A Security Constrained Environmental/Economic Power Dispatch Technique Using F-MSG Algorithm for a Power System Area Including Limited Energy Supply Thermal Units

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Abstract

In this paper, the modified subgradient algorithm based on feasible values (F-MSG) is applied to a security constrained environmental/economic dispatch problem for a power system area including limited energy supply thermal units. A nonlinear programming model is set up for the problem solution. Power system transmission loss is inserted into this model as equality constraints via load flow equations Unit generation constraints, transmission line capacity constraints, bus voltage magnitude constraints, off-nominal tap ratio constraints are added into the optimization problem as inequality constraints. Limited energy supply thermal units are assumed to be fueled under *take-or-pay* (T-O-P) agreement. The fuel constraint, which can take place due to T-O-P fuel agreement, is handled by using the effect of the *scaling factor* on the total fuel consumption by the limited energy supply thermal units. Usage of the scaling factor decreases the number of independent variables that is used in the solution of considered dispatch problem as well. Since all constraints in the nonlinear programming model are functions of complex bus voltages and off-nominal tap ratios (once there are off-nominal tap changing transformers in the power system), they are taken as independent variables. The proposed approach is tested on IEEE 30-bus test system. A portion of the dispatch problem was also solved by another dispatch technique that uses differential evaluation algorithm. Results obtained from both algorithms are also compared.

1. Introduction

A specific operation period of a lossy electric power system including limited energy supply thermal units is considered in this paper. During the operation period, system load values and the units that will supply those loads are assumed to be known. The total operation period is divided into subintervals where the system load values remain constant. The minimum value of the total system cost, which is made up of weighted sum of total fuel cost and total emission cost, for the operation period is calculated under some possible electric and fuel constraints.

Under *take-or-pay* (T-O-P) fuel contract, a minimum value of the total fuel amount to be spent by the limited energy supply thermal units during the operation period is determined in advance. The utility company agrees to use at least this minimum amount. If it fails to use the minimum amount, *it agrees to pay the cost of the minimum amount.* [1].

In the literature, the environmental economic dispatch problem for a power system area including limited energy supply thermal units was solved by various solution methods. Some of these methods use differential evolution algorithm [2], multi-objective particle swarm optimization [3], an ε-dominance-based multi-objective genetic algorithm [4], fuzzy based bacterial foraging algorithm [5]

The F-MSG method is a deterministic solution method, which uses deterministic equations at one point to produce the next solution point being closer to the optimum solution in the solution space; whereas the evolutionary methods [2-5] work on a solution population rather than on a single solution and uses probabilistic tools to produce new solutions. In general, solution times for the evolutionary methods are comparably high with respect to those of deterministic methods for the lossy security constrained economic dispatch problems with convex cost curves.

In the F-MSG algorithm [6], the upper bound for the cost function value is specified in advance and the algorithm tries to find a solution where the cost function is *less than or equal to* the upper bound and all constraint are satisfied. If it finds it (*feasible total cost*), the upper bound is *decreased* a certain amount, otherwise (*infeasible total cost*) the upper bound is *increased* a certain amount. The amount of decrease or increase on the upper bound for the next iteration depends on if any feasible or infeasible total cost value was obtained in the previous iterations. This process continues until absolute value of the change in the upper bound is less than a predefined tolerance value. The total fuel and emission costs are combined by means of weighted sum method by using a w factor changing between 0 and 1.

2. Statement of the problem

A nonlinear programming model for the economic/environmental power dispatch problem considered in this paper is given in the following:

$$Min\ F_{TOT} = w\,F_{tot} + \xi\,(1-w)\,E_{tot}, \quad (R), \quad 0 \le w \le 1 \tag{1}$$

where

$$F_{tot} = \sum_{j=1}^{j_{max}} \sum_{i \in \{N_s, N_T\}} F_i(P_{Gi,j})\,t_j \qquad (R) \tag{2}$$

$$E_{tot} = \sum_{j=1}^{j_{max}} \sum_{i \in \{N_s, N_T\}} E_i(P_{Gi,j})\,t_j \qquad (kg). \tag{3}$$

