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Different Scenario Analysis of PJM 5-Bus Test System by Changing Load Demand

Md. Kamrul Hasan
Dept. of EEE
Chittagong University of Engineering and Technology
Chattogram, Bangladesh
mkh21@cuet.ac.bd

Nur Mohammad
Dept. of EEE
Chittagong University of Engineering and Technology
Chattogram, Bangladesh
nur.mohammad@cuet.ac.bd

***Abstract* – Electricity is the key player of the modern era. Electrical Energy is produced from different natural sources, transmitted via a transmission system and delivered to load points. Engineers, design these generations, transmission and distribution systems to make sure that produced power is efficiently given to the consumer while simultaneously maintaining system stability, such as frequency, voltage magnitudes, angles, and real and reactive power flows through the line. Before production and marketing, the designs are put on some test systems for test purposes. PJM 5 bus system is one of the most known test system frameworks for power system economic investigations. Sometimes a big amount of sudden loads appears which need to be adjusted or sometimes some loads need to shed. At that time, it may be helpful for the engineers to decide that cases if there is a scenario analysis on these bases. This paper would like to propose a few adjustments in load information and transmission information on the PJM-5 framework and investigate the performance of the financial investment. Here, some cases have considered adding and curtailing loads on different buses and find the best bus to add loads or curtail loads in terms of the cost in $/ MWh. To solve optimal power flow problems, a simulation tool MATPOWER, which is a package of MATLAB M-files has been used here. By observing the changing results of the system, design and maintenance Engineers can easily decide about future load extension or load-shed.**

Index Terms* – *PJM 5-bus system, OPF, ELD, DC-OPF, MATPOWER.

I. INTRODUCTION

Continuity of power supply while maintaining it as economically as possible is the main objective of a power system. Power system maintenance and operation have been experiencing challenges due to increasing fuel prices, the depletion of coal and also the restructuring of the industry thorough worldwide. Optimal Power Flow (OPF), has been well defined from the 1960s by which grid-level power systems are designed to deliver power from generators to customers while maintaining the constraints [1]. OPF problem is difficult to solve as it is a set of non-linear equations. These non-linear equations have no exact solution, so, iterative algorithms are employed to solve the problem numerically [2]. In most cases, locational marginal price (LMP) and economic dispatch or constrained unit commitment have been studied in the different test systems to save millions of dollars per year.

There are a few standard test frameworks for economic studies of a power system, specifically, for LMP-based markets [3,4]. In a power system, a transmission loss occurs for the resistance and inductance having in the transmission line. Problems associated with non-linear AC optimal power flow (AC-OPF) are normally approximated by linearized DC-OPF problems to get real power solutions [5,6].

Transmission line resistance and inductance have been ignored in DC-OPF and all the voltage magnitudes throughout the power system are considered equal to the nominal voltage of the system but different in phase angles [7]. Continuous monitoring of load flow can give information about the total amount of real power and reactive power flow, voltage levels of certain buses, transmission line power consumption. Moreover, this will give a clear idea about the power flow pattern through the system which needs for the voltage stability study.

This paper will examine the load flow of the PJM 5-bus system as it depends on the linearized DC optimal power flow model. MATPOWER tool is used herein MATLAB to modify the system and analyze the results. Some parameters are adjusted to find out power flow and cost during modification. This paper recommends some sensible qualities for generation expenses during the load changing and transmission line limits. According to the cost analysis, engineers can decide from which bus we can add load or shed load while achieving the goal of minimizing the marginal price.

II. METHODOLOGY

An electrical power system has different types of load; a good system should meet all the demands of that load. The solution obtains to minimize the total generation cost by optimal power flow (OPF) is a more accurate estimation than the economic load dispatch (ELD) solution [8]. In the ELD method, it assumes that the transmission line has no power loss. ELD is formulated as an optimization problem of minimizing the total costs of generation units. The Major drawback of ELD is not to consider most of the system constraints in the problem formulation. The OPF can include many operating constraints. Specifically limits on reactive and real power generation, limits on power flow, limits on the transmission lines and bus voltages ensure the secure operation of the system [8].

