Linear Approximation Line Pack Model for Integrated Electricity and Natural Gas Systems OPF

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Project Description

This project aims to develop an integrated electricity and natural gas system optimal power flow (OPF) model considering the line pack effect in the natural gas network to better model the IEGS flexibility.

Background

- The penetration level of natural gas-fired generation units has substantially increased in the U.S. power system because of low gas prices and the reduced emissions compared to coal generators.
- Renewable generation penetration level is also substantially increasing. This leads to a higher flexible resource requirement for system operation.
- Gas-fired units have the capability of fast response; therefore, the interdependency of gas networks and electricity networks is critical to maintaining reliable system operation.

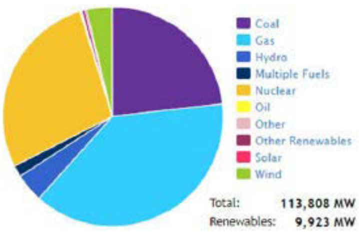

Figure 1. Generation fuel mix in PJM [1]

Case study focus:

- Reliability impact of IEGSs coordination

A small IEGSs consisting of a six-bus electricity system and a seven-node natural gas network is depicted in Fig. 3.
Case 1: OPF of only electricity network
Case 2: OPF of IEGSs with gas line pack model using mean as the pipeline average pressure
Case 3: OPF of IEGSs with gas line pack model using nonlinear average pressure model shown in Eq. (2)
Case 4: OPF of IEGSs with gas line pack model using proposed average pressure model.

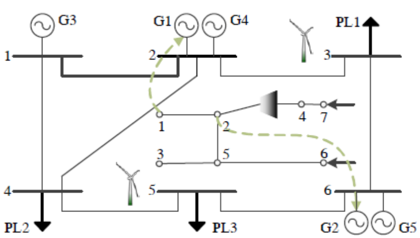

Figure 3. Six-bus system and generation parameters

Table 1 System operating cost and gas consumption in four cases

	Case 1	Case 2	Case 3	Case 4
System cost ($)	2,426,980	2,547,078	2,547,396	2,547,405
Gas consumption (Mcm)	288,920.4	264,000	264,000	264,000

Line Pack Linear Approximation

The pressure in a pipeline is quadratically related to the in-flow and out-flow node pressure shown in Fig. 2. The out-flow node pressure can be represented as in Eq. (3).

$$p_x = \sqrt{p_1^2 - (p_1^2 - p_2^2)\cdot\frac{x}{L}} \quad (1)$$

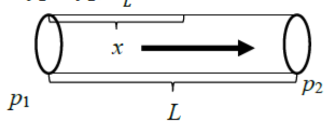

Figure 2. Illustration of gas pressure in a pipeline

$$\tilde{p}_{pl-mn,t} = \int_0^L \frac{1}{L}\sqrt{p_1^2 - (p_1^2 - p_2^2)\cdot\frac{x}{L}}\,dx = \frac{2}{3}\frac{p_1^2+p_1p_2+p_2^2}{p_1+p_2} = \frac{2}{3}\left(p_1 + p_2 - \frac{p_1p_2}{p_1+p_2}\right) \quad (2)$$

$$p_2 = r_{1,2}p_1 \quad (3)$$

$$\frac{p_1p_2}{p_1+p_2} = \frac{r_{1,2}}{1+r_{1,2}}p_1 = k_{1,2}p_1 \quad (4)$$

The procedure of the iterative linear approximation for the average pipeline gas pressure is:
Step 1: The constant k is chosen for each pipeline initially according to their nodal pressure differences (or with a flat start, these constants are set to 0.5 initially).
Figure 5. Node 2 gas pressure in four cases
Step 2: After solving the IEGSs OPF model, the constants are updated for every pipeline at every time interval with the updated in-flow and out-flow node gas pressures.
Step 3: The model is solved again with updated k values.
Step 4: The iteration stops when the difference of the objective function between two iterations is smaller than the predefined threshold value.
The value of k is updated from Step 1 to Step 4, and the gas line pack model is linearized.

