Multi-Objective Optimal Power Flow Considering System Emissions and Fuzzy Constraints

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***Abstract*— *This paper proposes a fuzzy multi-objective optimal real power flow (FMOPF) with transmission line limit and transformer loading constraints. In the proposed FMOPF algorithm, the total system operating cost, total system SO_2, NO_x, and CO_2 emissions fuzzy minimization objectives are solved simultaneously considering fuzzy line flow constraints, using fuzzy linear programming (FLP). The proposed FMOPF is tested with the IEEE 30 bus system. The simulation results shown that the proposed FMOPF can efficiently and effectively trade off among total system operating cost and total system SO_2, NO_x, and CO_2 emissions.*

***Keywords*— Optimal power flow, emission power dispatch, fuzzy linear programming.**

1. INTRODUCTION

In power system operation, optimal power flow (OPF) is an extended problem of economic dispatch (ED) to include several parameters such as; generator voltage, transformer tap change, SVC, and include constraints such as; transmission line and transformer loading limits, bus voltage limit, stability margin limit. The objectives may be; minimum generation cost, minimum transmission loss, minimum deviation from target schedule, minimum control shift to alleviate violation, minimum emission. Current interest in the OPF centers around its ability to solve for large scale power system optimal solution that takes account of more objectives, parameter, and constraints of the system.

The main purpose of optimal power dispatch is to minimize the operating cost of the power system satisfying power balance constraints. However, the operating cost minimization objective may not necessarily be the best in term of environment. Several alternatives for achieving emission reductions include adding gas cleaner, switching fuel to low sulfur fuel, and adopting new power dispatch. Among these methods, the power dispatch approach is preferred because it is easily implemented and requires minimum additional costs [1]. Therefore, the unit dispatch considering emission beside cost minimization has received widespread attention for effective short-term option with smaller capital outlay [1-6]. The major environmental concerns in optimal power dispatch include emission of SO_2 [1-2, 4-6], NO_x [2-6], and CO_2 [5].

In practical power system operation, the single objective such as total operating cost minimization may not be directly applied, since it may lead to unsatisfactory of other aspects such as system security, fuel security, environmental concern. In addition, constraints in conventional OPF are usually given fixed values that have to be met which may lead to over-conservative solutions. When the solution violates the inequality constraints, it is difficult to decide which constraint should be relaxed and the extent of relaxation. Therefore, in the system operator view point, certain trade-off among several objectives and constraints would be desirable rather than a single rigid minimum or maximum solution.

Techniques for treating emission in optimal power dispatch have formed of two major research directions. Many techniques treated the emission as constraints [1, 2, 4]. However, due to the conflicting and non-commensurable nature of operating cost and emission, the earlier techniques formulated the problem to combine emissions minimization in to the total operating cost minimization problem [3, 5, 7]. In [5] and [7], the emission minimization objectives were combined into the total cost minimization objective by weighting methods. Nevertheless, in the absence of sufficient information, defining the weighting factors or equivalent cost of emission is incredibly difficult. In [3], the bi-objective power dispatch using fuzzy satisfaction-maximizing decision approach was proposed. Nonetheless, the problem included only minimum NO_x emission and total operating cost objectives with the linear fuzzy membership function.

This paper proposes the fuzzy multi-objective optimal real power flow (FMOPF) for selecting a final compromise solution for operating cost and emissions minimization problems. In the proposed FMOPF algorithm, the total system operating cost, total system SO_2, NO_x, and CO_2 emissions fuzzy minimization objectives are solved simultaneously using fuzzy linear programming (FLP). The proposed FMOPF is tested with the IEEE 30 bus system. The simulation results shown that the proposed FMOPF can efficiently and effectively trade off among total system operating cost and total system SO_2, NO_x, and CO_2 emissions.

The organization of this paper is as follows. Section 2

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addresses the FMOPF problem formulation. The FLP for FMOPF problem is given in Section 3. Numerical results on the IEEE 30 bus test system are illustrated in Section 4. Lastly, the conclusion is given.

2. MOPF PROBLEM FORMULATION

Consider the fact that real power injected at a bus does not change significantly for a small change in the magnitude of bus voltage and the reactive power injected at a bus does not change for a small change in the phase angle of bus voltage. Therefore, the bus voltage magnitudes and transformer tap changes are not included in the total operating cost and emissions multi-objective fuzzy minimization subproblem. Similarly, the real power generations are not included in the total real power loss fuzzy minimization subproblem.

