Calculation of Nodal Pricing with Rescheduling of Generators in Deregulated Power System

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Abstract - The main objective of deregulation is to create competitive environment between producers and consumers. The transmission congestion is one of the technical problems that particularly appear in the deregulated power system. If congestion is not managed we face the problems of electricity price improvement, security and stability problems. Congestion relief can be handled using FACTS device such as TCSC and with the optimal power flow, where electricity price will be reduced. These FACTS devices are optimally placed on transmission system using Sensitivity approach method. The proposed methods are carried out on IEEE 14 bus system by using power world simulator 17 software.

Keywords - Deregulated power system, Nodal price, Optimal Power Flow (OPF), Thyristor Controlled Series Compensators (TCSC).

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1 INTRODUCTION

In present days all our basic needs are relates with electricity. As the population increases, the demand for electricity increases. People are expecting better quality of supply at most economical prices. This could only be achieved by unbundling the generation, transmission and distribution business and having sufficient competition in the power generation business. Overall this phenomenon is generally termed as deregulation. To induce efficient use of both the transmission grid and generation resources by providing correct economic signals, a nodal price or spot price theory for the deregulated power systems was developed [1], [2].

The deregulated electricity markets had to deal with number of issues such as congestion, losses, pricing, ancillary services, market power etc. [4]. The most fundamental of these is the problem of congestion. Fundamental concept on which these congestion management techniques are based on the Nodal price also called the Spot Price.

Nodal price is the marginal cost of supplying the next increment of electric energy at a specific bus while considering the generation marginal cost and the physical limits of the transmission system. More general Nodal price decomposition was presented in [7], [8], [9] with three components: marginal energy, loss, and congestion components.

Many of these now established technologies fall under the title of FACTS [10] (Flexible AC Transmission Systems). Introducing FACTS technology is used to controlling power and losses in transmission line. To achieve minimum losses in transmission line, find the optimal place of transmission line & locate the FACTS device. Thyristor Controlled Series Capacitor (TCSC) is a variable impedance type FACTS device and is connected in series within the transmission line to increase the power transfer capability, improve transient stability, and reduce transmission losses [11].

2 THYRISTOR CONTROLLED SERIES COMPENSATOR (TCSC)

Thyristor controlled series compensator (TCSC) is connected in series with transmission lines. It is equivalent to a controllable reactance inserted in series with a line to compensate the effect of the line inductance. The net transfer reactance is reduced and leads to an increase in power transfer capability. The basic structure of TCSC, shown in Figure 1.

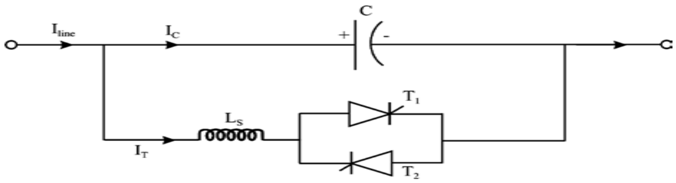


Figure 1: Basic structure of Thyristor Controlled Series Capacitor

2.1 Modelling of TCSC:

The transmission line model with a TCSC connected between the two buses *i* and *j* is shown in Fig 3. Equivalent model is used to represent the transmission line. TCSC can be considered as a static reactance of magnitude equivalent to$-jX_C$. The controllable reactance is directly used as control variable to be implemented in power flow equation

$$S_{ij}^* = P_{ij} - Q_{ij} = V_i^* I_{ij} (1)$$

$$= \left[\left(V_i - V_j\right)Y_{ij} + V_i\left(jB_c\right)\right] (2)$$

$$= V_i^*\{\left[G_{ij} + j\left(B_{ij} + B_c\right)\right] - V_i^* V_j\left(G_{ij} + jB_{ij}\right)\} (3)$$

$$G_{ij} + jB_{ij} = \frac{1}{R_L + jX_L - jX_c} (4)$$

From the above equations the real and reactive power equations can be written as

$$P_{ij} = V_i^2 G_{ij} - V_i V_j G_{ij} \cos(\delta_i - \delta_j) - V_i V_j B_{ij} \sin\left(\delta_i - \delta_j\right) (5)$$

$$Q_{ij} = -V_i^2\left(B_{ij} + B_{sh}\right) - V_i V_j G_{ij} \sin\left(\delta_i - \delta_j\right) + V_i V_j B_{ij} \cos\left(\delta_i - \delta_j\right) (6)$$

Similarly the real and reactive powers from bus *j* to *i* can also be represented replacing *Vi* by *V*j.

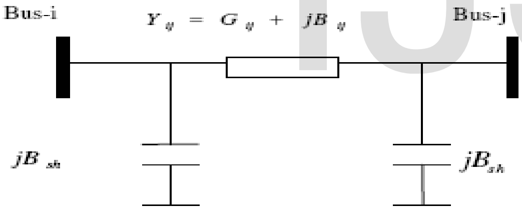


Figure 2: Modal of transmission line.

The real and reactive power flow from bus- i to bus -j, of a line having series impedance and a series reactance are,

$$P_{ij}^c = V_i^2 G_{ij}^{'} - V_i V_j G_{ij}^{'} \cos(\delta_i - \delta_j) - V_i V_j B_{ij}^{'} \sin\left(\delta_i - \delta_j\right) (7)$$

$$Q_{ij}^c = -V_i^2\left(B_{ij}^{'} + B_{sh}\right) - V_i V_j G_{ij}^{'} \sin\left(\delta_i - \delta_j\right) + V_i V_j B_{ij}^{'} \cos\left(\delta_i - \delta_j\right) (8)$$

Similarly the real and reactive powers from bus *j* to *i* can also be represented replacing *Vi* by *V*j.

