ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 1, July 2017

Congestion Management in Deregulated Power System Using Market Splitting Based Approach

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Abstract— ***Congestion management in deregulated power system is a major issue which hinders the fair competition among various players. Congestion in deregulated power system occurs mainly due to the insufficient capacity of transmission lines, which is unable to accommodate all the desired power transactions. This research work proposes market splitting based approach for congestion management. The objective of this research work is to minimize the generation cost of generation companies subject to various constraints such as power balance equality constraints and generator operating limits, line flow limits and bus voltage limits inequality constraints. The proposed problem has been solved for base case without congestion and then with including the effect of congestion. In base case, as the location marginal prices (LMPs) are same everywhere, hence the market can be cleared at single price. In case of congestion, different zones are used for market splitting. Within a particular zone, a single LMP is obtained by taking average of all the LMPs at different locations of one zone. The zone with highest LMP can be used for placement of DG which further helps for congestion management. The proposed problem has solved with DC Optimal Power Flow (DCOPF) in MATLAB environment. The results obtained after DCOPF are used to obtain state of the power system and actual line flows with the aid of MiPOWER software. The simulation results are obtained for modified IEEE 14 bus system. The proposed approach has the advantage that it can be applied to Indian market scenarios for congestion management.***

Index Terms—**AC power flow (ACPF), Congestion management, DC optimal power flow (DCOPF), Locational marginal price.**

I. INTRODUCTION

The need for higher economic efficiency has led to privatization, restructuring and deregulation of the electric power industries in several countries.The main objective of restructuring of electric power industry was to allow private market player to take part in the planning and operation of power system. The basic motive behind the change of power industry was that its efficiency would increase and also customers would get new choices and economic benefits. Competition in restructured power system has brought new technical problems and challenges for power engineers and researchers. In order to meet the increasing demand of electricity around the world transmission system has to drive even beyond or close to their thermal limits, stability limits, voltage limits etc. thus endangering the transmission system security [1]. If the power exchanges through the transmission lines are not controlled, some of the lines may get overloaded and this phenomenon is called congestion. In deregulated power system congestion occurs due to insufficient capacity of transmission line to accommodate all the power transactions in order to satisfy all customers' demands. Higher load demands and outages of some power system components also cause congestion in the transmission network. When congestion occurs it also affects deregulated power market equilibrium, security and reliability. Therefore it is very necessary to manage congestion in deregulated power system. There are number of congestion management methodologies.

Numerous congestion management techniques are available in the literature based on generation side and demand side approaches. In [1] distributed generator (DG) has proposed to tackle congestion in deregulated power system. For finding the optimal location of DG, locational marginal pricing (LMP) has been used. In [2] flexible alternating current transmission system device (FACTS) such as thyristor controlled series compensators (TCSCs) has been used for congestion management. A suitable approach for optimal size and optimal locations of distributed resources (DRs) for mitigating congestion has been proposed in [3]. Factors like congestion rent, DR, deferred upgrading investment costs also considered. Reference [4] proposes that optimum selection of participation generators for rescheduling can be done by using generator sensitivity to the power flow on the congested lines. In [5], a zonal/cluster based congestion management approach has been presented. The proposed method uses two sensitivity indexes named as real transmission congestion distribution factors and reactive transmission congestion distribution factors for congestion management in deregulated power system. Reference [6] presented a method for generation rescheduling and load shedding to alleviate line overloads, with the help of local optimization concept. In order to tackle the congestion in an effective manner generation and demand side approaches can be used together with the market splitting based approach presented in this paper.

The aim of the present paper is to manage congestion in deregulated electricity market using market splitting based approach such that generation cost can be minimized. In this paper two cases have solved, first is the base case without congestion and second are considering congestion in the system. It has shown that when there is no congestion in the system, prices are same at every bus. Thus the market can be cleared at single price. When there is congestion in the system prices are different everywhere, depending upon the prices the system is divided into different zones. The price of single zone has obtained by taking average of all the

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ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 1, July 2017

prices at different locations of one zone. The problem is stated by the mathematical modeling. There are two methods which can be used for the mathematical modeling, one is the DC optimal power flow (DCOPF) [7] and other is the AC optimal power flow (ACOPF) [7]. In This paper DC optimal power flow (DC OPF) has used in MATLAB environment to solve the problem. DCOPF is preferred over the ACOPF because of its simplicity, high speed of convergence. Load flow analysis (LFA) has also obtained by using Newton-Raphson method with the help of MiPOWER software.

