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Sustainable Economic and Emission Control Strategy for Deregulated Power Systems

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ABSTRACT

The electric power system operation and control is a multifaceted problem aims at assuring an economic, reliable, and environmentally acceptable power supply to its consumers at all times. So as to be environmentally acceptable, electric utilities are required to reduce their power plant emissions. Due to significant consumers' responsiveness on clean electrical energy, varied operational performance schemes have developed in time. The integration of renewable energy resources, implementation of advanced pollution control equipment, adoption of multi-fuel dispatching techniques, up gradation of inefficient power generating units, and emission constraint generation scheduling are a few of them. This paper proposes a non-iterative analytical algorithm for generation scheduling of deregulated energy systems with economic and emission control strategies subject to line load ability constraints. The objectives are achieved through changes in operating and control policies only without any changes in the system configuration. Application to a modified IEEE 30-bus test system validates the suitability of the proposed control schemes for real-time implementation.

Keywords: Economic Control, Emission Control, Transmission Line Load Ability, Generation Scheduling, Non-iterative Analytical Method
JEL Classifications: C82, L94, P18, Q42

1. INTRODUCTION

For well over a century, the electric power sector has made vital contributions to the augmentation of the global economy and the quality of human life. Conventional power grids initially comprised of mainly three sections as the generation, transmission, and distribution. Electric utilities functioned as merged cartels and recovered all costs of their investment successfully from energy customers (Palanichamy et al., 1999; International Energy Agency, 2007).

From the beginning of the new millennium, there are significant changes in the global electrical energy sector from the integrated stature to a deregulated structure to meet the competitive energy market. Thus, GENCOs, TRANSCs, DISCOs, and RECOs became to existence (Su and Kirschen, 2009; Nguyen et al., 2013). Within the deregulated competitive energy market, GENCOs have the autonomy to decide their own operational policies such as fixing the energy cost to meet out their investments with profit, competing with others with stable energy cost and infrastructural polices such as the addition of renewable energy sources to avail environmental credit, up gradation of their existing generating plants for fuel efficiency, and deletion of some of them, etc., (Litvinov et al., 2004; Taha and Panchal, 2014). Though disaggregation is wished-for creating healthy competition resulting in discriminated facility offering, competitive energy prices, and improved market efficiency; unluckily, this energy market leads to a few defies related with upholding a reliable, economical, and environmentally friendly energy supply (Litvinov et al., 2004; Woo et al., 2006; Su and Kirschen, 2009, Nguyen et al., 2013; Tang and Che, 2013; Taha and Panchal, 2014).

- Energy producers are not assured of recovering all energy costs from their energy customers
- The prime share of the energy production cost is the fuel cost for fossil-fueled power plants; hence the frequent escalation

of the fuel cost is a risk for investors on achieving the return on their investments
- The existing energy firms are being suffered from limited/uncertain fuel supplies and cash collection from the government and energy sector
- The availability of intermittent forms of renewable generation, storage and backup issues, the unattractive energy buy back policies and energy cost and their high capital investment with limited funding resources
- Energy consumers previously used to meet the costs incurred on additional emission controls, however, due to the restructured scenario, it forms an additional menace on the return on investment and
- The higher percentage of transmission losses and pilferage losses due to theft of power and faulty electricity meters.

Despite the above challenges, there is evidence (Agency, 2003; International Energy Agency, 2007; Arabali et al., 2014) to put forward that deregulation has resulted in an attractive operational cost through manpower planning and optimization, up keeping of maintenance policy and strategic planning for fuel purchase, etc., The attractive operational cost as a result of deregulation gave room for many investors in the energy sector which are expected to result in a healthy competitive energy market. Construction of additional generating plants and the up gradation of the aged and inefficient plant is few options to strengthen the viable market. Besides, performance optimization through cost-effective operating and control strategies and making use of fuel efficient generators, necessitate utility concern significantly (Xia et al., 1997; Chung et al., 2004; Petoussis et al., 2008; Maghouli et al., 2009; Suharto et al., 2011; Hassan et al., 2012; Arabali et al., 2014).