2.1 Total operating cost and emissions multi-objective fuzzy minimization subproblem

The operating cost of the generating unit is expressed as the sum of polynomial function of the real power generation of the unit. Therefore, objective is to minimize total system operating cost,

$$FC = \sum_{i \in BG} F(P_{Gi}) \tag{1}$$

The environment aspect cover a myriad of air quality concerns including control of power plant emissions of constituents of acid rain specifically sulfur dioxide (SO_2) and oxide of nitrogen (NO_x). The carbon dioxide (CO_2) emission is also taken into account since it is considered as a global warming gas.

The emission functions for the unit i can be expressed as polynomial function of real power generation of the unit. Therefore, the addition objective functions are minimize total NO_x emission,

$$EC_{NO_x} = \sum_{i \in BG} E_{NO_x}(P_{Gi}), \tag{2}$$

and minimize total SO_2 emission,

$$EC_{SO_2} = \sum_{i \in BG} E_{SO_2}(P_{Gi}), \tag{3}$$

and minimize total CO_2 emission,

$$EC_{CO_2} = \sum_{i \in BG} E_{CO_2}(P_{Gi}) \cdot \tag{4}$$

subject to the power balance constraints,

$$P_{Gi} - P_{Di} = \sum_{j=1}^{NB} |V_i||V_j||y_{ij}| \cos(\theta_{ij} - \delta_{ij}), i = 1,..., NB, \tag{5}$$

$$Q_{Gi} - Q_{Di} = -\sum_{j=1}^{NB} |V_i||V_j||y_{ij}| \sin(\theta_{ij} - \delta_{ij}), i = 1,..., NB, \tag{6}$$

and the line flow limit and transformer loading constraints,

$$|f_l| \tilde{\leq} f_l^{\max}, \text{ for } l=1, \ldots, NL, \tag{7}$$

and fuzzy generator ramprate constraint,

$$P_{Gi}^{o} - R_{Gi}^{dec} \cdot Min \tilde{\leq} P_{Gi} \tilde{\leq} P_{Gi}^{o} - R_{Gi}^{inc} \cdot Min, \; i = 1,\ldots, NR, \tag{8}$$

and the generator minimum and maximum operating limit constraints,

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max}, \; i \in BG. \tag{9}$$

2.2 Real power loss fuzzy minimization subproblem

To minimize the total real power loss, the total real power loss minimization subproblem is solved iteratively with the total fuel cost fuzzy minimization subproblem. The objective is formulated as,

$$\text{Minimize } \Delta P_{loss} = \left[\frac{\mathbf{dP_{loss}}}{\mathbf{d|V|}} \; \frac{\mathbf{dP_{loss}}}{\mathbf{dT}}\right] \begin{bmatrix} \mathbf{\Delta|V|} \\ \mathbf{\Delta T} \end{bmatrix}, \tag{10}$$

subject to the fuzzy bus voltage limits constraints,

$$\Delta|V_i^{\min}| \tilde{\leq} \Delta|V_i| \tilde{\leq} \Delta|V_i^{\max}|, \text{ for } i = 1,\ldots, NV, \tag{11}$$

where

$$\Delta|V_i^{\min}| = |V_i^{\min}| - |V_i|, \text{ for } i = 1,\ldots, NV, \tag{12}$$

$$\Delta|V_i^{\max}| = |V_i^{\max}| - |V_i|, \text{ for } i = 1,\ldots, NV, \tag{13}$$

and the transformer tap-change limits constraints,

$$\Delta T_i^{\min} \leq \Delta T_i \leq \Delta T_i^{\max}, \text{ for } i = 1,\ldots, NT, \tag{14}$$

where

$$\Delta T_i^{\min} = T_i^{\min} - T_i, \text{ for } i = 1,\ldots, NT, \tag{15}$$

$$\Delta T_i^{\max} = T_i^{\max} - T_i, \text{ for } i = 1,\ldots, NT, \tag{16}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, \; i \in BG. \tag{17}$$

$|V_i|$, $i \in BG$, and T_i, $i = 1,\ldots,NT$, are the unknown control variables obtained from the total real power loss fuzzy minimization subproblem.

P_{Gi}, where $i \in BG$, is the output of the FMOPF algorithm. The method is intended to line flow and transformer loading limits constrained economic dispatch in power system. The bus voltages and reactive power optimal controls are not included in the paper.