This paper is organized as follow: Section I is introduction. Section II is market splitting approach for congestion management. Section III is mathematical modeling. Section IV is solution methodology. Section V is algorithm procedure. Section VI is results and discussion. Section VII is conclusion and future scope.

II. MARKET SPLITTING APPROACH FOR CONGESTION MANAGEMENT

There are various methods that are used to tackle congestion as discussed in literature. But market splitting based approach is one of the most suitable methods for tackling the congestion problem in deregulated power market. By using this approach market is divided into different zones. The price shall reduce for the zones that have higher generation and low demand and the price shall increase for the zones that have high demand and less generation. Thus the purchases would increases in the zone that have low prices and it would decreases in the zone that have high prices. Therefore the flow through the congested line is reduced to match the available transfer capability. This market splitting approach for congestion management has successfully used by Indian energy exchange (IEX) [8]. By using this approach IEX has divided the system into different zones. It is shown in the Figure 1.

Fig. 1: representation of different zones [8]

Figure 1 shows the map of India in which the states are divided into different zones or areas as N1, N2, N3, S1, S2, S3, E1, E2, E3, W1, W2, W3, A1, A2. These zones represent different states of India and price for each zone or area is given. The price is given for every 15 minutes. This market is called day-ahead market

III. MATHEMATICAL MODELING

To obtain the prices, DCOPF has been performed in MATLAB environment. For this work lossless DCOPF model has been considered. In DCOPF various assumptions are considered such as (i) losses are neglected, (ii) reactive power flows are not accounted for and (iii) voltage magnitudes at various buses are taken to be one per unit. The decision variables are chosen from N-bus system.

Decision variable= $(\delta_1, \delta_2, \dots \dots \dots . \delta_N, P_{G_1}, P_{G_2}, \dots, P_{G_K})$ (1)

Where, $\delta_1, \delta_2, \dots \dots \dots . \delta_N$= load angles at buses 1 to N,
$P_{G_1}, P_{G_2}, \dots, P_{G_K}$ = power generations at buses 1 to K

The objective function is to minimize the cost function given by equation (2) i.e.

$$F=\sum_{i=1}^{K}(a_i \times P_{G_i}^2 + b_i \times P_{G_i} + c_i) \quad (2)$$

Where, (a_i,b_i,c_i) are the cost coefficients

The objective function given by equation (2) subject to various constraints such as

A. Power balance constraint`

$$P_{G_i} - P_{D_i} = \sum_{j=1}^{N} b_{ij}\left(\delta_i - \delta_j\right) \quad for\ i = 1,2,3, \dots N \quad (3)$$

Where, P_{G_i}= real power generation at i^{th} bus, P_{D_i}= real power demand at i^{th} bus, b_{ij}= i^{th} row and j^{th} column element of bus susceptance matrix, δ_i=load angle at bus i, δ_j=load angle at bus j

To obtain susceptance matrix, reactance data of line impedance is used. The diagonal element of susceptance matrix is obtained by taking the reciprocal of sum of all reactances value at the bus. The off diagonal elements are obtained by taking the negative sign of the reciprocal of series elements between the respective buses [9].