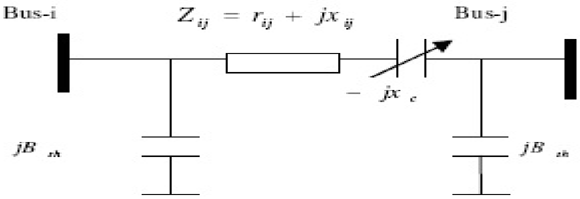


Figure 3: Model of Transmission line with TCSC.

The active and reactive power loss in the line having TCSC can be written as

$$P_L = P_{ij}^c + P_{ji}^c$$

$$= G_{ij}^{'}\left(V_i^2 + V_j^2\right) - 2V_i V_j G_{ij}^{'} \cos(\delta_i - \delta_j) (9)$$

$$Q_L = Q_{ij}^c + Q_{ji}^c$$

$$= -\left(V_i^2 + V_j^2\right)\left(B_{ij}^{'} + B_{sh}\right) + 2V_i V_j B_{ij}^{'} \cos(\delta_i - \delta_j) (10)$$

Where $G_{ij}^{'} = \frac{r_{ij}}{r_{ij}^2 + (x_{ij} - x_c)^2}$

$$B_{ij}^{'} = -\frac{(x_{ij-x_c})}{r_{ij}^2 + (x_{ij} - x_c)^2}$$

The change in the line flow due to series capacitance can be represented as a line without series capacitance with power injected at the receiving and sending ends of the line asshowninFigure

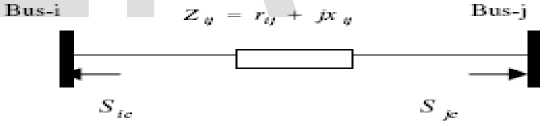


Figure 4: Injection Model of TCSC.

The real and reactive power injections at bus-i and bus-j can be expressed as

$$P_{ic} = V_i^2 \Delta G_{ij} - V_i V_j\left[\Delta G_{ij} \cos\left(\delta_i - \delta_j\right) + \Delta B_{ij} \sin(\delta_i - \delta_j)\right] (11)$$

$$P_{jc} = V_j^2 \Delta G_{ij} - V_i V_j\left[\Delta G_{ij} \cos\left(\delta_i - \delta_j\right) - \Delta B_{ij} \sin(\delta_i - \delta_j)\right] (12)$$

$$Q_{ic} = -V_i^2 \Delta B_{ij} - V_i V_j\left[\Delta G_{ij} \sin\left(\delta_i - \delta_j\right) + \Delta B_{ij} \cos(\delta_i - \delta_j)\right] (13)$$

$$Q_{jc} = -V_j^2 \Delta B_{ij} + V_i V_j\left[\Delta G_{ij} \sin\left(\delta_i - \delta_j\right) - \Delta B_{ij} \cos(\delta_i - \delta_j)\right] (14)$$

Where $\Delta G_{ij} = \frac{r_{ij} x_c (x_c - 2x_{ij})}{\left(r_{ij}^2 + \left(x_{ij} - x_c\right)^2\right)\left(r_{ij}^2 + x_{ij}^2\right)}$

$$\Delta B_{ij} = \frac{-x_c(r_{ij}^2 - x_{ij}^2 + x_{ij}x_c)}{(r_{ij}^2 + (x_{ij} - x_c)^2)(r_{ij}^2 + x_{ij}^2)}$$

This Model of TCSC is used to properly modify the parameters of transmission line with TCSC for optimal location

3. SENSITIVITY APPROACH FOR OPTIMAL LOCATION OF TCSC

Generally, the location of FACTS devices depends on the objective of the installation. The reactive power loss sensitivity factors with respect to these control variables may be given as follows [17]:

1. Loss sensitivity with respect to control parameter of X_{ij}TCSC placed between buses i and j,

$$\boldsymbol{a_{ij} = \frac{\partial QL}{\partial x_{ij}} = [Vi^2 + Vj^2 - 2ViVj\cos(\delta_i - \delta_j)]\frac{Rij^2 - Xij^2}{(Rij^2 + Xij^2)^2}} \quad (15)$$

Where, V_i is the voltage at bus i,

V_j is the voltage at bus j,

R_{ij} is resistance of line between bus i and j,

X_{ij} is the reactance connected between bus i and j.

4. OPTIMAL POWER FLOW

In 1962, Carpentier introduced a generalized nonlinear programming (NLP) formulation of the economic dispatch (ED) problem including voltage and other constraints. The problem was later termed as OPF. Today OPF plays a very important role in power system operation and planning.

4.1 Example 3 Bus System

For example consider a simple three bus system. For three bus system branch data and generator data is given below.

Table 1: Branch data for the three bus system.

Branch	Reactance(p.u)	Capacity (MW)
1 – 2	0.2	126
1-3	0.2	150
2-3	0.1	130

Table 2: Generator data for the three bus system.

