Optimal Power Flow of Power Networks with Batteries via Distributed-Cooperative Predictive Control

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Outline

- Introduction
- Power Network
- Cooperative Control
- Simulation

Introduction

Power Network

a network to send from various power supplies to each consumer

Optimal Power Flow(OPF)

optimize a certain objective over power network variables

■**constraints**

(bounds on voltages, line loading, etc.)

http://www.mhi.co.jp/products/expand/a-si_introduction_case_03.html

⇨ we must optimize under certain constraints

■**renewable energy**

(solar, or wind power, etc.)

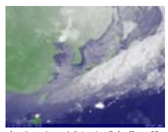
output fluctuates widely and randomly, but predictably

⇨ formulate an optimal power flow problem with battery

Introduction

OPF has been studied static optimization, but…

Introduction of battery
⇨ **Dynamics of battery in OPF**

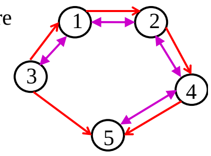


http://www.jma.go.jp/jp/gms/smallc.html?area=0&element=0&time=201012161730

⇩

distributed predictive control

- applicable { —predictive information in the future / — constraints
- only by local information



cooperative control

- simply enhance the power network

objective of this work

Optimize power consumption by applying the distributed-cooperative predictive control to power network

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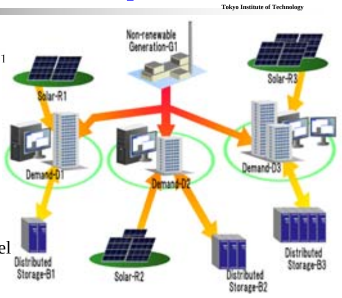
Power Network - example

Node

•Demand D_1, D_2, D_3 •Generation G_1
•Battery B_1, B_2, B_3 •Calculator
•Renewable energy R_1, R_2, R_3



Link

$\mathcal{E}_{DG} = \{(G_1, D_1), (G_1, D_2), (G_1, D_3)\}$

$\mathcal{E}_{DR} = \{(R_1, D_1), (R_2, D_2), (R_3, D_3)\}$

$\mathcal{E}_{DB} = \{(B_1, D_1), (B_2, D_2), (B_3, D_3)\}$

Objective

•move battery level closer to target level
•curb costs
•equate supply and demand

Constraints

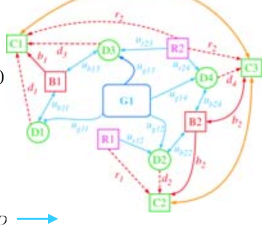
•Cannot charge battery more than the supply by the others
•Supply is always nonnegative (without battery)
•about battery level
•Upper bound M in the sum of the supply to some demands

Power Network

Network structure

- Node $\mathcal{V}=\mathcal{D}\cup\mathcal{G}\cup\mathcal{R}\cup\mathcal{B}\cup\mathcal{C}$

Demand $\mathcal{D}$ — customer
Generation $\mathcal{G}$ — nonrenewable generation (Gas, Coal, Nuclear, Hydro, etc.)
Renewable energy $\mathcal{R}$ — renewable, variable (Solar, Wind, tidal force, etc.)
Battery $\mathcal{B}$ — distributed storage
Calculator $\mathcal{C}$ — scheduling flows of electricity



- Link $\mathcal{E}\subseteq\mathcal{V}\times\mathcal{V}$

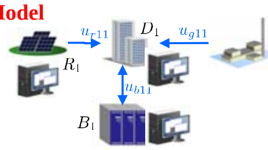
energy flow $\mathcal{E}_E$
- to demand $\mathcal{E}_D$
- to battery $\mathcal{E}_B$

information flow $\mathcal{E}_I$
- battery info $\mathcal{E}_S$
- Predictive info $\mathcal{E}_P$
- communication info $\mathcal{E}_C$

Power Network is composed of several different links and nodes

Power Network model

Model



each node has a calculator and own objective function, they demand only to achieve his goal

Node **Objective function**

Demand $\mathcal{D}$

$$J_d=\sum_{k=0}^{N}\sum_{j\in\mathcal{D}}w_{D,j}\Big(\sum_{i\in\mathcal{N}_{GD,j}}u_{gij}(k)+\sum_{i\in\mathcal{N}_{RD,j}}u_{rij}(k)+\sum_{i\in\mathcal{N}_{BD,j}}u_{bij}(k)-d_j(k)\Big)^2$$

$$J_g=\sum_{k=0}^{N}\sum_{i\in\mathcal{G}}\sum_{j\in\mathcal{N}_{DG,i}}w_{G,ij}u_{gij}^2(k)$$