B. Generator operating limit constraint

$$P_{G_k}^{min} \leq P_{G_k} \leq P_{G_k}^{max} \quad (4)$$

Where, $P_{G_k}^{min}$= minimum value of real power generation at k^{th} bus, $P_{G_k}^{max}$= maximum value of real power generation at k^{th} bus

C. Line flow limit constraint

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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$L_{mn}^{min} \leq L_{mn} \leq L_{mn}^{max}$ For mn = 1,2, 3…NL (5)

Where, NL = total number of lines, L_{mn}^{min}= minimum line flow between bus m and bus n, L_{mn}^{max}=maximum line flow between bus m and bus n

To find prices for base case without congestion a non-linear programming solver has used in MATLAB environment. This non- linear programming solver is called as FMINCON function in MATLAB environment [10], FMINCON stands for find minimum of constrained nonlinear multivariable function.
FMINCON function minimize the cost function (F)
Subject to equality constraint i.e.

$A_{eq}.X = B_{eq}$ (6)

Where, A_{eq}= It is matrices of the order $m \times n$ where m is number of equality constraints and n is number decision variables. This matrix represents elements of susceptance matrix and decision variables i.e. $(P_{G_1}, P_{G_2}, \dots, P_{G_K})$

X = It is a vector of order n×1 and represents vector of decision variables $(\delta_1, \delta_2, \dots \dots \dots, \delta_N, P_{G_1}, P_{G_2}, \dots, P_{G_K})^T$

E= Is also a vector of order m 1 that represents load at each bus i.e. ($P_{D_1}, P_{D_2}, \dots \dots \dots P_{D_K}$

A. Locational Marginal Pricing (LMP) [8]

LMP is a tool which can be used for market clearance in deregulated power industry. LMP at a particular bus represents incremental costs at that bus due to per unit increment of load or power drawn at the same buses shown in Fig. 2.

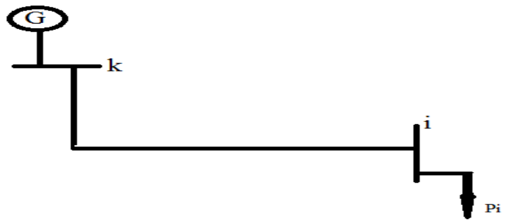

Fig. 2: single line diagram of two bus system to explain LMP

Mathematically LMP is defined as:

$LMP_i = \frac{dC_i}{dP_i}$ (7)

Or $\lambda_i = \frac{\Delta C_i}{\Delta P_i}$ (8)

It is equal to summation of energy, loss and congestion component.

$\lambda_i = \lambda_e + \lambda_{loss} + \lambda_{cong}$ (9)

Where, λ_i = LMP at bus i, ΔC_i= incremental cost at bus i, ΔP_i =incremental power at bus i, λ_e= energy component, λ_{loss}= loss component, λ_{cong}= congestion component

B. Calculation of LMP for Base Case

The LMPs that is given in the section A has obtained by the lossless DCOPF model for base case without congestion. LMP at any bus can be obtained as lagrangian multiplier of equality constraint at that bus. It has obtained same at every bus therefore market operator can clear the market at single price. The results for base case have shown in the section VI.

C. Calculation of LMP for Congestion Case

In case of congestion, the LMPs can be different everywhere, depending on the LMPs values the whole system is divided into different zones. The LMP for each zone has obtained by taking average of all the LMPs at different locations of one zone. Let us consider N-bus system. After the congestion occurs it is divided into M number of zones. Therefore LMP for Jth zone is calculated as follow

LMP of Jth zone= $\frac{\sum_{k=1}^{h} LMP_k \times P_{D_k}}{\sum_{k=1}^{h} P_{D_k}}$ For j=1, 2, M (10)

Where, h = Number of buses in jth zone, LMP_k = locational marginal price at kth bus, P_{D_k} = real power demand at kth bus

IV. SOLUTION METHODOLOGY

In this paper the proposed problem has been solved with the help of DC Optimal power flow (DCOPF) in MATLAB environment. The results obtained after DCOPF are used to obtain state of the power system and actual line flows with the aid of MiPOWER software

V. ALGORITHM

Step1. Input standard IEEE bus system data.
Step2. Solve for base case without congestion and then with including the effect of congestion.
Step3. To obtain LMPs for base case perform DCOPF in MATLAB environment.
Step4. Compare the results of base case with the results of MATPOWER.
Step5. In case of congestion in any one of the line, obtain the LMP using MATPOWER.
Step6. According to LMPs values divide the system into different zones.
Step7. To obtain LMP for a particular zone taking average of all the LMPs at different locations of one zone.
Step8. The zone with highest LMP can be used for placement of DG which further helps for congestion management.
Step9. To know the actual line and power flow and state of power system obtain the Load Flow Analysis (LFA) using Newton-Raphson method in MiPOWER software.