subject to

$$P_{Gi,j} - P_{Load\ i,j} - \sum_{k \in N_{Bi}} p_{ik,j} = 0$$
$$Q_{Gi,j} - Q_{Load\ i,j} - \sum_{k \in N_{Bi}} q_{ik,j} = 0,\ i = 1,2,..,N,\ j = 1,2,..,j_{max} \qquad (4)$$

$$C_{spent} = \left(\sum_{j=1}^{j_{max}} \sum_{T \in \boldsymbol{N_T}} C_T(P_{GT,j}) t_j \right) \geq C_{tot} \qquad (5)$$

$$P_{Gs}^{min} \leq P_{Gs,j} \leq P_{Gs}^{max},\quad Q_{Gs}^{min} \leq Q_{Gs,j} \leq Q_{Gs}^{max}$$
$$s \in N_s,\ \ j = 1,2,\cdots,j_{max} \qquad (6)$$

$$P_{GT}^{min} \leq P_{GT,j} \leq P_{GT}^{max},\quad Q_{GT}^{min} \leq Q_{GT,j} \leq Q_{GT}^{max}$$
$$T \in N_T,\ \ j = 1,2,\cdots,j_{max} \qquad (7)$$

$$p_{l,j} \leq p_l^{max},\qquad l \in L,\ \ j = 1,2,\cdots,j_{max} \qquad (8)$$

$$U_i^{min} \leq U_{i,j} \leq U_i^{max}, i=1,2,\cdots,N,\ i \neq ref, vc,\ j=1,\cdots,j_{max} \qquad (9)$$

$$a_i^{min} \leq a_{i,j} \leq a_i^{max},\ i \in N_{tap},\ \ j = 1,\cdots,j_{max}. \qquad (10)$$

2.1. Determination of Line Flows and Power Generations

To express the total system cost function in terms of independent variables of our optimization model, line flows should be written in terms of complex bus voltages and off-nominal tap ratios (see equations (1) and (2)). The following equations give the active and reactive power flows over the line being connected between buses i and k in the j^{th} subinterval.

$$p_{ik,j} = U_{i,j}^2 \left(\frac{g_{ik}}{a_{i,j}^2} + g_{sh\,i} \right) - \frac{U_{i,j} U_{k,j}}{a_{i,j}} \times \left[g_{ik} \cos(\delta_{i,j} - \delta_{k,j}) + b_{ik} \sin(\delta_{i,j} - \delta_{k,j}) \right] \qquad (11)$$

$$p_{ki,j} = U_{k,j}^2 \left(g_{ik} + g_{sh\,k} \right) - \frac{U_{i,j} U_{k,j}}{a_{i,j}} \times \left[g_{ik} \cos(\delta_{k,j} - \delta_{i,j}) + b_{ik} \sin(\delta_{k,j} - \delta_{i,j}) \right] \qquad (12)$$

$$q_{ik,j} = -U_{i,j}^2 \left(\frac{b_{ik}}{a_{i,j}^2} + b_{sh\,i} \right) - \frac{U_{i,j} U_{k,j}}{a_{i,j}} \times \left[g_{ik} \sin(\delta_{i,j} - \delta_{k,j}) - b_{ik} \cos(\delta_{i,j} - \delta_{k,j}) \right] \qquad (13)$$

$$q_{ki,j} = -U_{k,j}^2 \left(b_{ik} + b_{sh\,i} \right) - \frac{U_{i,j} U_{k,j}}{a_{i,j}} \times \left[g_{ij} \sin(\delta_{k,j} - \delta_{i,j}) - b_{ij} \sin(\delta_{k,j} - \delta_{i,j}) \right] \qquad (14)$$

In the above equations, $U_{i,j}$ and $\delta_{i,j}$ are voltage magnitude and phase angle of bus i in the j^{th} subinterval, respectively, $r_{ik} + jx_{ik}$ is the series impedance of the line between buses i and k, $g_{ik} + jb_{ik}$ is the *series* admittance of the line between buses i and k where $g_{ik} + jb_{ik} = 1/(r_{ik} + jx_{ik})$, $g_{shi} + jb_{shi}$ is the sum of the half line charging admittance and external shunt admittance if any at bus i, and $a_{i,j}$ is the off-nominal tap setting in the j^{th} subinterval with tap setting facility at bus i, $p_{ik,j}$ and $q_{ik,j}$ are the active and reactive power flows going from bus i to bus k at bus i border in the j^{th} subinterval, respectively. $-p_{ki,j}$ and $-q_{ki,j}$ are the active and reactive power flows going from bus i to bus k at bus k border in the j^{th} subinterval, respectively.