Due to significant consumers' responsiveness on clean electrical energy, utilities need to control their power plant emissions as per statutory requirements; hence wide-ranging operational performance schemes have developed over time (Talaq et al., 1994; Abido, 2009; Elaiw et al., 2012; Park and Baldick, 2015). The integration of renewable energy resources, implementation of advanced pollution control equipment, adoption of multi-fuel dispatching techniques, up gradation of inefficient power generating units, and emission controlled generation scheduling are a few of them. Among these tactics, the emission controlled generation scheduling option is cost- effective and easy to implement.

This paper proposes a non-iterative analytical algorithm for generation scheduling of deregulated energy systems with economic and emission control strategies subject to line load ability constraints. In the deregulated electricity market, the participants are obliged to cover the power losses either through additional power or paying for the losses. In practice, this is extremely difficult to identify the share of generators and loads for the transmission power losses incurred in a transmission network. Besides, the cross-terms related to the quadratic loss functions don't permit on assigning power losses directly to the generators and consumers. The foremost role of this paper is that it proposes a new approach that accounts for the transmission losses in a practical way while optimizing the objective function for economic and emission control of the deregulated power system.

2. THE PROBLEM DESCRIPTION AND FORMULATION

As the intentions of the electricity producers are commonly investment return driven, the generating power plants must produce energy at the minimum cost with environmental friendliness without violating the equality, inequality, and transmission line loss constraints.

2.1. Transmission Loss Constraint

The cost of electrical energy mainly consists of generation capacity creation cost, proprietorship cost, and functional cost. The most significant component of the operating cost is the fuel cost and another sizeable constituent is the cost associated with energy losses. Energy losses characterize a significant operating cost assessed to add 6.8% to the cost of energy and 25% to the price of energy supply to consumer destinations (Price and Gibbon, 1983; Davidson et al., 2002). These power losses are innate and unavoidable in the generation, transmission and distribution stages but controllable to capitalize on returns on investments.

Lesser power transmission losses reduce the electrical energy generation costs with a positive influence on economic growth and enhanced lifespan of the grid system. It lessens the system's peak power demand, hence decreasing the power required of the grid at peak load conditions when the energy production cost/kWh is generally the maximum. Power losses during peak demand periods furthermore have noteworthy monetary repercussions since peaking generating units are obligatory to encounter the upsurge in demand, which is commonly costlier to run than base-load stations. Hence, even small reductions in system power losses would contribute to considerable financial hoards to electric utilities along with customers (Price and Gibbon, 1983; Palanichamy et al., 1999; Davidson et al., 2002; Palanichamy and Babu, 2005). The effect of transmission power losses on the merit order loading of generating units is also significant. While performing economic power dispatch, a reduction in power losses influences the production costs of associated units and hence their economic ranking gets altered (Pérez-Arriaga, 2013).

The apportionment of transmission losses among various demands and generating units is an edgy task. It is difficult to decide which generator or power demand is accountable for the power flow and power loss in a specified transmission line and the mixed term related with the quadratic loss functions won't permit assigning straightly losses to generators and consumers (Visakha et al., 2004; Abdelkader, 2006). Therefore, the existence of an exclusive technique for transmission loss apportionment is foreseeable; hence, numerous diversified approaches were introduced (Exposito et al., 2000; Chang and Lu, 2002; Conejo et al., 2002, Abdelkader, 2006; Panta et al., 2007; Greenwood and Taylor, 2014).

This paper aims at estimating the transmission power loss contributed by each generator. The power loss is then converted to fuel cost by means of a conversion coefficient, ɤ. For instance, if ɤ assumes a value 1.0, then the cost of transmission losses is the fuel cost (the major portion of the operating cost).

2.2. Individual Plant Generations

For a given configuration of existing as well as newly added generators, without considering transmission losses, the optimization function for economic control of the power generation is expressed as:

$$\phi = \text{Min}\sum_{i=1}^{n} F_i \quad \$/h \tag{1}$$

The fuel cost ($/hr.) of the generator, i is stated by a quadratic function of its real power generation as:

$$F_i = a_i P_i^2 + b_i P_i + c_i \quad \$/h \tag{2}$$

Transmission losses are commonly characterized by means of transmission loss B-coefficients (Palanichamy and Srikrishna, 1991, Talaq et al., 1994).

$$P_L = \sum_{i=1}^{n}\sum_{j=1}^{n} P_i B_{ij} P_j \quad MW \tag{3}$$

The transmission loss associated with generator *i*, and the associated transmission network is given by

$$P_{Li} = P_i^2\left(B_{ii} + \sum_{i\neq j} B_{ij}\pm_{ij}\right) + P_i\left(\sum_{i\neq j} B_{ij}^{2}\ _{ij}\right) MW \tag{4}$$