Battery $\mathcal{B}$

$$J_b=\sum_{k=0}^{N}\sum_{i\in\mathcal{B}}w_{B,i}(b_i(k)-b_{i,ref})^2$$

Renewable energy $\mathcal{R}$

$$J_r=r_i(k)-\sum_{j\in\mathcal{N}_{DR,i}}u_{rij}(k)$$

Optimize global power network to cooperate each other

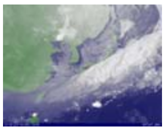
Power Network

Problem of this system

•Instability of renewable energy

Mainly controlled by the weather

⇒ It is possible to predict at some level



•Dynamics of battery

$$\Sigma_i : b_i(k+1)=b_i(k)-\sum_{j\in\mathcal{N}_{DB,i}}u_{bij},\ i\in\mathcal{B},\qquad\cdots(1)$$

Past information ($b_i(k)$) $b_i(k)$: remaining battery level

⇒ There is relativity around of a time period

We must use dynamic optimization across multiple time periods

⇒ **distributed predictive control**

• simply enhance the power network

⇒ **cooperative control**

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Cooperative Control

Power network tends to become large-scale

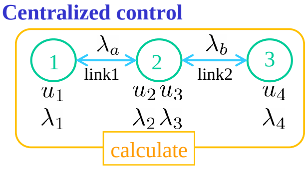
⇒ The amount of calculation become huge

Distributed control

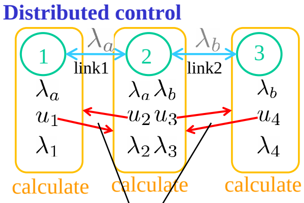
Each grid controls only by local information

⇒ When the power network is reconnected, it is necessary to think about the optimization problem again

Centralized control



Distributed control



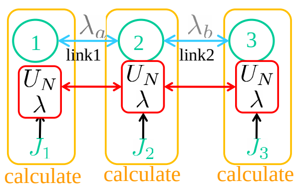
Cooperative Control

Cooperative Control

Each grid calculates all inputs only by local objective function

$$U(k+1)=k_c\left(\frac{\partial D}{\partial U^N}\right)_{U=U(k)}+\sum U(k)$$

average of $U_i(k)$ and $U_i(k)$ in the node i connected directly

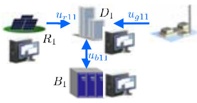


- each node has own objective function, not need to allocate the common term
- even if it reconnects, the object that takes the average only changes

Cooperative Control - Simulation block

Block diagram

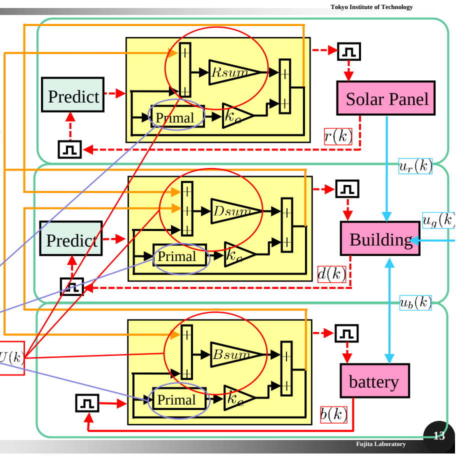
Cooperative control



- each node has a calculator
- each node has own objective function

$U(k+1) = k_c \left(\frac{\partial D}{\partial U^N}\right)_{U=U(k)} + \sum U(k)$

- average of the node connected directly



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Simulation -24hours

Constant

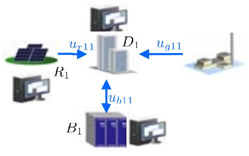
- Predictive control horizon number $N = 4$
- each objective function's weight $k_g = 0.005$ $k_d = 0.5$ $k_r = 0.5$ $k_b = 0.01$
- Battery $b_{max} = 50$ $b_0 = 23$ $b_{ref1} = 25$

Cooperative control method

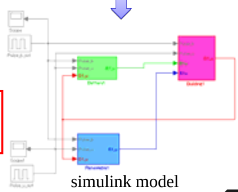
$$U(k+1) = k_c \left(\frac{\partial D}{\partial U^N}\right)_{U=U(k)} + \sum U(k)$$

$k_c = 0.5$

- calculate simulink model during 24 hours
- compared with quadprog

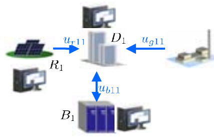


Power network model



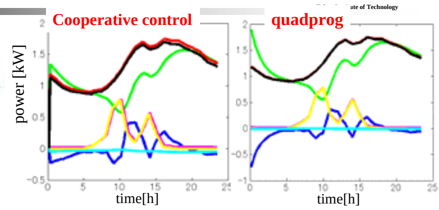
simulink model

Simulation -24hours



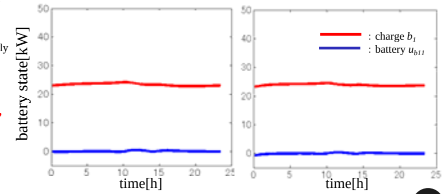
$u_{g11} \leftarrow D_1$
$u_{b11} \leftarrow B_1$
$u_{r11} \leftarrow R_1$