The total loss of the network in the j^{th} subinterval can be calculated by the following equations:

$$p_{loss\ ik,j} = p_{ik,j} + p_{ki,j} \qquad (15)$$

$$P_{LOSS,j} = \sum_{i \in N} \sum_{k \in N, k \neq i} p_{ik,j},\quad j = 1,2,\cdots,j_{max}. \qquad (16)$$

The cost rate and emission rate function values of the i^{th} unit in the j^{th} subinterval are taken as

$$F_i(P_{Gi,j}) = b_i + c_i P_{Gi,j} + d_i P_{Gi,j}^2,\ (R/h)$$
$$E_i(P_{Gi,j}) = 10^{-2}\left[\alpha_i + \beta_i P_{Gi,j} + \gamma_i P_{Gi,j}^2 \right] + \zeta_i\, e^{(\lambda_i P_{Gi,j})}\ (kg/h) \qquad (17)$$
$$i \in \{N_s, N_T\},\ j = 1,2,\cdots j_{max}$$

where b_i, c_i, d_i; $\alpha_i, \beta_i, \gamma_i, \zeta_i, \lambda_i$; $i \in \{N_s, N_T\}$ are constant coefficients.

2.2. Converting Inequality Constraints into Equality Constraints

Since the F-MSG algorithm requires that all constraints need to be expressed in equality constraint form, the inequality constraints in the optimization model should be converted into the corresponding equality constraints. The following method is used for this purpose, since it does not add any extra independent variable into the optimization model in the conversion process [6]. The double sided inequality $x_i^- \leq x_{i,j} \leq x_i^+$ in the j^{th} subinterval can be written as the following two inequalities:

$$h_{i,j}^+(x_{i,j}) = (x_{i,j} - x_i^+) \leq 0$$
$$h_{i,j}^-(x_{i,j}) = (x_i^- - x_{i,j}) \leq 0,\quad j = 1,2,\cdots j_{max} \qquad (18)$$

Then, we can rewrite the above inequalities as continuous equality forms by the following:

$$h_{i,j}^{eq+}(x_{i,j}) = \max\left\{0,\ \left(x_{i,j} - x_i^+\right)\right\}$$
$$h_{i,j}^{eq-}(x_{i,j}) = \max\left\{0,\ \left(x_i^- - x_{i,j}\right)\right\},\quad j = 1,2,\cdots j_{max} \qquad (19)$$

If $x_i^- \leq x_{i,j} \leq x_i^+$, it is obvious that $(x_{i,j} - x_i^+) \leq 0$, $(x_i^- - x_{i,j}) \leq 0$ and, $\max\left\{0,\ \left(x_{i,j} - x_i^+\right)\right\} = 0$, $\max\left\{0,\ \left(x_i^- - x_{i,j}\right)\right\} = 0$. So the inequality constraints in (18) can be represented by the corresponding equality constraints in (19). In this paper the inequality constraints, given in equations (6)-(10), are converted into the corresponding equality constraints in this way.

3. The Modified Subgradient Algorithm Based on Feasible Values

The nonlinear optimization problem for subinterval j can be represented in the standard form given below:

$$\text{Min}\ F_{TOT,j}(\boldsymbol{x}),\quad \textit{Subject to} \begin{cases} \boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0} \\ \boldsymbol{x} \in K \end{cases} \qquad (20)$$

where

$\boldsymbol{x}=[U_{1,j},U_{2,j},\cdots\cdots,U_{N,j},\delta_{1,j},\delta_{2,j},\cdots\cdots\delta_{N,j},a_{1,j},a_{2,j},\cdots,a_{N_{tap},j}]$ is the independent variable vector in subinterval *j*. $F_{TOT,j}(\boldsymbol{x})$ is the objective function which is given as

$$F_{TOT,j}=w\sum_{i\in\{N_s,N_T\}}F_i(P_{Gi,j})t_j+\xi(1-w)\sum_{i\in\{N_s,N_T\}}E_i(P_{Gi,j})t_j \quad (21)$$

