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VOLTAGE DEPENDENT LOAD IN POWER FLOW ANALYSIS

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ABSTRACT

Conventional load flow methods model the load at the buses as constant active and reactive powers. In actuality these can be constant current, constant impedance, constant power or any combination of these types of loads. In this paper attempt has been made to change the load flow mathematical formulation in order to incorporate the models of constant impedance and constant current type of load in addition to conventional constant power one at a time. The changed load flow formulation is tested on standard 5- bus system and the results are presented here.

KEYWORDS

Constant current loads, Constant impedance loads, Constant power loads, Voltage sensitive loads.

1. INTRODUCTION

The load flow studies are performed for power system planning, operation, and control. Load flow studies data are also used for contingency analysis, outage security assessment, as well as for optimal dispatching and stability. The load flow problem has received more attention than all the other power system problems combined. [1]

Load flow calculations provide power flow and voltage for a specified power system subjected to the regulating capability of generators, condensers and tap changing under load transformers as well as specified net interchange between individual operating system [2].

In conventional load flow studies, it is presumed that the active and reactive power demands are specified constant value, independent of the voltage value. Though in actuality, the various kind of residential, commercial and Industrial load demand active and reactive power which are functions of system voltage and frequency. This effects, if taken into account can cause major changes in the results of load flow and optimal power flow studies. Also the voltage dependence of system load largely affects the dynamic behaviour of a power system, and the impedance of its proper representation in power system stability studies has also been recognized [5].

The effects of voltage and frequency on active and reactive power loads have been studied by several researchers for some time [3-19]. The literature on the incorporation of load models in load flow studies is limited to only a few studies [4-6, 10, 20-22]. It has been shown that load modelling has significant effects for some systems [21].

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Frequency deviation is considered insignificant in case of static analysis like, load flow studies. The effects of voltage deviations are mainly taken into account for getting faster and accurate results. In recent year, much effort has been devoted to load modeling and the evaluation of model parameters through field measurements [6].

Few studies have been done on incorporating load modeling in load-flow algorithms. The literature is limited to two studies done by El-Hawary [23] and Murty [24]. The first study proposes a generalised nonlinear model for which P = I $*jVbJ$ but does not discuss the practical details involved in the evaluation of the proposed parameters. Murty considers an exponential model with applications to a 5-bus system, which proposed the alteration of the power equations to incorporate the effect of Varing load models. This consequently changed the Jacobian Matrix of the N-R Algorithm.

In some studies done on load modelling by Ontario Hydro [5, 6] some aspects of load flow have also been considered briefly. Some other literature available on web is based on the similar concept as 1 and 2 and the simulation is carried out using software like ETAP and others. However, the user-defined power flow software do not allow users to directly modify the Jacobian matrix and only provide the facilities for the iteration between the main program and the user defined model. This iteration sometimes diverges, especially when the system is heavily loaded or ill-conditioned.

The objective here is to study the behaviour of the load-flow solution when load models are incorporated using MATLAB programming. The code developed is generalized such that it can solve any number of bus systems at a time. It also gives the flexibility to change the type of the loads at the buses and to compare results with the conventional load-flow results. Available load-flow data and some available model parameters of a particular model are used in this study.

2. POWER FLOW FORMULATION WITH VOLTAGE SENSITIVE LOADS

The exponential model for representating the dependence of active power (P) and reactive power (Q), on the bus voltage magnitude at a load bus in an electric power network takes the following form,

$$\Delta P_i^* = \left(Q_i - Q_i^{SP}\right)\left(V_i\right)^b = 0 \qquad (1)$$

$$Q_i^* = Q_{i(n)}\left(\frac{v_i}{v_{i(n)}}\right)^b \qquad (2)$$

The coefficient $P_{i(n)}$ and $Q_{i(n)}$ represents the active and reactive powers at nominal voltage $v_{i(n)}$. An alternate form of equation (1) and (2) can be written as

$$P_i^* = P_i\left(v_i\right)^a \qquad (3)$$

$$Q_i^* = Q_i\left(v_i\right) b \qquad (4)$$

Where V_i is the voltage in per unit base voltage taken as $v_{i(n)}$

In conventional load flow studies the 2n-1 equations normally solved are:

$$\Delta P_i = P_i - P_i^{sp} = 0 \quad \text{for } i = 2,\ldots\ldots.., n \qquad (5)$$

$$\Delta Q_i = Q_i - Q_i^{sp} = 0 \quad \text{for } i = m+1,\ldots\ldots., n \qquad (6)$$

