

Evaluation of Active Power Cost in Combined AC-DC Systems

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ABSTRACT:

In this paper, the economic dispatch problem in combined AC-DC systems is studied based on the equivalent losses matrix of power flow. The proposed method starts with calculation of the power flow for the combined AC-DC system, and continues with the calculation of the losses matrix. Afterwards, the economic dispatch problem is calculated by the interior point method. The active powers which are founded by the economic dispatch problem, are used to recalculate the new power flow. The procedure will be iterated until the results convergence. Finally, several simulations carried out on a 14-bus system including five generation units, with and without DC links.

KEYWORDS: Combined AC-DC System, Power Flow, Interior Point Method, Economic Dispatch, Optimization.

1. INTRODUCTION

Operating a system, means to choose an optimal operation that satisfies all constraints while obtaining the best profit. Nowadays, the power systems become more difficult and more complicated to control, because they support very high energy and contain several nonlinear systems. In this work, we try to share the best amount of active powers between all production units by ED problem. Several techniques and ideas are developed by the researchers to offer the minimum cost of total active power at the real time. From 1930, the engineers were concerned with the problem of the proper distribution of the load between the available production units [1]. Production techniques are based on the successive loading plants depending on their production capability. The ED problem has been a subject of intensive research, including the classical methods as, linear and dynamic programming, nonlinear methods and others based on the AIT (artificial inelegance technical) by simple and hybrid methods [2-5]. With the modification in our networks, ED problems are not concerned only by the methods of calculation, also, it handles with the constraint of network elements and others. In [6] the authors presented the calculation of ED problem taking to consideration the constraint of the transmission capacity line between two areas. In [7] authors were interested by the influence of the thermal limits of transmission lines in the economic dispatch, where others treated the problem in the presence of different fossil-fired in thermal generator units, wind power units, solar, etc. in [8] the problem of multiple fossil fired in

thermal units studied for minimizing the total cost. In [9] the authors coordinated the wind and thermal generator for minimizing the total cost of generation units. Also, in [10] the authors introduced the wind and solar thermal energies in ED calculation, introducing the constraints of speed wind, solar radiating and temperature. On the other hand, many authors treated the ED calculation with the minimization of emission of polluting gas [11-14]. Because of the great importance to operate each system in the lowest cost, we focus on the optimal cost in the presence of DC links into the AC networks. In this research, we calculate the realizable best PF with a minimum total cost of the active power, by means of the calculation of ED problem after the extraction of the equivalent losses matrix of the AC-DC system.

2. ECONOMIC PROBLEM

The problem is to ensure the balance of powers at the lowest cost when the total load is known. Frequency, voltage level and security were held constant. All nodes are assumed to be known voltage.

2.1. Mathematical Model

The mathematical model of the minimization the total cost problem is given by the following system

$$F_T = \sum_{i=1}^{ng} F_i \quad (1)$$

$$\sum_{i=1}^{ng} P_{Gi} = P_L + P_D \quad (2)$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (3)$$

$$F_i = a_i P_{Gi}^2 + b_i P_{Gi} + c_i \quad (4)$$

Where F_i is the cost function of unit i and P_{Gi}, P_L, P_D are respectively, the active power of unit i , the total active power losses and the total demand of active power. To calculate the transmission losses in AC networks, we use the known losses formula:

$$P_L = P_G^T B P_G + P_G^T B_0 + B_{00} \quad (5)$$

Where, B terms represent the losses coefficients.

2.2. Losses Coefficients Calculation

The calculation of the transmission losses can be deduced after calculating the PF, or, by means of losses matrix. Several studies have been carried out for determining this matrix; we invite you to consult [15-16]. In this work we calculate the power losses by the matrix of B -coefficients. Because of the mixture of the transmission network, we write P_L as follow:

$$P_L = P_{LAC} + \sum_j^{Ndc} P_{LDC}^j \quad (6)$$

P_{LAC} is the losses of the AC equivalent network devoid of all DC links. P_{LDC} is the losses of all DC links and Ndc is its number. For calculating P_{LAC} we use the (5)

$$P_{LAC} = P_G^T B_{AC} P_G + P_G^T B_{AC0} + B_{AC00} \quad (7)$$

For calculating P_{LDC} , several manners can be used such as, subtracting between all rectifier powers to all inverters power:

$$P_{LDC} = \sum_j P_{dr}^j - \sum_j P_{di}^j \quad (8)$$

3. HVDC SYSTEM

3.1. Mathematical Model of HVDC System

The main equations of converter stations can be written as follows [17]

$$V_{dk} = T_k V_k \cos \theta_{dk} - X_{ck} I_{dk} \quad (9)$$

$$V_{dk} = K_\gamma T_k V_k \cos \phi_k \quad (10)$$

$$P_{dk} = V_{dk} I_{dk} \quad (11)$$

$$Q_{dk} = V_{dk} I_{dk} \tan(\phi_k) \quad (12)$$

$$I_d = (V_{dr} - V_{di}) / R_{dc} \quad (13)$$

Where k indicates the converter, $K_\gamma = 0,995$, θ_{dk} is the angle of firing delay for the rectifier and the extinction angle for the inverter, ϕ_k is the power factor at the converter, T_k is the transformation ratio of the load tap changer, X_{ck}, R_{dc} are the equivalent reactance of the

converter transformer and resistance of DC line, respectively. Also, $V_k, V_{dk}, P_{dk}, Q_{dk}, I_d$, are the voltage on the primary side of the converter transformer, the DC voltage, the injected active power, the injected reactive power and the DC line current, respectively. Below, in Fig. 1, we show the studied DC system called HVDC-CSC (high voltage DC- current source converter).

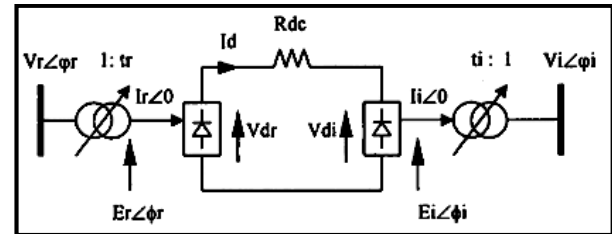


Fig. 1. Scheme of HVDC-CSC (current source converter).

3.2. Control Equations

For the AC-DC system operation, we must choose the model control for each converter station as:

$$\text{Fixed current control: } I_d - I_d^{sp} = 0 \quad (14)$$

$$\text{Fixed voltage control: } V_d - V_d^{sp} = 0 \quad (15)$$

$$\text{Fixed power control: } V_d I_d - P_d^{sp} = 0 \quad (16)$$

$$\text{Fixed angle control: } \cos \theta_d - \cos \theta_d^{sp} = 0 \quad (17)$$

$$\text{Fixed ratio control: } T - T^{sp} = 0 \quad (18)$$

4. POWER FLOW CALCULATION

4.1. Power Flow Equations

The power equations in AC-DC nodes are given by:

$$\Delta P_i = P_i^{sp} - V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \pm V_{dk} I_{dk} = 0 \quad (19)$$

$$\Delta Q_i = Q_i^{sp} - V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \pm V_{dk} I_{dk} \tan(\phi_k) = 0 \quad (20)$$

The positive and negative signs correspond, respectively, to the inverter and the rectifier. The index k corresponds to the converter of node i . If the nodes are purely alternative, the last terms of converters in equations (19) -(20) will be eliminated. G_{ij}, B_{ij} are respectively the real and imaginary parts elements of admittance bus matrix of the system devoid of all DC links.

4.2. Converter Equations

For the DC system, the following equations are used:

$$\Delta d_{1k} = V_{dk} - T_k V_k \cos \theta_{dk} + X_{ck} I_{dk} = 0 \quad (21)$$

$$\Delta d_{2k} = V_{dk} - K_{\gamma} T_k V_k \cos \phi_k = 0 \quad (22)$$

$$\Delta d_{3k} = \pm I_{dk} - \sum_{j \in N_c} g_{kj} V_{dk} = 0 \quad (23)$$

The N_c is the set of terminal nodes, g_{kj} are the elements of bus admittance matrix G_d . For example, for one DC link, we obtain G_d equal to:

$$G_d = \begin{bmatrix} 1/R_{dc} & -1/R_{dc} \\ -1/R_{dc} & 1/R_{dc} \end{bmatrix} \quad (24)$$

The power equations, established earlier, are similar to those of the classical PF. Therefore, the solution can be done by the same methods, where

$$\Delta D = [M] \Delta X \quad (25)$$

Where, $X = [V_d^T \ I_d^T \ T_k^T \ \cos \theta_d^T \ \phi_d^T]^T$ and, $\Delta D = [\Delta d_1 \ \Delta d_2 \ \Delta d_3 \ \Delta d_4 \ \Delta d_5]$. M is the matrix of the partial derivatives system $\partial f(D)/\partial(X)$.

