OPTIMIZED MULTI-UTILITY WHEELING WITH ECONOMIC GENERATION DISPATCH

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Abstract: *With the experience of economic benefits received from the deregulation of industries such as airlines, telecommunications and gas industries, the electric power industry is going through restructuring process throughout the world, with the traditional vertically integrated monopolistic utility structure being deregulated. Under deregulation, the former vertically integrated utility, which took care of generation, transmission and distribution of power, is detached into individual companies dedicated to each function. The electricity industries in many countries have recently been deregulated, allowing private companies to participate in order to introduce competition in generation and distribution activities, for attaining higher efficiency in electricity production and consumption. The transmission service provider is still a natural monopoly due to the non-availability of feasible way to replace transmission lines. The transmission service provider charges 'wheeling' cost for its service and for meeting extra losses that occurs with the inclusion of private power producers in the network of transmission service provider. The electricity bill for the end consumer involves a component from the power generating company and the other from transmission and distribution network operator responsible for its services. Many of the optimal power dispatch models proposed have the objective of minimizing either production cost or wheeling cost. This paper introduces the need of deregulation of electric power industry, concepts of wheeling and wheeling cost, need of power flow tracing methods and provides a detailed presentation of Bialek's tracing method and of an 'embedded' wheeling cost methodology namely 'MW-mile' method to determine the wheeling cost. The generation and wheeling costs are calculated and compared before and after the application of optimal power dispatch with the objective of minimization of both generation and wheeling costs, to an application example illustrated.*

Key words: *Deregulation, Wheeling, Tracing, Transmission pricing paradigms, Optimal power dispatch.*

NOMENCLATURE

no.	-	number
p.u.	-	per unit
R	-	Line resistance (p.u.)
X	-	Line inductive reactance (p.u.)
B	-	Half-line charging susceptance (p.u.)
l	-	Line length (km)
V	-	Bus voltage magnitude (p.u.)
δ	-	Bus voltage phase angle (degrees)
Pg	-	Generated active power (MW)
Pd	-	Demanded active power (MW)
Qg	-	Generated reactive power (MVAr)
Qd	-	Demanded reactive power (MVAr)
p	-	Sending-end bus number of line-pq
q	-	Receiving-end bus number of line-pq
P_pq	-	Active power flow from p to q (MW)
P_qp	-	Active power flow from q to p (MW)
Q_pq	-	Reactive power flow from p to q (MVAr)
Q_qp	-	Reactive power flow from q to p (MVAr)
P_L	-	Active power loss in line-pq (MW)
Q_L	-	Reactive power loss in line-pq (MVAr)
N	-	Stage no. with N generators shut down
m	-	Number of branches of the bus system
n	-	Number of nodes of the bus system
P	-	(nx1) sized matrix of nodal flows
P_G	-	(nx1) sized matrix of nodal generations
P_D	-	(nx1) sized matrix of nodal demands
F	-	(mx1) sized matrix of branch flows

1. INTRODUCTION

Since 1910s, large electric utilities under federal and state rulings, owned generating stations to generate electrical power and also owned transmission and distribution network to carry the generated power to the end users. Also the electric utilities provided energy meters for billing purpose. Such utilities are referred to as vertically integrated utilities which are found to be monopolistic particularly in fixing the unit cost of electrical energy.

In the 1980s, there was a worldwide push of such monopolistic utilities like railroads, airlines, telephone services, gas industries and banks, from its vertically integrated environment to open market systems. This kind of process is called as deregulation or restructuring. However, during the nineties, many electric utilities worldwide have been forced to change their way of operation and business. The reasons for alteration have been several and have fluctuated over countries. For developing countries, the main issues have been a demand progress in elevation coupled with ineffective system management and irrational tariff strategies. It has affected the handiness of financial means to support investments in improving generation and transmission capacities. In such circumstances, many utilities were forced to restructure their power sectors. However in developed countries, the driving force has been to provide cheaper electricity and offer consumers a greater choice in purchasing economic electricity [1].

With deregulation, the former giant vertically integrated electric utilities were segregated into three portions namely 'Power producers of electricity' who owns plants to generate power and sell it on the open market, 'Transmission and distribution service provider' who owns wires for conduction of generated power up to end consumers and owns meters for billing purpose, and 'Retail electric provider' who buys power from the power producers and sells it to end users. The main objectives of deregulation are to provide consumers cheaper electricity, new choices of electricity providers and better service [2].