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A. *Problem Formulation*

The standard optimization problem takes the following form [9]:

$$\min_{(x)} \; f(x) \tag{1}$$

subject to-

$$g(x) = 0 \tag{2}$$

$$h(x) \le 0 \tag{3}$$

$$x_{\min} \le x \le x_{\max} \tag{4}$$

In eq. (1), *f(x)* is the objective function. For thermal power plant *f*(*x*) can be given by

$$f(x) = ax^2 + bx + c \tag{5}$$

In eq. (5), *a, b* and *c* denotes for quadratic cost coefficient in \$/MWh^2 linear cost coefficient in \$/MWh and constant in \$ respectively. These coefficients vary from plant to plant and are usually found by using the least square method.

In eq. (2), *g*(*x*) represents the equality constraints that take care of the supply balance of the system. The *h*(*x*) in eq. (3) represents inequality constraints of the branch flow limits. The flows are typically apparent power flows but can be real power. The $x_{\min}$ and $x_{\max}$ bounds in eq. (4) include reference bus angles (θ_m), voltage magnitudes (V_m) and generator injections (P_g, Q_g) [10,11].

In standard AC OPF problem, the optimization vector *x* consists of the $n_b \times 1$ vectors of voltage angles θ and magnitudes V_m and the $n_g \times 1$ vectors of generator real and reactive power injections P_g and Q_g [12].

$$x = \begin{bmatrix} \theta \\ V_m \\ P_g \\ Q_g \end{bmatrix} \tag{6}$$

Now the objective function $f(x)$ in (1) is the summation of individual polynomial cost functions for both real and reactive power injections for each generator:

$$f(P_g, Q_g) = \sum_{i=1}^{n_g} f_P^i(p_g^i) + f_Q^i(q_g^i) \tag{7}$$

The real and reactive power balance equation for equality constraints is as follows:

$$g_P(\theta, V_m, P_g) = P_{bus}(\theta, V_m) + P_d - C_g P_g = 0 \tag{8}$$

$$g_Q(\theta, V_m, Q_g) = Q_{bus}(\theta, V_m) + Q_d - C_g Q_g = 0 \tag{9}$$

The inequality equation is formulated as the nonlinear function of the bus voltage angles and magnitudes.

$$h_f(\theta, V_m) = \left| F_f(\theta, V_m) \right| - F_{\max} \le 0 \tag{10}$$

$$h_t(\theta, V_m) = \left| F_t(\theta, V_m) \right| - F_{\max} \le 0 \tag{11}$$

In standard DC OPF problem, reactive power and voltage magnitudes are completely not in consideration only real power flows are modeled as the linear function of voltage angles [13,14]. So, the variable is

$$x = \begin{bmatrix} \theta \\ P_g \end{bmatrix} \tag{12}$$

The overall problem reduces to the following form

$$f(P_g) = \min_{\theta, P_g} \sum_{i=1}^{n_g} f_P^i(p_g^i) \tag{13}$$

which is subject to,

$$g_P(\theta, P_g) = B_{bus}\theta + P_{f,shift} + P_d + G_{sh} - C_g P_g = 0 \tag{14}$$

$$h_f(\theta) = B_f\theta + P_{f,shift} - F_{\max} \le 0 \tag{15}$$

$$h_f(\theta) = B_f\theta - P_{f,shift} - F_{\max} \le 0 \tag{16}$$

B. *Solution Method*

To solve the problem formulated in section II(A), we have to define the Lagrangian function, *L*(*x, λ, μ*). The Lagrangian function is defined by:

$$L(x, \lambda, \mu) = f(x) + \lambda g(x) + \mu h(x) \tag{17}$$

In eq. (8) *λ* denotes for a multiplier of equality constraint and *μ* denotes for a multiplier of inequality constraint. The Lagrange multiplier *λ* is interpreted as the incremental (marginal) cost. A set of conditions that are necessary and sufficient for solving the problem refers to Kharush-Khun-Tucker (KKT) condition. The conditions are given as follows,

$$\frac{\partial L(x, \lambda, \mu)}{\partial x} = 0 \tag{18}$$

$$\frac{\partial L(x, \lambda, \mu)}{\partial \lambda} = 0 \tag{19}$$

$$\frac{\partial L(x, \lambda, \mu)}{\partial \mu} = 0 \tag{20}$$

$$g(x) = 0 \tag{21}$$

$$h(x) \le 0 \tag{22}$$

$$\mu h(x) \le 0, \mu \ne 0 \tag{23}$$

Equations (18) - (20) refer to stationary conditions found by partial derivation of the Lagrangian function with respect to *x, λ,* and *μ*. A good understanding of different data is needed before the load flow analysis. After this understanding, this problem solution was done by the MATPOWER tool. Fig. 1 shows the flow chart of the problem solution in MATPOWER.