3. FUZZY LINEAR PROGRAMMING ALGORITHM FOR FMOPF PROBLEM

To solve the FMOPF problem, the goal of decision-maker can be expressed as a fuzzy set and the solution space is defined by constraints that can be modeled by fuzzy set [8]. The multi-objective fuzzy minimization subproblem of the proposed FMOPF can be formulated as,

$$\text{Maximize } \min\ \{\mu_1(x), \mu_2(x), \mu_3(x), \mu_4(x)\}\ , \tag{9}$$

$$\text{subject to}\quad \mathbf{B}\cdot\mathbf{P}_{\mathbf{Gi}} \tilde{\leq} \mathbf{d} \tag{10}$$

and power balance constraints in (2) and (3), crisps inequality line flow limit and transformer loading constraints in (7), and low and high limits of P_{Gi} in (8).

$\mathbf{P}_{\mathbf{Gi}}$ is the column matrix representing the set of real power generation of the generator connected to bus *i*. **d** is the vector representing of fuzzy objective functions in Eqs. (1)-(4). Each row of **B** in (10) is represented by a fuzzy set with the membership functions of $\mu_i(x)$. $\mu_i(x)$ can be interpreted as the degree to which $\mathbf{P}_{\mathbf{Gi}}$ satisfies the fuzzy objective function. Here, $\mu_1(x)$ is the degree of satisfaction of $\mathbf{P}_{\mathbf{Gi}}$ for the objective function, whereas $\mu_2(x)$ to $\mu_4(x)$ are the degrees of satisfactions of $\mathbf{P}_{\mathbf{Gi}}$ for the, total system NO_x, SO_x, and CO_2 emissions, respectively. In this paper, the hyperbolic function is used to represent the nonlinear, S-shaped, membership function [9]. The function can be expressed as,

$$\mu_i(x) = \frac{1}{2}\cdot\tanh\left(\left(\mathbf{B}_{\mathbf{i}}\cdot\mathbf{P}_{\mathbf{Gij}} - \frac{\alpha_i+\beta_i}{2}\right)\cdot\gamma_i\right) + \frac{1}{2}\cdot \tag{11}$$

where α_i, β_i, and γ_i are the parameters representing the shape of $\mu_i(x)$ depending on the decision maker and $\mathbf{B}_{\mathbf{i}}$ is the row *i* of **B**.

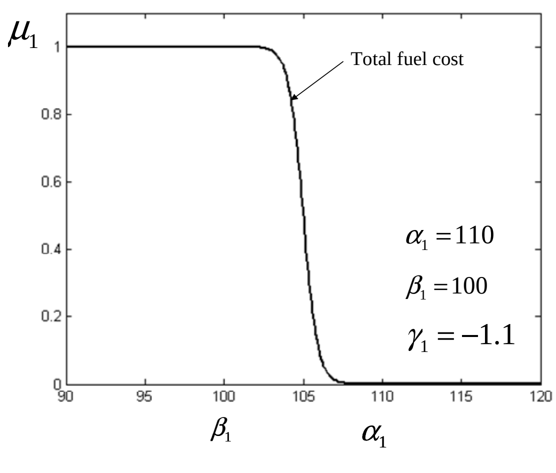

Fig. 1. Membership function for total operating cost.

The fuzzy linear programming approach translates the multiple objectives into additional constraints by assigning membership function to each objective. Due to complexity in computation, many literatures set the parameters by heuristics based on operators' intuition. In this paper, the parameters were set by the worst case principle, which is based on the concept that none of the objective functions can be reduced any further by increasing other objective functions. This can reflect the optimal trade off among the objectives.

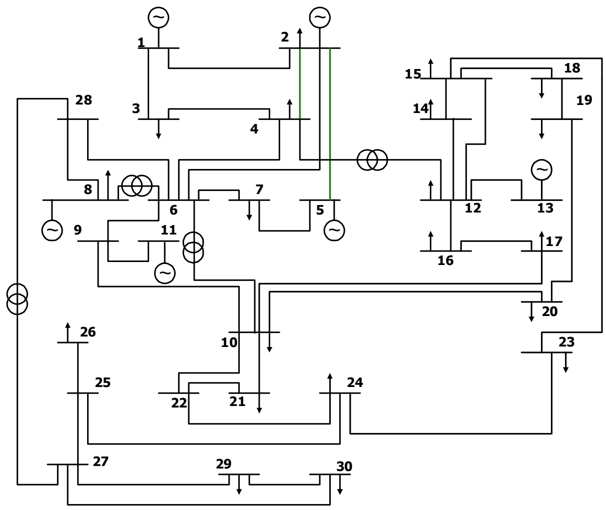

Fig. 2. IEEE 30 bus test system network diagram.