2. WHEELING COST OR TRANSMISSION PRICING

2.1. Wheeling

Entry of private power generating companies called 'Independent Power Producers (IPPs)' in the deregulated power environment proposes more choice for customers, but necessitates the usage of third party owned transmission and distribution network for delivery of power generated to its customers. The process of power delivery through third party network is called 'wheeling'.

2.2. Effect of wheeling on line losses

Fig. 1 shows the power flow diagram of a five-bus seven-line system [3] in the presence of flow of wheeled power, with a seller at bus-5 selling 100 MW to a buyer at bus-3.

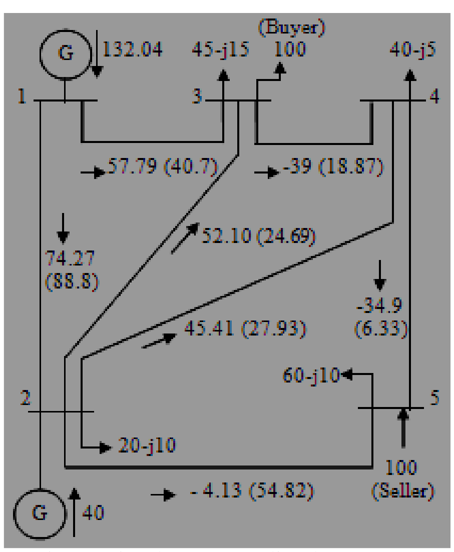

Fig. 1. Five-bus, seven-line bus system

The real and reactive powers are in MW and MVAR respectively. The values in the parenthesis represent the real power flows in the absence of flow of wheeled power. Wheeling leads to compulsory change of magnitude as well as probable change of direction of line flows along with a definite rise in line losses.

2.3. Wheeling cost or Transmission pricing

The wheeling party is paid charge per unit cost called 'wheeling cost' [4] for its service and for meeting extra losses, considering the capital cost of all transmission lines as the power flow magnitude in all lines.

3. TRANSMISSION PRICING PARADIGMS

In these paradigms, the infrastructure setup cost, operational cost, maintenance cost and forthcoming investment cost are summed up together and the sum is allocated to various wheeling customers on various bases [5]. In brief, the transmission pricing paradigms are the overall processes of translating transmission costs into transmission charges [6].

Practically all transmission pricing paradigms are cost based with the objective of allocating all or part of both existing transmission system cost and the new costs of both system operation and expansion, to various users of the transmission system [7].

Different types of transmission pricing paradigms available are: (i) Rolled-in transmission pricing paradigms and (ii) Incremental transmission pricing paradigms.

3.1. Rolled-In transmission pricing paradigms

In this paradigm all existing and new costs of transmission system are first summed up and the total cost is allocated among various users of the transmission system, including the utility native customers, according to their "extent of use" of transmission system.

Different Rolled-in transmission pricing methodologies defined by the "extent of use" of transmission system are Postage stamp methodology, Contract path methodology, Distance based and Power flow based Line-by-line methodologies or MW-mile methodologies.

As these paradigms ignore transmission resources shortage, they are considered to be economically ineffective which may not be pointed out as the new reinforcement cost is usually spread among all energy customers.

Line-by-line methodology is applied to the application example which is considered in this paper.

3.2. Incremental transmission pricing paradigms

According to these paradigms, the existing transmission system costs will be assigned to utilities' native customers and new transmission costs to new users of transmission network. These incremental transmission pricing methodologies include Short-Run Incremental Cost pricing (SRIC) methodology, Long-Run Incremental Cost pricing (LRIC) methodology, Short-Run Marginal Cost pricing (SRMC) methodology and Long-Run Marginal Cost pricing (LRMC) methodology.

4. POWER FLOW TRACING METHODS

Wheeling could be done by a single entity or by multiple entities. In the latter case, wheeling party is paid by every IPP connected to the wheeling network. It involves the determination of contribution of each IPP for line flows and line losses [8]. It leads to the need of power flow tracing methods which are used to determine how much of a particular generator's output supplies a particular load or a particular line flow [9].

The power flow tracing methods fix the share of transmission system usage by various generators and loads and so may be used for fixing wheeling cost in order to recover fixed transmission costs by allotting it to various entities connected to the transmission network. In general, by notional decomposition of line flows and losses [10], the tracing algorithms provide information regarding the contribution of k^{th} generator in meeting j^{th} load as well as losses incurred during this operation, decomposition of power flows on a line into its constituent generators and loads, losses supplied by various generators and losses due to various loads [11].