Where $\alpha_{ij} = \dfrac{a_i}{a_j}$; $\beta_{ij} = \dfrac{b_i - b_j}{2a_j}$

The power loss is then converted into the fuel cost by means of a conversion coefficient, ɤ. Then the cost of transmission power loss (F_{Li}) of generator, i is given by:

$$F_{Li} = \gamma P_i^2\left(B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right) + \gamma P_i\left(\sum\nolimits_{i\neq j} B_{ij}\beta_{ij}\right) \ \$/hr \tag{5}$$

As the proposed approach aims at charging the transmission losses of a generator at the same rate of its fuel cost which is the major portion of the operating cost; the conversion factor ɤ becomes 1.0. Hence equation (5) becomes:

$$F_{Li} = P_i^2\left(B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right) + P_i\left(\sum\nolimits_{i\neq j} B_{ij}\beta_{ij}\right) \$/hr \tag{6}$$

The total fuel cost of generator i, (F_{it}) including its transmission loss cost is obtained by adding (2) and (6) resulted as (8).

$$Fit = Fi + F_{Li} \tag{7}$$

$$F_{it} = \left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right) P_i^2 + \left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right) P_i + c_i \quad \$/hr \tag{8}$$

Then

$$\frac{dF_{it}}{dP_i} = 2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right) P_i + \left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right) = \lambda \quad \$/MWh \tag{9}$$

From equation (9), the individual plant generation, P_i (MW) in terms of λ ($/MWh) is attained as:

$$P_i = \left[\lambda - \left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right)\right] / 2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right) \quad MW \tag{10}$$

2.3. Economic Control

The approach aims at minimizing the fuel cost of all participating generating units (existing and new additions). There are several conformist approaches available to resolve economic dispatch problems such as the Lagrange multiplier method, the Lambda iteration method and Newton- Raphson method (Palanichamy and Srikrishna, 1991; Talaq et al., 1994; Davidson et al., 2002; Panta et al., 2007; Abido, 2009; Elaiw et al., 2012), etc., However, an obstacle in an optimal economic dispatch of conventional methods is the necessity to find the optimal economic dispatch outcome whenever the demand changes (commonly in every 20 min). Moreover, current methods need to repeat the vast time-consuming calculations for a new solution again even the advent of advanced computing technologies exists. Hence, this paper proposes a fast and direct method for economic power dispatch.

For a given configuration of existing as well as newly added generators, considering transmission power losses, the objective function for economic dispatch as given in (11) is optimized subject to equality and inequality constraints.

$$\phi = \text{Min}\sum_{i=1}^{n} F_{it} \quad \$/hr \tag{11}$$

Subject to the following constraints:

i. Power balance constraint

$$\sum_{i=1}^{n} P_i = P_D + \sum_{i=1}^{n} P_{Li} \quad MW \tag{12}$$

ii. Transmission loss constraints

$$P_{Li} \leq P_{Limax}\ MW \tag{13}$$

And

iii. Plants capacity constraints

$$P_{imin} \leq P_i \leq P_{imax} \tag{14}$$

Substituting the values of P_i from (10) and P_{Li} from (4) in (12) and simplifying:

$$\lambda^2 \sum \frac{B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}}{4\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)^2} + \lambda \sum \left\{ \frac{\sum_{i\neq j} B_{ij}\beta_{ij} - 1}{2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)} - \frac{\left(B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)\left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right)}{2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)^2} \right\} + \lambda \sum \left\{ \frac{\sum_{i\neq j} B_{ij}\beta_{ij} - 1}{2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)} - \frac{\left(B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)\left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right)}{2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)^2} \right\} + \square\square\square\square \quad (15)$$

Equation (15) is of the form $A\lambda^2 + B\lambda + C = 0$ where

$$A = \sum \frac{B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}}{4\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)^2}$$

$$B = \sum \left\{ \frac{\sum_{i\neq j} B_{ij}\beta_{ij} - 1}{2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)} - \frac{\left(B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)\left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right)}{2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)^2} \right\}$$