Generator	Capacity(MW)	Marginal cost ($/MWh)
A	140	7.5
B	285	6
C	90	14
D	85	10

4.1.1 Economic dispatch

If we ignore the constraints in the network, the total load of 410 MW should be dispatched solely on the basis of bids or marginal costs of the generators in a way that minimizes the total cost of supplying the demand. We have assumed that these generators have the constant marginal cost over the entire range of operation. The generators are ranked in order of increasing marginal cost and loaded up to their capacity limit [20].

$$P_A = 125\text{MW}$$

$$P_B = 285\text{MW}$$

$$P_C = 0\text{MW}$$

$$P_D = 0\text{ MW} \quad (16)$$

The total cost of economic dispatch is

$$C_{ED1} = MC_A P_A + MC_B P_B = (7.5*125 + 6*285)$$

$$= 2647.50\ \$/\text{h} \quad (17)$$

We would calculate the branch flows using a power flow diagram, this will be given below. We can write the power balance equation at each bus or node as follows.

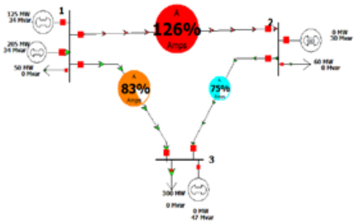


Figure 5: Basic dispatch in three bus system.

Node 1: $F_{12} + F_{13} = 157.28 + 202.68 = 360\ MW$(18)

Node 2: $F_{12} - F_{23} = 157.28 - 97.28 = 60 MW$(19)

Node 3: $F_{13} + F_{23} = 202.68 + 97.28 = 300\ MW$(20)

The above three equations are linearly dependent, so it is difficult to solve these equations. For example subtracting node 2equation from node 1equation gives node 3 equation, then one equation is eliminated with no loss of information, we are left with two equations with three unknowns. This is hardly surprising because we have not taken into account the impedances of the branches. Our original problem can be decomposed into two simpler problems. By using the super position theorem we can easilyfindtheflows.

$$F_{12} = F_1^A + F_2^A (21)$$

$$F_{13} = F_1^B + F_2^B (22)$$

$$F_{23} = F_1^A - F_2^B (23)$$

Let us consider the first problem. 300MW is injected at bus 1 and taken out at bus 3. Power flow along the paths A, B is

$$F_1^A + F_1^B = 300MW (24)$$

The reactances of paths A and B are

$$x_1^A = x_{12} + x_{23} = 0.1 + 0.2 = 0.3\ p.u (25)$$

$$x_1^B = x_{13} = 0.2\ p.u$$

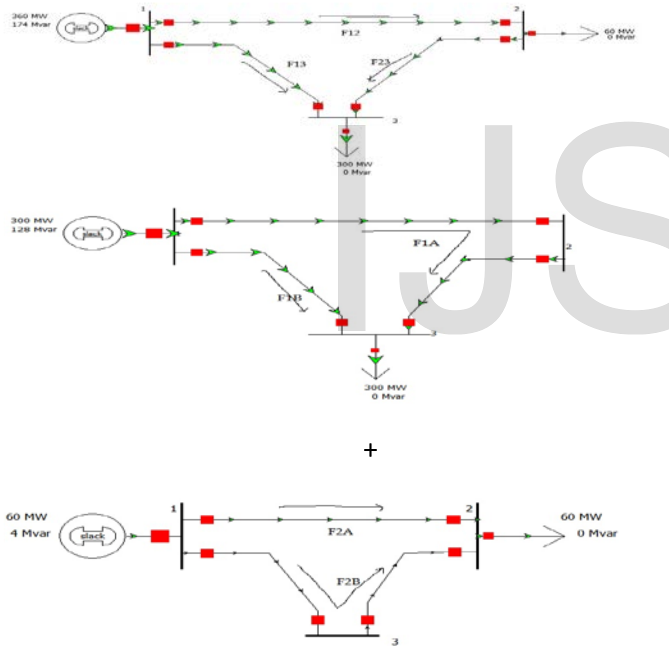


Figure 6: Application of super position theorem to calculate line flows in three bus system.

Since these 300MW divides themselves between the two paths

$$F_1^A = \frac{0.2}{0.3+0.2} * 300 = 120MW (26)$$

$$F_1^B = \frac{0.3}{0.3 + 0.2} * 300 = 180MW (27)$$

Similarly for second circuit 60 MW is injected at bus 1 and taken out at bus 2. In this case, the impedances of the two paths are

$$x_2^B = x_{13} + x_{23} = 0.1 + 0.2 = 0.3\ p.u (28)$$

$$x_2^A = x_{12} = 0.2 p.u (29)$$

$$F_2^A = \frac{0.3}{0.3 + 0.2} * 60 = 36MW (30)$$

$$F_2^B = \frac{0.2}{0.3 + 0.2} * 60 = 24MW (31)$$

The power flows in the original system are:

$$F_{12} = F_1^A + F_2^A = 120 + 36 = 156\ MW\ (32)$$

$$F_{13} = F_1^B + F_2^B = 180 + 24 = 204MW\ (33)$$

$$F_{23} = F_1^A - F_2^B = 120 - 24 = 96MW (34)$$

From the above results we conclude that the economic dispatch would overload the branch 1-2 by 30 MW because it would have to carry 156 MW when its capacity is only 126 MW. This is clearly not acceptable.

4.1.2 Correcting the Economic Dispatch

The economic dispatch minimizes the total production cost, but obtained solution is not acceptable because this is not satisfies the security criteria. Therefore we began least cost modifications that will remove the line overload. To reduce the flow on line 1-2, we can increase the generation at bus2 or bus 3.

