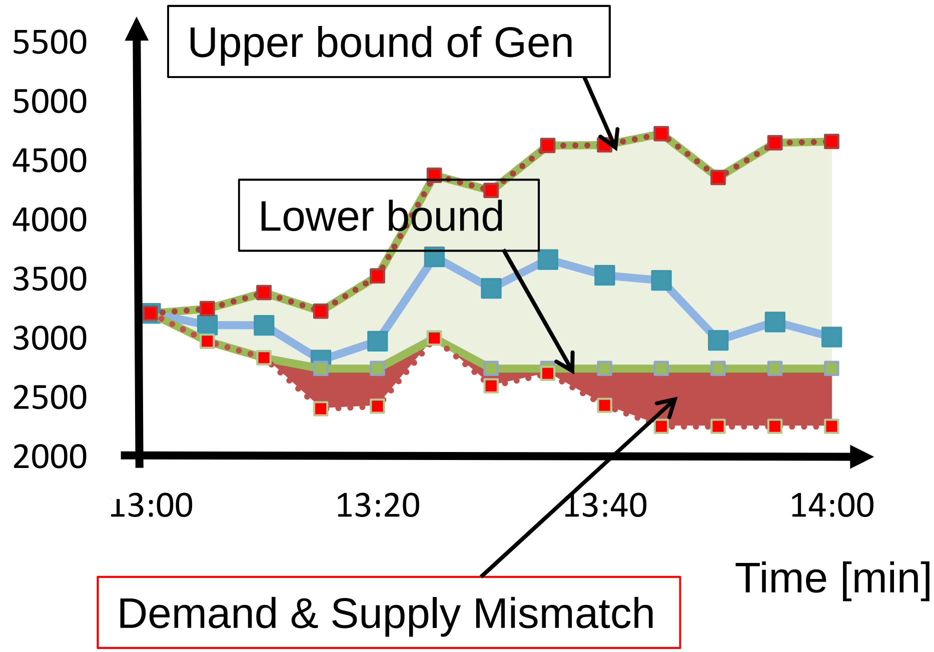
$c^T u = \textit{Total Generation}$

Total Thermal Generation



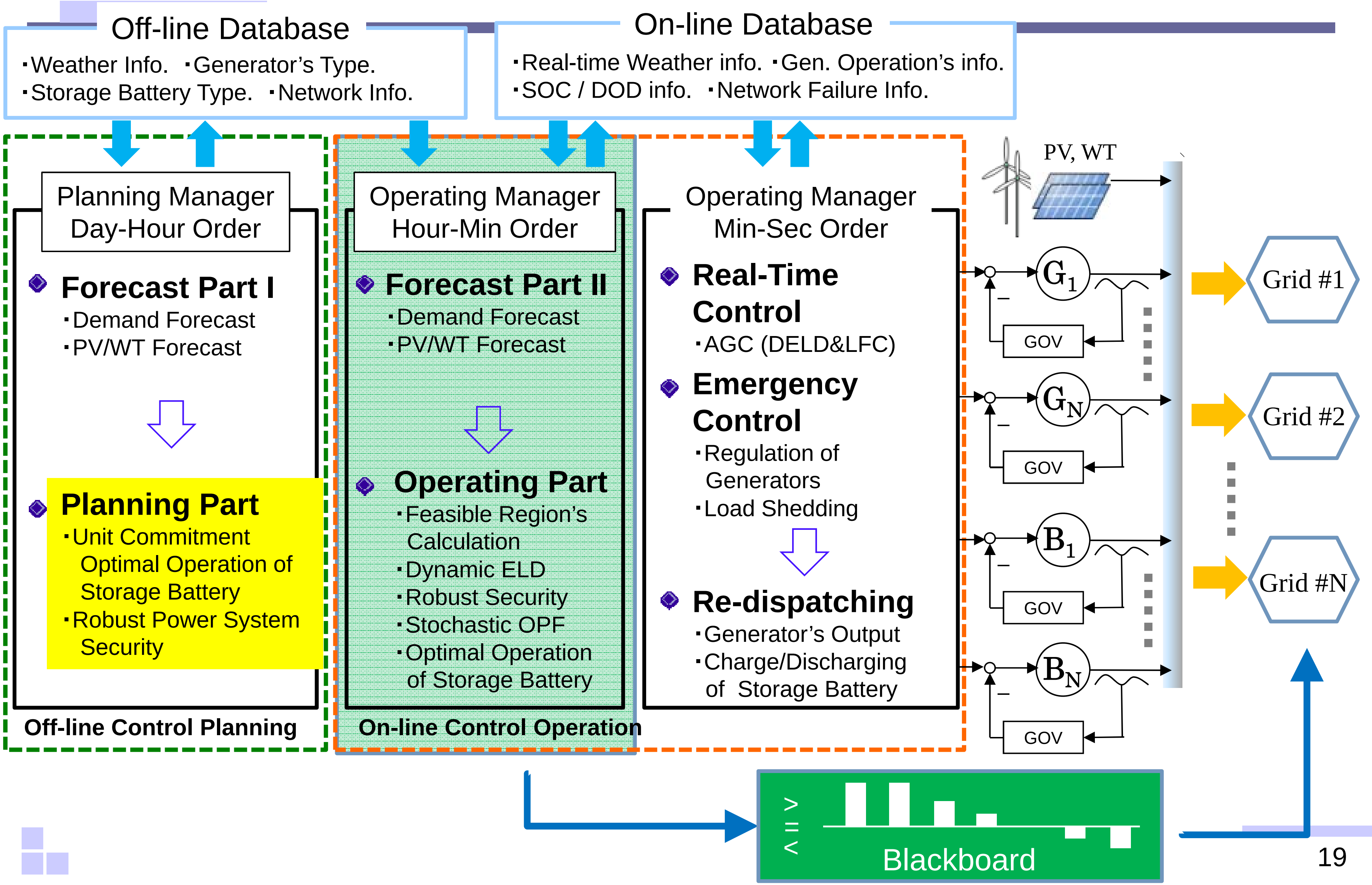
Case 1

Total Thermal Generation



Case 2

Micro EMS Simulator



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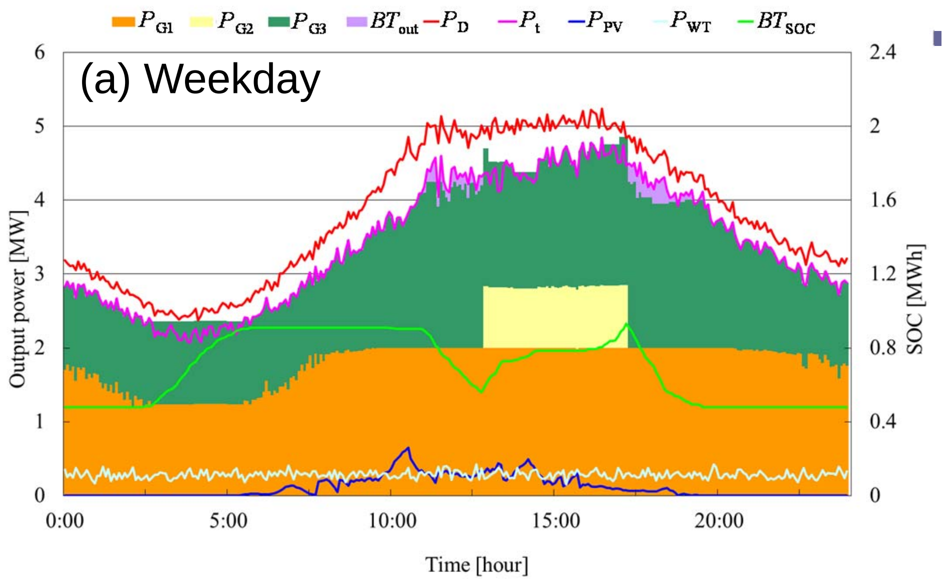
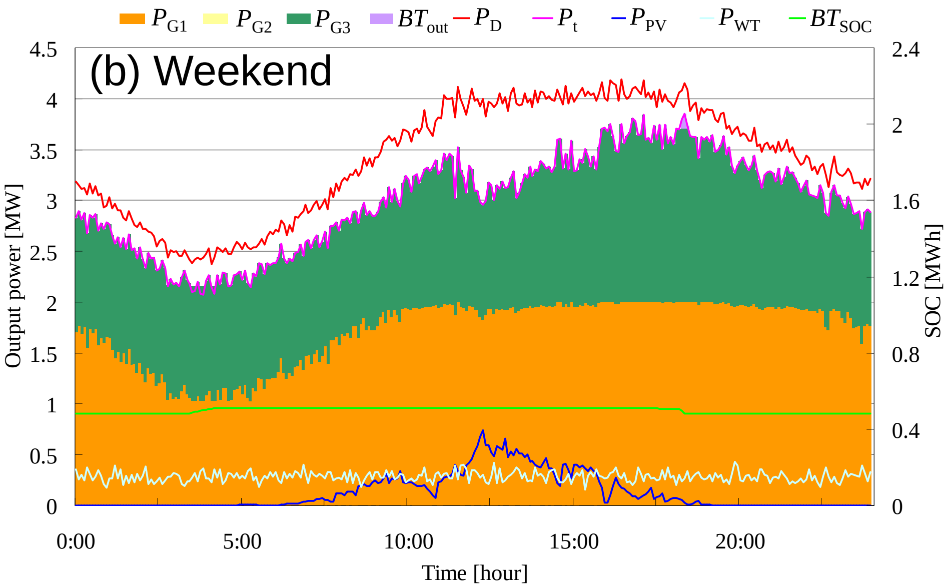