$\boldsymbol{h}(\boldsymbol{x})=\left[h_1(\boldsymbol{x}),h_2(\boldsymbol{x}),\cdots\cdots,h_{N_{EQ}}(\boldsymbol{x})\right]$ in (20) is the equality constraint vector in subinterval *j*. It includes all the original equality constraints, which are shown in (4), and the equality constraints, which are obtained from converting all the inequality constraints shown in equations (6)-(10), into the corresponding equality constraints via the method given in Section 2.2. K is a sufficiently large compact set containing the potential values of $\boldsymbol{x}$. Region K is bounded by the upper and the lower limits of the voltage magnitudes of the buses in subinterval *j* and the upper and the lower limits of the tap settings of the transformers in subinterval *j*. Note that the voltage magnitude and phase angle of the reference bus, *are not* included into $\boldsymbol{x}$ since they are not independent variables and remain constant during the solution process. In solving the constrained optimization problem given by equation (20), the first step is to convert it into unconstrained one by constructing the dual problem. This can be done by using various LaGrange functions [7]. LaGrange function must guarantee that the optimal solution of the dual problem be equal to that of the primal constrained problem. Otherwise, there will be a difference between the optimal values of these problems; in other words, a duality gap will occur. The classical LaGrange function guarantees the zero duality gaps for the convex problems. However, if the objective function or some of the constraints are not convex, then the classical LaGrange function cannot guarantee this. Therefore, for the non-convex problems, suitably selected augmented LaGrange functions should be used. Considering the non-convex nature of our problem, we form the dual problem by using the following sharp augmented LaGrange function:

$$\begin{aligned}L(\boldsymbol{x},\boldsymbol{u},c)&=F(\boldsymbol{x})+c\left\|\boldsymbol{h}(\boldsymbol{x})\right\|-\langle\boldsymbol{u},\boldsymbol{h}(\boldsymbol{x})\rangle\\&=F(\boldsymbol{x})+c\left(\left[h_1(\boldsymbol{x})\right]^2+\left[h_2(\boldsymbol{x})\right]^2+..+\left[h_{N_{EQ}}(\boldsymbol{x})\right]^2\right)^{1/2}\\&-\left(u_1h_1(\boldsymbol{x})+u_2h_2(\boldsymbol{x})+\cdots+u_{N_{EQ}}h_{N_{EQ}}(\boldsymbol{x})\right)\end{aligned}\quad (22)$$

where $u_1,u_2,\cdots,u_{N_{EQ}}\in R$ and $c\geq 0$ are LaGrange multipliers (dual variables). The dual function associated with the constrained problem is defined as

$$H(\boldsymbol{u},c)=\underset{\boldsymbol{x}\in K}{\text{Min}}\ L(\boldsymbol{x},\boldsymbol{u},c). \quad (23)$$

Then, the dual problem is given by

$$\underset{(\boldsymbol{u},c)\in R^{N_{EQ}}\times R_+}{\text{Max}}\ H(\boldsymbol{u},c) \quad (24)$$

For the given dual problem, the conditions of guaranteeing zero duality gaps are proven in [8].

3.1. The F-MSG Algorithm Applied into the j^{th} Subinterval of the Dispatch Problem

Application of the F-MSG algorithm into the j^{th} subinterval of the dispatch problem is explained in the following.

Initialization Step: Select arbitrary initial active and reactive power generations for subinterval *j*. Then, perform an AC power flow calculation with selected active and reactive power generations to obtain the initial values for the voltage magnitudes and phase angles of the buses in subinterval *j*. Calculate the initial total cost $F_{TOT,j}$ in subinterval *j*.

Step 1) Choose positive numbers $\varepsilon_1,\varepsilon_2,\Delta_1$ and M (upper bound for m). Set $n=1$, $p=0$, $q=0$, and $H_n=F_{TOT,j}$.