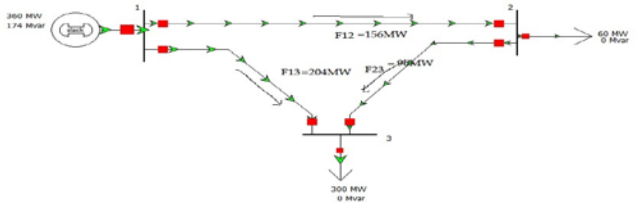


Figure7: Flows for economic dispatch in three bus system.

Case 1: Let us first consider the increase in generation at bus 2 by 1MW. We neglect losses that must reduce the generation at bus 1 by 1MW.figure below shows the incremental re dispatch of the three bus system. In this incremental flow ΔF^A is the opposite direction to the flow F_{12}, increasing the generation at bus 2 and reducing the generation at bus 1 will reduce the overload on branch 1-2.

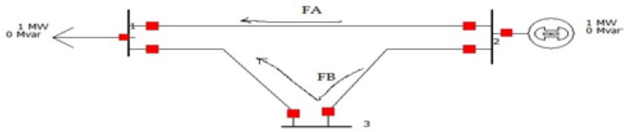


Figure 8: Effect of incremental change in the generation at bus 2

The reactances of paths A and B are

$$x^A = x_{12} = 0.2\,p.u(35)$$

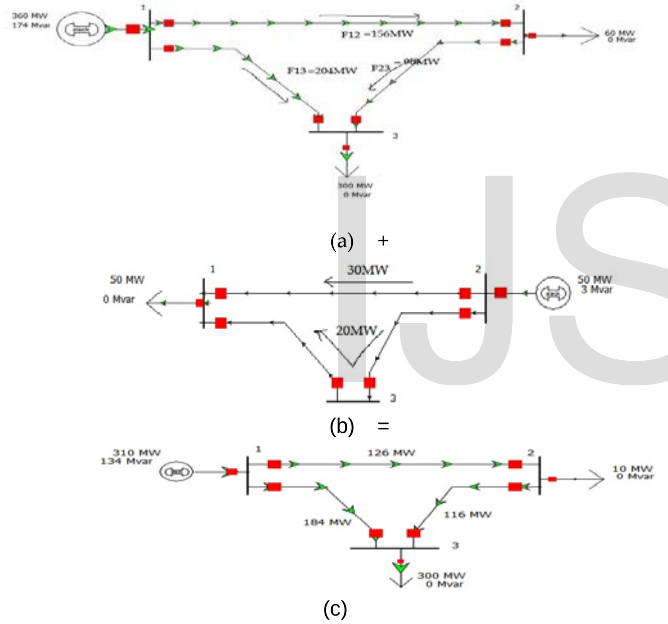
$$x^B = x_{13} + x_{23} = 0.3\,p.u(36)$$

Sum of two flows must be equal to 1 MW, we get

$$\Delta F^A = 0.6MW \ (37)$$

$$\Delta F^B = 0.4MW \ (38)$$

Every megawatt injected at bus 2 and taken out at bus 1 thus reduces the flow on branch 1-2 by 0.6 MW. Line 1-2 is overloaded by 30 MW, a total of 50MW of generation is shifted from bus 1 to bus 2 to satisfy line capacity constraint. Figure below shows the re dispatch and its superposition with the economic dispatch to obtain a constraindispatch.



(a) +

(b) =

(c)

Figure 9: Superposition of re dispatch of generation from bus 1 to bus 2 (b) on the economic dispatch (a) to produce a constrained dispatch that meets the constraints on line flows (c)

From the above figures it would be concluded that flow on the branch 1-3 is also reduces but the flow on the branch 2-3 is increases.

To produce the constrained dispatch generators connected at bus 1 must produce 360 MW to meet the local load of 50 MW and inject the 310 MW into the network. The generator at bus 2 must produce 50 MW and an additional 10 MW is taken from the network to supply a local load of 60 MW. The least cost generation dispatch is

$$P_A = 75 \text{ MW}$$

$$P_B = 285 \text{ MW}$$

$$P_C = 50 \text{ MW}$$

$$P_D = 0 \text{ MW} \ (39)$$

From the above equations, we comparing that output of generator A has been reduced than that of output of generator B, because the generator A has the highest marginal cost.

The total cost of constrained dispatch is

$$C_{ED2} = MC_A P_A + MC_B P_B + MC_c P_c$$

$$= (7.5*75+6*285+14*50) = 2972.5 \ \$/h \ (40)$$

Comparing the costs this cost is higher than the cost of the economic dispatch. The difference represents the cost of achieving the security using this re dispatch.

Case 2: We mentioned above we could also relieve overload on the branch 1-2 by increasing the output of generator D connected at bus 3. In this case extra MW is injected at bus 3 and taken out at bus 1.

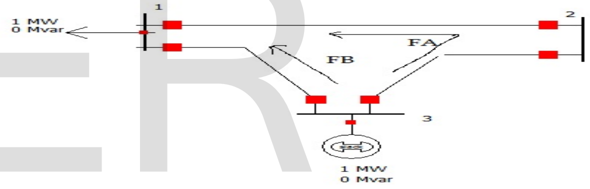


Figure 10: Effect of incremental change in the generation at bus 3.