5. CALCULATION OF OPTIMAL SOLUTION

In this study, we calculate the optimal solution of the AC-DC system by reiterating, sequentially, the computes of AC-DC PF, losses matrix and ED problem.

5.1. Calculation of Power Flow

5.1.1. Simultaneous method

This method solves all equations of AC-DC system simultaneously. So, we have

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \dots \\ \Delta D \end{bmatrix} = \begin{bmatrix} J_{11} J_{12} : A_1 \\ J_{21} J_{22} : A_2 \\ \dots \dots \dots \\ C_1 \ C_2 : M \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \\ \dots \\ \Delta X \end{bmatrix} \quad (26)$$

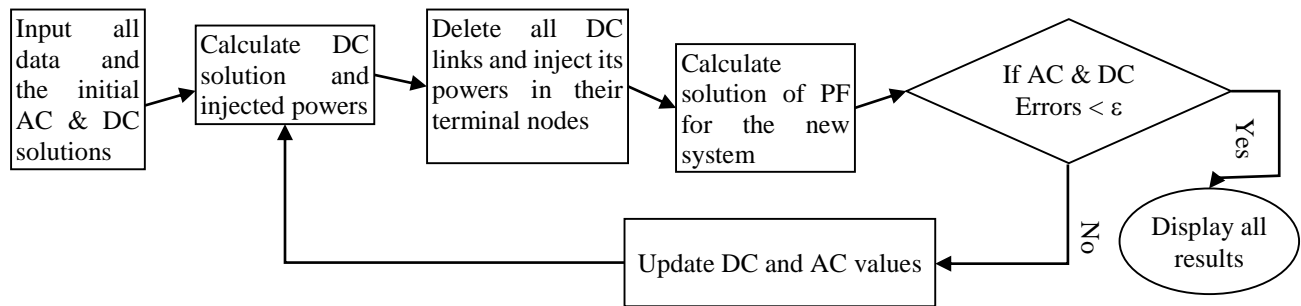


Fig. 2. Flowchart of AC-DC PF by the sequential method.

5.2. Calculation of the Economic Dispatch

We will not detail the method of calculation of the ED problem. In this work we use the IPM for calculating nonlinear problems, because it can handle equalities and inequalities constraints. To calculate the optimal solution, we are basing on the combination of two research directions, called affine scaling and centralization. The combination of the search directions

Where J , A , C and M are the submatrix that we can easily obtain. The system of (26) has the same nature as that of the conventional PF. Therefore, the solution can be done by the iterative methods such as Newton's method.

5.1.2. Alternative method

After separation of AC and DC sub-systems, we proceed to calculate the active and reactive powers at each converter, using (25) and (11)-(12), and we inject them in their equivalent nodes of the purely AC system to calculate the voltage profile. The voltages calculated at terminal nodes will be used to recalculate the new converter powers, the sequential iteration process continues until the convergence of the calculations.

5.1.3. The algorithm of sequential (alternative) method

Step 1. Enter the data of overall system in the separate forms of AC and DC systems.

Step 2. Choose the initial values of AC and DC systems.

Step 3. Calculate for the DC system, the active and reactive powers injected into the converters.

Step 4. Inject the DC powers calculated, previously, in the terminal nodes of the purely AC system.

Step 5. Calculate the voltage profile of the purely AC system.

Step 6. If there is convergence, display the results. If not, go to step 3 using the calculated voltages, of the AC system, in the terminal nodes of the DC system.

The flowchart of this algorithm is shown below in Fig 2.

increases the potential of the optimization algorithm in terms of speed and reliability with the exact result [18]. The IPM solution is based on the modification of the KKT (Karush-Kuhn-Tucker) conditions where the solution of the obtained equation system can be done by two steps; the first is the calculation of control variables and Lagrange equality multipliers, and the second is the calculation of slack variables and Lagrange inequality

multipliers. The details and explications of this method are shown also in [18].