Step 2) Choose $(\boldsymbol{u}_1^n,c_1^n)\in R^{N_{EQ}}\times R_+$ and $\ell(1)>0$ and set $m=1,\boldsymbol{u}_m=\boldsymbol{u}_1^n,c_m=c_1^n$,

Step 3) Given $(\boldsymbol{u}_m,c_m)$, solve the following constraint satisfaction problem (CSP)

$$\begin{aligned}&\textit{Find a solution } \boldsymbol{x}_m\in K \textit{ such that}\\&F_{TOT,j}(\boldsymbol{x}_m)+c_m\left\|\boldsymbol{h}(\boldsymbol{x}_m)\right\|-\langle\boldsymbol{u}_m,\boldsymbol{h}(\boldsymbol{x}_m)\rangle\leq H_n\end{aligned}\quad (25)$$

If a solution to (25) does not exist or $\ell(m)>M$, then go to Step 6; otherwise, if a solution $\boldsymbol{x}_m$ exists then check whether $\boldsymbol{h}(\boldsymbol{x}_m)=\boldsymbol{0}$. If $\boldsymbol{h}(\boldsymbol{x}_m)=\boldsymbol{0}$ (or if $\left\|\boldsymbol{h}(\boldsymbol{x}_m)\right\|\leq\varepsilon_1$) then go to step5, otherwise go to step 4.

Step 4). Update dual variables as

$$\boldsymbol{u}_{m+1}=\boldsymbol{u}_m-\alpha\,s_m\,\boldsymbol{h}(\boldsymbol{x}_m) \quad (26)$$

$$c_{m+1}=c_m+(1+\alpha)\,s_m\left\|\boldsymbol{h}(\boldsymbol{x}_m)\right\| \quad (27)$$

where s_m is a positive step size parameter defined as

$$0<s_m=\frac{\mu\,\alpha\left(H_n-L(\boldsymbol{x}_m,\boldsymbol{u}_m,c_m)\right)}{\left[\alpha^2+(1+\alpha)^2\right]\left\|\boldsymbol{h}(\boldsymbol{x}_m)\right\|^2} \quad (28)$$

where α and μ are constant parameters with $\alpha>0$ and $0<\mu<2$. Step size s_m corresponding to the dual variables $(\boldsymbol{u}_m,c_m)$ should also satisfy the following property:

$$\left(s_m\left\|\boldsymbol{h}(\boldsymbol{x}_m)\right\|+c_m-\left\|\boldsymbol{u}_m\right\|\right)>\ell(m). \quad (27)$$

Set $m=m+1$, update $\ell(m)$ in such a way that $\ell(m)\to+\infty$ as $m\to+\infty$, and go to step 3.

Step 5) If $p=0$, it means that any infeasible total cost rate value has not been chosen yet, then set $\Delta_{n+1}=\Delta_n$, otherwise set $\Delta_{n+1}=(1/2)\Delta_n$. If $\Delta_{n+1}<\varepsilon_2$, then stop, $\boldsymbol{x}_m$ is an approximate optimal primal solution, and $(\boldsymbol{u}_m,c_m)$ is an approximate dual solution; otherwise set $H_{n+1}=\min\left\{F_{TOT,j}(\boldsymbol{x}_m),\ H_n-\Delta_{n+1}\right\}$, $q=q+1$, $n=n+1$, and go to step 2.

Step 6) If $q=0$, it means that any feasible cost rate value has not been chosen yet, then set $\Delta_{n+1}=\Delta_n$; otherwise, set $\Delta_{n+1}=(1/2)\Delta_n$. If $\Delta_{n+1}<\varepsilon_2$ then stop, and in this case, the last calculated feasible $\boldsymbol{x}_m$ is an approximate optimal primal solution, and $(\boldsymbol{u}_m,c_m)$ is an approximate dual solution; otherwise, set $H_{n+1}=H_n+\Delta_{n+1}$, $p=p+1$, $n=n+1$ and go to step-2.

In this algorithm, steps 3 and 4 can be considered as the inner loop, and steps 2, 5 and 6 can be considered as the outer loop. We call any outer loop, in which a feasible cost rate value is generated by the algorithm, as a *feasible state*, n_f. The following problem is solved by using GAMS® solver:

$$\text{Minimize} \quad f = 0$$

$$\text{Subject to} \begin{cases} L(\boldsymbol{x},\boldsymbol{u},c) - H_n \le 0 \\ \boldsymbol{x} \in K \end{cases} \tag{28}$$

where f is a 'fictitious' objective function which is identically zero, or can be taken as any constant value [5]. The way of updating the dual variables $(\boldsymbol{u}_m, c_m)$ in step 4 will force the solution in Step 3 to converge to the feasible solution (see Theorems in [9]).

