Comparative Analyses of Min-Max and Max-Max Price Penalty Factor Approaches for Multi Criteria Power System Dispatch Problem with Valve Point Effect Loading Using Lagrange's Method

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Abstract: ***The objective of the economic dispatch problem of electrical power generation is to schedule the committed generating unit's output so as to meet the required load demand while satisfying the system equality and inequality constraints. This paper solves the combined economic emission dispatch problem by Min-Max and Max-Max price penalty factor approaches using Lagrange's method. The price penalty factor for the combined economic emission dispatch (CEED) is the ratio of fuel cost to emission value. The literature papers reported that most of them use Max-Max Price penalty factor for the CEED problem. This paper analyses Min-Max and Max-Max price penalty factors for CEED problem. This problem is solved for a five generator system by considering the valve point effect for both fuel cost and emission function. The total fuel cost by considering valve point effect of the combined economic emission dispatch problem is less when using Min-Max price penalty factor approach in comparison to Max-Max price penalty factor.***

Keywords: ***Power System Optimization, Combined Economic Emission Dispatch, Valve Point Effect, Multi Criteria dispatch problem, Price Penalty Factor, and Lagrange's Method.***

I. INTRODUCTION

Energy management has to perform complicated and timely restricted system control function to operate a large power system reliably and effectively. In electric power system operation, the objective is to achieve the most economical generation policy that could supply the local demands without violating constraints. But the thermal power plants play a major role in power production and they burn fossil fuels that generate toxic gases. This creates pollution for the environment.

This work was supported in part by the National research foundation (NRF) grant UID 62364 "Substation Automation and Energy Management Systems".

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978-1-4577-1510-5/11/$26.00 ©2011 IEEE

The cost minimum condition corresponds to minimum cost with considerable amount of emission. Similarly the emission minimum condition produces minimum emission with higher deviation from the minimum cost. These two conditions cannot be implemented simultaneously. Hence, the feasible optimum corresponds to a small deviation in cost with an allowable tolerance in emission taking into account emission constraints. This has been termed as emission constrained economic dispatch [10-12]. It is compulsory for the electric utilities to reduce the pollution level by reducing production of sulphur dioxide, nitrogen oxide and carbon dioxide gases. Modern thermal power plants consist of generating units having multiple valve steam turbines. The effects of valve point loading is modeled as recurring rectified sinusoidal function and added to the quadratic fuel cost function in order to obtain an accurate and practical economic dispatch solution. The multi-criteria dispatch problem with valve point effect is considered in [5],[8],[9],[13], and [14].

The paper solves a multi-criteria power dispatch problem using Lagrange's method by simultaneously minimizing the operational costs and pollutant emissions with valve point effect.

The optimization problem is formulated as a bi-objective combined economic emission dispatch problem by introducing the penalty factor h_i [4]. The price penalty factor h_i is the ratio between maximum fuel cost and maximum emission of corresponding generator [12] and it is expressed as

$$h_i = \frac{F_C(P_{i,\max})}{E_C(P_{i,\max})}, i = \overline{1,n}$$

where

$F_C(P_{i,\max})$ is the maximum fuel cost

$E_C(P_{i,\max})$ is the maximum emission

n is the number of generating units

P_i is the active power produced by the i^{th} generator

The above definition gives an appropriate value of price penalty factor for the corresponding load demand. The literature review of the papers proposing solutions of the CEED problem shows that various price penalty factors are used. Most of the papers [4-11] used the Max-Max price penalty factor to solve the CEED problem.