III. PJM 5 Bus System

In 1999, the PJM 5-bus framework was initially published [3]. The fundamental framework setup appears in Fig. 2. Here, 5 generators represent 5 different cities.

There are 5 buses, bus A contains two generators of Alta and Park city, bus B is the load bus and contains no generator, bus C and D contain both generator and load, and bus E contains only one generator.

Table I shows all the generation data where the $/MWh gives the status of the cost related to each generator [11,15]. Load data are given in Table II where the MW and MVAR load of each bus is given. Here, a 0.95 lagging power factor is accepted for each load [3]. Table III gives the information about line parameters. Each bus is assumed to have 1.1 per unit as the voltage upper limit and 0.9 as the lower limit. The generation dispatch, line flow, and LMP results in different buses in base-case data are shown in Tables IV [3].

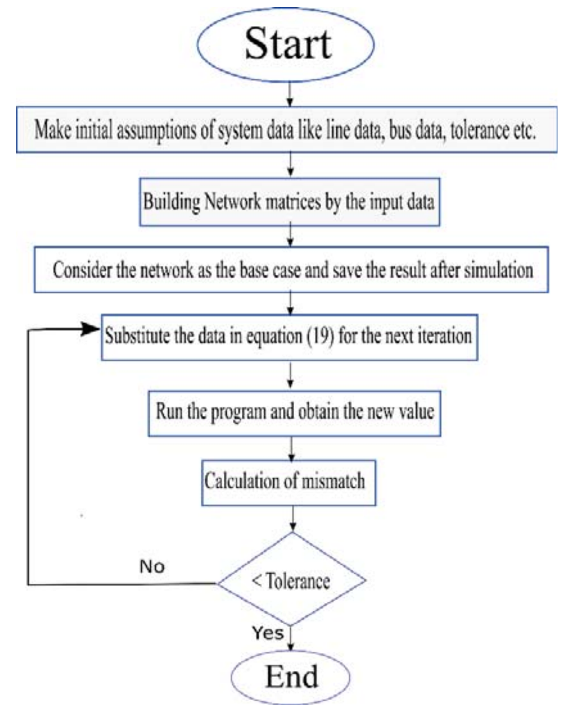

Fig. 1. Flow chart of optimal power flow

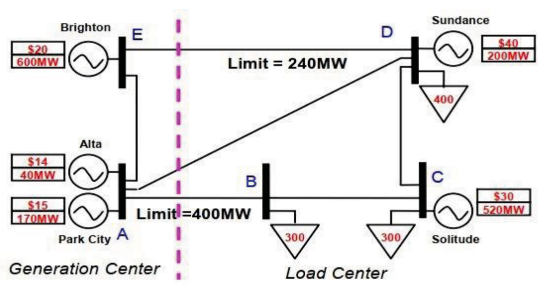

Fig. 2. The PJM 5-bus system [3]

TABLE I. GENERATION PARAMETERS AT DIFFERENT LOCATION [3]

Gen. Name	Alta	Park City	Solitude	Sundance	Brighton
Bus	A	A	C	D	E
Cost($/MWh)	14	15	30	40	10
MVAR Limit	±30	±127.5	±390	±150	±450
MW Limit	40	170	520	200	600

TABLE II. REACTIVE AND REAL LOAD DATA AT DIFFERENT BUS [3]

Bus	A	B	C	D	E
MW	0	300	300	400	0
MVAR	0	98.61	98.61	131.47	0

TABLE III. LINE PARAMETER AND FLOW LIMIT [6]

Line	AB	AD	AE	BC	CD	DE
R (%)	0.281	0.304	0.064	0.108	0.297	0.297
X (%)	2.81	3.04	0.64	1.08	2.97	2.97
B/2 (10^{-3})	3.56	3.29	15.63	9.26	3.37	3.37
Limit (MVA)	400	0	0	0	0	240