5.3. Calculation Algorithm of Optimal Solution

- Step 1.** Introduce the initial data to calculate the AC-DC PF.
- Step 2.** Calculate the voltage profile and the DC powers in the AC-DC system.
- Step 3.** Calculate the active power losses in the DC system.

- Step 4.** Delete all DC links and inject their powers in the equivalent terminal nodes.
- Step 5.** Calculate the losses matrix for the new system (purely CA).
- Step 6.** Calculate the ED problem by IPM.
- Step 7.** If the PG powers calculated by ED problem are identical to those of the AC-DC PF, display the results and the optimal cost. Otherwise, inject the obtained PG powers by ED problem in the generator nodes and go to step 2. The flowchart of the combined method is represented in Fig. 3.

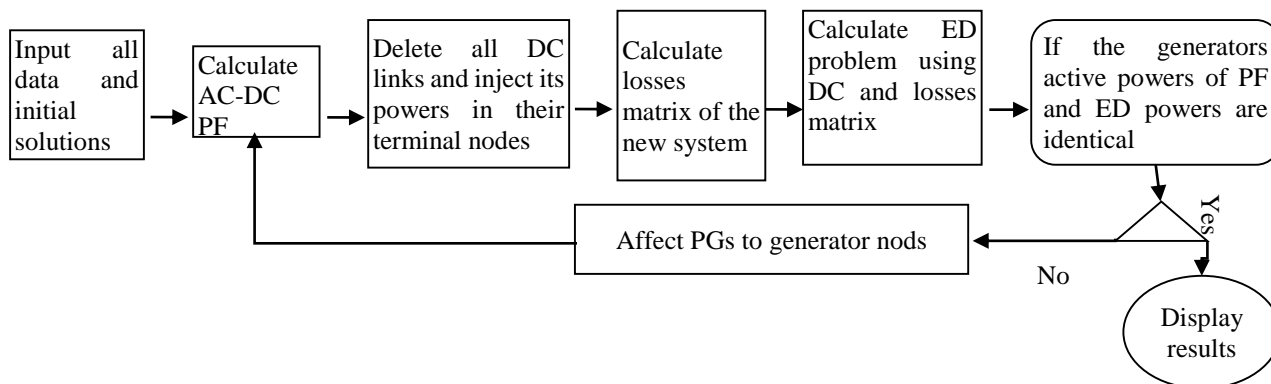


Fig. 3. The Flowchart of the applied technique

6. APPLICATION SYSTEM

In this section we will use IEEE 14 bus system with 5 generation units. First, without introducing DC links in the AC system; second with an HVDC connected between nodes 4 and 5 and finally; with a multi-terminal DC system connected between bus 4, 5 and 2. The data HVDC-CSC systems are shown in Tables 1-2. For the calculation of PF, we use the alternating Iteration method, and for the ED problem we use the IPM with the combination of two search directions, affine scaling direction and centralization direction. At the end, the details of generation units are given in Table 3.

Table 1. The HVDC data.

	Rectifier	Inverter
Bus	4	5
X_C [pu]	0.054831	0.054831
$R_{dc} (n_i - n_j)$ [pu]	0.01272	

Table 2. The Multi-terminal DC system data.

	Rectifier	Rectifier	Inverter
bus	2	4	5
X_C [pu]	0.054831	0.054831	0.054831
$R_{dc} (n_i - n_j)$ [pu]	(2-4) 0.05537	(2-5) 0.05426	(4-5) 0.01272

Table 3. Data of generation units

Unit (i)	c_i [\$]	b_i [\$/MW]	a_i [\$/MW ²]
P_{G1}	200	7.0	0.008
P_{G2}	180	6.3	0.009
P_{G3}	140	6.8	0.007
P_{G6}	200	7	0.008
P_{G8}	200	7	0.008

7. RESULTS AND COMMENTS

The objective of these simulations is to obtain a minimum total cost of active powers production of the AC-DC systems, the voltage profile and the equivalent losses matrix. After simulations, the Tables 4-5 show the PF results, before and after ED calculation. DC control variables for a system with one DC link are shown in Table 6. The results of total costs show amelioration in the costs after the ED calculation and the best amount is obtained for the system without DC links. The

equivalent losses matrixes are shown in (27) -(29) and in (30) -(32) respectively, for the systems with one DC link and multi-terminal DC links. Comparing with mixed systems, the lowest cost is obtained for the multi-terminal AC-DC system by an economy of 57 [\$/h]. The introductions of DC links affect the costs because they consummate the reactive powers that influence the active power productions. Adding DC links do not necessarily improve the total cost. Whereas, our simulations have improved the total cost for a multi-

terminal DC network, because we have added the third converter station in a generation node; where its need for reactive power is locally supplied. Fig. 4-6 show the

different values that take the total cost by PF and ED calculations; where, all simulations have the same form.

