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# Optimal Load Flow for 11/220/66 KV Industrial Network

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***Abstract:*** *This Paper shows analysis of an industrial network which consists of Generators, Step-up and Step-down transformers, Transmission Line, Buses, and Industrial Load. The network is designed to supply a continuous process plant which will be having varying demand. In order to meet reliability constraint system capacities are set higher than required which causes power flow mismatch in load flow. So this paper presents a comprehensive analysis of the system and provides a suggestion for optimal load flow solution.*
***Keywords:*** *Load Flow Analysis, Optimal Power Flow, LTC, Newton-Raphson Method*

## I. Introduction

The industrial needs keep varying with varying demands, market scenarios. In order to meet future demands, the electrical network is made capable of supplying higher demands in future. Moreover, in any industrial installation cost constraint plays the major role. Often due to financial limitations, required adjustments are not being made in the electrical network if it is not creating any major disturbance to the plant.

The present paper focuses on such electrical installation. The network consists of a thermal power plant with generation capacity of 92 MW. The total generated power is divided into two process plants having a demand of 68 MW and 12.5 MW respectively.This power is being transferred by transmission lines having a capacity of 220 kv (3.5 km) and 66 kv(13.5 km) respectively. The power transmission capacity is higher than the requirement of load, but as stated earlier in order to save new installation cost and considering future demand growth, the transmission line capacity is kept unaltered.This may cause errors in load flow solutions.To analyze the effects of such overrated system detailed load flow analysis is required to be performed so that proper protection schemes can be employed for the present system.

The power is being generated at 11 kv voltage level and stepped up within generating substation only to 220 kv. The stepped up power is collected at 220 kV bus and transmitted to one of the process plants at 220 kV transmission voltage. The 66kv transmission lines and 66/6.9 kV substation are already available at another process plan, and hence, in order to save new installation cost power is being transmitted at 66 kV voltage level. At both plant power is stepped down and collected at 6.9 kV bus. From 6.9 kV bus power is distributed at with different feeders to the plant loads.[4]

## II. Load Flow Analysis

The basic analysis of any system includes knowledge of complex voltages, active and reactive power flows at each bus of the network. Load flow analysis is a tool for such computations. Load flow analysis uses various iterative methods in order to compute complex voltages at different buses. Once the flows are known further analysis and computations can be carried out for given system. There are several methods being used for load flow analysis, such as Gauss seidal method, Newton-Rhapson method, fast decoupled load flow etc.[1]

The goal of load flow analysis is to find voltage magnitude and angle at each bus. The buses are defined according to their functionality. The bus containing largest source connected with it is named as a slack bus or generator bus. The bus without any generators connected to it is known as load bus. So voltage magnitude and angle are known at the slack bus whereas active and reactive power are known at load bus. The power equations are required to be solved to find unknown quantities at different buses.

The Gauss-Seidel method is a most common method to solve power equations. It requires less computer memory as well as good accuracy. But as a number of buses increases the number of equations to be solved increase. And the slow rate of convergence increases the number of iterations. Newton –Raphson method is very useful method for solving load flows for complex power networks. The calculation is based on Taylor's series and partial derivative equations. The N-R method requires less number of iterations to reach convergence , hence takes less computational time. Moreover, N-R method is independent of factors such as slack bus selection, transformer regulation etc., and most important factor is number of iterations is independent of system size. [6]

## III. System Data

The detailed system single line diagram is as following.