TABLE IV. BASE SYSTEM LOAD AND THEIR CORRESPONDING COST FUNCTION AND POWER FLOW CONDITION [3]

Bus	A	B	C	D	E
Load (MW)	0	300	300	400	0
Cost Function ($/MWh)	F = 17552				

Power Flow (MW)					
AB	AD	AE	BC	CD	DE
252.377	187.86	-230.21	-49.20	-24.95	-238.50

IV. MODIFIED PJM 5 BUS SYSTEM

Here, modifications have been done to the existing PJM 5-bus system by changing the load demand at one bus at a time while keeping the other bus demand and constraints like the base case. At first, increase the load demand at different buses of load center side and study the behavior of how the branch flow or cost function varies with load changing. In the second part, decrease the load demand at different buses of load center side and analyze the output. The last part shows what will happen if a new large load, like say, 200 MW is introduced.

CASE I: LOAD INCREMENT AT DIFFERENT BUS

At the base case, 300 MW, 300 MW and 400 MW load is at bus B, bus C and bus D respectively. Here load at bus B is increased to 5% (315 MW) while keeping the load at bus C and bus D same as a base case which is shown in Fig. 3. The same analysis has also been done for bus C and bus D shown in Fig. 4 and Fig. 5 respectively. Fig. 6 shows the cost function response and Table V shows data about power flow through the branch at different load demands after simulation.

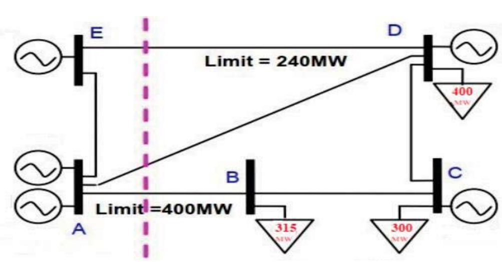

Fig. 3. 5% increment of base-load at B bus

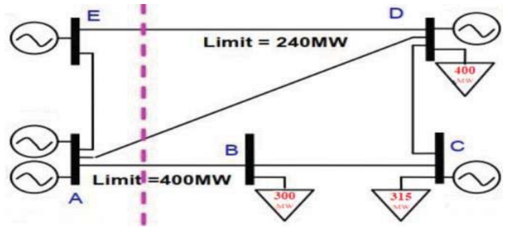

Fig. 4. 5% increment of base-load at C bus

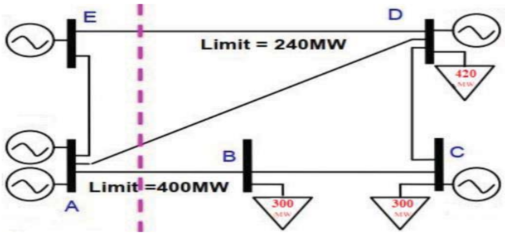

Fig. 5. 5% increment of base-load at D bus

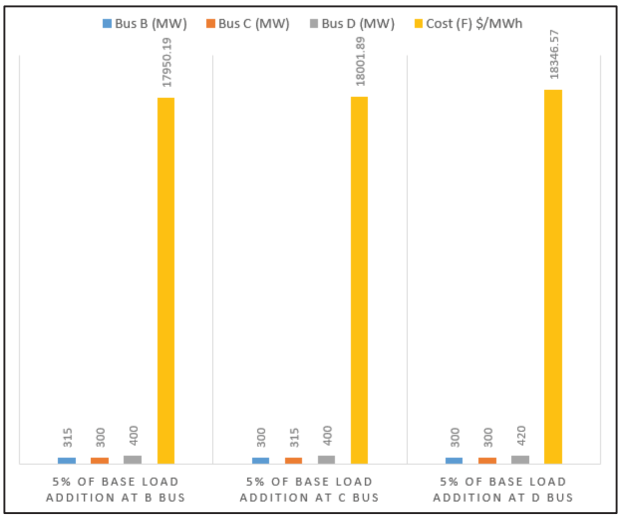

Fig. 6. Cost response to load addition

TABLE V. BRANCH POWER FLOW DURING 5% ADDITION OF BASE LOAD AT DIFFERENT BUS

Branch	Load addition at B bus	Load addition at C bus	Load addition at D bus
AB	255.60	252.38	240.34
AD	187.30	187.87	189.99
AE	-232.90	-230.25	-220.32
BC	-61.02	-49.21	-61.11
CD	-24.39	-24.95	-7.06
DE	-238.50	-238.50	-238.50

