Y9.HIL.3: Integration of Intelligent Energy Management in a FREEDM System

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1. Project Goals

The objective of this work is to integrate and evaluate the developed distributed IEM control algorithm for the FREEDM system in the HILTB. The specific tasks are as follow:

- Investigation of DGI: Investigate DGI functionalities and capability in collaboration with MS&T. The purpose is to acquire the necessary information in communication and programming for the IEM application development.
- HIL Test Bed (HILTB) refinement: Configure a real-time FREEDM system model for at least three SSTs in utility grid-connected mode in RTDS. Develop the required models for devices under each SST. Setup physical distributed controllers above SSTs.
- Develop a distributed power management algorithm (IPM) in SSTs to fulfill the need for the IEM, as IEM will generate power commands to distributed resources under each SST.
- IEM control module development: Configure the required input/output for the module. Program and test the IEM algorithm for the module in the development platform provided in DGI.
- CHIL demo: Deploy and test the developed IEM control module in at least three physical controllers, which manage the operation of the FREEM system running in RTDS.

2. Fundamental Research, Technological Barriers and Methodologies

In this work, we propose a distributed energy management scheme based on demand response for FREEDM distribution systems to benefit the microgrids (SST) in terms of reduction in their electricity utility bills. The distribution system in this figure contains n microgrid systems $(S_1, S_2, \ldots, S_n)$. The proposed algorithm based on a negotiation process will consider the line loss and line limits to optimize the power flows among microgrids and utility. Results of the proposed control method are the optimized power references for DERs such as energy storages (ES) in each microgrid, and the power flows among microgrids and utility. This work then presents a simulation case and discusses the results for a notional FREEDM system to validate the effectiveness of the technique.

The system contains n microgrids, which interchange power with each other and the cluster of these microgrids exchange power with the utility via a communication link. One agent controller U_i controls each node $(i = 0, 1, 2, 3, \ldots, n)$. Please note that the index $i = 0$ represents utility grid.

$$\min_{p_{ji}} \sum_{j \in N_i} f_i(p_{ji}) \tag{1a}$$

subject to

$$\sum_{j \in N_i} p_{ji} + p_{RE,i} = p_{ES,i} + p_{L,i} \tag{1b}$$

$$P_{ji}^{min,0} \le p_{ji} \le P_{ji}^{max,0} \tag{1c}$$

$$P_{ES,i}^{min} \le p_{ES,i} \le P_{ES,i}^{max} \tag{1d}$$

$$E_{ES,i}^{min} \le E_{ES,i} \le E_{ES,i}^{max}, \tag{1e}$$

where $p_{RE,i}$, $p_{ES,i}$, p_{ji}, $p_{L,i}$ (kW), $E_{ES,i}$ (kWh), and c ($/kWh) are the power prediction vectors for renewable energy system, energy storage system, power receiving from node j, load device, energy of ES, and market price respectively.

As seen, the solution of the problem (1) will be the optimal p_{ji}. Therefore, we rewrite the problem as

$$\min_{p_{ji},z_{ji}} \sum_{j\in N_i} \left(f_i(p_{ji}) + g_i(z_{ji})\right) \tag{2a}$$

subject to

$$\begin{aligned} p_{ij} &\in \mathcal{C}_i \\ p_{ij} - z_{ji} &= 0, \end{aligned} \tag{2b}$$

where $\mathcal{C}_i = \{p_{ji} \mid P_{ji}^{min,0} \le p_{ij} \le P_{ji}^{max,0}$ & $P_{ji}^{min,1} \le \sum_{j\in N_i} p_{ji} \le P_{ji}^{max,1}$ & $P_{ji}^{min,\phi} \le \phi \sum_{j\in N_i} p_{ji} \le P_{ji}^{max,\phi}\}$, and g_i is the indicator function of $\mathcal{C}_i$.