Table 4. Results obtained without ED calculation.

N°	System without DC links				System with one DC link				System with three DC links			
	V	δ	P	Q	V	δ	P	Q	V	δ	P	Q
1	1.06	0.00	-5.00	41.11	1.06	0.00	11.21	80.77	1.06	0.00	3.81	67.50
2	1.05	0.69	102.00	-12.18	1.03	-0.80	102.00	34.48	1.05	-1.16	102.00	2.42
3	1.01	-4.61	-81.88	2.91	0.96	-10.72	-81.88	16.17	0.98	-10.51	-81.88	14.43
4	1.02	-1.18	-66.92	-10.00	0.92	-10.20	-66.92	-43.97	0.94	-9.90	-66.92	-13.08
5	1.02	-0.43	-10.64	-2.24	1.00	4.78	-10.64	-45.32	0.96	6.65	-10.64	-47.65
6	1.06	2.50	84.32	13.94	1.03	3.49	84.32	16.50	1.02	4.93	84.32	24.66
7	1.02	3.15	0.00	0.00	0.95	-2.52	0.00	0.00	0.96	-2.24	0.00	0.00
8	1.05	11.68	90.00	25.94	1.04	6.68	90.00	58.38	1.04	6.89	90.00	54.03
9	1.00	-0.08	-41.30	-23.24	0.92	-4.89	-41.30	-23.24	0.93	-4.47	-41.30	-23.24
10	1.00	-0.03	-12.60	-8.12	0.93	-3.76	-12.60	-8.12	0.93	-3.18	-12.60	-8.12
11	1.02	1.08	-4.90	-2.52	0.97	-0.20	-4.90	-2.52	0.96	0.79	-4.90	-2.52
12	1.04	1.13	-8.54	-2.24	1.00	1.65	-8.54	-2.24	0.99	3.01	-8.54	-2.24
13	1.03	0.95	-18.90	-8.12	0.99	1.13	-18.90	-8.12	0.98	2.40	-18.90	-8.12
14	0.98	-1.16	-20.86	-7.00	0.92	-3.91	-20.86	-7.00	0.92	-3.14	-20.86	-7.00
Total cost			3671.37		3793.52				3737.19			

Table 5. Results obtained after ED calculation.

N°	System without DC links				System with one DC link				System with three DC links			
	V	δ	P	Q	V	δ	P	Q	V	δ	P	Q
1	1.06	0	22,65	36,50	1,06	0	-0,38	67,50	1,06	0	-0,38	70,59
2	1,04	0,13	80	0,24	1,04	-0,41	80	40,60	1,05	-0,28	98,33	-35,88
3	1,01	-2,94	-36,58	-10,5	0,99	-6,38	-31,88	13,65	1,01	-6,50	-31,88	17,46
4	1,01	-2,28	-66,92	-10	0,93	-7,89	-66,92	-77,93	0,96	-8,25	-66,92	-16,15
5	1,02	-1,73	-10,64	-2,24	1,00	4,15	-10,64	-88,40	0,96	3,78	-10,64	-91,68
6	1,05	-2,25	47,34	13,69	1,02	0,65	45,67	12,10	1,02	-1,07	36,06	27,46
7	1,01	0,10	0	0	0,96	-0,55	0	0	0,98	-2,67	0	0
8	1,04	7,28	74,70	20,67	1,04	10,10	105,04	55,42	1,04	6,35	90,34	44,59
9	0,99	-3,28	-41,3	-23,24	0,94	-3,97	-41,3	-23,24	0,95	-5,79	-41,3	-23,24
10	0,99	-3,52	-12,6	-8,12	0,94	-3,58	-12,6	-8,12	0,95	-5,39	-12,6	-8,12
11	1,02	-3,05	-4,9	-2,52	0,97	-1,61	-4,9	-2,52	0,98	-3,38	-4,9	-2,52
12	1,03	-3,53	-8,54	-2,24	0,99	-0,96	-8,54	-2,24	0,99	-2,68	-8,54	-2,24
13	1,02	-3,62	-18,9	-8,12	0,98	-1,27	-18,9	-8,12	0,98	-3,01	-18,9	-8,12
14	0,98	-4,98	-20,86	-7	0,93	-4,48	-20,86	-7	0,94	-6,25	-20,86	-7
Total cost			3627,32		3731,89				3674,89			

Table 6. The converter results of one DC link.