The sequential approach with matrix framework method is used in [16] for multi-criteria power dispatch problem using Max-Max price penalty factor. The Max-Max price penalty factor converts the multi-objective optimization problem into a single objective optimization problem. For the case of quadratic type cost functions the maximum price penalty factor of each generator is the ratio between the fuel cost and emission at its maximum power output as [16]

$$h_i = \frac{(a_i P_{i,\max}^2 + b_i P_{i,\max} + c_i)}{(d_i\ P_{i,\max}^2 + e_i\ P_{i,\max} + f_i)} \qquad [\$/kg]$$

Where

a_i, b_i, c_i are the cost coefficients

d_i, e_i, f_i are the emission coefficients

$P_{i,\max}$ is the maximum real power output of the generating unit i

In [2] the CEED problem is solved using Particle Swarm Optimization (PSO) method for the following cost function

$min\ f = \omega F_1 + (1-\omega) F_2$

Where

ω is the weighing co-efficient in the range *0* and *1*.

F_1 is the cost function,

F_2 is the emission function

when ω=*1*, only the economic objective is accounted for and when ω=*0*, only the emission objective is considered. The value of ω indicates the relative significance between the two objectives. By varying the value of ω the tradeoff between the fuel cost and the emission cost can be determined over the range of values of ω. The Max-Max penalty factor introduced in most of the existing papers allows two criterion optimization problems to be solved as a problem with a single criterion. This penalty factor multiplies the emission criterion by a ratio of the maximum allowed values of the both criteria. This means that the emission criterion participates with bigger weight in the CEED criterion. The Min-Max penalty factor will introduce the emission criterion in the CEED criterion with smaller weight as used in [6]. This means that bigger attention will be paid to the energy cost minimization. Investigation is needed to be done to analyze in which case the CEED optimal cost will be smaller. This paper solves the CEED problem using Min-Max and Max-Max price penalty factors to evaluate the best optimization solution.

The paper has seven parts. Economic dispatch problem and multicriterial dispatch problems are formulated in parts II and III respectively. The proposed Min-Max price penalty factor is described in part IV. The Lagrange's method developed to solve the multicriterial dispatch problem is described in part V. The simulations results for a generating system with five generators are given in part VI. Part VII gives discussion of the result and conclusion.

II. ECONOMIC DISPATCH PROBLEM

The objective of economic dispatch is to simultaneously minimize the generation cost rate and to meet the load demand of a power system over some appropriate period while satisfying various operating constraints. The objective function of an economic dispatch problem can be formulated as,

Minimize

$$F_{CVP} = \sum_{i=1}^{n} F_i(P_i) = \left[\sum_{i=1}^{n} (a_i P_i^{\,2} + b_i P_i + c_i) + \left| w_i \sin[x_i (P_{i,\min} - P_i)] \right| \right] \qquad (1)$$

Where

F_{CVP} - *Total* Fuel Cost with valve point effect

$F_i(P_i)$ - Fuel cost of the i^{th} generator

P_i - Real power generation of unit i

a_i, b_i, c_i - Cost coefficients of generating for unit i

w_i, x_i - Valve point effect cost coefficients for unit i

n - Number of generating units

Under the constraints

1) Power balance constraint

$$\sum_{i=1}^{n} P_i = P_G = P_D \qquad [MW] \qquad (2)$$

where

P_G - Total power generation of the system

P_D - Total demand of the system

P_L - Total transmission loss of the system

2) Generator operational constraints

$$P_{i,\min} \le P_i \le P_{i,\max}, i = \overline{1,n} \qquad [MW] \qquad (3)$$

Where

$P_{i,min}$ - Minimum value of real power allowed at generator i

$P_{i,max}$ - Maximum value of real power allowed at generator i

It is assumed that the losses in power lines are negligible.

III. MULTI-CRITERIA DISPATCH PROBLEM

The various pollutants like sulphur dioxide, nitrogen oxide and carbon dioxide are the major pollutants from the thermal power plants. The problem is formulated by including the reduction of these emissions as an objective given by the following equation

$$E_{TVP} = \sum_{i=1}^{n} \left[(d_i P_i^2 + e_i P_i + f_i) + y_i \exp(z_i P_i) \right] \quad [Kg/hr] \tag{4}$$

Where

E_{TVP} - Total emission with valve point effect

d_i, e_i, f_i - Emission coefficients of generating unit i

y_i, z_i - Valve point effect emission coefficients for unit i

The criterion (4) can be added to be considered together with the economic dispatch problem (1) – (3). Then a multi-criteria dispatch problem can be formulated.