Where;

$$P_i = V_i \sum_{i=1}^{n} V_j Y_{ij} Cos(\theta_i - \theta_j) \qquad (7)$$

$$Q_i = V_i \sum_{i=1}^{n} V_j Y_{ij} Sin(\theta_i - \theta_j) \qquad (8)$$

m= number of generator buses including the swing bus
n= total number of buses

The set of load equation (7) & (8) are non-linear and solved by Newton Raphson iterative method which requires finding a jacobian matrix to update the current estimates of improved solutions. Since instead of constant specified powers, model of the form as in equations (3) and (4) are used, then equation (5) & (6) change to

$$\Delta P_i = \left(P_i - P_i^{SP}\right)\left(V_i\right)^a = 0 \quad \text{for } i = 2,\ldots., n \qquad (9)$$

$$\Delta Q_i = \left(Q_i - Q_i^{SP}\right)\left(V_i\right)^b = 0 \quad \text{for } i = m+1,.., n \qquad (10)$$

Let the equations (9) & (10) be denoted as ΔP_i^* and ΔQ_i^*. In conventional Newton Raphson algorithm the matrix vector relationship between the changes in real and reactive powers and the bus voltages and angle are represented as,

$$\left[\Delta P_i\right] = \left[\partial P_i / \partial \theta_i\right].\left[\Delta \theta_i\right] + \left[\partial P_i / \partial V_i\right].\left[\Delta V_i\right]$$
$$\left[\Delta Q_i\right] = \left[\partial Q_i / \partial \theta_i\right].\left[\Delta \theta_i\right] + \left[\partial Q_i / \partial V_i\right].\left[\Delta V_i\right]$$

Where,

$$\left[\Delta P_i\right] = \left[\Delta P_2 \ldots. \Delta P_n\right]^T$$
$$\left[\Delta Q_i\right] = \left[\Delta Q_2 \ldots. \Delta Q_n\right]^T$$
$$\left[\Delta \theta_i\right] = \left[\Delta \theta_2 \ldots. \Delta \theta_n\right]^T$$
$$\left[\Delta V_i\right] = \left[\Delta V_2 \ldots. \Delta V_n\right]^T$$
$$\left[\partial P_i / \partial \theta_i\right] = \left[\partial P_2 / \partial \theta_2 \ldots. \partial P_n / \partial \theta_n\right]^T$$
$$\left[\partial P_i / \partial V_i\right] = \left[\partial P_2 / \partial V_2 \ldots. \partial P_n / \partial V_n\right]^T$$
$$\left[\partial Q_i / \partial \theta_i\right] = \left[\partial Q_2 / \partial V_2 \ldots. \partial Q_n / \partial V_n\right]^T$$

Where bus 1 is the slack bus and the jacobian sub matrix are:

$$J_1 = \left[\partial P_i \,/\, \partial \theta_i \right] \quad , \quad J_2 = \left[\partial P_i \,/\, \partial V_i \right]$$

$$J_3 = \left[\partial Q_i \,/\, \partial \theta_i \right] \quad , \quad J_4 = \left[\partial Q_i \,/\, \partial V_i \right]$$

When voltage dependent loads are considered, the powers P_i and Q_i will change to P_i^* and Q_i^* as in equation (3) and (4). This change the jacobian elements of the jacobian with voltage dependent loads are derived from the bus power equation (3) and (4).