	Solution before optimization		Solution after optimization	
	Rectifier	Inverter	Rectifier	Inverter
V [PU]	0.915	1.01	0.933	0.999
Vd [PU]	0.9832	0.97*	0.9832	0.97*
KT	1.13	1.06	1.116	1.062
θ_d [°]	5*	15*	5*	15*
Pd [PU]	1.02*	1.0063	1.02*	1.0063
Qd [PU]	0.3396	0.4308	0.3396	0.4308
$\cos\phi$ [°]	18.417	23.176	18.417	23.176
Id [PU]	1.0374		1.0374	
Pd _{Loss} [PU]			0.0137	

* indicate specified value

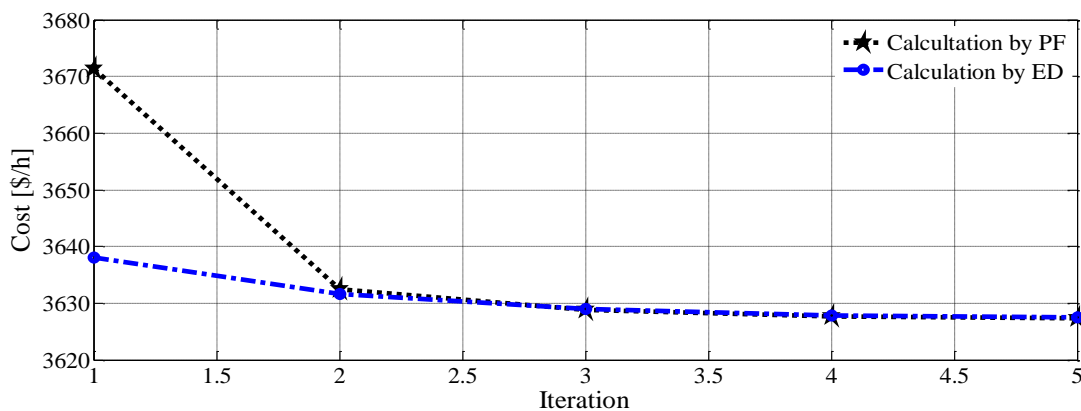


Fig. 4. Variations of total costs of the AC system without DC links.

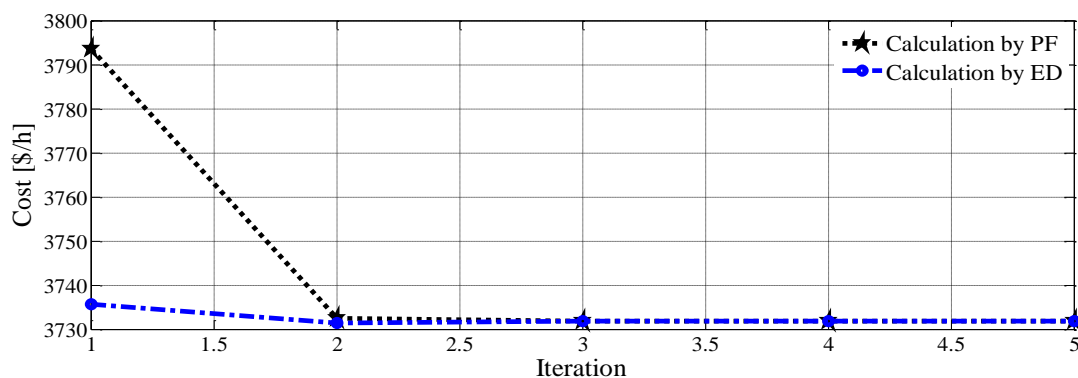


Fig. 5. Variations of total costs of the system in presence of one DC link.