Therefore, to obtain the membership function of objective function, α_1 is the minimum total operating cost solved by the LP without consideration of emissions. On the other hand, β_1 is the maximum total fuel cost among the solution of minimization of other fuzzy objective functions. γ_1 is obtained by α_1/β_1. Similarly, α_2, α_3, and α_4 are the minimum SO_2, NO_x, and CO_2 emissions solved by the LP without consideration of total fuel cost and each other fuzzy objective functions. β_2, β_3, and β_4 are the maximum NO_x, SO_2, and CO_2 emissions among the solution of minimization of the total fuel cost and each other fuzzy objective functions.

Table 1. The generator fuel cost function

Gen bus	Min (MW)	Max (MW)	$F(P_{Gi}) = a_i\cdot P_{Gi}^3 + b_i\cdot P_{Gi}^2 + c_i\cdot P_{Gi} + d_i$			
			a_i	b_i	c_i	d_i
1	50	200	0.0010	0.092	14.5	-136
2	20	80	0.0004	0.025	22	-3.5
5	15	50	0.0006	0.075	23	-81
8	10	50	0.0002	0.1	13.5	-14.5
11	10	50	0.0013	0.12	11.5	-9.75
13	12	40	0.0004	0.084	12.5	75.6

With the defined membership functions of objective function and fuzzy constraints, the fuzzy optimization problem can be reformulated as,

$$\text{Maximize } \mu', \tag{12}$$

$$\text{subject to}\quad \mu' \leq \mu_i(x)\text{, for } i = 1,\ldots, 4, \tag{13}$$

Table 2. The SO_2, NO_x, and CO_2 emissions functions

$$E_{SO_2}(P_{Gi}) = a_{SO_2 i} \cdot P_{Gi}^3 + b_{SO_2 i} \cdot P_{Gi}^2 + c_{SO_2 i} \cdot P_{Gi} + d_{SO_2 i}$$
$$E_{NO_x}(P_{Gi}) = a_{NO_x i} \cdot P_{Gi}^3 + b_{NO_x i} \cdot P_{Gi}^2 + c_{NO_x i} \cdot P_{Gi} + d_{NO_x i}$$
$$E_{CO_2}(P_{Gi}) = a_{CO_2 i} \cdot P_{Gi}^3 + b_{CO_2 i} \cdot P_{Gi}^2 + c_{CO_2 i} \cdot P_{Gi} + d_{CO_2 i}$$

Gen bus	SO_2				NO_x				CO_2			
	$a_{SO_2 i}$	$b_{SO_2 i}$	$c_{SO_2 i}$	$d_{SO_2 i}$	$a_{NO_x i}$	$b_{NO_x i}$	$c_{NO_x i}$	$d_{NO_x i}$	$a_{CO_2 i}$	$b_{CO_2 i}$	$c_{CO_2 i}$	$d_{CO_2 i}$
1	0.0005	0.150	17.0	-90.0	0.0012	0.052	18.5	-26.0	0.0015	0.092	14.0	-16.0
2	0.0014	0.055	12.0	-30.5	0.0004	0.045	12.0	-35.0	0.0014	0.025	12.5	-93.5
5	0.0010	0.035	10.0	-80.0	0.0016	0.050	13.0	-15.0	0.0016	0.055	13.5	-85.0
8	0.0020	0.070	23.5	-34.5	0.0012	0.070	17.5	-74.0	0.0012	0.010	13.5	-24.5
11	0.0013	0.120	21.5	-19.75	0.0003	0.040	8.5	-89.0	0.0023	0.040	21.0	-59.0
13	0.0021	0.080	22.5	25.6	0.0014	0.024	15.5	-75.0	0.0014	0.080	22.0	-70.0

and $0 \le \mu' \le 1$, (14)

and power balance constraints in (2) and (3), crisps inequality line flow limit and transformer loading constraints in (7), and low and high limits of P_{Gi} in (8).

The FLP computational procedure is as follow,

Step 1: Solve the linear programming for individual objective function in Eqs. (1)-(4)

Step 2: Compute individual objective value of each case.

Step 3: Obtain α_i and β_i from the minimum and maximum of all objective values computed in step 2.

Step 4: Solve the fuzzy linear programming of multi-objective problem using α_i and β_i from step 3.