The most popular and widely used power tracing methods available are Bialek's tracing method based on simultaneous equations approach and the other based on graph theoretic approach. These methods are based on proportionate sharing principle i.e., proportionate sharing of nodal inflows among nodal outflows [12]. This proportional sharing principle is based on Kirchhoff's current law and is topological in nature. The pre-requisite for tracing of power flow is an effective power flow solution [13].

4.1. Bialek's tracing method

Bialek's tracing method determines the contribution of individual generators based on the calculation of topological distribution factors which would always be positive in this tracing method. So this method would exclude the counter flow issue.

This method uses either the upstream looking algorithm or the downstream looking algorithm. In the former case, the wheeling charge is allocated to individual generators and losses are distributed to individual loads and vice-versa in latter case.

The Bialek's tracing procedure to determine the generator-wise contribution is as follows:

B = (mxn) sized matrix called 'Incidence matrix' with its elements value equal to 1 when power flows from 'm' bus to 'n' bus, -1 when power flows from 'n' bus to 'm' bus and 0 when no power flows between 'm' bus and 'n' bus.

B_d = (mxn) sized matrix derived from incidence matrix, consisting of 1's and other element values equal to zero.

B_u = (mxn) sized matrix derived from incidence matrix, consisting of -1's and other element values equal to zero.

$$F_d = -B_d^T.\text{diag}(F).B_u \tag{1}$$

$$A_d = I + B_d^T.\text{diag}(F).B_u.\text{diag}(P^{-1}) \tag{2}$$

$$A_u = I + B_u^T.\text{diag}(F).B_d.\text{diag}(P^{-1}) \tag{3}$$

Equation (1) results in an (nxn) sized matrix with the (i, j) element indicating line flow from i^{th} bus to j^{th} bus

Equations (2) and (3) provide two non-singular matrices, each of size (nxn).

$$P_{G_{ki}} = \frac{P_{D_i}.P_{G_k}.[A_u^{-1}]_{ik}}{P_i} \tag{4}$$

$$P_{G_{kj}} = \frac{F_{D_j}.P_{G_k}.[A_u^{-1}]_{ik}}{P_i} \tag{5}$$

Equation (4) can be used to find the k^{th} generator's active power contribution to i^{th} bus active load whereas equation (5) to determine k^{th} generator's active line power flow contribution to j^{th} line's active line flow. The same equations can be dealt with reactive loads and other types of powers also. Thus these two equations can be used to determine the transmission network usage due to individual generators and individual loads.

5. LINE-BY-LINE METHODOLOGY

This method bases the cost on a computed set of parallel paths for a particular transaction, considering line flows and line lengths [14]. The two versions of the Line-by-line methodology are Distance based MW-Mile methodology and Power flow based MW-Mile methodology.

5.1. Distance based MW-Mile methodology

This is a simple method evaluating the usage of each transmission network user according to the product of the quantity of the transacted power and the geographical distance between the seller and buyer. However, this method does not make use of any power flow simulation to take into consideration the effect of actual power flow and so this methodology is usually referred to as non-power flow method. Thus it is quite a rough and an approximate method.

Practically, due to the effect of meshed network, there is no fixed relationship between the geographical distance and the actual costs and so the transmission network users do not receive correct economic signals. Automatically it does not lead to efficient power system operation.

5.2. Power flow based MW-Mile methodology

This method employs power flow simulation to determine the flow of transacted power in various lines. It takes into account both the quantity of transacted power and the electrical distance between source and sink, and allocates total costs in direct relation to the MW-Mile of transactions.

The formula to determine the wheeling cost for a particular transaction is as follows [15]:

$$WC_t = \sum_j \left[\frac{P_{j,t} L_j C_j}{\sum_i P_{j,t}} \right]$$

Where:

WC_t = wheeling cost for transaction t (Rs./MVA)

$P_{j,t}$ = flow in line j due to transaction t (MVA)

L_j = length of line j (Km)

C_j = pre-determined unit cost reflecting the cost per unit capacity of the line (Rs./MVA-Km)

i = total number of transmission lines

Since this methodology allocates transmission charges based on maximum usage of a transmission line, it emulates the actual system reinforcement planning process which is based on local considerations rather than coincident overall system peak condition.