: renewable r
: renewable u_{r11}
: generation u_{g11}
: demand d_1
: battery u_{b11}
: supply
: demand - supply



Time Responses of D_1's each Power Transmission

some behavior is different , but almost meets demands



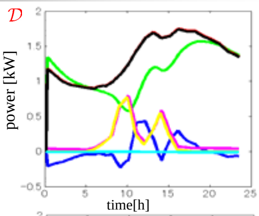
Time Responses of B_1's Battery State

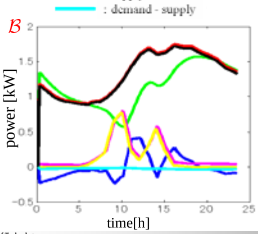
Simulation 24hour D B R

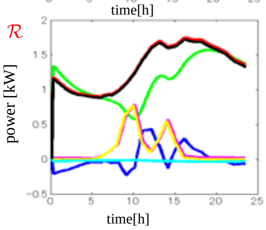
the value of calculated by each node

→ There is no difference on each node so much

: renewable u_{r11}
: generation u_{g11}
: battery u_{b11}
: supply
: demand - supply







Simulation -24hours random

Constant

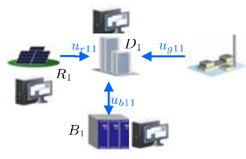
- Predictive control horizon number $N = 4$
- each objective function's weight $k_g = 0.005$ $k_d = 0.5$ $k_r = 0.5$ $k_b = 0.01$
- Battery $b_{max} = 50$ $b_0 = 23$ $b_{ref1} = 25$
- demand $d(k)$ + random(-0.5,0.5) × 0.1

Cooperative control method

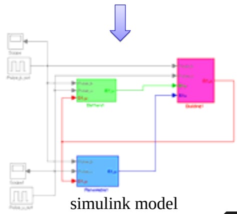
$$U(k+1) = k_c \left(\frac{\partial D}{\partial U^N}\right)_{U=U(k)} + \sum U(k)$$

$k_c = 0.5$

add a random element to demand, calculate again



Power network model

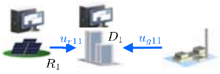


simulink model

Simulation -24hours random, no battery

first, calculate behavior on the network without battery

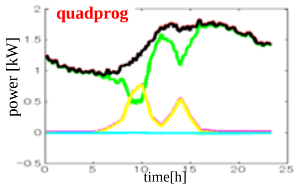
Power network model

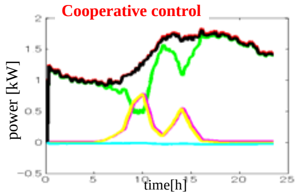


$u_{g11} \leftarrow D_1$

$u_{r11} \leftarrow R_1$

: renewable r
: renewable u_{r11}
: generation u_{g11}
: demand d_1
: supply
: demand - supply

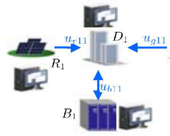




Both correspond to an irregular change only by u_{g11}

Time Responses of D_1's each Power Transmission

Simulation -24hours random



$u_{g11} \leftarrow D_1$

$u_{b11} \leftarrow B_1$

$u_{r11} \leftarrow R_1$

: renewable r
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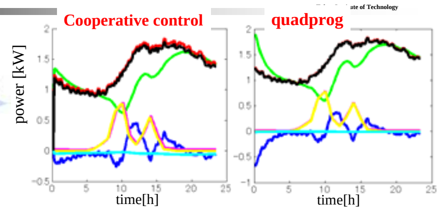
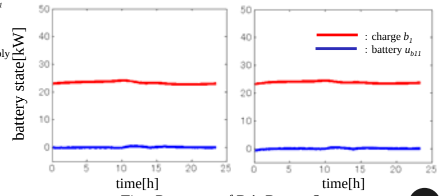


Time Responses of D_1's each Power Transmission



Both correspond to an irregular change only by u_{b11}

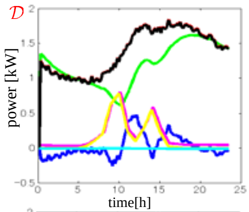
Time Responses of B_1's Battery State

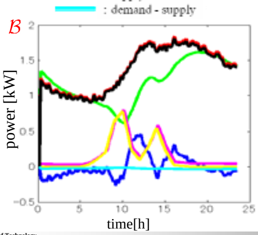
Simulation 24hours random D B R

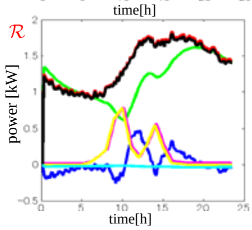
the value of calculated by each node

→ There is no difference on each node so much

: renewable u_{r11}
: generation u_{g11}
: battery u_{b11}
: supply
: demand - supply







Conclusion

- Introduction of cooperative control
- verification of the utility of distributed cooperative predictive control by simulation

Future work

- enhance the power network