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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Step10. Solve LFA for base case without congestion and then with including the effect of congestion (with the help of Mipower software).

VI. RESULTS AND DISCUSSION

The methodology discussed in section IV has been applied to the IEEE 14 bus system [11].

A. IEEE 14 bus system

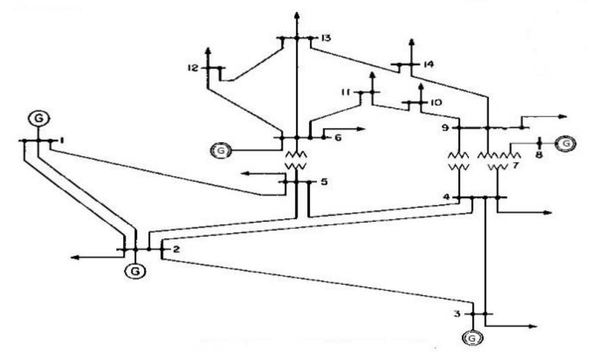

Fig. 3: IEEE 14 bus system

In this paper the proposed problem has solved for IEEE 14 bus system. Figure 3 shows the IEEE 14 bus system, which consists of 5 generators, 14 buses, 20 lines, 4 transformers and 11 loads.

B. Case1 LMP for base case without congestion

LMP for base case without congestion has been obtained by DCOPF in MATLAB environment. In this paper, LMPs for base case have been obtained by using non-linear programming solver. This solver is called FMINCON function as explained in section III. Figure 4 shows the LMPs when no congestion occurs.

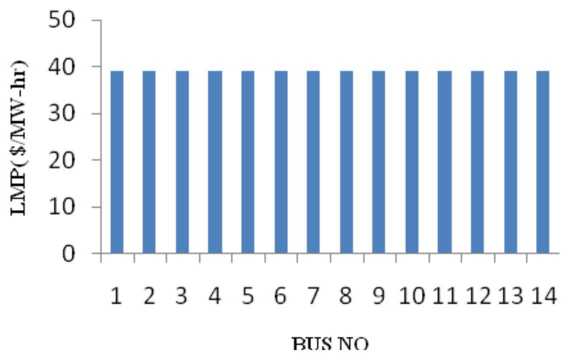

Fig. 4: LMP when no congestion occurs

As shown in the Figure 4 buses are taken on the horizontal axis and LMPs are taken on the vertical axis. As the LMPs are same at every bus, market operator can clear the market at a single price.

C. Case 2 LMPs when congestion occurs

It has been consider that transformer connected between bus 5 and bus 6 has limited capacity of 40 MW. Without considering congestion 42.8 MW (case 1) was flowing through it. Considering the effect of congestion the result for LMPs vs bus numbers are shown in figure 5. When congestion occurs, LMPs are different at every bus as shown in the Figure 5 below. Hence in this case market operator shall clear the market at different prices. Therefore according to these LMP values, the system has been divided into three zones as shown in the Figure 6. The LMP for each zone has been obtained by taking average of all the LMPs at different locations of one particular zone. Zone first includes five buses (1, 2, 3, 4, 5), zone second includes two buses (6, 12) and zone third includes seven buses (7, 8, 9, 10, 11, 13, 14).