5.2.1. Advantages

1. No priority order is maintained by this method in case of multiple wheeling transactions.
2. It provides correct economic signals irrespective of entities' distance involved in wheeling process.

5.2.2. Disadvantages

1. The real power system is modeled by a set of non-linear equations. Usage of DC approximation of the power system by this method leads to inaccuracy in calculating the "extent of use" of the network for a particular transaction. To overcome this drawback, the apparent power flow is calculated by the usage of AC approximation, in calculating the wheeling cost. Line lengths in kilometers are considered.
2. This method leads to the reduction of system loading, as no merit is attributed to the transactions giving counter flows.

6. PROPOSED ALGORITHM FOR OPTIMAL POWER DISPATCH

A technique similar to heuristic technique is employed to achieve the reduction of both line losses, generation cost and hence per unit generation cost [16]. The reduction of line losses leads to drop of wheeling cost of some generators which would increase the transmission network usage cost of other generators [17].

The stepwise procedure in the technique proposed is as follows:

1. Assuming all generators or units are on-line i.e., N = 0, solve a normal optimal power flow with all limits in place.
2. Save the solution as the current best.
3. Increment N.
4. Using the best solution from previous stage as the base case for current stage, form a candidate list of units with minimum generation limits binding.
5. If there are no candidates, return the current best solution as the final solution.
   If candidates are present, then for each unit on the candidate list, solve an optimal power flow to find total system cost with this generator shut down. If the total system cost is reduced further, replace the current best solution with the solution obtained. If any of the candidate solutions results in any improvement, return to step 3.

7. CASE STUDY

A six-bus eleven-line system [18, 19] shown in Fig. 2 is considered for the effect of optimal power flow united with economic generation dispatch on the per unit cost of generated energy, generation cost and wheeling cost of each generator.

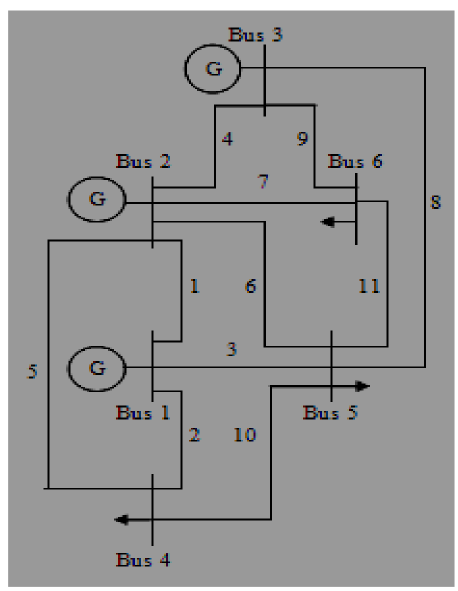

Fig. 2. Six-bus, eleven-line bus system

Table 1 presents the parameters and length of each transmission line of the bus system considered.
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Table 1. Line data

Line no.	p	q	R	X	B	l
1	1	2	0.10	0.20	0.020	578
2	1	4	0.05	0.20	0.020	289
3	1	5	0.08	0.30	0.030	463
4	2	3	0.05	0.25	0.030	289
5	2	4	0.05	0.10	0.010	289
6	2	5	0.10	0.30	0.020	578
7	2	6	0.07	0.20	0.025	405
8	3	5	0.12	0.26	0.025	694
9	3	6	0.02	0.10	0.010	116
10	4	5	0.20	0.40	0.040	1156
11	5	6	0.10	0.30	0.030	578

Table 2 shows the type, voltage details and both active and reactive load magnitudes details at all buses of the bus system. IPPs are assumed to be available at all the generator buses. All the bus voltages are assumed to have a lower limit of 0.94 p.u. and an upper limit of 1.06 p.u.

Table 2. Bus data

Bus no.	Bus type	V	δ	Pd	Qd
1	Slack	1.05	0	---	---
2	PV	1.05	0	---	---
3	PV	1.07	0	---	---
4	Load	1.00	0	70	70
5	Load	1.00	0	70	70
6	Load	1.00	0	70	70

Table 3 presents the bus power generation details at all generator buses of the bus system. All the generator buses are assumed to have a lower limit of -150 MVAr and an upper limit of 150 MVAr for its reactive power generation capacity.