Differentiating (3) the diagonal elements of J_2 are

$$\frac{\partial P_i^*}{\partial V_i} = P_{i(n)}.a.V_i^{a-1} + \frac{\partial P_{i(n)}}{\partial V_i} V_i^a$$

but

$$\frac{\partial P_{i(n)}}{\partial V_i} = 2V_i Y_{ii} \mathrm{Cos}\theta_{ii} - \sum_{\substack{k=1 \\ k \neq i}}^{n} V_i Y_{ik} \mathrm{Cos}(\theta_i - \theta_k)$$

hence

$$\frac{\partial P_i^*}{\partial V_i} = a.P_{i(n)}.V_i^{a-1} + \left\{ 2V_i Y_{ii} \mathrm{Cos}\theta_{ii} - \sum_{\substack{k=1 \\ k \neq i}}^{n} V_i Y_{ik} \mathrm{Cos}(\theta_i - \theta_k) \right\} V_i^a \qquad (11)$$

The off- diagonal element of J_2 will be

$$\frac{\partial P_i^*}{\partial V_j} = \frac{\partial P_{i(n)}}{\partial V_j} V_i^a$$

Similarly differentiating equation (4) the diagonal elements of J_4 are

$$\frac{\partial Q_i^*}{\partial V_i} = Q_{i(n)}.b.V_i^{b-1} + \frac{\partial Q_{i(n)}}{\partial V_i} V_i^b \quad \text{but}$$

$$\frac{\partial Q_{i(n)}}{\partial V_i} = -2V_i Y_{ii} \mathrm{Sin}\theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} V_i Y_{ik} \mathrm{Sin}(\theta_i - \theta_k)$$

So,

$$\frac{\partial Q_i^*}{\partial V_i} = b.P_{i(n)}.V_i^{b-1} - \left\{ 2V_i Y_{ii} \mathrm{Sin}\theta_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^{n} V_i Y_{ik} \mathrm{Sin}(\theta_i - \theta_k) \right\} V_i^b \qquad (12)$$

And the off-diagonal element of J_4 are

$$\frac{\partial Q_i^*}{\partial V_j} = \frac{\partial Q_{i(n)}}{\partial V_j} V_i^b$$

The diagonal and off diagonal terms of J_1 are

$$\frac{\partial P_i^*}{\partial \theta_i} = \frac{\partial P_{i(n)}}{\partial \theta_i} V_i^a \text{ and } \frac{\partial P_i^*}{\partial \theta_j} = \frac{\partial P_{i(n)}}{\partial \theta_j} V_i^a \text{ respectively.}$$

Similarly the diagonal and off diagonal term of J_3 are

$$\frac{\partial Q_i^*}{\partial \theta_i} = \frac{\partial Q_{i(n)}}{\partial \theta_i} V_i^b \text{ and } \frac{\partial Q_i^*}{\partial \theta_j} = \frac{\partial Q_{i(n)}}{\partial \theta_j} V_i^b \text{ respectively.}$$

The estimated bus voltages and powers are used to evaluate the elements of jacobian, and then the new estimates for the bus voltage are

$$\theta_i^{k+1} = \theta_i^k + \Delta\theta_i^k$$

$$V_i^{k+1} = V_i^k + \Delta V_i^k$$

The process is repeated until ΔP_i^* and ΔQ_i^* for all buses are within a specified tolerance. The line flows can be calculated with the final bus voltages, the given values of line charging and line admittances.

3. TEST CASE AND SIMULATION

Standard 14 bus test network is used to analyze the different types of load models at the buses. The codes are developed in MATLAB. The value of exponential parameters a and b for the active and reactive powers, that represents the constant current, constant power loads , constant impedance loads are give in table 1.

Table 1 Load type and exponent values

S.NO	**Type of Load**	**Range of Exponent**	
		Active power (a)	Reactive Power (b)
1	Constant Power Loads	0	0
2	Constant Current Loads	1	1
3	Constant Impedance Loads	2	2

Newton Raphson Power flow algorithm:
It consists of following steps.

1. Form the bus admittance matrix.
2. Assume bus voltages.
3. Set Iteration count C=0

   Calculate Bus Powers and Power mismatch ΔP, ΔQ Δf Δg

If the mismatch is less than the given tolerance, output the result else go to 5.

4. Calculate the Bus Currents and the elements of Jacobian matrix and find the Voltage corrections Vector
5. Update the Voltage, increment the counter.
6. Go to step 4.

Test Data of 14-bus system is given in table 2, 3.