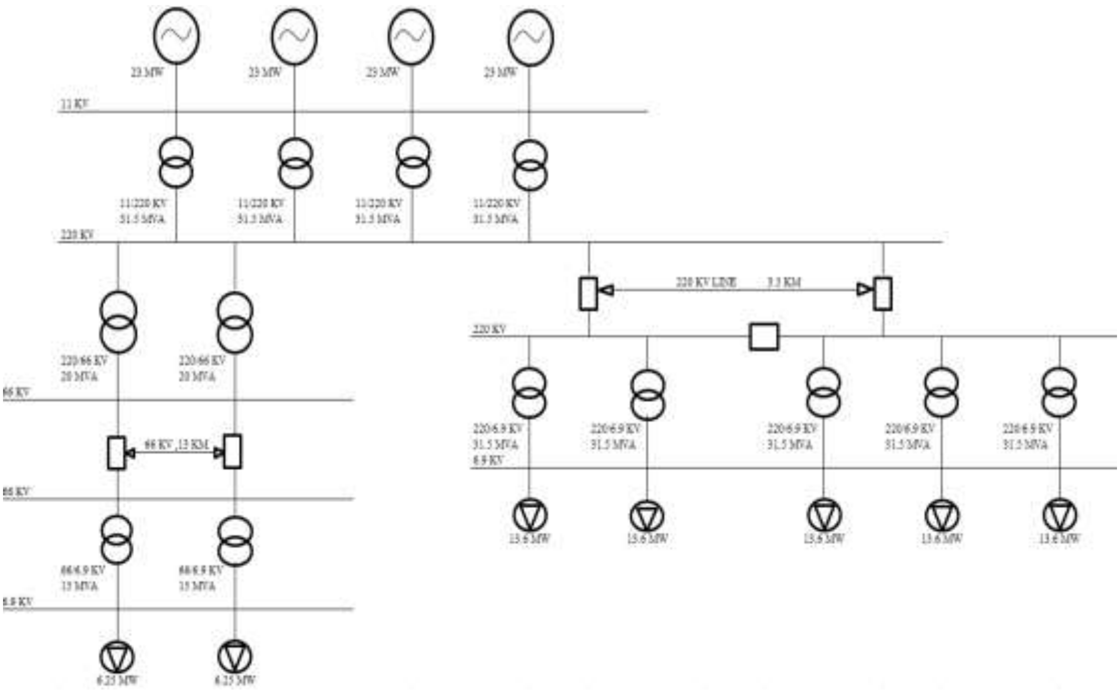


**Fig.1 :** System SLD

(*[2] Keval Velani, S.M.Takalkar, Lightening Protection System Study Report on 220/6.9 kv MRSS, Ultratech cement Plant,Kovaya,Takalkar Power Engineers and Consultants, 2015* )

The detailed system data is shown in following tables:

**Table I**: Generator Details

| ID | Rating | | | | |
|---|---|---|---|---|---|
| | MW | KV | MVA | P.F. | FLA |
| Gen 1 | 23 | 11 | 27.059 | 85 | 1420 |
| Gen 2 | 23 | 11 | 27.059 | 85 | 1420 |
| Gen 3 | 23 | 11 | 27.059 | 85 | 1420 |
| Gen 4 | 23 | 11 | 27.059 | 85 | 1420 |

**Table II**: Transformer Data

| ID | Rating | | | | | | |
|---|---|---|---|---|---|---|---|
| | kV | MVA | %Z | FLA prim | FLA sec | %Z p.u. | Parallel X'mer |
| T-1 | 11/220 | 31.5 | 12.5 | 1653 | 82.67 | 39.68 | |
| T-2 | 11/220 | 31.5 | 12.5 | 1653 | 82.67 | 39.68 | |
| T-3 | 11/220 | 31.5 | 12.5 | 1653 | 82.67 | 39.68 | 9.92 |
| T-4 | 11/220 | 31.5 | 12.5 | 1653 | 82.67 | 39.68 | |
| T-5 | 220/66 | 20 | 10 | 52.49 | 175 | 50 | |
| T-6 | 220/66 | 20 | 10 | 52.49 | 175 | 50 | 25 |
| T-7 | 66/6.9 | 15 | 10 | 131.2 | 1255 | 66.67 | |
| T-8 | 66/6.9 | 15 | 10 | 131.2 | 1255 | 66.67 | 33.335 |
| T-9 | 220/6.9 | 31.5 | 12.5 | 82.67 | 2636 | 39.68 | |
| T-10 | 220/6.9 | 31.5 | 12.5 | 82.67 | 2636 | 39.68 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| T-11 | 220/6.9 | 31.5 | 12.5 | 82.67 | 2636 | 39.68 | 7.936 |
| T-12 | 220/6.9 | 31.5 | 12.5 | 82.67 | 2636 | 39.68 | |
| T-13 | 220/6.9 | 31.5 | 12.5 | 82.67 | 2636 | 39.68 | |

**Table III**: Transmission Line Data

| ID | Rating (kv) | Length(km) | R1 (ohms/km) | X1 (ohms/km) |
|---|---|---|---|---|
| Line-1 | 220 kv | 3.5 | 0.04428 | 0.44839 |
| Line-2 | 66 kv | 13 | 0.17346 | 0.37337 |

## IV. Results And Discussion

Load flow analysis is done with the help of ETAP software. Newton- Raphson method of load flow solution is used to perform load flow analysis. Permissible variation in voltage and power are kept +/- of rated value. A maximum number of iterations performed are 10 with the precision of 0.0001.

The load flow analysis in ETAP gives the following result.