Table 3. Generator power data

PV bus no.	Pg	Limits of Pg (MW)		Qg
		Lower	Upper	
1	0	10	85	0
2	50	10	80	0
3	60	10	70	0

Table 4 shows the fuel cost coefficients of all PV buses of the bus system.

Table 4. Generator cost data

PV bus no.	Fuel cost coefficients		
	a (Rs./MW^2)	b (Rs./MW)	c (Rs.)
1	0.008	7.0	200
2	0.009	6.3	180
3	0.007	6.8	140

Table 5 presents the details of both bus voltage and bus power generation at all buses of the bus system under normal load flow case. Table 6 shows the same details but under optimized case. It is observed that gross totals of both active and reactive power generations are reduced under the latter case due to the reduction of line losses due to optimization.

Table 5. Bus voltages and bus power generations before the improvement of generation dispatch

Bus no.	Before improvement			
	V	δ	Pg	Qg
1	1.05	0.00	108.44	23.11
2	1.05	-3.72	50.00	86.86
3	1.07	-4.33	60.00	98.83
4	0.98	-4.17	0.00	0.00
5	0.98	-5.22	0.00	0.00
6	1.00	-5.97	0.00	0.00
		Total	218.47	208.81

Table 6. Bus voltages and bus power generations after the improvement of generation dispatch

Bus no.	After improvement			
	V	δ	Pg	Qg
1	1.06	0.00	67.12	44.94
2	1.05	-1.26	79.99	81.51
3	1.06	-1.37	69.99	78.23
4	0.99	-2.53	0.00	0.00
5	0.98	-3.25	0.00	0.00
6	0.99	-3.29	0.00	0.00
		Total	217.12	204.68

Without and with optimal power flow united with economic generation dispatch, Table 7 shows the line power flows and line losses, Table 8 presents the contribution of each generator to the load demands including line power losses, Table 9 shows the contribution of each generator to the line power flows and Table 10 presents the contribution of each generator to the line-wise wheeling costs.

Table 7. Line power flows and line losses

Line no.	Before optimal power dispatch						After optimal power dispatch					
	P_pq	Q_pq	P_qp	Q_qp	P_L	Q_L	P_pq	Q_pq	P_qp	Q_qp	P_L	Q_L
1	29.12	-14.50	-28.19	14.16	0.93	-0.34	11.01	-3.77	-10.90	1.77	0.11	-2.01
2	43.70	22.73	-42.57	-20.31	1.12	2.42	30.58	28.37	-29.78	-27.26	0.80	1.11
3	35.63	14.89	-34.51	-13.78	1.12	1.11	25.53	20.35	-24.72	-20.44	0.81	-0.09
4	2.98	-10.63	-2.94	7.46	0.04	-3.17	0.38	-3.91	-0.38	0.57	0.00	-3.34
5	33.28	49.60	-31.64	-47.35	1.64	2.25	45.60	44.37	-43.76	-41.74	1.84	2.64
6	15.50	18.47	-14.93	-18.84	0.57	-0.37	18.74	19.19	-18.05	-19.21	0.69	-0.02
7	26.43	15.27	-25.81	-16.13	0.62	-0.86	26.18	20.09	-25.46	-20.67	0.72	-0.57
8	19.33	26.88	-18.10	-26.84	1.23	0.04	23.33	20.68	-22.23	-20.89	1.10	-0.22
9	43.62	64.50	-42.55	-60.21	1.07	4.29	47.05	56.99	-46.07	-53.13	0.98	3.86
10	4.21	-2.34	-4.17	-1.45	0.04	-3.79	3.54	-1.00	-3.51	-2.83	0.03	-3.83
11	1.71	-9.10	-1.65	6.34	0.06	-2.75	-1.49	-6.64	1.52	3.80	0.03	-2.84
				Total	8.45	-1.19				Total	7.12	-5.32

Table 8. Generator-wise contribution to bus-wise power demands including line power losses

PV bus no.	Bus-wise power demand contribution including line power losses											
	Active power demand contribution including active line power loss (MW)						Reactive power demand contribution including reactive line power loss (MVAr)					
	Before optimal power dispatch			After optimal power dispatch			Before optimal power dispatch			After optimal power dispatch		
	Bus-4	Bus-5	Bus-6	Bus-4	Bus-5	Bus-6	Bus-4	Bus-5	Bus-6	Bus-4	Bus-5	Bus-6
1	52.90	43.85	11.68	34.36	29.62	3.13	13.77	9.34	0.00	26.55	18.39	0.00
2	20.07	11.42	18.50	38.20	19.02	22.76	51.33	23.05	12.47	43.95	19.37	18.18
3	0.00	17.98	42.01	0.00	24.19	45.80	3.72	34.89	60.21	0.30	23.74	54.18