Reactances of paths A and B are

$$x^B = x_{13} = 0.2\,p.u \ (41)$$

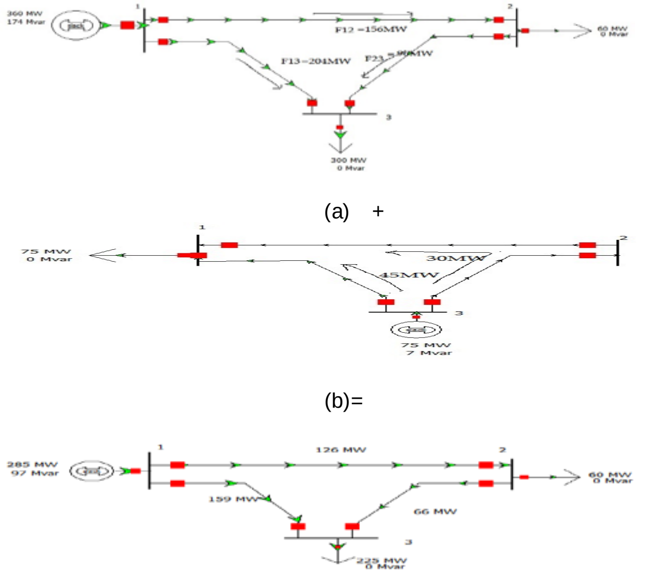
$$x^A = x_{12} + x_{23} = 0.3\,p.u \ (42)$$

And the sum of two flows must be equal to 1MW

$$\Delta F^A = 0.4MW \ (43)$$

$$\Delta F^B = 0.6MW \ (44)$$

Every MW is injected at bus 3 and taken out at bus 1 that reduces the flow on the branch 0.4 MW and increases the flow on the branch 1-3. This means that we need to shift 75MW of generation from bus 1 to bus 3 to reduce the overload on the branch 1-2. Below figures shows the superposing this re dispatch on the economic dispatch reduces the flows through all the branches of the network.



(a) +

(b)=

(c)

Figure 11: super position of the re dispatch of generation from bus 1 to bus 3 (b) on the economic dispatch (a) to produce a constrained dispatch that meets the constraints on line flows (c)

Flow on the branch 1-2 is equal to the maximum capacity of that branch. Total power produced at bus 1 is now reduced by 75 MW the generation dispatch of this case is

$$P_A = 50 \text{ MW}$$

$$P_B = 285 \text{ MW}$$

$$P_C = 0 \text{ MW}$$

$$P_D = 75 \text{ MW} \quad (45)$$

The total cost of this constrained dispatch is

$$C_{ED3} = MC_A P_A + MC_B P_B + MC_D P_D$$

$$= (7.5*50+6*285+10*75) = 2835 \text{ \$/h} \quad (46)$$

Let us compare the ways of removing the over load on the branch 1-2. If we make use of the generation at bus 3 we would re dispatch 75 MW. On the other hand we make use of the generation at bus 2 we would re dispatch 50 MW. This is because flow on the branch 1-2 is less sensitivity at bus 3 compared to bus 2. Since marginal cost of generator D is less compared to generator C. So case 2 is more preferred. The difference between the cost of constrained dispatch and the cost of economic dispatch is the cost used to make the system more secure.

$$C_S = C_{ED3} - C_{ED1} = 2835 - 2647.5 = 187.5 \ \$/\square\square h \quad (47)$$

4.1.3 Nodal Prices

The nodal marginal price is equal to the cost of supplying an additional megawatt of load at the node under consideration by the cheapest possible means.

In our above three bus example output of generator D has been increased to remove overload on the branch 1-2. At node 1 it is clear that an additional megawatt of load should be produced by generator A. The marginal cost of generator A is lower than the marginal cost of generators C, D, while it is higher than the generator B. Generator B is already loaded up to their maximum capacity and therefore it is unable to produce additional megawatt.

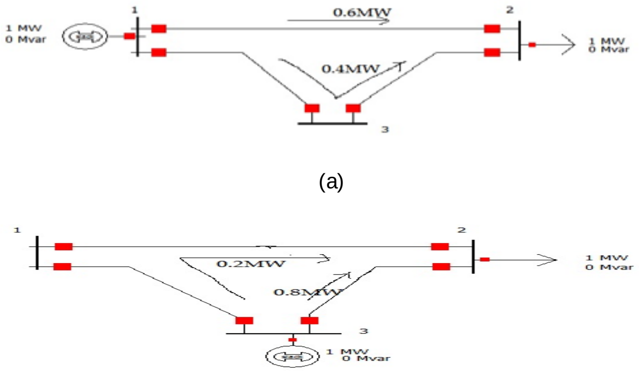
The nodal marginal price at bus 1 is

$$\pi_1 = MC_A = 7.5 \ \$/MWh \quad (48)$$

Increasing the generation at bus 1 then overload the branch 1-2. The next cheapest option is to increase the output of generator D. Since generator is located at bus 3. So the nodal marginal price at bus 3 is

$$\pi_3 = MC_D = 10 \ \$/MWh \quad (49)$$

Supplying an additional MW at bus 2 is more complex matter we could generate it locally at bus 2 using the generator C. But it is more expensive because the marginal cost of generator C is 14 $/MWh, it is higher than all the generators marginal cost.



(a)

(b)

Figure 12: Incremental flows in the network due to an additional MW of load at node 2 when the MW is produced at (a) bus 1 (b) bus 3.

We can see that in both cases the power flow on the branch 1-2 is increased. Since flow on the branch 1-2 is reached its maximum capacity so neither solution is acceptable. We would increase the generation at bus 3 by 2 MW and reduce it at bus 1 by 1MW. The net increase is additional load at bus 2. Below diagrams shows this.