Table 2 Bus Data

Bus No	**BUS VOLTAGE**		**GENERATOR**		**LOAD**	
	Voltage magnitude(pu)	Phase angle (deg)	(MW, MVAR)	Qmin, Qmax	P(MW)	Q(MVAR)
1	1.06	0	0.4,0	-0.4,0.5	0.21	0.0
2	1.045	0	0,0	0,0.4	0.94	0.127
3	1.010	0	0,0	-0.06,0.24	0.47	0.19
4	1	0	0,0	-0.06,0.24	0.076	0.039
5	1	0	0,0	0,0	0.11	0.075
6	1	0	0,0	0,0	0.0	0.0
7	1	0	0,0	0,0	0.0	0.0
8	1	0	0,0	0,0	0.295	0.166
9	1	0	0,0	0,0	0.09	0.058
10	1	0	0,0	0,0	0.035	0.018
11	1	0	0,0	0,0	0.061	0.016
12	1	0	0,0	0,0	0.135	0.058
13	1	0	0,0	0,0	0.149	0.05
14	1	0	0,0	0,0	0.0	0.0

Table 3 Line data

Transmission Line	**Sending Bus**	**Receiving Bus**	**Line resistance (pu)**	**Line reactance (pu)**	**Line suseptance (pu)**
1	1	2	0.01938	0.05917	0.0528
2	2	3	0.08	0.24	0.0438
3	2	4	0.06	0.18	0.0492
4	1	5	0.06	0.18	0.034
5	2	5	0.04	0.12	0.0346
6	3	4	0.01	0.03	0.0128
7	4	5	0.08	0.24	0.0
8	5	6	0.02	0.06	0.0
9	4	7	0.08	0.24	0.0
10	7	8	0.06	0.18	0.0
11	4	9	0.06	0.18	0.0
12	7	9	0.04	0.12	0.0
13	9	10	0.01	0.03	0.0
14	6	11	0.08	0.24	0.0
15	6	12	0.02	0.06	0.0

16	6	13	0.08	0.24	0.0
17	9	14	0.06	0.18	0.0
18	10	11	0.06	0.18	0.0
19	12	13	0.04	0.12	0.0
20	13	14	0.01	0.03	0.0

4. RESULTS OF LOAD FLOW CALCULATION WITH VOLTAGE SENSITIVE LOADS

The test network is tested first with Conventional load flow. Then it is analyzed with voltage sensitive loads at each of the bus.

For constant power load the convergence is achieved in 6 iteration while for constant current types of loads the convergence is in 9 iteration and for constant impedance type of loads it is 10 iteration with standard 14-bus system. The simulation yield the Bus Active and Reactive power flow with constant power, constant current and constant impedance loads as shown in Fig.1-2 respectively.

Voltages at the buses with different types of loads are given in table 4, 5, 6.

Line active and reactive power flow with constant power, constant current and constant impedance loads as shown in Fig. 3-4 respectively.

The simultaneous yield Active and Reactive power losses in the transmission line with constant power, constant current and constant impedance loads as shown in Fig. 5-6 respectively.

Active power at bus is minimum for constant impedance type of load and maximum for constant power type of load. But at bus 4 active power for constant power type of load is less as compared to the constant impedance type of load.

Also Reactive power at bus is minimum for constant power type of load and maximum for constant impedance type of load.

Active and reactive power at line is maximum for constant power type of load and minimum for constant impedance type of load.

Active and reactive power losses at line are maximum for constant power type of load and minimum for constant impedance type of load.

Table 4 Voltage at the buses with constant power Loads

Bus No	**Bus Voltage**	
	|V|	**θ**
1	1.06	0
2	1.045	-4.9403
3	1.01	-12.9616
4	1.0150	-11.8381
5	1.0427	-7.6192
6	1.07	-8.9013
7	1.0525	-11.4871
8	1.09	-12.1690
9	1.0464	-10.8432
10	1.0479	-10.7110
11	1.0572	-9.9262
12	1.0674	-9.1099
13	1.0621	-9.5302
14	1.0598	-9.7154

Table 5 Voltage at the buses with constant current Loads

Bus No	**Bus Voltage**	
	|V|	**θ**
1	1.06	0
2	1.045	-4.8521
3	1.01	-12.744
4	1.0154	-11.636
5	1.0455	-7.4861
6	1.07	-8.7104
7	1.0527	-11.285
8	1.09	-11.964
9	1.0466	-10.645
10	1.0481	-10.513
11	1.0574	-9.7313
12	1.0674	-8.9182
13	1.0622	-9.3368
14	1.0599	-9.5213