A multi-objective optimization is converted into a single objective optimization problem by introducing price penalty factor h_i as follows,

$$F_{TVP} = \left[\sum_{i=1}^{n} \begin{matrix} (a_i P_i^{\,2} + b_i P_i + c_i) + \left| w_i \sin[x_i (P_{i,\min} - P_i)] \right| + \\ + h_i \left[(d_i P_i^2 + e_i P_i + f_i) + y_i \exp(z_i P_i) \right] \end{matrix} \right] [\$/hr] \tag{5}$$

Where

F_{TVP} - CEED's fuel cost with valve point effect

h_i - Price penalty factor

IV. FORMULATION OF THE MIN-MAX AND MAX-MAX PRICE PENALTY FACTOR FOR CEED PROBLEM

This paper uses the Min-Max and Max-Max price penalty factor approaches for CEED dispatch problem. The ratio between the minimum fuel cost and maximum emission of the corresponding generators is proposed as a new penalty factor. It is called Min-Max price penalty factor and is described as:

$$h_i = \frac{(a_i P_{i,\min}^2 + b_i P_{i,\min} + c_i)}{(d_i P_{i,\max}^2 + e_i P_{i,\max} + f_i)} \quad [\$/kg] \tag{6}$$

The Max-Max price penalty factor is described as the ratio between the maximum fuel cost and maximum emission of the corresponding generator units. It is called Max-Max price penalty factor and is described as:

$$h_i = \frac{(a_i P_{i,\max}^2 + b_i P_{i,\max} + c_i)}{(d_i P_{i,\max}^2 + e_i P_{i,\max} + f_i)} \quad [\$/kg] \tag{7}$$

V. LAGRANGE'S METHOD FOR COMBINED ECONOMIC EMISSION DISPATCH PROBLEM

Method of Lagrange's solution for the CEED problem equation (5), subject to the constraints (2), (3) with penalty factors (6) or (7) is developed. The function of Lagrange by introduction of Lagrange's multiplier λ is formed:

$$L = F_T + \lambda \left(P_D - \sum_{i=1}^{n} P_i \right) \tag{8}$$

$$L = \sum_{i=1}^{n} \begin{pmatrix} (a_i P_i^2 + b_i P_i + c_i) + \left| w_i \sin[x_i (P_{i,\min} - P_i)] \right| + \\ h_i (d_i P_i^2 + e_i P_i + f_i) + y_i \exp(z_i P_i) \end{pmatrix} + \lambda \left(P_D - \sum_{i=1}^{n} P_i \right) \tag{9}$$

The optimization problem (5), subject to the constraints (2), (3), and penalty factors (6) or (7) is transferred to the problem for minimization of L according to $P_{i,}\ i = \overline{1,n}$, under the constraints (3).

Necessary conditions for optimality for solution of the problem (8) , are:

According to P_i, $\frac{\partial L}{\partial P_i} = 0, i = \overline{1,n}$ (10)

According to λ, $\frac{\partial L}{\partial \lambda} = 0$ (11)

Derivation of the condition (10)

$$\frac{\partial L}{\partial P_i} = \begin{pmatrix} b_i + 2a_i P_i + \left| -w_i x_i \cos\left(x_i \left(P_{i,\min} - P_i \right) \right) \right| + \\ + h_i e_i + 2 d_i h_i P_i + y_i z_i h_i \exp\left(z_i P_i \right) \end{pmatrix} = \lambda \tag{12}$$

$$\frac{\partial L}{\partial P_i} = \begin{pmatrix} 2P_i \left(a_i + d_i h_i \right) + \left| -w_i x_i \cos\left(x_i \left(P_{i,\min} - P_i \right) \right) \right| + \\ + y_i z_i h_i \exp\left(z_i P_i \right) + b_i + h_i e_i - \lambda \end{pmatrix} \tag{13}$$