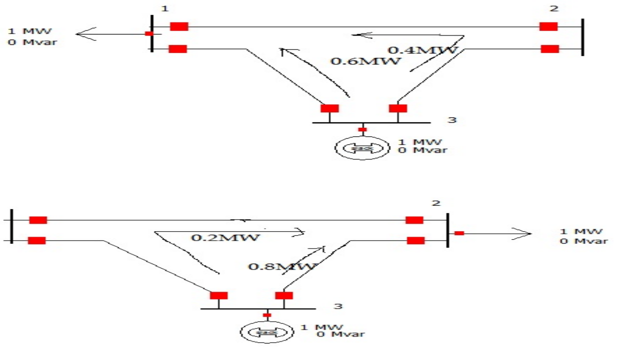


Figure 13: Application of super position theorem diagrams.

The first diagram shows that if 1 MW is injected at bus 3 and taken out at bus 1, the flow on the branch 1-2 would decrease by 0.4 MW. The other diagram shows that another 1MW is injected at bus 3 and taken out at bus 2 increases the flow on the branch by o.2 MW. This is acceptable because the total flow on the branch 1-2 is decreases by 0.2 MW and it is below the maximum capacity limit, and it is not optimal

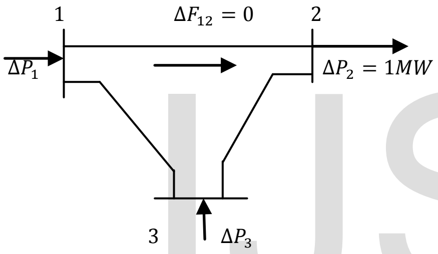


Figure14: Formulation of an additional megawatt of load at bus 2 without changing the flow on the branch 1-2.

We can supply an additional megawatt at bus 2 by redispatching generation at buses 1 and 3 without overloading branch 1-2. We must have

$$\Delta P_1 + \Delta P_3 = \Delta P_2 = 1MW \quad (50)$$

Using the sensitivities shown in the figure 12, we can also write

$$0.6\Delta P_1 + 0.2\Delta P_3 = \Delta F_{12} = 0MW \quad (51)$$

Solving the above two equations, we get

$$\Delta P_1 = -0.5 \text{ MW} \quad (52)$$

$$\Delta P_3 = 1.5 \text{ MW} \quad (53)$$

Supplying at minimum cost an additional megawatt at bus 2 therefore requires that we increase the output of generator D by 1.5 MW and reduce the output of generator A by 0.5 MW. Hence the nodal price at bus 2 is

$$\pi_2 = 1.5\, MC_D - 0.5\, MC_A = 1.5 * 10 - 0.5 * 7.5$$

$$= 11.25\ \$/MWh \quad (54)$$

In summary, we observe that

- Generator A sets a price of 7.5 $/MWh at bus 1. Generator B has the lowest marginal cost 6.0 $/MWh but has no influence on nodal prices because it operates at its maximum capacity.
- Generator D has a nodal price of 10 $/MWh at bus 3.
- At bus nodal price is set to 11.25 $/MWh by a combination of other generators.

5.SIMULATION AND RESULTS DISCUSSION

The study has been conducted on the calculation of nodal prices of an IEEE14 bus system using power world simulator 17.0.

For this system nodal prices are calculated by placing the FACTS device TCSC in optimal location using sensitivity approach method and with optimal power flow method.

Case study: IEEE 14 BUS SYSTEM

5.1 IEEE 14 bus system without compensation

This system consists of 14 buses, 17 line sections, 5 generator buses and 8 load buses.

The below figure shows the transmission line flows. The nodal prices of IEEE 14 bus system is as follows.

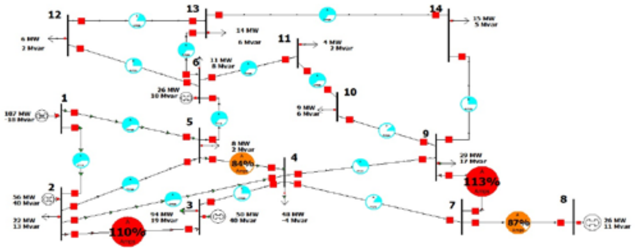


Figure 15: single line diagram of IEEE 14 bus system.

Table 3: Nodal prices of IEEE 14 bus system

Bus Number	MW Marg. Cost $/MWh	Energy cost $/MWh	Congestion cost $/MWh	Losses cost $/MWh
1	5000	5000	0	0
2	5104.73	5000	-31.35	136.08
3	5880.89	5000	528.54	352.36

4	5467.05	5000	138.56	328.49
5	5381.41	5000	112.49	268.92
6	5525.22	5000	270.55	254.67
7	5168.85	5000	-169.94	338.79
8	5173.3	5000	-163.85	337.14
9	5937.6	5000	590.19	347.4
10	5907.36	5000	590.19	367.61
11	5740.61	5000	408.99	331.62
12	5649.22	5000	296.73	352.48
13	5713.56	5000	325.27	388.29
14	5990.61	5000	491.62	498.99

Nodal price is sum of energy component cost, loss component cost and a congestion component cost. In IEEE 14 bus system congestion is formed so the congestion cost is included so the total nodal price is increases. To minimize the congestion cost we will use rescheduling of generators (optimal power flow control) so the total cost is decreases.