4. SIMULATION RESULTS

The IEEE 30 bus system is used as the test data. It network diagram is shown in Fig.2. The generator fuel cost, and SO2, NOx, and CO2 emissions functions are given in Tables 1 and 2. The generator fuel cost, and SO2, NOx, and CO2 emissions functions are linearized in to 5 piece-wise linear functions.

Table 3. Dispatch results of minimum total operating cost condition

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** ** Generation Cost ** **
--------------------------
 BUS      P_GEN        Cost          Inc-Cost
          (MW)        ($/h)          ($/MWh)
  1       50.00      944.00015       21.60000
  2       68.00     1733.87260       25.54960
  5       36.00      872.19306       26.47760
  8       50.00      935.49803       18.99999
 11       43.07      812.15973       19.08103
 13       40.00      735.59962       16.50000
Total Cost = 6033.32319 $/h
Total SO2  = 7035.94301 ton/h
Total NOX  = 5060.62788 ton/h
Total CO2  = 5917.43863 ton/h
```

Tables 3-6 address the dispatch results of minimum operating cost, SO_2 emission, NO_x emission, and CO_2 emission, respectively. Table 7 shows the dispatch results of the FMOPF result. The results show that the sigle objective approaches result in the inferior results in the others objective and less degree of satisfaction.

Table 4. Dispatch results of minimum SO_2 emission condition

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** ** Generation Cost ** **
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 BUS      P_GEN        Cost          Inc-Cost
          (MW)        ($/h)          ($/MWh)
  1       50.00      944.00013       21.60000
  2       68.00     1733.87267       25.54960
  5       50.00     1331.49953       28.25000
  8       36.68      625.17418       17.43752
 11       42.00      781.24482       18.83320
 13       40.00      735.59969       16.50000
Total Cost = 6151.39102 $/h
Total SO2  = 6709.76760 ton/h
Total NOX  = 5009.04237 ton/h
Total CO2  = 5976.29335 ton/h
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Table 5. Dispatch results of minimum NO_x emission condition

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** ** Generation Cost ** **
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 BUS      P_GEN        Cost          Inc-Cost
          (MW)        ($/h)          ($/MWh)
  1       50.00      944.00000       21.60000
  2       69.86     1791.70996       25.69841
  5       43.00     1094.37920       27.33440
  8       34.00      567.96080       17.13120
 11       50.00     1027.75000       20.75000
 13       40.00      735.60000       16.50000
Total Cost = 6161.39996 $/h
Total SO2  = 6874.94078 ton/h
Total NOX  = 4897.48710 ton/h
Total CO2  = 6104.20084 ton/h
```

The comparison on the results with total cost minimization, SO2 minimization, NOx Minimization, CO2 minimization, and the proposed FMOPF is shown in Fig.3.

In this test case, the minimum operating cost solution results in the highest SO2 emission of 7035.94 ton/h. Meanwhile, the minimum NOx emission results in the highest total operating cost and CO2 emissions, of

6161.4 \$/h and 6104.2 ton/h, respectively and the minimum CO2 solution results in the highest NOX emission of 5187.67 ton/h.

In contrast, the proposed FMOPF is effectively trades off all objectives in the fuzzy reasoning sense leading to the most compromise solution. Note the FMOPF results in the degree of satisfaction (μ') of 0.881.

Table 6. Dispatch results of minimum CO_2 emission condition

** ** Generation Cost ** **

BUS	P_GEN (MW)	Cost (\$/h)	Inc-Cost (\$/MWh)
1	50.00	943.99989	21.60000
2	68.00	1733.87299	25.54960
5	50.00	1331.50050	28.25000
8	50.00	935.50167	19.00001
11	34.00	571.06491	17.08280
13	34.68	626.79931	15.89414

Total Cost = 6142.73928 \$/h
Total SO2 = 6766.27879 ton/h
Total NOX = 5187.67201 ton/h
Total CO2 = 5805.99644 ton/h

Table 7. Dispatch results of the proposed FMOPF

** ** Generation Cost ** **

BUS	P_GEN (MW)	Cost (\$/h)	Inc-Cost (\$/MWh)
1	49.98	943.48013	21.59680
2	63.29	1590.34897	25.18430
5	44.74	1151.97467	27.55687
8	45.35	822.01699	18.44621
11	43.82	833.92697	19.25416
13	39.56	726.39639	16.44944

Total Cost = 6068.14412 \$/h
Total SO2 = 6822.92570 ton/h
Total NOX = 5018.07405 ton/h
Total CO2 = 5889.96324 ton/h