P_i can be expressed from equation (13) in the following way:

$$P_i = \frac{\begin{pmatrix} \lambda - \left| -w_i x_i \cos\left(x_i \left(P_{i,\min} - P_i \right) \right) \right| - \\ - y_i z_i h_i \exp\left(z_i P_i \right) - b_i - h_i e_i \end{pmatrix}}{2\left(a_i + d_i h_i \right)} \tag{14}$$

If the value of the Lagrange's multiplier λ is known and some initial guess for the values of the active power P_i produced by the generator is available, the equation (14) can be solved to determine an updated value of the active power P_i,

The value of λ is unknown and has to be found from the necessary condition for optimality $\frac{\partial L}{\partial \lambda} = 0$.

This condition is found from (9) to be:

$$\frac{\partial L}{\partial \lambda} = \left(P_D - \sum_{i=1}^{n} P_i = 0 = \Delta\lambda \right) \tag{15}$$

Equation (15) is not a function of λ, but represents the gradient of L according to λ. At the optimal solution this gradient has to be equal to zero. As analytical solution is not possible the gradient procedure for calculation of λ has to be developed as follows

$$\lambda^{(k+1)} = \lambda^k + \alpha \Delta\lambda^{(k)}, \lambda \neq 0 \tag{16}$$

Where

k is the iteration number and , $k = \overline{0:m}$,

m is the given maximum number of iterations.

$\Delta\lambda^{(k)}$ is determined by the equation (15) and α is the step of the gradient procedure. The calculations start from some given initial value of the Lagrange's

variable $\lambda^{(0)}$. When during the iterations $\Delta\lambda = 0$, the optimal solution for the Lagrange's variable is obtained. It will determine the optimal solution for the power that has to be produced by the generators.

The obtained solutions for $P_i, i = \overline{1,n}$ have to belong to the constraint domain (3). That is why for every step of the gradient procedure, the obtained solution is fit to the constraint domain following the procedure

$$P_i^{(k)} = \begin{cases} P_{i,\min,} & if \quad P_i^{(k)} \langle P_{i,\min} \\ P_i^{(k)}, & if \quad P_{i.\min} \le P_i^{(k)} \langle P_{i,\max} \\ P_{i,\max,} & if \quad P_i^{(k)} \rangle P_{i,\max} \end{cases} \qquad (17)$$

The condition for end of the iteration is $\Delta\lambda^{(k)} \le \varepsilon$ (18)

Where $\varepsilon \rangle 0$ is a small number.

The algorithm of the method is:

1) Initial value of the Lagrange's multiplier is guessed: $\lambda^{(0)}$, and the value of the condition for optimality ε is given.
2) Initial value of the active power $P_i^0, i = \overline{1,n}$ is guessed.
3) Equation (14) is solved and $P^{(1)}$ is determined.
4) The obtained vector P is fit to the constraints (17).
5) $\Delta\lambda^{(0)}$ is calculated using equation (15) where $P^{(0)}$ is substituted.
6) The condition (17) is checked. If it is fulfilled the calculations stop, if not, improved value of $\lambda \to \lambda^{(1)}$ is calculated using equation (16)
7) Calculations of the improved values of $P_i \to P_i^{(2)}$ is done as using equations (14). Iterations continue until condition (18) is satisfied and so on….
8) The optimal solution is used to calculate the total cost, using equation (5).

VI. SIMULATION RESULTS

The five generating unit system is considered in this paper to solve the CEED problem using Min-Max and Max-Max price penalty factors. The five different power demand values are considered.

P_D= [200; 250; 300; 350; 400] [MW].