Based on [1], the augmented Lagrangian for the problem (2) is

$$L_{\rho i}(p_{ji}, z_i) = \sum_{j\in N_i} \left(f_i(p_{ji}) + g_i(z_{ji}) + \frac{\rho}{2}\left\|p_{ji} - z_{ji} + u_{ji}\right\|_2^2\right) \tag{3}$$

where ρ is a positive number called penalty parameter, $u_{ji} = (1/\rho)\lambda_{ji}$ is the scaled dual variable, and λ_i is the Largrangian multiplier. Therefore, the distributed algorithm is expressed as

$$p_{ji,h+1} = \underset{p_{ji}}{\operatorname{argmin}} \left(f_i(p_{ji}) + \frac{\rho}{2}\left\|p_{ji} - z_{ji,h} + u_{ji,h}\right\|_2^2\right) \tag{4a}$$

$$z_{ji,h+1} = \underset{z_{ji}}{\operatorname{argmin}} \left(\sum_{j\in N_i} \left(g_i(z_{ji}) + \frac{\rho}{2}\left\|p_{ji,h+1} - z_{ji} + u_{ji,h}\right\|_2^2\right)\right) \tag{4b}$$

$$u_{ji,h+1} = u_{ji,h} + \left(p_{ji,h+1} - z_{ji,h+1}\right), \tag{4c}$$

where h is the iteration index.

The analytical update of $p_{ji,h+1}$, and $z_{ji,h+1}$ is shown in the Appendix A and Appendix B, respectively.

To specify the stopping criteria of the algorithm the primal residual $r_{i,h}$ and dual residual $s_{i,h}$ are defined as

$$\begin{aligned} r_{i,h} &= (p_{1i,h} - z_{1i,h}, \dots, p_{N_j i,h} - z_{N_j i,h}) \\ s_{i,h} &= -\rho\left(z_{1i,h+1} - z_{1i,h}, \dots, z_{N_j i,h+1} - z_{N_j i,h}\right). \end{aligned} \tag{5}$$

Therefore, the stopping criteria of the control algorithm is selected as

$$\begin{aligned} \left\|r_{i,h}\right\|_2^2 &= \sum_{j=1}^{N_j} \left\|p_{ji,h} - z_{ji,h}\right\|_2^2 \le \epsilon_i^{pri} \\ \left\|s_{i,h}\right\|_2^2 &= \rho^2 \sum_{j=1}^{N_j} \left\|z_{ji,h+1} - z_{ji,h}\right\|_2^2 \le \epsilon_i^{dual}, \end{aligned} \tag{6}$$

where ϵ_i^{pri}, and ϵ_i^{dual} are a small positive numbers.

Algorithm Implementation for Controller i
1. Initialize parameters $z_{ji,h}$, and $u_{ji,h}$
2. Solve (4a) for $p_{ji,h+1}$
3. Send $p_{ji,h+1}$ to its neighbors and receive $p_{ij,h+1}$ from its neighbors
4. Solve (4b) for $z_{ji,h+1}$
5. Update scale dual variable $u_{ji,h+1}$
6. If the stopping criteria is not satisfied go to step 2 Else, go to step 7
7. Update $p_{ES,i}$ based on (1b) and send it to the power control routine of the storage device

3. Achievements

We illustrate our proposed control approach in a notional 12.47 kV distribution system (**Figure 1**). The distribution system include three sub-systems $S_1, S_2,$ and S_3, which are the three renewable energy microgrids. In details, microgrid S_1 includes a residential area (P_{L1}) with a PV system (P_{RE1}), and an energy storage system (P_{ES1}); microgrid S_2 includes a residential area (P_{L2}) with a wind energy system (P_{RE2}), and an energy storage system (P_{ES2}); and microgrid S_3 includes a residential area (P_{L3}) with a PV and wind energy system (P_{RE3}), and an energy storage system (P_{ES3}).