5.2 IEEE 14 bus system with OPF

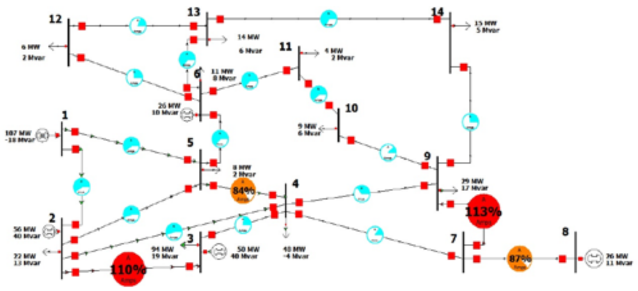


Figure 16: single line diagram of IEEE 14 bus system with OPF.

Table 4: Nodal prices of IEEE 14 bus system with OPF.

Bus Number	MW Marg. Cost $/MWh	Energy cost $/MWh	Congestion cost $/MWh	Losses cost $/MWh
1	5000	5000	0	0
2	5136.08	5000	0	136.08
3	5352.36	5000	0	352.36
4	5328.49	5000	0	328.49
5	5268.92	5000	0	268.92
6	5254.67	5000	0	254.67
7	5338.79	5000	0	338.79
8	5337.14	5000	0	337.14
9	5347.4	5000	0	347.4
10	5367.61	5000	0	367.61
11	5331.62	5000	0	331.62
12	5352.48	5000	0	352.48
13	5388.29	5000	0	388.29
14	5498.99	5000	0	498.99

By using optimal power flow control congestion cost is zero but the losses cost is exist so we minimize the losses in the system by placing different FACTS devices like TCSC in optimal location using sensitivity approach method. By using TCSC congestion and losses are going to be reduced.

5.3 IEEE 14 bus system with TCSC

The sensitivity indices table of IEEE 14 bus system is shown below.

Table 5: Sensitivity indexes for IEEE 14 bus system.

Line number	From bus	To bus	With compensation		
			20%comp	30%com	40%com
1	1	2	-0.3734	-0.3395	-0.2836
2	1	5	-0.1303	-0.1246	-0.1161
3	2	3	-0.1328	-0.1272	-0.1188
4	2	4	-0.088	-0.0785	-0.0655
5	2	5	-0.0558	-0.0508	-0.043
6	3	4	-0.0173	-0.0154	-0.0122

7	4	5	-0.1068	-0.0986	-0.0866
8	4	7	-0.0102	-0.0142	-0.0217
9	4	9	-0.0079	-0.0079	-0.0081
10	5	6	-0.061	-0.0678	-0.0793
11	6	11	-0.0059	-0.0044	-0.0027
12	6	12	-0.0035	-0.0026	-0.0016
13	6	13	-0.0185	-0.0135	-0.0072
14	7	8	-0.0778	-0.0787	-0.0808
15	7	9	-0.1297	-0.1293	-0.1288
16	9	10	-0.00099	-0.00087	-0.00074
17	9	14	-0.0037	-0.0029	-0.0018
18	10	11	-0.0028	-0.0022	-0.0016
19	12	13	**0.000152**	**0.000199**	**0.000235**
20	13	14	-0.0027	-0.002	-0.0011

From the above table 5 the line12-13 have the most positive sensitivity index. So this is the best location for placement of TCSC to relieve congestion and minimize the losses in the network. The single line diagram of IEEE 14 bus system after placing TCSC is shown below.

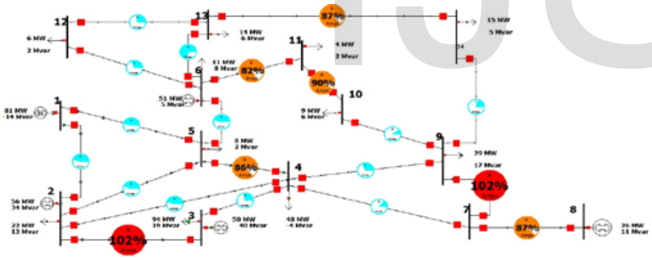


Figure 17: single line diagram of IEEE 14 bus system with TCSC in line 12-13.

After placing TCSC in line 12-13, the congestion in the network is relieved and also losses are minimized. So the nodal prices of the system are reduced. The nodal prices of IEEE 14 bus system with TCSC are shown below.

Table6: Nodal prices of IEEE 14 bus system with TCSC.

Bus Number	MW Marg. Cost $/MWh	Energy cost $/MWh	Congestion cost $/MWh	Losses cost $/MWh
1	5000	5000	0	0
2	5073.37	5000	-31.01	104.38
3	5832.79	5000	527.13	305.66
4	5401.35	5000	139.14	262.21
5	5307.06	5000	110.01	197.05
6	5393.59	5000	248.42	145.17
7	5146.5	5000	-145.48	291.98
8	5152.09	5000	-138.41	290.49
9	5888.83	5000	578.09	310.74
10	5846.14	5000	526.08	320.06
11	5645.51	5000	390.51	255
12	5512.11	5000	274.2	237.91
13	5594.68	5000	304.04	290.64
14	5911.41	5000	475.99	435.43

Comparison of Nodal prices without compensation, with TCSC and with OPF are as follows.