3.2 The Proposed Solution Technique for the Dispatch Problem

When the F-MSG algorithm is applied to the dispatch problems in all subintervals of the considered problem with specific w value, if the fuel constraint of the limited energy supply units is satisfied (see equation (5)), it means that the optimal solution is found. But if the fuel constraint is *not* satisfied, the system, excluding the limited energy supply thermal units, can be scheduled to minimize the total system cost subject to the constraint that the total fuel consumption for the operation period for the limited energy supply thermal units is equal to the minimum amount (T-O-P fuel contract). This type of scheduling can decrease the total system cost further. The following solution technique, where the F-MSG algorithm and a common scaling factor (ψ) for the fuel cost rate functions of the limited energy supply units are used, is proposed to solve the dispatch problem described in the above. The total fuel cost of the system in this technique is calculated as follows:

$$F_{tot} = \sum_{j=1}^{j_{max}} \left\{ \sum_{i \in \{N_s\}} F_i(P_{Gi,j}) + \psi \sum_{i \in \{N_T\}} F_i(P_{Gi,j}) \right\} t_j \tag{29}$$

Step-1) Select a $0 < \psi < 1$ value, set, $\psi_{old}^{up} = 1$, $\psi_{old}^{low} = \psi$

Step-2) Set $Init = 0$, $j = 1$

Step-3) Get the initial values of the independent variables for the current subinterval and solve the dispatch problem by using the F-MSG algorithm.

Step-4) Set $j = j + 1$. If $j > j_{max}$ then go to step-5; otherwise go to step-3.

Step-5) Calculate $Error = C_{spent} - C_{tot}$. If $|Error| \le TOL$ then stop, the solution is obtained; otherwise go to step-6.

Step-6) If $Error > 0$ and $Init = 0$ then set, $Init = 1$ $\psi_{new}^{up} = \psi_{old}^{up}$, $\psi_{new}^{low} = \psi_{old}^{low}$ and go to step-10; otherwise go to step-7

Step-7) If $Error < 0$ and $Init = 0$ then, set $\psi = 0.5\psi_{old}^{low}$, $j = 1$ and go to step-3; otherwise go to step-8.

Step-8) If $Error > 0$ and $Init = 1$ then set, $\psi_{new}^{up} = \psi_{old}^{up}$, $\psi_{new}^{low} = \psi$ and go to step-10; otherwise go to step-9

Step-9) If $Error < 0$ and $Init = 1$ then set $\psi_{new}^{up} = \psi$ $\psi_{new}^{low} = \psi_{old}^{low}$.

Step-10) Set $\psi = 0.5\,(\psi_{new}^{low} + \psi_{new}^{up})$, $j = 1$ and go to step-3.

Note that the optimal scaling factor value, where *Error* becomes approximately equal to zero, is calculated by means of *bisection* method in the above algorithm.

3. Numerical Example

The proposed dispatch technique was tested on IEEE 30-bus test system. Please refer to reference [2] for the necessary data for the test system. The initial parameters, explained in section 3.1, and 3.2, are chosen as $\varepsilon_1 = 1\times10^{-4}$, $TOL = 5\ ccf$, $\varepsilon_2 = 0.05$, $\Delta_1 = 5\ R$, $M = 500$, $\boldsymbol{u}_1^1 = [0,0,...0,0]_{(1\times113)}$ $c_1^1 = 1$, $\ell(m) = m$. The maximum active power transmission capacity limit for all transmission lines is taken as 150 *MW*. Bus 1 is taken as the reference bus and its complex voltage is taken as $1.06\angle 0\ pu$. The upper and lower limits of the bus voltage magnitudes for all buses are taken as $U_i^{min} = 0.9$, $U_i^{max} = 1.1\ pu$, $i \ne 1$. Units that are connected to buses 2 and 13 are taken as gas fired limited energy supply thermal units. Their fuel price is taken as 2.0 *R/ccf*. The minimum amount of gas that should be burned by the limited energy supply thermal units, according to T-O-P fuel contract, during the operation period is taken as $C_{tot} = 2500\ ccf$. The scaling factor ξ is taken as equal to 6046.173677 *R/kg*. The operation period is taken as 24*h* long

Table 1. p.u active load schedule ($S_{base} = 100\ MVA$).