And

$$C = \sum \left\{ \frac{\left(B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)\left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right)^2}{4\left(a_i + B_{ii} + \sum_{E\neq j} B_{ij}\alpha_{ij}\right)^2} + \frac{\left(b_i + \sum_{i\neq j} B_{ij}\beta_{ij}\right)\left(1 - \sum_{i\neq j} B_{ij}\beta_{ij}\right)}{2\left(a_i + B_{ii} + \sum_{i\neq j} B_{ij}\alpha_{ij}\right)} \right\} + P_D$$

And the solution of the equation gives two values for λ as

$$\lambda = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad \$/\text{MWh} \quad (16)$$

Considering the positive rational value of λ and substituting in (10) gives the individual plant generations, P_i (i = 1 to n). Once the individual plant generations are known, then the transmission power losses of the individual generators are given by (4) and the fuel costs by (2). This economic control strategy on the cost of the generation is reliable and suitable for any size of the power system.

2.4. Emission Control

Least cost control can no longer be the objective of power generation if humanity is to have a clean atmosphere (Palanichamy et al., 1999). The implementation of emission control on power generation has generated great challenges for the electric power industry. As the electric power sector is a significant contributor to global warming, it must effectively reduce emissions to ensure its sustainable development either by introducing advanced emission capture and storage technology in the generation process or through control and operational management (Tang and Che, 2013). Apart from economic control on operating cost, generation scheduling is also suitable to control the emission levels of electric energy systems (Talaq et al., 1994).

The focal objective of the emission control task is to minimize the emission level irrespective of fuel cost. It can be precisely described as the optimization of the following objective function for emission control.

$$\Psi = \text{Min} \sum_{i=1}^{n} E_i \quad \text{kg/h} \quad (17)$$

The emission of the generator, i is represented by a quadratic function of its active power produced as:

$$E_i = d_i P_i^2 + e_i P_i + f_i \quad \text{kg/h} \quad (18)$$

The optimization of emission is precisely identical to the economic control strategy excluding the fuel and emission coefficients parameters. The emission control dispatch results in the least emission while the corresponding operating cost is used to be very high.

2.5. Combined Economic and Emission Control

The collective economic and emission dispatch approach is of conflicting nature since the economic control decreases the total fuel (operating) cost of the system at an augmented level of power plant emissions while the emission control lessens the total power plant emissions at an upsurge in the operating (mainly the fuel) cost. The blended economic and emission control problem pursues an equilibrium between operating cost and system overall emission. The bi-objective problem of emission controlled economic dispatch can be transformed into a single objective optimization problem by presenting a price penalty factor, h (Palanichamy and Srikrishna, 1991; Talaq et al., 1994; Abido, 2009; Elaiw et al., 2012). The price penalty factor, h_i (\$/kg) of a generator, i is the ratio between the fuel cost and emission at its maximum power output.

$$h_i = \left(a_i P_{imax}^2 + b_i P_{imax} + c_i\right) \Big/ \left(d_i P_{imax}^2 + e_i P_{imax} + f_i\right) \quad \$/\text{kg} \quad (19)$$

The above price penalty factor offers realistic values only when the generating units are operating at their designed maximum capacity and for other generation levels (i.e., at part load conditions), computed values widely differ from the practical values. Figure 1 depicts the output versus heat rate of conventional thermal power plants. It is observed that, at part load conditions, heat rate requirements are higher and the power plants become less efficient. Besides, the power plant emission becomes high. Hence, the penalty factor price defined in (19) is not ideally suitable for part load operating conditions. In this paper, a new price penalty factor suitable for all operating load conditions is introduced as in (20). The price penalty factors of all the generating plants taking part in the generation scheduling task are first calculated at their maximum generating capacity limits by (19). Then, the highest value of the penalty factor is assumed to be the penalty factor (h_{PD}^{min}) at the minimum loading capacity of the system and likewise, the lowest value of penalty factor is assumed to be the penalty factor (h_{PD}^{max}) at the maximum loading capacity of the system. The two mentioned factors are used to calculate the proposed penalty factor (h_{PD}) at part load condition as

$$h_{PD} = h_{PD}^{min} + \frac{[h_{PD}^{max} - h_{PD}^{min}]}{[P_D^{max} - P_D^{min}]} \times [P_D - P_D^{min}] \quad \$/kg \tag{20}$$

Once the price penalty factor is known, objective for the combined economic and emission dispatch becomes

$$\phi_c = \text{Min} \sum_{i=1}^{n} (F_{it} + h_{PD} E_i) \tag{21}$$

For all three dispatches, solution technique remains the same except the difference in the coefficients of three objective functions.