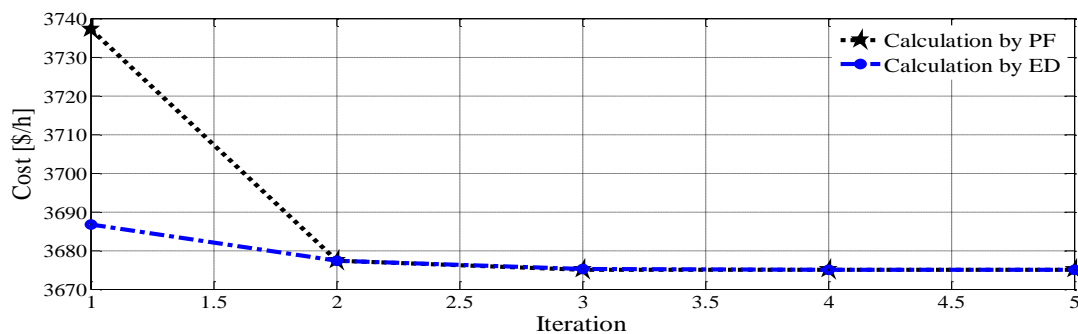


Fig. 6. Variations of total costs of the system in presence of the multi-terminal DC network.

During the calculations, we have noted that the DC power losses are not affected and remain constant in the iterative computation; this is due to the variations of the converter transformers ratios which kept the other control parameters without variation.

$$B = \begin{bmatrix} 0.2581 & 0.0390 & -0.0064 & 0.0392 & -0.0118 \\ 0.0390 & 0.0247 & 0.0040 & 0.0164 & -0.0016 \\ -0.0064 & 0.0040 & 0.0236 & 0.0000 & -0.0070 \\ 0.0392 & 0.0164 & 0.0000 & 0.0495 & -0.0057 \\ -0.0118 & -0.0016 & -0.0070 & -0.0057 & 0.0107 \end{bmatrix} \quad (27)$$

$$B_0 = [0.0201 \quad 0.0036 \quad -0.0007 \quad 0.0060 \quad -0.0017] \quad (28)$$

$$B_{00} = 0.0011 \quad (29)$$

$$B = \begin{bmatrix} 0.2873 & 0.0140 & -0.0101 & 0.0506 & -0.0307 \\ 0.0140 & 0.0259 & 0.0043 & 0.0008 & -0.0115 \\ -0.0101 & 0.0043 & 0.0212 & -0.0123 & -0.0086 \\ 0.0506 & 0.0008 & -0.0123 & 0.0763 & -0.0128 \\ -0.0307 & -0.0115 & -0.0086 & -0.0128 & 0.0236 \end{bmatrix} \quad (30)$$

$$B_0 = [0.0147 \quad -0.0001 \quad -0.0006 \quad 0.0068 \quad -0.0017] \quad (31)$$

$$B_{00} = 9.0992 \cdot 10^{-4} \quad (32)$$

8. CONCLUSION

In this article, we have studied the power flow in combined AC-DC systems for a single DC link and a multi-terminal DC system. The combination of the power flow calculation with the economic dispatch problem, and the technique of injection powers in AC-DC nodes, has successfully optimized the total cost of the total production of active powers in presence of DC power transmissions. The use of interior point method (IPM) for economic dispatch optimization with the Newtonian's methods of AC-DC power flow calculation has successfully converged the active power solution of the economic dispatch problem to those of power flow, which means the efficiency of the calculation technique and the validity of obtained economic results. In an acceptable margin of errors for new load demands, we can directly use the obtained losses matrix and losses DC powers to recalculate in real time the new economic solutions only by the economic dispatch problem calculation.

Nomenclature

F_i	The cost function of unit i
P_{Gi}	The active power of unit i
P_L	The total active power losses
P_D	Total demand of active power
P_{LAC}	The losses of the AC equivalent network devoid of all DC links.
P_{LDC}	The losses of all DC links
N_{dc}	Number of DC links.
θ_{tk}	The angle of firing delay for the rectifier and the extinction angle for the inverter

φ_k	The power factor at the converter,
T_k	The transformation ratio of the load tap changer
X_{ck}	The equivalent reactance of the converter transformer
R_{dc}	Resistance of the DC line,
V_k	The voltage on the primary side of the converter transformer
V_{dk}	The DC voltage
P_{dk}	The injected active power
Q_{dk}	The injected reactive power
I_d	The DC line current

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