The CEED problem is simulated in MATLAB 2009b version of 3GB RAM. The data for the five generating units is shown in Table 1. The real power limits of the generators, fuel cost coefficients, emission coefficients and valve point effect coefficients are given in the Table 1.

The Solution of the Multi-criteria dispatch problem using Min-Max price penalty factor is shown in Table 2 and Max-Max price penalty factor is shown in Table 3. The tables include the power demand *[MW]*, lambda value, Fuel cost in [$/hr], Emission in [kg/hr], CEED fuel cost in [$/hr], fuel cost with valve point effect in [$/hr], emission with valve point effect in [kg/hr], and CEED fuel cost with valve point effect in *[$/hr]* for the five different power demands from 200 to 400 *[MW]*. The CEED problem uses the Min-Max and Max-Max price penalty factor h_i given by the equation (6) or (7) in order to evaluate the optimal solution using Lagrange's method. The initial lambda (λ^0) value is assumed as 8. The different lambda optimal values are computed for the corresponding load demand.

The flow chart of the Lagrange's algorithm for Multi-Criteria Dispatch Problem is given in Figure 1.

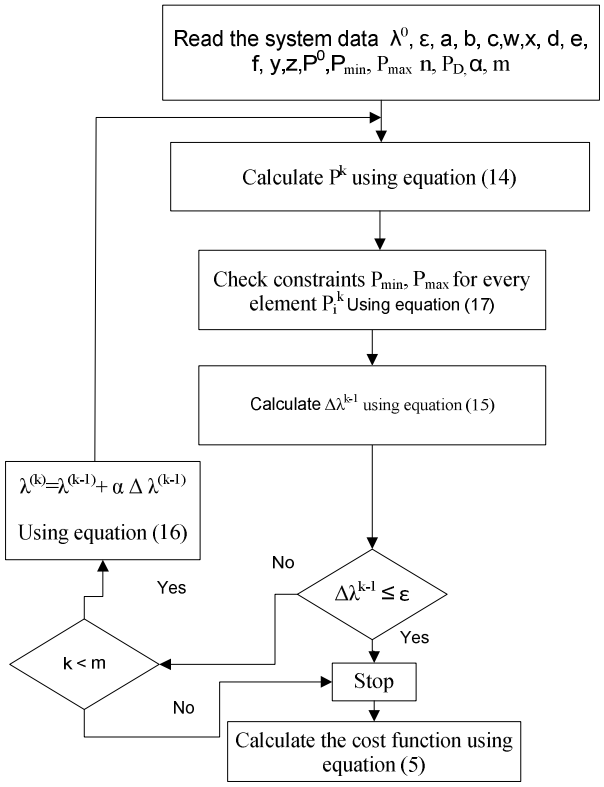

Figure 1: Flow diagram of Multi-Criteria Dispatch Problem with valve point effect using Lagrange's method

Figure 2 shows the variation of CEED fuel cost with valve point effect for the Multi-criteria dispatch problem using Min-Max and Max-Max price penalty factors. The upper points show the CEED fuel cost values with valve point effect in [$/hr] when using Max-Max price penalty factor. The bottom points show the fuel cost values with valve point effect in [$/hr] when using Min-Max price penalty factor.

Table 1 Multi-criteria power system dispatch problem data for five generator system

Generator Numbers	*Generator limits[MW]*		*Fuel cost coefficients with valve point effect*					*Emission coefficients with valve point effect*				
	P_{min}	P_{max}	*a*	*b*	*c*	*w*	*x*	*d*	*e*	*f*	*y*	*z*
1	10	75	25	2.0	0.0080	100	0.042	80	-0.805	0.0180	0.6550	0.02846
2	20	125	60	1.8	0.0030	140	0.040	50	-0.555	0.0150	0.5773	0.02446
3	30	175	100	2.1	0.0012	160	0.038	60	-1.355	0.0105	0.4968	0.02270
4	40	250	120	2.0	0.0010	180	0.037	45	-0.600	0.0080	0.4860	0.01948
5	50	300	40	1.8	0.0015	200	0.035	30	-0.555	0.0120	0.5035	0.02075