i/j	1	2	3	4	5	6
2	0.2170	0.2250	0.2300	0.2350	0.2250	0.2200
3	0.0240	0.0250	0.0300	0.0300	0.0275	0.0245
4	0.0760	0.0800	0.0900	0.1000	0.0850	0.0775
5	0.9420	0.9750	1.0000	1.0000	0.9750	0.9600
7	0.2280	0.2500	0.2750	0.2750	0.2625	0.2350
8	0.3000	0.3250	0.3500	0.3500	0.3275	0.3150
10	0.0580	0.0750	0.0800	0.0900	0.0775	0.0650
12	0.1120	0.1150	0.1200	0.1250	0.1175	0.1120
14	0.0620	0.0650	0.0750	0.0800	0.0700	0.0625
15	0.0820	0.0850	0.0900	0.0900	0.0875	0.0825
16	0.0350	0.0400	0.0500	0.0500	0.0450	0.0400
17	0.0900	0.1000	0.1000	0.1250	0.1000	0.0950
18	0.0320	0.0350	0.0500	0.0500	0.0425	0.0350
19	0.0950	0.1000	0.1000	0.1250	0.1000	0.1000
20	0.0220	0.0250	0.0500	0.0500	0.0375	0.0250
21	0.1750	0.1800	0.1900	0.2000	0.1850	0.1785
23	0.0320	0.0350	0.0500	0.0500	0.0425	0.0350
24	0.0870	0.0900	0.1000	0.1000	0.0950	0.0900
26	0.0350	0.0400	0.0500	0.0500	0.0450	0.0400
29	0.0240	0.0250	0.0500	0.0500	0.0375	0.0250
30	0.1060	0.1100	0.1200	0.1250	0.1150	0.1075
$\sum$	2.834	3.000	3.250	3.350	3.100	2.925

Table 2. p.u reactive load schedule

i/j	1	2	3	4	5	6
2	0.1270	0.1275	0.1300	0.1300	0.1280	0.1275
3	0.0120	0.0125	0.0150	0.0150	0.0130	0.0125
4	0.0160	0.0175	0.0200	0.0200	0.0185	0.0175
5	0.1900	0.1900	0.2000	0.2000	0.1925	0.1900
7	0.1090	0.1100	0.1150	0.1150	0.1120	0.1095
8	0.3000	0.3200	0.3500	0.3500	0.3300	0.3100
10	0.0200	0.0200	0.0250	0.0250	0.0220	0.0200
12	0.0750	0.0750	0.1000	0.1000	0.0875	0.0750
14	0.0160	0.0175	0.0250	0.0250	0.0200	0.0170
15	0.0250	0.0250	0.0500	0.0500	0.0350	0.0250
16	0.0180	0.0200	0.0250	0.0250	0.0225	0.0200
17	0.0580	0.0600	0.0750	0.0750	0.0700	0.0600
18	0.0090	0.0100	0.0150	0.0150	0.0150	0.0090
19	0.0340	0.0350	0.0500	0.0500	0.0400	0.0345
20	0.0070	0.0075	0.0100	0.0100	0.0100	0.0075
21	0.1120	0.1125	0.1250	0.1250	0.1150	0.1125
23	0.0160	0.0175	0.0250	0.0250	0.0180	0.0175
24	0.0670	0.0675	0.0750	0.0750	0.0700	0.0675
26	0.0230	0.0250	0.0300	0.0300	0.0250	0.0240
29	0.0090	0.0100	0.0150	0.0150	0.0110	0.0095
30	0.0190	0.0200	0.0250	0.0250	0.0200	0.0190
$\sum$	1.262	1.300	1.500	1.500	1.375	1.285

having six equal time subintervals. The active and reactive load schedules for the test system are given in Table 1 and Table 2, respectively. Reactive power generation limits of the units are given in Table 3. Initial bus voltage magnitudes and phase angles in each subinterval are calculated by carrying out a load-flow solution with the selected initial active and reactive generation powers, which are given in Table 4, in each subinterval. No more load flow calculation is carried out in the subsequent stages of the solution process. The simulation program was coded in MATLAB.