We assume that each subsystem will receive the price signal from its ISO/RTO. The ISO we consider in the paper is the California ISO. The region considered in the paper is via the NP15 Trading hub – Node 0096WD_7_N001 , which has a day ahead data forecasted from October 14, 2016 to October 15, 2016 with one hour data resolution. Data includes forecasted market price, renewable energy profile (PV and Wind). The forecasted price will be kept the same. The Load data in each subsystem will be normalized to 1 MW capacity. The renewable energy in each subsystem will be leveraged up to 50% penetration. The three energy storage systems, ES_1, ES_2, and ES_3 have the capacity of 3 MWh, 5 MWh, and 10 MWh, respectively. The line resistances R_{01}, R_{12}, and R_{23} are 5 Ω, 6 Ω, and 7 Ω, respectively. Other information about the system limits are shown in TABLE I.

The positive number ρ is selected as $\rho = 10$. Choose stopping criteria as $\epsilon_i^{pri} = \epsilon_i^{dual} = 0.01$. The algorithm is implemented in MATLAB. The computer running MATLAB is a core i7, 8GB RAM computer desktop. Schedule power flows and storage powers are shown in Figure 3. The convergence of the algorithm is illustrated in Figure 4.

TABLE I

PHYSICAL POWER FLOW LIMITS

Symbol	Quantity	Values
p_{01}^{min}	Minimum power flow between node 0 and 1	-3000 kW
p_{01}^{max}	Maximum power flow between node 0 and 1	3000 kW
p_{12}^{min}	Minimum power flow between node 1 and 2	-2000 kW
p_{12}^{max}	Maximum power flow between node 1 and 2	2000 kW
p_{23}^{min}	Minimum power flow between node 2 and 3	-1000 kW
p_{23}^{max}	Maximum power flow between node 2 and 3	1000 kW
$P_{ES,1}^{min,0}$	Maximum power discharged by ES_1	-3000 kW
$P_{ES,1}^{max,0}$	Maximum power charged by ES_1	1500 kW
$P_{ES,2}^{min,0}$	Maximum power discharged by ES_2	-5000 kW
$P_{ES,2}^{max,0}$	Maximum power charged by ES_2	2500 kW
$P_{ES,3}^{min,0}$	Maximum power discharged by ES_3	-10000 kW
$P_{ES,3}^{max,0}$	Maximum power charged by ES_3	5000 kW