Table 2 Multi-criteria power system dispatch problem solution using Min-Max price penalty factor

Power demand [MW]	Lambda	P1	P2	P3	P4	P5	F_{CVP}	E_{TVP}	F_{TVP}	Computation time
200	42.55	39.13	36.32	43.53	40.00	50.00	529342.33	406934.63	543259.49	3.20
250	55.33	52.45	51.92	48.68	46.93	50.00	832799.18	671089.80	854695.47	3.54
300	65.39	61.10	62.81	61.03	58.22	56.80	1239748.92	968739.64	1272452.03	3.41
350	74.87	69.51	70.63	72.55	69.94	67.34	1716417.40	1307904.17	1761812.97	3.26
400	84.67	74.61	78.92	80.55	82.66	83.24	2249640.85	1690782.82	2309050.36	3.32

Table 3 Multi-criteria power system dispatch problem solution using Max-Max price penalty factor

Power demand [MW]	Lambda	P1	P2	P3	P4	P5	F_{CVP}	E_{TVP}	F_{TVP}	Computation time
200	41.57	38.25	35.94	35.80	40.00	50.00	534878.98	405432.08	1069099.53	3.52
250	54.12	51.63	51.21	49.85	47.30	50.00	841917.47	669022.40	1682947.10	3.77
300	64.20	60.29	62.38	62.32	58.67	56.31	1253988.40	968360.42	2506900.42	3.45
350	73.79	68.76	70.27	73.46	70.56	66.93	1732214.80	1307253.24	3463235.17	3.25
400	88.65	77.88	78.61	81.52	83.09	78.88	2265987.10	1690162.67	4530767.37	3.25

It concludes that the Min-Max price penalty factor has less CEED fuel cost value with valve point effect when compared to Max-Max price penalty factor approach for the multi-criteria power system dispatch problem for all values of the given power demand.

Figure 3 shows the variation of computation time in [Seconds] for the multi-criteria dispatch problem using Min-Max and Max-Max price penalty factors for the five different power demands.

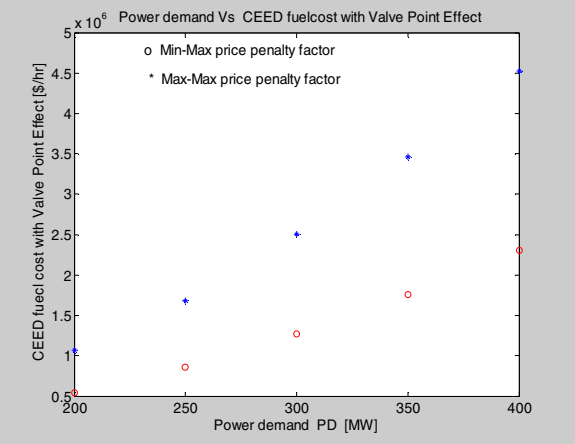

Figure 2 Comparison of CEED fuel cost with valve point effect using Min-Max and Max-Max price penalty factors

In Figure 3, x-axis shows the power demand ranges form 200–400 [MW] and y-axis shows the computation time in [Seconds].

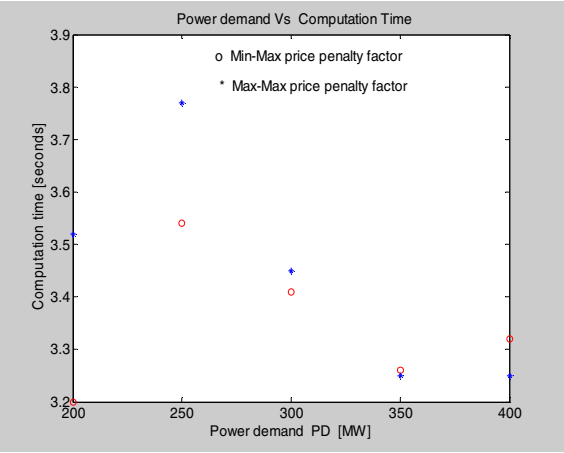

Figure 3 Comparison of computation time using Min-Max and Max-Max price penalty factors