Table 7.5: Nodal price list without compensation, with TCSC and with OPF of an IEEE 14 bus system

Bus number	Nodal prices $/MWh		
	Without compensation	With TCSC	With OPF
1	5000	5000	5000
2	5104.73	5073.37	5136.08
3	5880.89	5832.79	5352.36
4	5467.05	5401.35	5328.49
5	5381.41	5307.06	5268.92
6	5525.22	5393.59	5254.67
7	5168.85	5146.5	5338.79
8	5173.3	5152.09	5337.14
9	5937.6	5888.83	5347.4
10	5907.36	5846.14	5367.61
11	5740.61	5645.51	5331.62
12	5649.22	5512.11	5352.48
13	5713.56	5594.68	5388.29
14	5990.61	5911.41	5498.99

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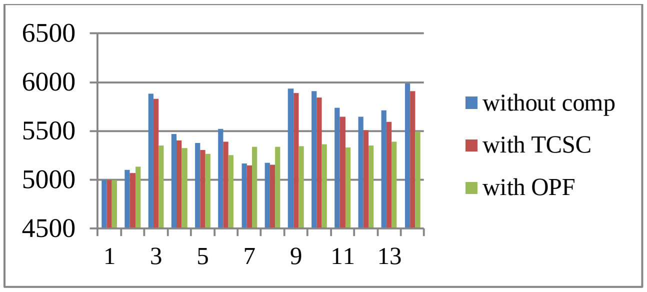

Graph 1: Nodal price comparison without compensation, with TCSC and with OPF of an IEEE 14 bus system.

6. CONCLUSION

The challenge for engineers is to produce and provide an electrical energy to consumers in a safe, economical and environmentally friendly manner under various constraints. In deregulated environment, the location of FACTS devices and their control can significantly affect the operation of the system.

In this paper a simple sensitivity approach is proposed, it will give a solution for determining optimal location of FACTS devices in a deregulated power system to relieve congestion on system and then nodal prices of the system reduces. An optimal power flow model minimizing the congestion cost for re - dispatch of generators and then congestion cost is reduces to zero, then nodal prices of the system reduces. This method was successfully tested on IEEE 14 bus system. The nodal prices with OPF and with FACT device were described in this paper.

REFERENCES:

[1] S. Stoft, *Power System Economics—Designing Markets for Electricity* New York: IEEE/Wiley, 2002.

[2] M. Ilic, F. Galiana, and L. Fink, *Power Systems Restructuring Engineering and Economics*. Norwell, MA: Kluwer, 1998.

[3] M. L. Baughman, S. N. Siddigi, and J. W. Zarnikau, “Advanced pricing in electrical systems,” *IEEE Trans. Power Syst.*, vol. 12, pp. 489–502, Feb. 1997.

[4] F. C. Schweppe, M. C. Caramanis, R. D. Tabors, and R. E. Bohn *Spot Pricing of Electricity*. Boston, MA: Kluwer, 1988.

[5] R.D. Christie, B.F. Wollenberg and I. Wangstein, “Transmission Management in the Deregulated Environment”, *Proc. of the IEEE*, Vol. 88, No.2, Feb. 2000, pp. 170-195.

[6] A.J. Conejo, E. Castillo, R. Mínguez and F. Milano, "Locational Marginal Price Sensitivities," IEEE Trans. Power Syst., vol. 20, no. 4, pp. 2026- 2033, Nov. 2005

[7] R. J. Kaye, F. F. Wu, and P. Varaiya, “Pricing for system security in *Proc. IEEE Winter Power Meeting*, 1992, Paper 92-WM-100-8.

[8] S. Oren, P. Spiller, P. Varaiya, and F. F.Wu, “Nodal prices and transmission rights: A critical appraisal,” *Electricity J.*, vol. 8, no. 3, pp. 24–35,1995.

[9] M.C. Caramanis, R.E. Bohn and F.C. Schweppe, "Optimal Spot Pricing: Practice and Theory,"IEEE Transactions on PAS, Vol 101, No. 9, pp. 3234-3245, Sept. 1982.

[10] Introduction to Deregulation in Power Industry. A. R. Abhyankar Prof S. K. K hapardhe, Indian Institute of Technology, Mumbai.

[11] Deregulation nptel notes. www.nptel.ac.in

[12] Global Journal of Researches in Engineering: F Electrical and Electronics Engineering Volume 14 Issue 6 Version 1.0 Year 2014 Online ISSN: 2249-4596 & Print ISSN: 0975-5861

[13] Transmission congestion management, power system stability, nptel notes by ravinder kumar.www.nptel.ac .in

[14] “Understanding FACTS, Concepts & Technology of Flexible AC Transmission Systems” N. G. Hingorani & L.Gyugyi New York: IEEE, 2000.

[15] Modelling and Analysis of SVC,TCSC, TCPAR in power flow Studies N. M. G Kumar, P.

[16] K. Vijayakumar, “Optimal location of FACTS Devices for Congestion management in Deregulated power system,” International Journal of Computer Applications, Vol 16, pp.0975-8887, feb, 2011

[17] Abouzar samimi, Peyman Naderi “*A New Method for Optimal Placement of TCSC based on Sensitivity Analysis for Congestion management*,” Smart Grid and Renewable Energy, 2012, 3, 10-16.

[18] Modern power system analysis by X.F Wang et al.

[19] Power systems analysis and design by J. Duncan Glover, mulukutla Sharma, Thomas over bye.

[20] Fundamentals of power system economics Daniel Kirchen and Goran Strbac © 2004 John Wiley & Sons Ltd ISBN: 0-470-84572-4

[21] The power world software and case files in www.powerworld.com/GloversarmaOverbye

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