3. OPTIMAL DECISION LOGIC

The proposed algorithm offers two optimal decisions for deregulated power system performance control. For instance, the existing generating units might not be producing energy at an attractive cost to face the competitive market. This depends on the operating characteristic of the thermal power plant, its aging and designed generating capacity. Not only the cost; the environmental friendliness of the plant also plays a significant role in the competitive market as well as in availing environmental credit. Apart from two factors, transmission power loss and transmission efficiency of the power plant and its associated transmission network along with the capacity of the power plant also become the deciding factors in performance control. Performing economic dispatch with all the participating generating units identifies the units offering attractive generation cost to meet the varying demand. However, the outcome of economic control results in higher emission output from the participated plants which may even violate the stipulated environmental limit. Though emission control limits the power plant emissions to meet the stipulated environmental threshold, the operational costs are unattractive to a competitive market. However, the additional cost due to environmental concern could be compensated by availing environmental credit. Moreover, significant transmission power losses aggravate the generation cost and the power plant emissions since the plants need to generate more to meet the demand. The need of the day is - the competitive energy market should be economical and environmentally friendly. To achieve the said task, a combined economic and emission dispatch algorithm is discussed.

4. ILLUSTRATIVE EXAMPLE AND DISCUSSION

The economic and emission control strategy proposed in this paper is applied to a modified IEEE 30-bus test system (Figure 2 and Tables 1 and 2). All generating units are of the fossil-fueled type. The minimum and maximum generating capacity of the test system varies from 415 MW to 1540 MW. NO_x emission is considered for simplicity. Two demand (load) levels of 800 MW and 1200 MW are considered for analysis. The price penalty factor (h_{PD}) in part load conditions are determined as 19.92 \$/kg (800 MW) and 16.31 \$/kg (1200 MW). The outcome of the proposed direct approach is compared with the approach proposed in (Tang and Che, 2013), which is a mixed integer nonlinear programming methodology offering a near optimal solution. Tables 3-8 depict the study outcomes.

The economic dispatch results of Table 3 show that all 6-generating units are operating within their capacity limits and the transmission losses associated with the generators and their transmission network are within their P_{Lmax}. Generating units G_1, G_2 and G_{13} are lightly loaded (in the range of 32-41%) compared to other generating units, whereas unit G_{22} shares around 82% of its generating capacity to meet a demand of 800 MW. The % transmission loss of unit G_{22} and its associated network is