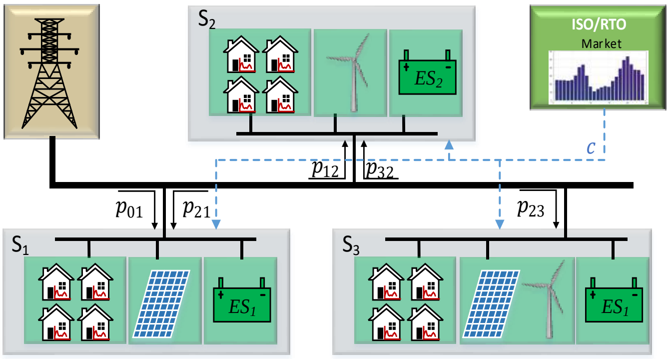

Figure 1: NOTIONAL FREEDM DISTRIBUTION SYSTEM

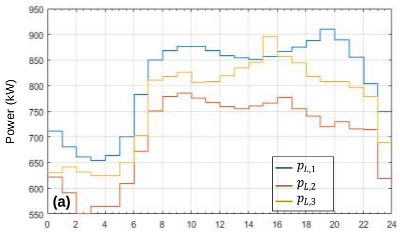

Figure 2a: LOAD PROFILE

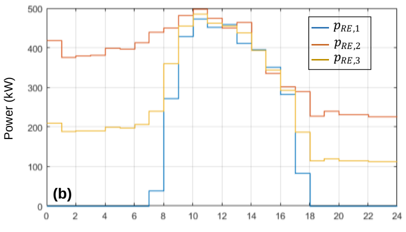

Figure 2b: RENEWABLE ENERGY

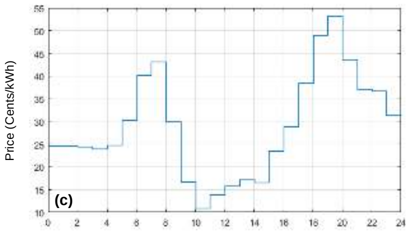

Figure 2c: MARKET PRICE

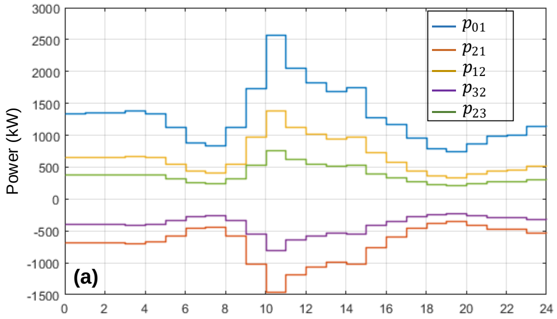

Figure 3a: POWER FLOW

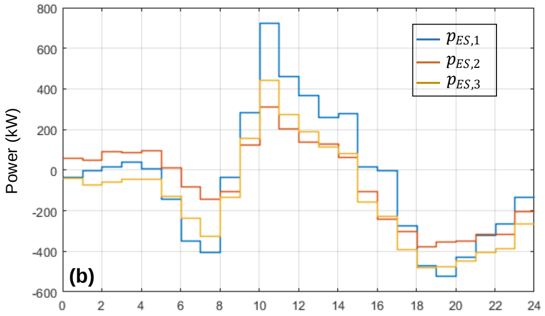

Figure 3b: STORAGE POWER

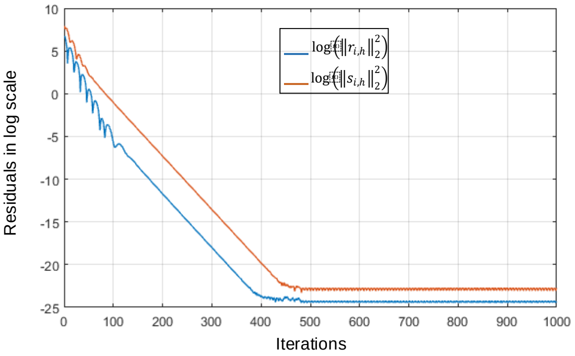

Figure 4: PRIMAL AND DUAL RESIDUALS IN LOG SCALE VERSUS THE NUMBER OF ITERATIONS

TABLE 2

OPERATION COSTS

	Cost with ES ($)	Cost without ES ($)	Benefit (%)
S_1	3958.60	5029.50	21.29
S_2	1625.50	2542.50	36.50
S_3	2344.80	3844.00	39.00

Power flow results shown in Figure 3a can be combined for the power reference in each microgrid. These flexible power flows are the results of the power schedule for ES devices shown in Figure 3b to benefit the microgrid customers in this demand response involving the distribution loss. The benefits these customers get are 21.29%, 36.5%, and 39% lower electric utility bills (TABLE II).

Results in Figure 4 demonstrate the convergence of the propose method when the norm squares of the primal and dual residuals exponentially decrease to 0 as the log values of these norm squares linearly decrease as the iteration increases. In terms of computation time, the case of two microgrids in the distribution system has a 0.71s computation time, and the case of three microgrids in the distribution system has a 1.02s computation time. Therefore, we can see that the computation of the algorithm increase linearly as the number of microgids increases. The linear increase in the computation for the system verify the computation feasibility of the method when the distribution system involves in a higher number of nodes.

4. Milestones and Deliverables

- **Deliverable for SV (04/2017):**
  Report on the IEM module developed with specifications available in DGI.
- **Final Deliverable (08/2017):**
  Final report on detailing results and discussions from testing and verifying the IEM in HILTB under various scenarios.

5. Plans for Year 10

- Configure a notional large-scale distribution system (hundreds to thousands of nodes) in RTDS
- Deploy and evaluate the IEM algorithm for the large-scale distribution system in the HILTB

6. References

[1] S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein, "Distributed Optimization and Statistical Learning via the Alternating Direction Method of Multipliers," *Foundations and Trends in Machine Learning*, vol. 3, no. 1, pp. 1–122, 2011.