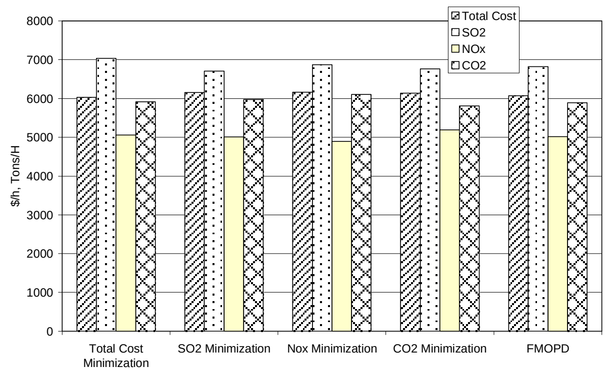

Fig. 3. The comparison on the results with different objective functions.

5. CONCLUSIONS

In this paper, a fuzzy multi-objective optimal real power flow (FMOPF) with transmission line limit and transformer loading constraints is successfully trading off between the total system operating cost, SO_2 emission, NO_x emission, and CO_2 emission, satisfying transmission line limits and transformer loading constraints. The proposed FMOPF results in a compromise solution and can potentially be applied to overcome the difficulties of obtaining the weight or equivalent cost of emission.

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NOMENCLATURE

Known Variables

EC_{NO_x} , EC_{SO_x} , and EC_{CO_2} : the total system NO_x , SO_x, and CO_2 emissions, respectively (ton/h),

$E_{NO_x}(P_{Gi})$, $E_{SO_x}(P_{Gi})$, and $E_{CO_2}(P_{Gi})$: the NO_x, SO_2, and CO_2 emissions of the generator connected to bus *i*, respectively (ton/h),

$F(P_{Gi})$: the operating cost of the generator connected to bus *i* (\$/h),

BG : set of buses connected with generators

$f_l^{\max}$: MVA flow limit of line or transformer *l* (MVA)

NB : total number of buses

NT : total number of on load tap-changing transformers

P_{Di} : total real power demand at bus *i* (MW)

$P_{Gij}^{\max}$: real power generation of the linearized cost function segment *j* of generator at bus *i* (MW)

$P_{Gij}^{\max}$: maximum real power generation of the linearized cost function segment *j* of generator at bus *i* (MW)

$P_{Gi}^{\max}$: maximum real power generation at bus *i* (MW)

$P_{Gi}^{\min}$: minimum real power generation at bus *i* (MW)

Q_{Di} : reactive power demand at bus *i* (MVAR)

$Q_{Gi}^{\max}$: maximum reactive power generation at bus *i* (MW)

$Q_{Gi}^{\min}$: minimum reactive power generation at bus *i* (MW)

R_{Gi}^{inc} : ramping rate limit of generator *i* when increasing real power generation (MW/min)

R_{Gi}^{dec} : ramping rate limit of generator *i* when decreasing real power generation (MW/min)

Min : time interval in minute (min)

S_{ij} : linearized incremental cost segment *j* of generator at bus *i* (\$/MWh)

$T_i^{\max}$: maximum tap setting of transformer *i* (MW)

$T_i^{\min}$: minimum tap setting of transformer *i* (MW)

$\left|V_i^{\max}\right|$: maximum voltage magnitude at bus *i* (kV)

$\left|V_i^{\min}\right|$: minimum voltage magnitude at bus *i* (kV)

$\left|y_{ij}\right|$: magnitude of the y_{ij} element of Y_{bus} (mho)

θ_{ij} : angle of the y_{ij} element of Y_{bus} (radian)

Unknown Control Variables

P_{Gi} : the real power generation of the generator connected to bus i (MW),

T_i : tap setting of transformer i (MW)

$|V_i|$: generator voltage magnitude at bus i, $i \in BG$ (kV)

State and Output Variables

FC : total system fuel cost ($/h)

f_l : MVA flow of line or transformer l (MVA)

NC : total number of line flow and transformer loading constraints

NR : total number of generator ramprate constraints

NV : total number of bus voltage magnitude constraints

P_i : injection real power at bus i (MW)

P_{loss} : total system real power loss (MW)

Q_{Gi} : reactive power generation at bus i (MVAR)

$|V_i|$: voltage magnitude at load bus i, $i \notin BG$ (kV)

δ_{ij} : voltage angle difference between bus i and j (radian)

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