The upper points in Figure 3 show the computation time in [Seconds] when using Max-Max price penalty factors for the given smaller power demands. It concludes that the Max-Max price penalty factor leads to higher computation time when compared to Min-Max price penalty factor approach for the multi-criteria power system dispatch problem in the cases for smaller power demands. The values of computation time are lower when using Max-Max price penalty factor for the highest power demand.

Table 4 shows the comparison of the simulation results of multi-criteria dispatch problem using Min-Max and Max- Max price penalty factor approaches. The comparison is done for the minimum power demand P_D = 200 [MW] because the biggest differences in the values of the criteria appeared for the minimum power demand. The values of the criteria for the case of Min-Max penalty factor are taken for basis and the difference for the Max-Max penalty factor is given in percentage in Table 4.

Table 4. Comparison of simulation results using Min-Max and Max-Max price penalty factors

Criterion	Min-Max price penalty factor	Max-Max price penalty factor
Fuel cost with valve point effect F_{CVP} [$/hr]	100 %	101.04 %
Emission value with valve point effect E_{TVP} [kg/hr]	100 %	99.63 %
CEED fuel cost with valve point effect F_{TVP} [$/hr]	100 %	196.79 %
Computation time [Seconds]	100 %	110 %

VII. CONCLUSION

New Min-Max price penalty factor is proposed for solution of the multi-criteria power system dispatch optimization problem in the paper. The Lagrange's method and algorithm for solution of five generating unit test system of Multi-criteria dispatch problem using Min-Max and Max-Max price penalty factors is developed. The simulated results show that Min-Max price penalty factor provides better optimization solution for the Multi-criteria dispatch problem in comparison with Max-Max price penalty factor. The simulation results show that Min-Max price penalty factor yields a minimum overall cost for multi-criteria power system dispatch problem. It can be concluded that the following results:

i. The minimum fuel cost with valve point effect for the Multi-criteria dispatch problem can be provided when using Min-Max Price penalty

factor in comparison to Max-Max price penalty factor.

ii. The emission values with valve point effect are less in Max-Max price penalty factor when compared to Min-Max price penalty factor, but the difference is very small 0.37%.

iii. The CEED fuel cost values with valve point effect are less with Min-Max price penalty factor in comparison to the solution using Max-Max price penalty factor.

iv. It concludes that the Min-Max price penalty factor by considering the valve point effect attains the minimum CEED fuel cost value as received when using Lagrange's method.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the authorities of Cape Peninsula University of Technology, South Africa for the facilities offered to carry out this work. The research work is funded by the National research foundation (NRF) grant UID62364 "Substation Automation and Energy Management Systems".

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BIOGRAPHY

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Professor Raynitchka Tzoneva has MSc and PhD in Electrical Engineering (control specialization) from the Technical University of Sofia (TUS), Bulgaria. She has been a lecturer at the TUS and an Associated Professor at the Bulgarian Academy of Sciences, Institute of Information Technologies between 1982 and 1997. Since 1998 she has been working as a Professor at the Department of Electrical Engineering, Cape Peninsula University of Technology, Cape Town.

R. Tzoneva is a leader of the Niche area Real Time Distributed Systems (RTDS) and of the Centre for Substation Automation and Energy management Systems supported by the South African Research Foundation (NRF). R. Tzoneva is a member of the Institute of Electrical and Electronic Engineers (IEEE). Her research interest is in the fields of optimal and robust control design and optimization of linear and nonlinear systems, energy management systems, real-time digital simulations, and parallel computation.