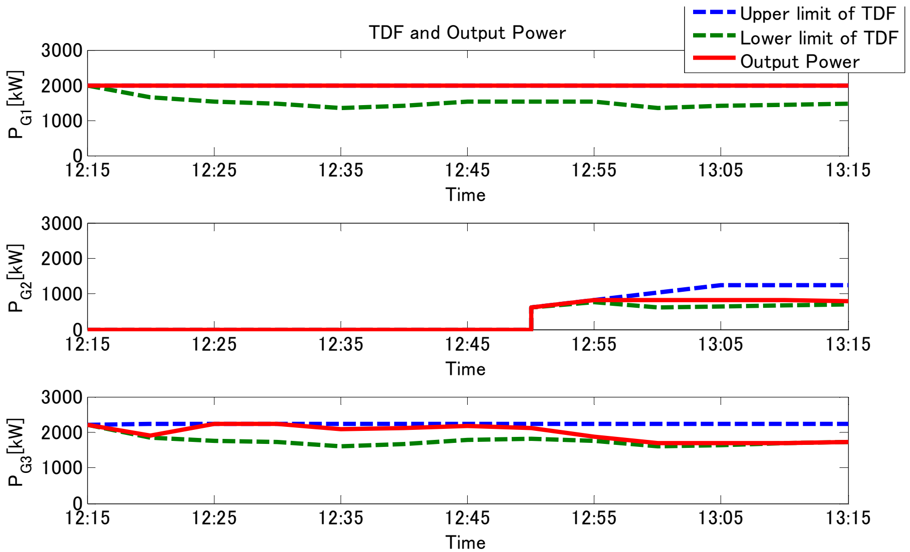
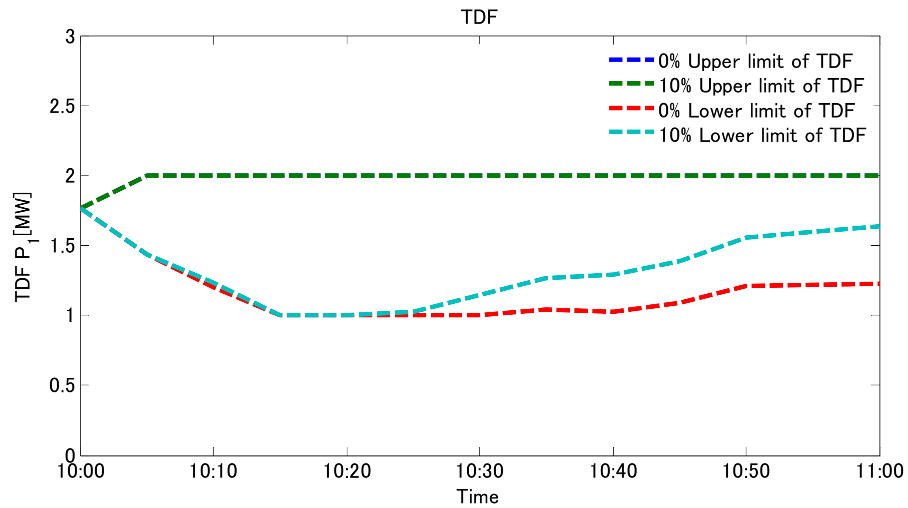
Operation Planning for 24 hours







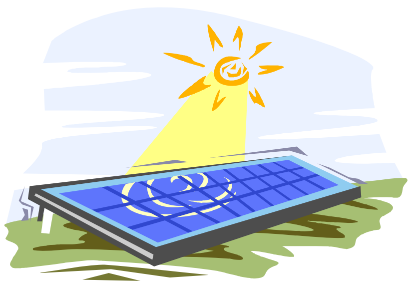
The feasible region and dispatch value on weekday



TDF at 10:00 on weekday.

Conclusions

- A Method of Robust Security (RS) Monitoring and Control is proposed.
- Proposed Method is based on deterministic treatment of system security using Confidence Intervals (CI) of Predictions.
- The method is implemented on micro EMS simulator, where effective use is being investigated.



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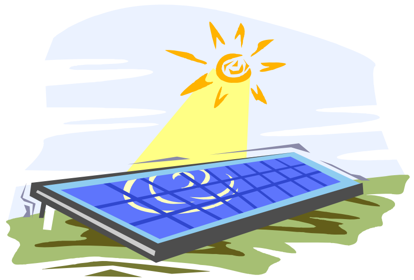
Thank you !



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