Table 6 Voltage at the buses with constant impedance Loads

Bus No	**Bus Voltage**	
	|V|	**θ**
1	1.06	0
2	10.45	-4.7682
3	1.01	-12.537
4	1.0156	-11.442
5	1.046	-7.3257
6	1.07	-8.5349
7	1.0528	-11.095
8	1.09	-11.772
9	1.0467	-10.458
10	1.0482	-10.327
11	1.0574	-9.5498
12	1.0674	-8.7415
13	1.0622	-9.1577
14	1.06	-9.3411

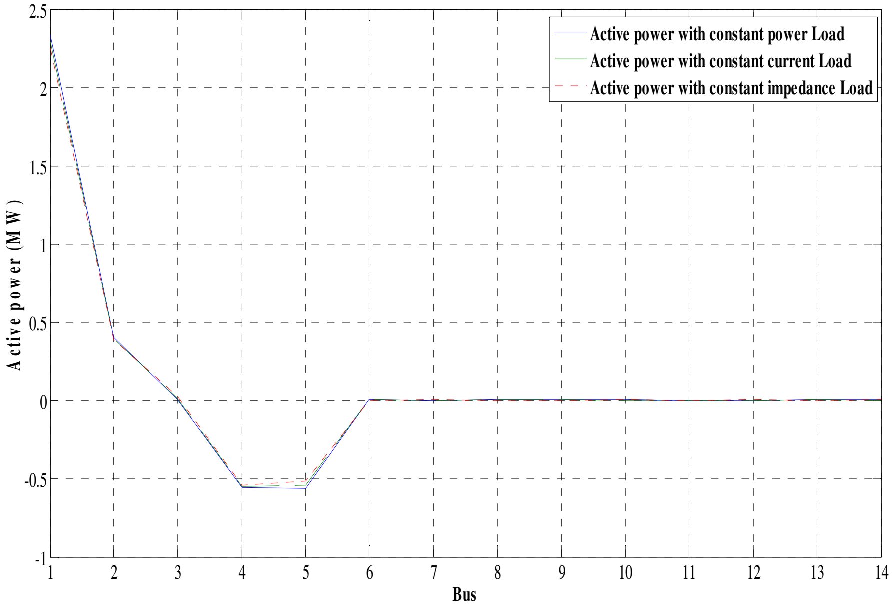

Figure.1. Active Power at Buses

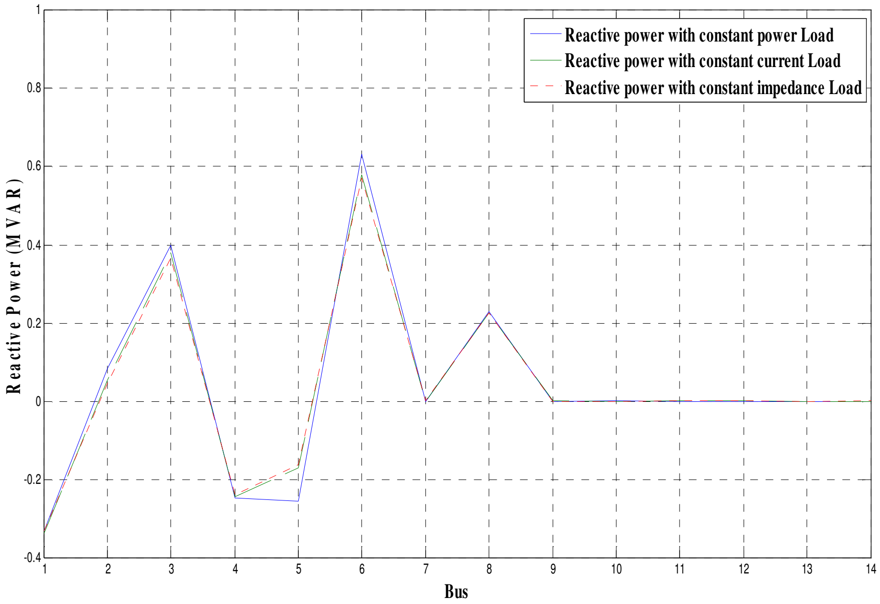