From the above Fig. 6 and Table V, it can be seen that whenever load increases it has a great impact on the cost function and power flow through the buses. Hereby increasing 5% of base-load at bus B, C and D, significant changes in cost function and power flow have occurred. From the result analysis, it can be said, 5% increment of loads at bus B will be more beneficial rather than others. So, whenever it is needed to increase load it will be preferable, to increase load at bus B.

CASE II: LOAD CURTAILMENT AT DIFFERENT BUS

Sometimes it needs to curtail load from the different buses when the generation is lower than the demand. In that scenario, it needs to calculate which bus load curtailment will be beneficial. Here, 5% of load demand is decreased from bus B while keeping the other bus demand the same, which is shown in Fig. 7. The curtailment demand on bus C and bus D are also shown in Fig. 8 and Fig. 9 respectively. Results from modification of 5% load decrease at different buses in base-case are shown in Tables VI and Fig. 10.

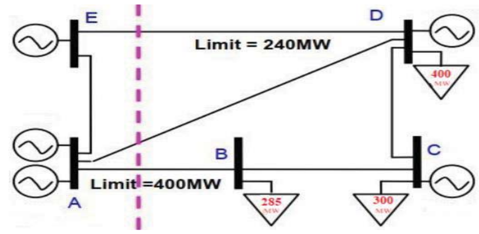

Fig. 7. 5% reduction of load at B bus

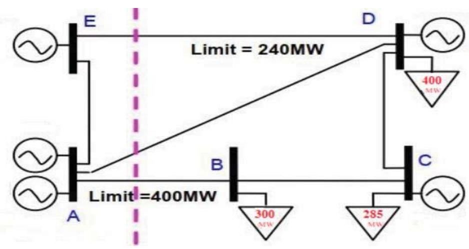

Fig. 8. 5% reduction of load at C bus

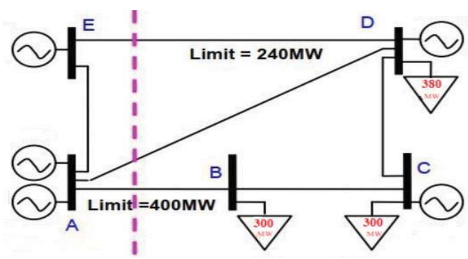

Fig. 9. 5% reduction of load at D bus

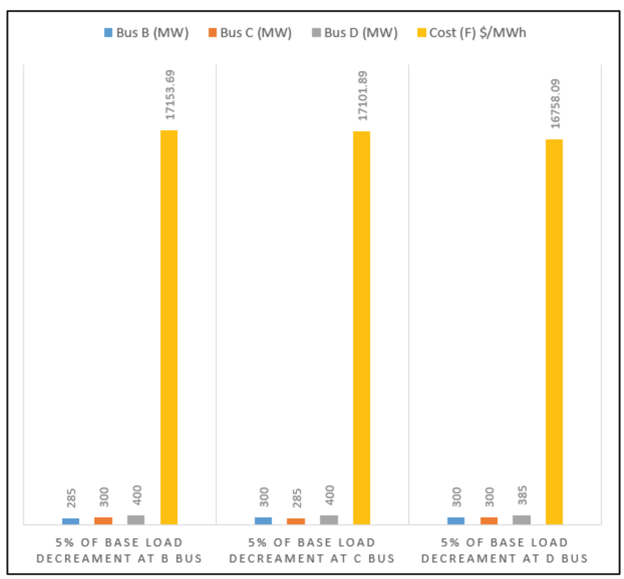

Fig. 10. Cost response to load decrement

TABLE VI. BRANCH POWER FLOW DURING 5% REDUCTION OF LOAD AT DIFFERENT BUS TABLE STYLES

Branch	5% load decrease at B bus	5% load decrease at C bus	5% load decrease at D bus
AB	249.16	252.38	264.41
AD	188.43	187.87	185.75
AE	-227.59	-230.25	-240.16
BC	-37.39	-49.21	-37.62
CD	-25.51	-24.95	-42.83
DE	-238.50	-238.50	-238.50

From the above data, it has been seen that whenever load decreases it has a great impact on the cost function and power flow through the buses. Hereby decreasing 5% in load at bus B, C and D results show that load decrement at bus D will be more benefitted rather than others as bus D refers to the lowest cost. Again power flow is at a limit. So, whenever it is needed to decrease load it will be preferable, to decrease load at bus B.