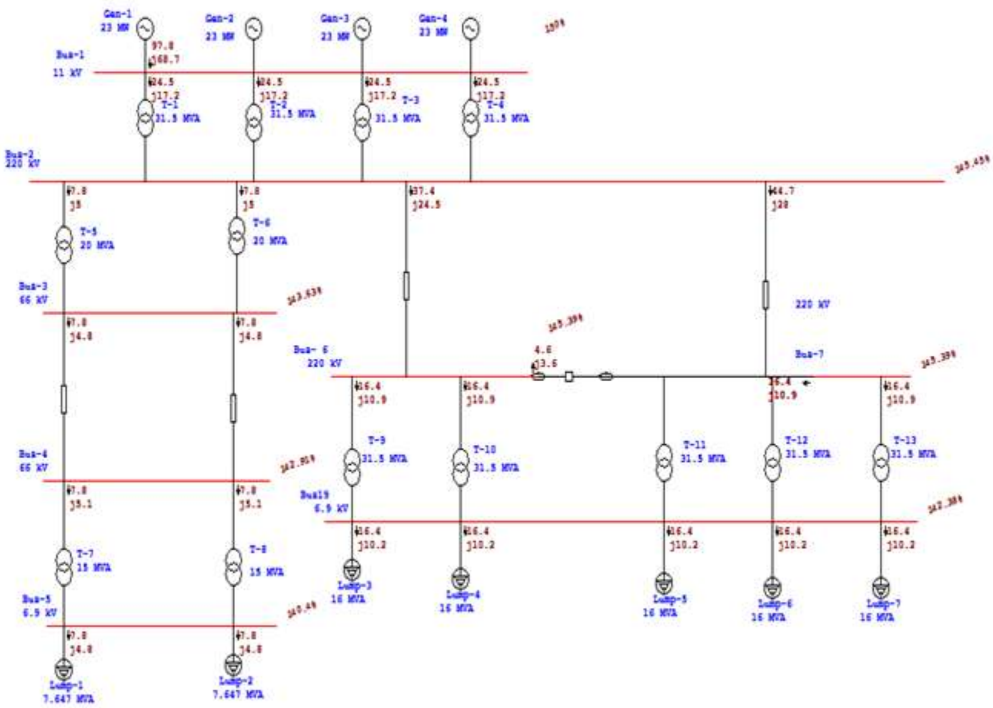

**Fig.2:** Load Flow in ETAP

Load flow results are as following:

**Table IV**: Load flow results

| BUS | | Voltage | | Generation | | Load | | Load flow | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | **KV** | **% Mag** | **Ang.** | **MW** | **Mvar** | **MW** | **Mvar** | **ID** | **MW** | **Mvar** | **Amp** | **%PF** |
| **Bus-1** | 11 | 100 | 0 | 80.11 | 67.09 | 0 | 0 | Bus-2 | 20.026 | 16.773 | 1371.1 | 76.7 |
| | | | | | | | | Bus-2 | 20.026 | 16.773 | 1371.1 | 76.7 |
| | | | | | | | | Bus-2 | 20.026 | 16.773 | 1371.1 | 76.7 |
| | | | | | | | | Bus-2 | 20.026 | 16.773 | 1371.1 | 76.7 |
| **Bus-2** | 220 | 93.494 | 25.2 | 0 | 0 | 0.01 | 0.002 | Bus-6 | 30.652 | 21.971 | 105.9 | 81.3 |
| | | | | | | | | Bus-7 | 36.685 | 25.146 | 124.8 | 82.5 |
| | | | | | | | | Bus-1 | -19.97 | -14.066 | 68.6 | 81.8 |
| | | | | | | | | Bus-1 | -19.97 | -14.066 | 68.6 | 81.8 |
| | | | | | | | | Bus-1 | -19.97 | -14.066 | 68.6 | 81.8 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Bus-1 | -19.97 | -14.066 | 68.6 | 81.8 |
| | | | | | | | | Bus-3 | 6.261 | 4.573 | 21.8 | 80.8 |
| | | | | | | | | Bus-3 | 6.261 | 4.573 | 21.8 | 80.8 |
| **Bus-3** | 66 | 90.942 | -6.8 | 0 | 0 | 0 | 0 | Bus-4 | 6.244 | 4.23 | 72.5 | 82.8 |
| | | | | | | | | Bus-4 | 6.244 | 4.23 | 72.5 | 82.8 |
| | | | | | | | | Bus-2 | -6.244 | -4.23 | 72.5 | 82.8 |
| | | | | | | | | Bus-2 | -6.244 | -4.23 | 72.5 | 82.8 |
| **Bus-4** | 66 | 89.991 | -7.1 | 0 | 0 | 0 | 0 | Bus-3 | -6.2 | -4.296 | 73.3 | 82.8 |
| | | | | | | | | Bus-3 | -6.2 | -4.296 | 73.3 | 82.8 |
| | | | | | | | | Bus-5 | 6.2 | 4.296 | 73.3 | 82.8 |
| | | | | | | | | Bus-5 | 6.2 | 4.296 | 73.3 | 82.8 |
| **Bus-4** | 6.9 | 86.696 | -40 | 0 | 0 | 12.4 | 7.656 | Bus-4 | -6.177 | -3.828 | 701.4 | 85 |
| | | | | | | | | Bus-4 | -6.177 | -3.828 | 701.4 | 85 |
| **Bus-6** | 220 | 93.405 | 25.2 | 0 | 0 | 0 | 0 | Bus-2 | -30.65 | -22.307 | 106.5 | 80.8 |
| | | | | | | | | Bus-9 | 13.465 | 9.569 | 46.4 | 81.5 |
| | | | | | | | | Bus-9 | 13.465 | 9.569 | 46.4 | 81.5 |
| | | | | | | | | Bus-7 | 3.716 | 3.17 | 13.7 | 76.1 |
| **Bus-7** | 220 | 93.405 | 25.2 | 0 | 0 | 0 | 0 | Bus-2 | -36.68 | -25.534 | 125.6 | 82.1 |
| | | | | | | | | Bus-9 | 13.465 | 9.569 | 46.4 | 81.5 |
| | | | | | | | | Bus-9 | 13.465 | 9.569 | 46.4 | 81.5 |
| | | | | | | | | Bus-9 | 13.465 | 9.569 | 46.4 | 81.5 |
| | | | | | | | | Bus-6 | -3.716 | -3.17 | 13.7 | 76.1 |
| **Bus-9** | 6.9 | 89.392 | -8.5 | 0 | 0 | 67.2 | 41.64 | Bus-6 | -13.44 | -8.328 | 1479.8 | 85 |
| | | | | | | | | Bus-6 | -13.44 | -8.328 | 1479.8 | 85 |
| | | | | | | | | Bus-7 | -13.44 | -8.328 | 1479.8 | 85 |
| | | | | | | | | Bus-7 | -13.44 | -8.328 | 1479.8 | 85 |
| | | | | | | | | Bus-7 | -13.44 | -8.328 | 1479.8 | 85 |