Figure 1: Output versus heat rate

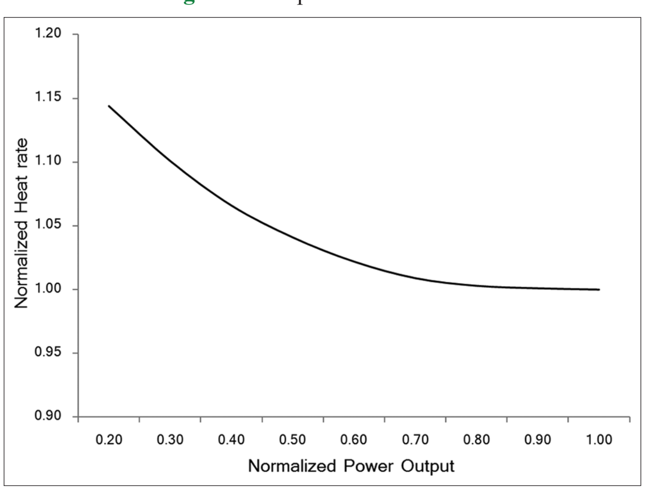

Figure 2: The IEEE 30-bus test system

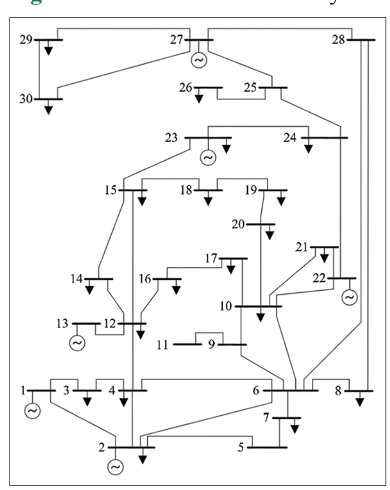

Table 1: Generators data

Unit	Production cost coefficients		NO_x emission coefficients		P_{min} MW	P_{max} MW	P_{Limax} MW
G_1	a_i	0.0462	d_i	0.0152	35	210	21
	b_i	43.5454	e_i	0.5557			
	c_i	311.6271	f_i	8.5156			
G_2	a_i	0.0558	d_i	0.0157	35	215	23
	b_i	43.9992	e_i	0.5276			
	c_i	335.5767	f_i	8.7855			
G_{13}	a_i	0.0455	d_i	0.0145	50	250	30
	b_i	43.0066	e_i	0.5408			
	c_i	321.5069	f_i	8.9632			
G_{22}	a_i	0.0289	d_i	0.0159	40	225	25
	b_i	40.9056	e_i	−1.4666			
	c_i	662.1819	f_i	9.3562			
G_{23}	a_i	0.0259	d_i	0.0147	130	325	35
	b_i	40.3774	e_i	−1.9011			
	c_i	682.9365	f_i	18.2348			
G_{27}	a_i	0.0266	d_i	0.0171	125	315	40
	b_i	40.9752	e_i	−1.9366			
	c_i	674.6163	f_i	19.4532			

Table 2: Transmission loss coefficients

0.000178	0.000019	0.000011	0.000023	0.000032	0.000091
0.000019	0.000152	0.000024	0.000039	0.000065	0.000036
0.000011	0.000024	0.000170	0.000071	0.000029	0.000027
0.000023	0.000039	0.000071	0.000210	0.000025	0.000019
0.000032	0.000065	0.000029	0.000025	0.000150	0.000021
0.000091	0.000036	0.000027	0.000019	0.000021	0.000225

Table 3: Economic dispatch ‑ system demand: 800 MW

Part load penalty factor: 19.92 $/kg						
Item	G_1	G_2	G_{13}	G_{22}	G_{23}	G_{27}
P_i (MW)	87.04	68.11	94.28	183.84	215.56	198.15
P_{Li} (MW)	2.69	1.68	3.19	12.01	12.94	14.48
Fuel cost ($/MWh)	51.15	52.73	50.71	49.82	49.13	49.65
Emission (kg/MWh)	1.98	1.73	2.00	1.51	1.35	1.55
Total energy cost ($/MWh)	90.59	87.19	90.55	79.90	76.07	80.53
Transmission loss (%)	3.09	2.47	3.38	6.53	6.00	7.31
Transmission η (%)	96.91	97.53	96.62	93.47	94.00	92.69
Proposed method Total cost: $ 42411.19 Total emission: 1354.14 kg Total power loss: 46.98 MW			Reference method (Tang and Che 2013) Total cost: $ 42412.38 Total emission: 1354.91 kg Total power loss: 46.98 MW			

Table 4: Economic dispatch ‑ system demand: 1200 MW

Part load penalty factor: 16.31 $/kg						
Item	G_1	G_2	G_{13}	G_{22}	G_{23}	G_{27}
P_i (MW)	145.20	116.31	153.39	276.64	319.30	298.84
P_{Li} (MW)	8.35	5.65	8.89	26.76	27.69	32.35
Fuel cost ($/MWh)	52.40	53.37	52.08	51.29	50.79	51.18
Emission (kg/MWh)	2.82	2.43	2.82	2.97	2.85	3.24
Total energy cost ($/MWh)	98.39	93.00	98.07	99.73	97.27	104.02
Transmission loss (%)	5.75	4.86	5.80	9.67	8.67	10.83
Transmission η (%)	94.25	95.14	94.20	90.33	91.33	89.17
Proposed method Total cost: $ 67506.65 Total emission: 3823.50 kg Total power loss: 109.68 MW			Reference method (Tang and Che 2013) Total cost: $ 67508.90 Total emission: 3824.21 kg Total power loss: 109.71 MW			