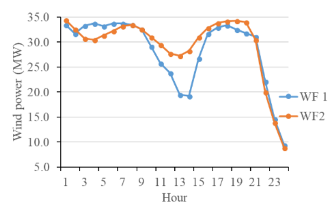

Figure 4. Demand and wind power

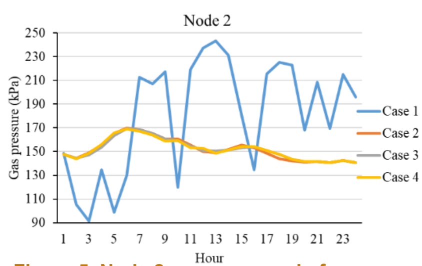

Figure 5. Node 2 gas pressure in four cases

IEGS OPF

$$\min \sum_{t\in T}\left(\sum_{i\in g}\rho_{i,gas}\left(c_{i,2}G_{i,t}^2 + c_{i,1}G_{i,t} + c_{i,0}\right)\right) \quad (5)$$

$$\boldsymbol{G_t - G_{t-1} \le R^U \cdot \Delta t} \quad (6)$$

$$\boldsymbol{G_{t-1} - G_t \le R^D \cdot \Delta t} \quad (7)$$

$$\boldsymbol{G^{min} \le G_t \le G^{max}} \quad (8)$$

$$\boldsymbol{I_G \times G_t + I_W \times P_t - I_D \times D_t = 0} \quad (9)$$

$$\boldsymbol{-LU \le GSF \times (G_t + P_t - D_t) \le LU} \quad (10)$$

$$F_{i,t} = c_{i,2}G_{i,t}^2 + c_{i,1}G_{i,t} + c_{i,0} \quad (11)$$

$$\boldsymbol{I_wS_w - I_dGD_{gl} + I_{l-t}FL_{pl-in} + I_{c-t}FC_c - I_{l-f}FL_{pl-out} - I_{c-f}FC_c - I_gF = 0} \quad (12)$$

$$S_{w,t}^{min} \le S_{w,t} \le S_{w,t}^{max} \quad (13)$$

$$FL_{pl,t} \le K_{mn}\frac{PI_{mn,s}}{\sqrt{PI_{mn,s}^2 - PO_{mn,s}^2}}p_{m,t} - K_{mn}\frac{PO_{mn,s}}{\sqrt{PI_{mn,s}^2 - PO_{mn,s}^2}}p_{n,t} \quad (14)$$

$$FC_{c,t} = -\frac{H_{c,0}}{k_{c,2} - k_{c,1}R_0^{\alpha_c}} + \frac{\partial F_{c,t}}{\partial H_{c,t}} \times (H_{c,t} - H_{c,0}) + \frac{\partial F_{c,t}}{\partial p_{m,t}} \times (p_{m,t} - p_{m0}) + \frac{\partial F_{c,t}}{\partial p_{n,t}} \times (p_{n,t} - p_{n0}) \quad (15)$$

$$R_c^{min} \le R_{c,t} = \frac{p_{n,t}}{p_{m,t}} \le R_c^{max} \quad (16)$$

$$p_{n,t}^{min} \le p_{n,t} \le p_{n,t}^{max} \quad (17)$$

$$FC_{c,t} \le FC_c^{max} \quad (18)$$

$$FL_{pl,t} = (FL_{pl-in,t} + FL_{pl-out,t})/2 \quad (19)$$

$$LP_{pl,t} = C_{mn}\tilde{p}_{pl-mn,t} \quad (20)$$

$$LP_{pl,t} = LP_{pl,t-1} + FL_{pl-in,t} - FL_{pl-out,t} \quad (21)$$

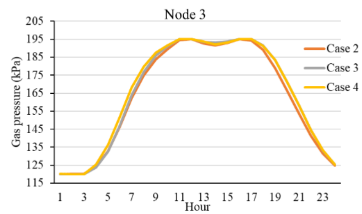

Figure 6. Node 3 gas pressure in cases 2 to 4

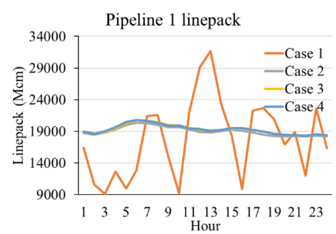

Figure 7. Line pack of Pipeline 1 in four cases

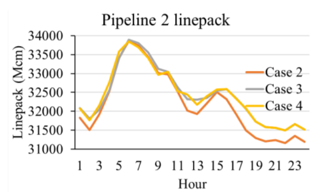

Figure 8. Line pack of Pipeline 1 in cases 2 to 4

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