CASE III: NEW LOAD ADDITION AT GENERATOR CENTER

While designing the structure of a power system there should be the provision for future addition of load in the plan. The planning should not be rigid there must be some flexibility for the new upcoming load. Say for example government wants to declare some area as an economic zone so for that purpose many industries may be set up for the economic purpose. So new industry means new big load. If we have the provision of adding a new load in our existing power structure, then we can easily allow the new load without changing the existing plan. This case is based on the scenario of the introduction of a new load on the different bus of generation center and analysis of which bus is more economical to connect the new load. First considering that new loads are introduced in bus A shown in Fig. 11 and second introduced to bus E shown in Fig. 12, then considerable effects can be seen in Fig.13 and Table VII respectively. From the table data, it has been seen that with the addition of a new load of 200 MW at bus A or E, there is a small difference in the cost function. So to use an extra new large load we can choose bus E over A, as well as we should consider the branch flow limit.

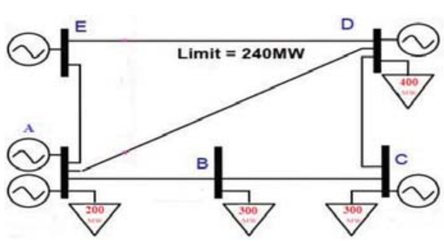

Fig. 11. New load addition at bus A

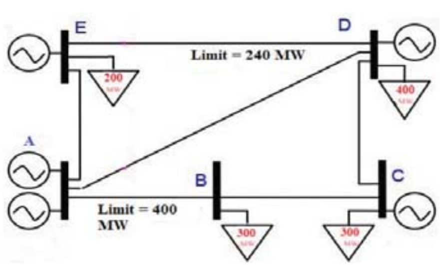

Fig. 12. New load addition at bus E

TABLE VII. POWER FLOW DURING THE ADDITION OF 200 MW LOAD

Branch	Power flow when load added at Bus A	Power flow when load added at Bus E
AB	208.83	214.90
AD	160.34	175.90
AE	-359.17	-180.79
BC	-92.23	-86.20
CD	2.11	7.03
DE	-238.52	-217.85