Table 9. Generator-wise contribution to line power flows

Line no.	Generator-wise contribution to line power flows											
	Active power flows (MW)						Reactive power flows (MVAr)					
	Before optimal power dispatch			After optimal power dispatch			Before optimal power dispatch			After optimal power dispatch		
	PV bus-1	PV bus-2	PV bus-3	PV bus-1	PV bus-2	PV bus-3	PV bus-1	PV bus-2	PV bus-3	PV bus-1	PV bus-2	PV bus-3.
1	29.11	0.00	0.00	11.01	0.00	0.00	0.00	12.61	1.08	0.00	1.68	0.01
2	43.69	0.00	0.00	30.58	0.00	0.00	13.96	7.62	0.65	26.17	0.98	0.00
3	35.63	0.00	0.00	25.53	0.00	0.00	9.15	4.99	0.42	18.77	0.70	0.00
4	1.11	1.90	0.00	0.04	0.33	0.00	0.00	0.00	7.45	0.00	0.00	0.56
5	12.39	21.28	0.00	5.52	40.13	0.00	0.00	44.19	3.79	0.00	42.34	0.29
6	5.77	9.90	0.00	2.26	16.48	0.00	0.00	16.45	1.41	0.00	18.31	0.12
7	9.84	16.90	0.00	3.17	23.03	0.00	0.00	13.60	1.16	0.00	19.17	0.13
8	0.34	0.58	18.42	0.01	0.11	23.20	0.00	0.00	26.87	0.00	0.00	20.67
9	0.77	1.32	41.57	0.03	0.22	46.79	0.00	0.00	64.49	0.00	0.00	56.98
10	3.18	1.20	0.00	1.73	1.93	0.00	-0.19	-0.47	-0.72	-0.38	-0.63	0.00
11	1.07	0.27	0.43	0.06	0.49	0.99	0.00	1.13	5.45	0.00	0.98	2.93

Table 10. Generator-wise contribution to line-wise wheeling costs

Line no.	Generator-wise contribution to line-wise wheeling costs (Rs. per MVA)					
	Before optimal power dispatch			After optimal power dispatch		
	PV bus-1	PV bus-2	PV bus-3	PV bus-1	PV bus-2	PV bus-3
1	16830.20	7290.06	1.083	6364.29	973.27	6.75
2	13257.89	2202.37	0.654	11631.99	283.38	1.97
3	17033.04	2311.25	0.429	14672.35	325.63	2.26
4	321.18	551.52	7.457	13.31	96.74	163.40
5	3581.74	14174.98	3.794	1596.52	16861.11	84.88
6	3335.31	11102.77	1.413	1311.75	14243.05	73.42
7	3986.26	8787.06	1.168	1284.27	12139.58	53.86
8	236.82	406.66	26.876	10.60	77.00	21568.03
9	89.33	153.40	64.498	3.57	25.96	8553.88
10	3684.56	1500.61	-0.723	2055.99	2348.37	5.05
11	619.08	672.93	5.456	39.39	637.93	1793.35
Total	62975.44	49153.61	41068.04	38984.05	48012.02	32306.83

8. CONCLUSION

With the main objective of minimization of both line power loss and generation cost, the per unit cost, generation cost and wheeling cost of some generators connected to the wheeling party would get reduced, however the same operation would raise the aforementioned costs of other generators, to meet the load demands.

Table 9 presents both per unit cost and generation cost of each generator in rupees and wheeling cost in rupees per MVA, in absence of the effect of optimal power flow shared with economic generation dispatch and Table 10 presents in the presence of the effect.

Table 9. Generator-wise costs before optimal power dispatch

Cost	PV bus-1	PV bus-2	PV bus-3
Per unit cost	0.51	0.38	0.32
Fuel cost	875.10	517.50	728.80
Wheeling cost	46980.23	43370.17	41781.20

Table 10. Generator-wise costs after optimal power dispatch

Cost	PV bus-1	PV bus-2	PV bus-3
Per unit cost	0.47	0.39	0.31
Fuel cost	705.91	741.59	650.29
Wheeling cost	37205.51	45980.56	32302.47

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