Figure 2. Reactive power at Buses

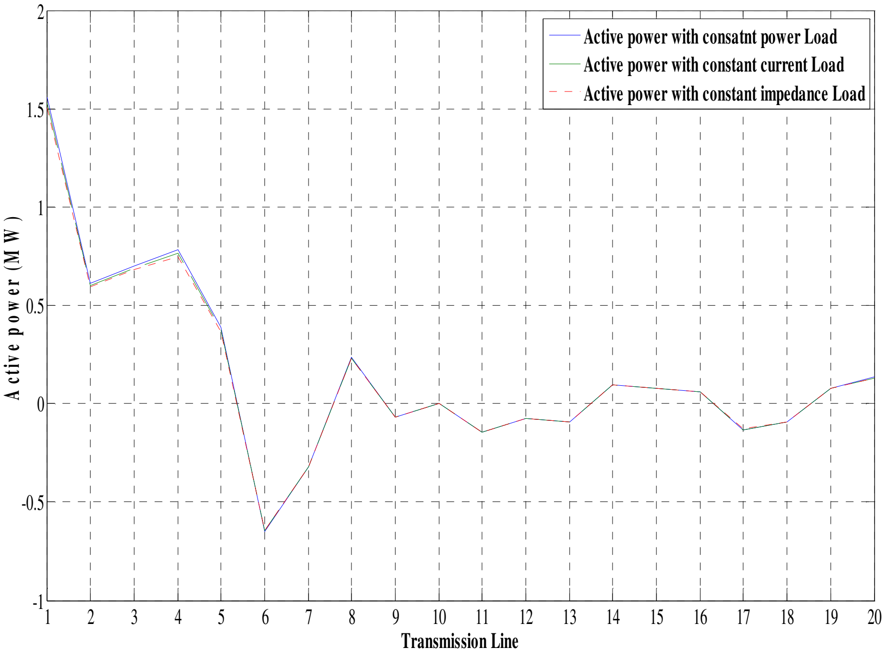

Figure 3. Active power at Line

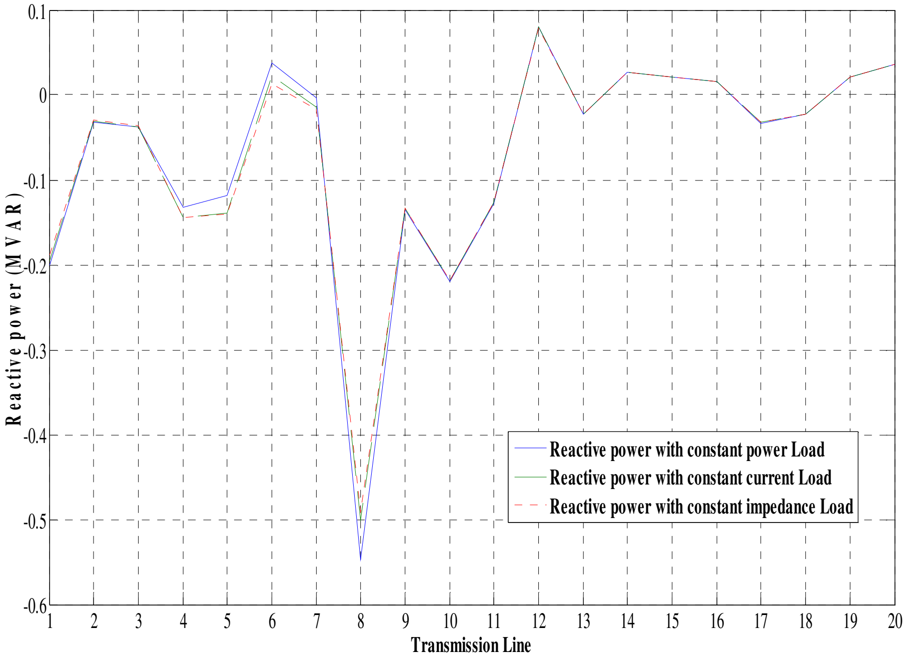

Figure 4. Reactive power at Line

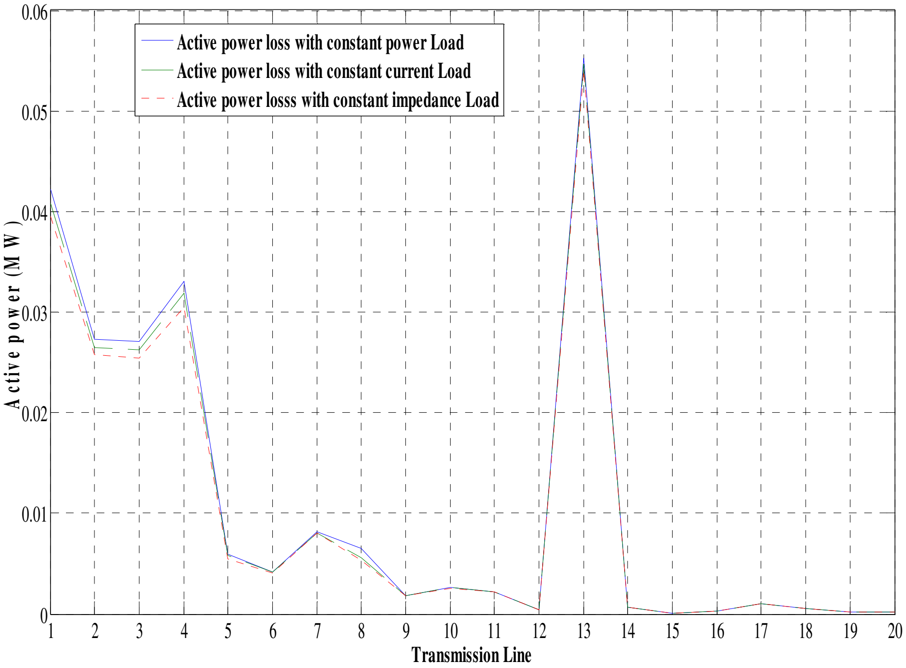

Figure 5. Active Power Losses at Line

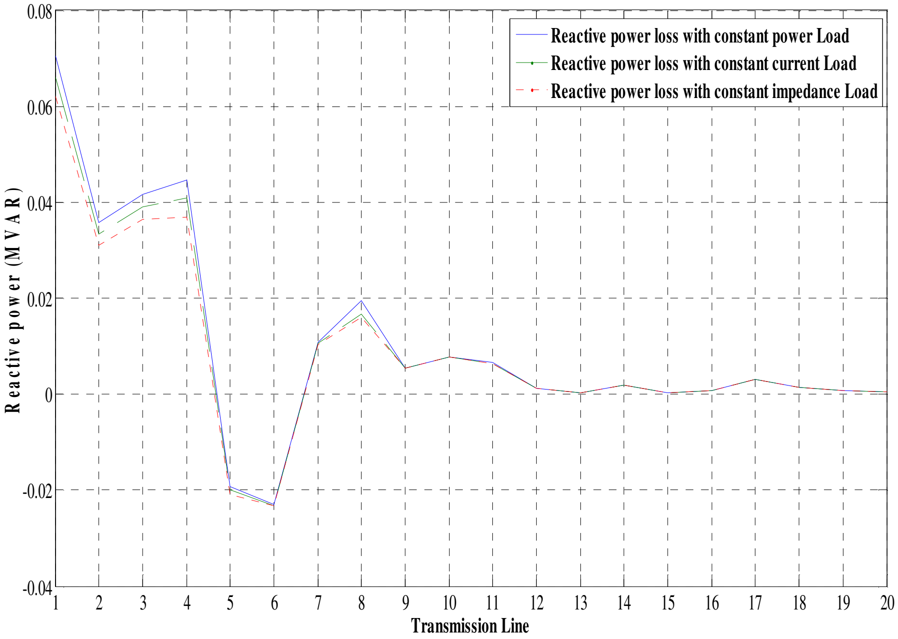

Figure 6. Reactive Power Losses at Line

5. CONCLUSIONS

In this paper, load flow analysis has been performed for voltage sensitive loads for a standard 14-bus system. The Numerical result for the standard 14 bus network has been presented. As compared with the constant current load, constant impedance loads require additional iteration to obtain the solution. So the load flow analysis with the voltage sensitive loads is more accurate than those for the constant power load.

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