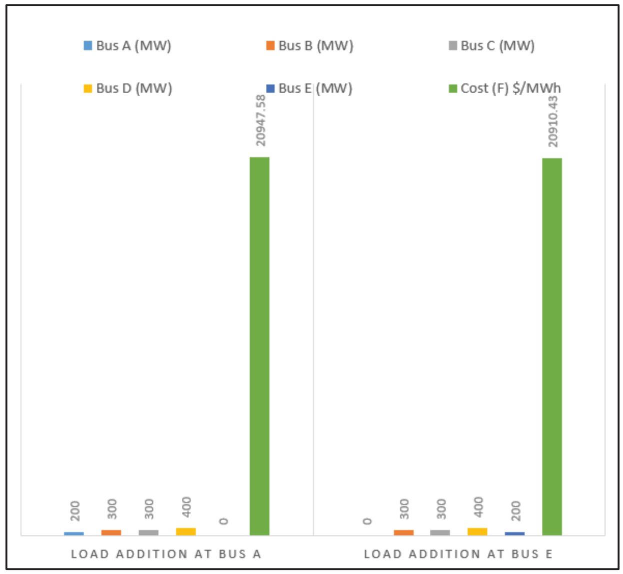

Fig. 13. Cost response to new incoming load

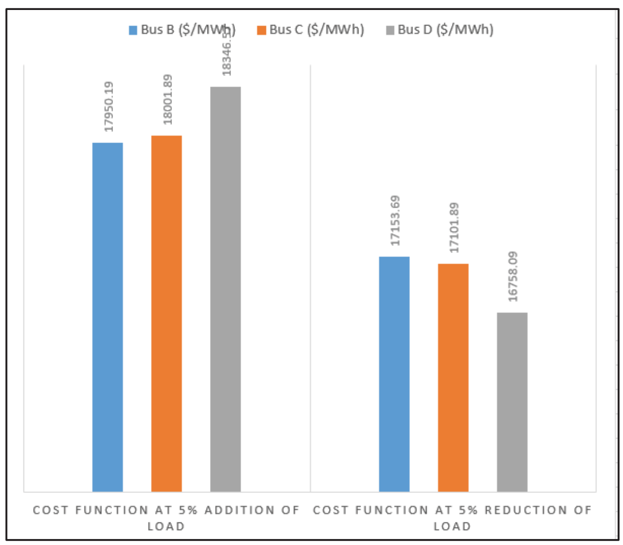

Fig. 14. Cost comparison between addition and reduction of load at different buses

V. CONCLUSION

In this paper, some changes recommend to PJM 5-bus system, just as new parameters are identified with changes in load and branch flow capacity. Fig.14 gives the graphical presentation of the cost function at the different buses while changing the load value.

From this graph, it may easily decide at which bus engineers may connect the incoming new load or shed load to minimize the cost of energy. This paper tries to create some scenarios for financial analysis and observation that helps to get decisions easier for the system engineers. Future work may incorporate other monetary investigations such as long-term and short-term planning, unit commitment, integrated economic-reliability stud*y,* etc*.*

"REFERENCES

[1] J. D. Glover et al., "Power Flows" in Power Systems Analysis and Design, 5th ed. Stamford: Cengage Learning, 2012, ch. 6, sec. 6, pp. 334-343

[2] Daniel R. Fisher and Dr. Cal Hardie, "The Optimal Power Flow Problem: Definitions, Solutions, and Challenges"

[3] Fangxing Li and Rui Bo, "Small Test Systems for Power System Economic Studies," Proceedings of the 2010 IEEE Power & Energy Society General Meeting 978-1-4244-6551-4/10/$26.00 ©2010

[4] Fangxing Li, Eugene Litvinov, Tongxin Zheng, "A combined LMP model considering reference independent decomposition and fictitious nodal demand", IEEE PES General Meeting, Providence, RI, USA, 25-29 July 2010.

[5] Zagros Shahooei, Guna R. Bharati and Barzin Moridian "Economic Load Dispatch and Optimal Power Flow in Power System"

[6] K. Battacharya, math H. J. Bollen and Jaap E. Daalder, "Operation of Restructured Power Systems," Kluwer Academic Publishers, London 2001.

[7] A. J. Wood and B. F. Wollenberg, "Power Generation, Operation, and Control," John Wiley and Sons, NewYork 1984.

[8] Ray D. Zimmerman and Carlos E. Murillo-S´anchez, "MATPOWER User Manual," October 31, 2018.

[9] Ray Daniel Zimmerman, Carlos Edmundo Murillo-Sánchez, Robert John Thomas "MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education", IEEE Transactions on Power Systems (Volume: 26, Issue: 1, Feb. 2011)

[10] PJM Training Materials (LMP101), PJM, http://www.pjm.com/training/training-material.aspx, accessed on 03/07/2019

[11] Fangxing Li and Rui Bo, "Congestion and Price Prediction under Load Variation," IEEE Trans. on Power Systems, vol. 24, no. 2, pp. 911-922, May 2009.

[12] Rui Bo, "Congestion and Price Prediction in Locational Marginal Pricing Markets Considering Load Variation and Uncertainty," Ph.D. Dissertation, University of Tennessee, Knoxville, TN, August 2009.

[13] Rui Bo and Fangxing Li, "Probabilistic LMP Forecasting Considering Load Uncertainty," IEEE Trans. on Power Systems, vol. 24, no. 3, pp. 1279-1289, August 2009.

[14] W. F. Tinney and C. E. Hart, "Power Flow Solution by Newton's Method", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-86, No. 11, Nov. 1967, pp. 1449-1460.

[15] Nur Mohammad, Yateendra Mishra, "Retailer's Risk-Aware Trading Framework with Demand Response Aggregators in Short-Term Electricity Markets", IET Generation Transmission & Distribution, 2019.'