Table 5: Emission dispatch ‑ system demand: 800 MW

Part load penalty factor: 19.92 $/kg						
Item	**G_1**	**G_2**	**G_{13}**	**G_{22}**	**G_{23}**	**G_{27}**
P_i (MW)	107.62	105.17	113.33	164.12	192.56	165.72
P_{Li} (MW)	2.84	2.65	3.09	12.03	13.58	14.31
Fuel cost ($/MWh)	51.41	53.06	51.00	49.68	48.91	49.45
Emission (kg/MWh)	2.27	2.26	2.26	1.20	1.02	1.01
Total energy cost ($/MWh)	96.63	98.08	96.02	73.58	69.23	69.57
Transmission loss (%)	2.64	2.52	2.73	7.33	7.05	8.64
Transmission η (%)	97.36	97.48	97.27	92.67	92.95	91.36
Proposed method Total cost: $ 42660.36 Total emission: 1301.03 kg Total power loss: 48.51 MW			Reference method (Tang and Che 2013) Total cost: $ 42661.55 Total emission: 1301.87 kg Total power loss: 48.52 MW			

Table 6: Emission dispatch ‑ system demand: 1200 MW

Part load penalty factor: 16.31 $/kg						
Item	**G_1**	**G_2**	**G_{13}**	**G_{22}**	**G_{23}**	**G_{27}**
P_i (MW)	185.51	180.66	195.03	238.41	273.20	234.73
P_{Li} (MW)	9.86	9.18	10.40	24.49	26.15	27.45
Fuel cost ($/MWh)	53.80	55.94	53.53	50.57	49.95	50.09
Emission (kg/MWh)	3.42	3.41	3.41	2.36	2.18	2.16
Total energy cost ($/MWh)	109.60	111.60	109.22	89.12	85.54	85.32
Transmission loss (%)	5.32	5.08	5.33	10.27	9.57	11.69
Transmission η (%)	94.68	94.92	94.67	89.73	90.43	88.31
Proposed method Total cost: $ 67987.55 Total emission: 3583.71 kg Total power loss: 107.54 MW			Reference method (Tang and Che 2013) Total cost: $ 67989.72 Total emission: 3584.42 kg Total power loss: 107.55 MW			

Table 7: Combined economic and emission dispatch ‑ system demand: 800 MW

Part load penalty factor: 19.92 $/kg						
Item	**G_1**	**G_2**	**G_{13}**	**G_{22}**	**G_{23}**	**G_{27}**
P_i (MW)	104.62	99.21	110.45	167.62	196.19	170.38
P_{Li} (MW)	2.76	2.44	3.04	12.16	13.58	14.49
Fuel cost ($/MWh)	51.36	52.92	50.94	49.70	48.94	49.47
Emission (kg/MWh)	2.23	2.17	2.22	1.25	1.08	1.09
Total energy cost ($/MWh)	95.78	96.15	95.16	74.60	70.45	71.18
Transmission loss (%)	2.64	2.46	2.75	7.25	6.92	8.50
Transmission η (%)	97.36	97.54	97.25	92.75	93.08	91.50
Proposed method Total cost: $ 42609.92 Total emission: 1301.48 kg Total power loss: 48.47 MW			Reference method (Tang and Che 2013) Total cost: $ 42610.14 Total emission: 1302.23 kg Total power loss: 48.48 MW			

significantly high and its transmission efficiency together with its transmission network is much lower compared to G_1, G_2, G_{13} and G_{23}. Hence the higher sharing of generation by G_{22} to meet demands higher than 800 MW is practically impossible that is clearly seen from the economic dispatch results of Table 4. The generation of G_{22} has exceeded its capacity limit and the transmission losses also surpassed the permissible limit. Moreover, the emission from this unit is much higher compared to units G_1, G_2, G_{13} and G_{23}. The only good thing about this unit is its attractive unit cost of generation ($/MWh) compared to units G_1, G_2, G_{13} and G_{23}. If generating capacity expansion is needed, G_{22} is prone for replacement (higher emission due to aging) by a higher capacity generating unit at the same location provided the associated transmission networks are upgraded in a cost-effective manner.