The dispatch problem for subinterval 1 in this paper was also solved for the best fuel cost (*w*=1.0) and for the best emission cost (*w*=0.0) cases via a dispatch method based on differential evolution algorithm [2]. For the best fuel cost solution, $F_{tot,1} = 608.0658\ R/h$ and $E_{tot,1} = 0.2193\ ton/h$ were obtained. When the same problem is solved via the proposed dispatch technique, the above quantities are found as $F_{tot,1} = 605.4186\ R/h$ and $E_{tot,1} = 0.22086\ ton/h$. For the best emission cost case, the dispatch technique in [2] gave $E_{tot,1} = 0.1942\ ton/h$ and $F_{tot,1} = 645.0850\ R/h$, but our proposed dispatch technique gives $E_{tot,1} = 0.19417\ ton/h$, and $F_{tot,1} = 646.8754\ R/h$ (see Table 5). We see from the above figures that the proposed technique gives lower total fuel and emission cost values for the best fuel and the best emission cost cases, respectively.

The dispatch problem considered in this paper is solved under three different cases via the proposed dispatch algorithm. Since the fuel constraint is satisfied ($C_{spent} \geq 2500\ ccf$) for *w* = 0.0,...,0.6, Pareto-optimal solutions for those *w* values remain the same in all three cases (see Table 6).

Case-1) T-O-P fuel contract (and naturally also the fuel constraint) is not considered and the problem is solved by the proposed algorithm. The obtained Pareto-optimal solution values are given on Table-6.

Case-2) T-O-P fuel contract is considered but the fuel constraint is not. The difference between case-1 and case-2 is the calculation of the total fuel cost when the fuel constraint is violated. This is seen in Table.6.

Case-3) T-O-P fuel contract and the fuel constraint are considered. Since the fuel constraint is satisfied for *w*= 0.7,…1.0 in this case, the total fuel and emission cost values in those Pareto-optimal solutions become smaller than those of in case-2 (see Table 6). The change of *Error* vs. scaling factor ψ in this case for $w = 1.0$ is given in Table 7. The effect of the scaling factor ψ on the convergence of C_{spent} to $C_{tot} = 2500\ ccf$ is clearly seen in Figure 1. Table 3 – Table 7 and Figure 1 can not be shown due to the restriction on the number of pages. They will be given during the presentation.

4. Discussion and Conclusion

In this paper, we propose a security constrained environmental/economic power dispatch technique using the F-MSG algorithm for a power system area including limited energy supply thermal units. The dispatch technique is tested on IEEE 30-bus test system. The dispatch problem for subinterval 1 in this paper was solved previously by means of a dispatch algorithm based on differential evolution algorithm for cases *w*=1 and *w*=0 [2]. From the comparison of the results, it is seen that the proposed technique provides *lower total fuel cost for w=1 and lower total emission cost for w=0.* We are currently performing research on application of the F-MSG method to some other economic/environmental power dispatch problems with *non-convex total cost curves.* To our knowledge, the proposed solution technique has not been applied to the problem considered in this paper.

5. List of Symbols

R : a fictitious monetary unit

N : number of buses in the network.

N_T , N_S : sets that contain all limited energy supply thermal and normal thermal units in the network, respectively.

N_{Bi} : set that contains all buses *directly* connected to bus *i*.

N_{tap} , L : sets that contains all tap changing transformers and lines in the network, respectively.

t_j : length of time interval *j.*

$p_{l,j}$: active power flow on line *l* in the j^{th} subinterval

$P_{Gi,j}$, $Q_{Gi,j}$: active and reactive power generations of the i^{th} unit in the j^{th} subinterval, respectively.

$P_{Load\ i,j}$, $Q_{Load\ i,j}$: active/reactive loads of the i^{th} bus in the j^{th} subinterval, respectively.

$P_{LOSS,j}$: total active loss in the j^{th} subinterval.

$C_T(P_{GT,j})$: fuel consumption rate for the T^{th} limited energy supply thermal unit in the j^{th} subinterval.

P_{Gi}^{min}, Q_{Gi}^{min} ; P_{Gi}^{max}, Q_{Gi}^{max} : lower/upper active/reactive generation limits of the i^{th} generation unit, respectively, $i \in \{N_S, N_T\}$.

p_l^{max} :maximum active transmission capacity of line l .

N_{EQ} , N_{VAR} : number of equality constraints and independent variables, respectively.

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