The LMP for each zone is calculated as shown below

$$LMP_{Z1} = \frac{38.718\times21.70+38.745\times94.20+38.769\times47.80+38.673\times7.60}{171}$$

$$LMP_{Z1} = 38.74 \text{ \$/MW-hr}$$

$$LMP_{Z2} = \frac{40.083\times11.20+40.022\times6.10}{17.3} = 40.06 \text{ \$/MW-hr}$$

$$LMP_{Z3} = \frac{39.307\times29.50+39.445\times9+39.759\times3.50+39.974\times13.50+39.599\times14.90}{70.7}$$

$$LMP_{Z3} = 39.36 \text{ \$/MW-hr}$$

Where, LMP_{Z1}= location marginal price for zone 1, LMP_{Z2}= location marginal price for zone 2, LMP_{Z3}= location marginal price for zone 3

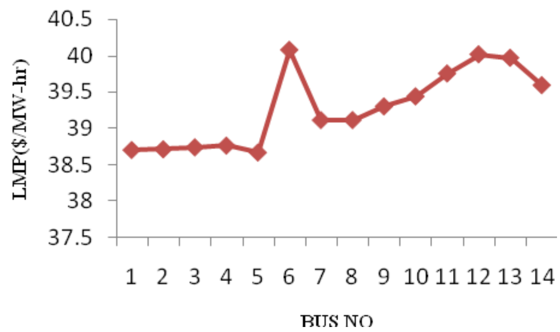

Fig. 5: LMP when congestion occurs

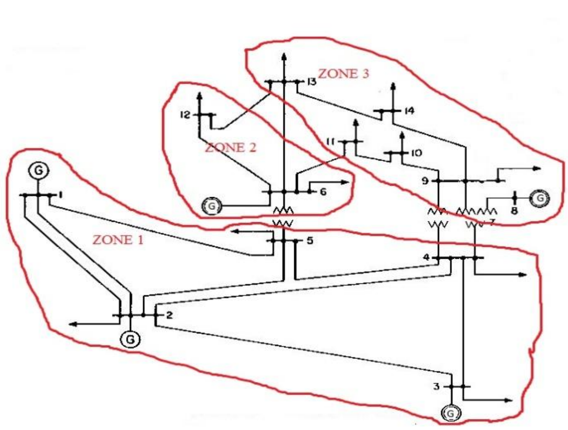

Fig. 6: IEEE 14 bus system with different zones

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ISO 9001:2008 Certified
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As shown in the Table I, zone 2 has highest LMP. Thus the customers who want to do transaction from this zone will have to pay more prices than other two zones. To manage congestion further distribution generator (DG) can be placed on the zone 2.

Table I LMP of different zones after splitting the market

S.NO.	Zones	LMP ($/MW-hr)
1.	1	38.74
2.	2	40.06
3.	3	39.36

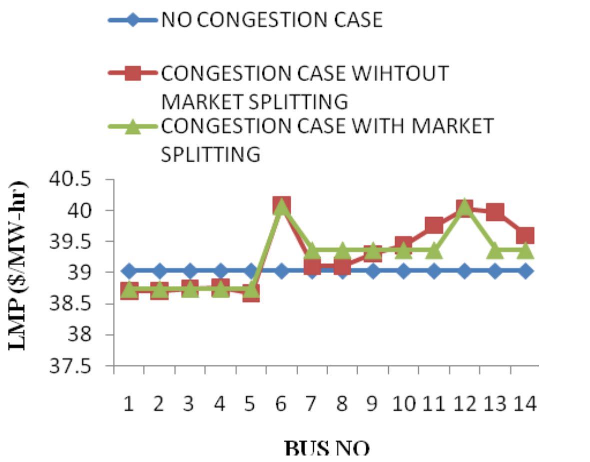

Fig. 7: Comparisons of LMPs of base case and congestion case with market splitting and without market splitting

Figure 7 shows the comparisons of LMPs of base case and congestion case with market splitting and without market splitting. In case no congestion occurs LMP is same everywhere. When congestion occurs, LMP is different everywhere. Depending upon LMP values of congestion case, system is divided into different zones. Hence the highest LMP zone is obtained. Thus the congestion has tackled by splitting the market into different zones.

D. Results For Load Flow Analysis (LFA)

Load flow analysis has been obtained by Newton-Raphson method for base case without congestion and including the effect of congestion. MiPOWER software has been used to obtain the load flow results. MiPOWER software is professionally designed and developed by PRDC Bangalore. It make use of interactive user-friendly graphical user interfacing based system to perform steady state and transient analysis of the power system [12].