Tables 5 and 6 display the emission dispatch results of demands 800 MW and 1200 MW respectively. All 6 units are operating within their capacity limits and transmission power loss upper limits for 800 MW demand. However, unit G_{22} exceeded its generating capacity limit when the demand is 1200 MW. Hence as discussed earlier, G_{22} is highly prone for replacement with the higher capacity unit or needs up gradation. From the results of Tables 5 and 6, it is also observed that the total unit cost of energy (fuel cost & emission cost, $/MWh) of unit G_2 is the highest among all the units. The generation share of

Table 8: Combined economic and emission dispatch - system demand: 1200 MW

Part load penalty factor: 16.31 $/kg						
Item	**G_1**	**G_2**	**G_{13}**	**G_{22}**	**G_{23}**	**G_{27}**
P_i (MW)	179.87	169.65	188.99	245.20	280.40	243.73
P_{Li} (MW)	9.57	8.44	10.10	25.04	26.44	28.24
Fuel cost ($/MWh)	53.59	55.44	53.31	50.69	50.08	50.23
Emission (kg/MWh)	3.34	3.24	3.33	2.47	2.29	2.31
Total energy cost ($/MWh)	108.02	108.33	107.60	90.98	87.36	87.92
Transmission loss (%)	5.32	4.97	5.34	10.21	9.43	11.59
Transmission η (%)	94.68	95.03	94.66	89.79	90.57	88.41
Proposed method			Reference method			
Total cost: $67830.98			(Tang and Che 2013)			
Total emission: 3589.26 kg			Total cost: $67833.07			
Total power loss: 107.82 MW			Total emission: 3589.98 kg			
			Total power loss: 107.93 MW			

Unit G_2 is around 84% of its full capacity for a demand of 1200 MW. Hence further loading of this unit is not possible and it is not cost effective and environmentally friendly too. However, the transmission loss of its associated network is only 9.18 MW (23 MW is the upper limit of load ability) and its transmission efficiency is the highest among all the units. Hence, no need for upgrading the transmission network. If generators connected to this line are of higher capacity, the transmission system could be effectively utilized.

The combined economic and emission control dispatch has been performed for the same loads of 800 MW and 1200 MW and results are presented in Tables 7 and 8. As in the earlier two cases, unit G_{22} exceeded its capacity limit and the power transmission limit. Its transmission efficiency is found to be very low; however, it is less polluting. The fuel cost, as well as the total energy cost and the emission levels, are much attractive compared to other units such as G_1, G_2, and G_{13}. Hence, the unit G_{22} shall be retained and permitted to the lesser generation level below 1200 MW provided the dispatching option is combined economic and emission. Unit G_2 has the highest total cost of energy among all the units and highly polluting. Financially as well as environmentally, it is unattractive. However, its associated transmission network has more room for higher load ability.

5. CONCLUSIONS

This paper has addressed the issue of economic and emission control of deregulated power systems. As the transmission power loss is of sizeable magnitude and it affects the unit cost of generation, while decision making, the transmission loss constraints is also duly considered. Three types of dispatching were proposed namely economic, emission, and combined economic and emission dispatching for the performance of deregulated power systems. A single direct dispatching algorithm is used for all the three dispatches. An IEEE modified 30-bus test system is considered to assess the efficacy of the proposed algorithm. The total unit cost of generation ($/MWh), unit emission (kg/MWh), transmission power loss (MW), the transmission efficiency (%), the magnitude of individual unit generation in MW, and capacity violations are the criteria followed while decision making. Being a direct optimization algorithm, the solution time is practically less besides less memory space. There is no need for any initial guess to start with and further updating while iterating. Further, the proposed single approach is appropriate for the said economic, emission and combined economic and emission controls avoiding switching over of algorithms depending on the objectives.

Nomenclature

a_i, b_i, c_i: Fuel cost coefficients of generator, i
B_{ii}, B_{ij}: Self and mutual transmission loss coefficients
d_i, e_i, f_i: Emission coefficients of generator, i
E_i: Emission of generator, i (kg/h)
F_i: Fuel cost of generator, i
F_{Li}: Cost of transmission power loss of generator, i
h_i: Price penalty factor of generator, i ($/kg)
h_{PD}: Price penalty factor at part load condition ($/kg)
n: Number of existing and newly added generators
P_D: Total load demand (MW)
P_i: Generation of plant, *i* (MW)
P_j: Generation of plant, *j* (MW)
P_{imin}: Minimum generation limit (MW)
P_{imax}: Maximum generation limit (MW)
P_{Limax}: Maximum permissible power losses associated with generator, *i* and its transmission network
P_L: Transmission power loss (MW)
ϒ: The conversion coefficient
λ: The incremental cost of received power ($/MWh)
ϕ: The optimum cost of generation or fuel cost
Ψ: The optimum amount of emission.

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