D.1 Case 1 base case without congestion

Figure 8 shows the single line diagram for base case without congestion that is obtained with the help of Newton-Raphson method in MiPOWER software. It represents bus voltage magnitude, bus voltage angles, bus powers, line flows, generation capacity and transformer rating. Total load is supplied by only two generators (1 & 2), other three generators have zero generation. Real power in MW and reactive power in MVAr is shown for each bus and load on the single line diagram. The real and reactive power flows through the transformer and between the respective buses also shown. Negative sign associated with the real power flow between the respective buses shows that the flow is in opposite direction i.e. the flow is from bus 2 to 1.

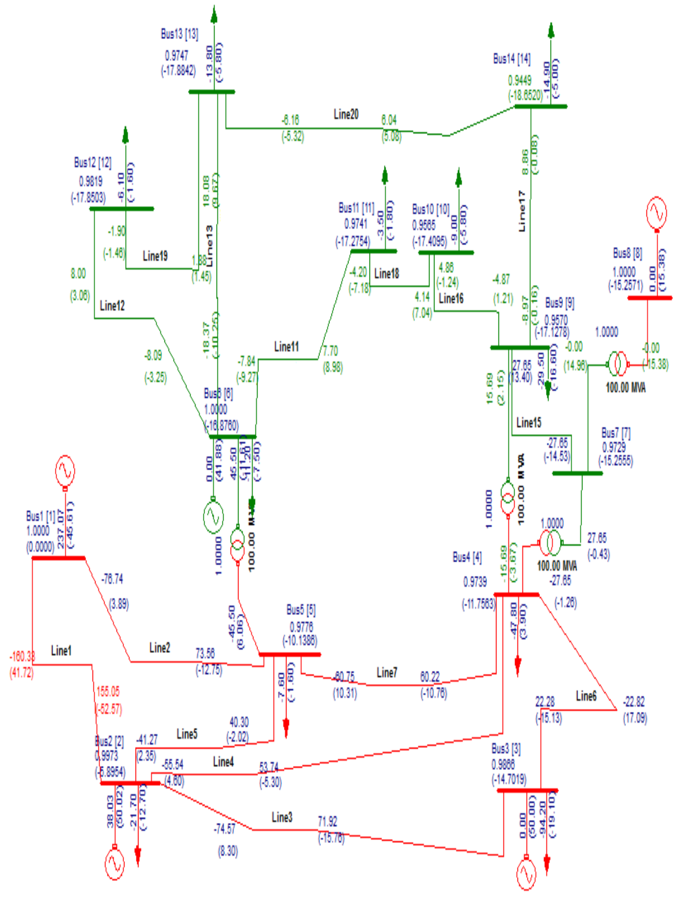

Fig. 8: single line diagram without congestion

D.2 Case 2 when congestion occurs

Figure 9 shows the single line diagram when congestion occurs. In case 1 the actual power transform by the transformer connected between bus 5 and bus 6 was 45.503 MW. Whereas in case 2 this flow has limited to 39.594 MW.

From the results of base case and congestion case it has cleared that when congestion occurs in the system it will result in change in line flows and line losses, bus voltages and powers, transformers flows and transformer losses .

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ISO 9001:2008 Certified
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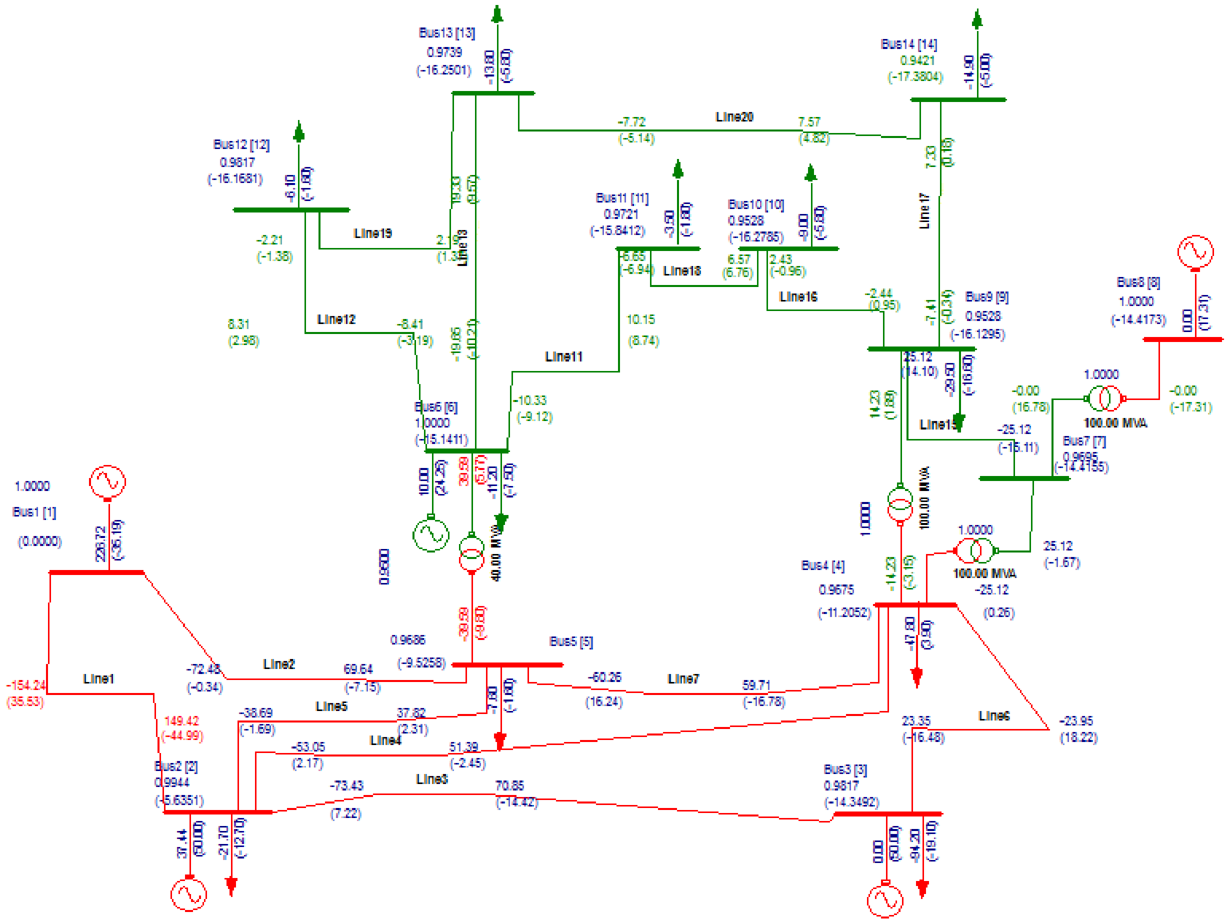

Fig.9: single line diagram with congestion

VII. CONCLUSION

In this paper market splitting based approach has been used for congestion management. By using this approach system has divided into different zones after congestion occurs. The following points are obtained from this paper.

1. Locational marginal prices (LMPs) obtained by DCOPF for base case without congestion is same everywhere hence market can be cleared at single price.

2. LMPs for congestion case obtained with the help of MATPOWER that is a toolbox of MATLAB are different at every bus. Depending upon LMP values system has divided into different zones. For single zone LMPs has obtained by taking average of all the LMPs at different locations of one zone. Hence the market has cleared at different prices

3. Load flow analysis (LFA) has obtained with the help of MiPOWER software for base case and congestion case to know the actual line flows, bus voltages and powers etc.

4. The actual line flows, bus voltages and powers etc. that are obtained for congestion case are different from base case.

To completely alleviate the congestion distribution generator (DG) can be placed in the highest LMP zone. FACTS devices and reactive power compensator can also be used together with the method used in this work to tackle congestion.

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