From load flow results losses can be calculated at various branches which are tabulated as following:

**Table V:** Loss Summary

| **Branch** | **Losses** | | **%Bus Voltage Drop** |
|---|---|---|---|
| **ID** | **kW** | **kVAR** | |
| T-1 | 60.2 | 2707.2 | 6.51 |
| T-2 | 60.2 | 2707.2 | 6.51 |
| T-3 | 60.2 | 2707.2 | 6.51 |
| T-4 | 60.2 | 2707.2 | 6.51 |
| LINE 1 ACSR ZEBRA | 6.2 | -336.9 | 0.090 |
| LINE 1 ACSR ZEBRA | 8.7 | -388.9 | 0.09 |
| T-5 | 17.2 | 343.3 | 2.55 |
| T-6 | 17.2 | 343.4 | 2.55 |
| LINE 3 ACSR DOG | 43 | -66.4 | 0.95 |
| LINE 4 ACSR DOG | 43 | -66.4 | 0.95 |
| T-7 | 23.4 | 467.8 | 3.29 |
| T-8 | 23.4 | 467.8 | 3.29 |
| T-9 | 27.6 | 1240.8 | 4.01 |
| T-10 | 27.6 | 1240.8 | 4.01 |
| T-11 | 27.6 | 1240.8 | 4.01 |
| T-12 | 27.6 | 1240.8 | 4.01 |
| T-13 | 27.6 | 1240.8 | 4.01 |
| **Total** | **560.6** | **17796.8** | |

As shown in results there is a very large reactive power loss in the present power network. The present source is unable to supply the system reactive power demand and hence resulting in voltage collapse at system buses.

In order to maintain voltage stability, reactive power compensation is required. In order to analyse the actual generation requirements and required measures to be taken to minimize the active and reactive power losses, optimal load flow analysis is done.[3]

### A. Optimal Load Flow

Optimal load flow is a software optimization tool for adjusting the power flow in a power network to achieve an optimal value of predefined objective such as losses or production costs. In conventional load flow analysis, active power generations are specified, whereas in optimal load flow analysis the optimal generations are sought to minimize the losses and operating cost of the system The OLF analysis seeks to find an optimal profile of active and reactive power along with voltage magnitude in such a manner as to minimize costs of all thermal electric power system while satisfying network security constraints.[4]. The constraints include the bus real and reactive power balance, the generator voltage set points, transmission line /transformer /interface flow limits etc.

The optimal load flow analysis is performed with the help of ETAP Software and results are obtained as following:

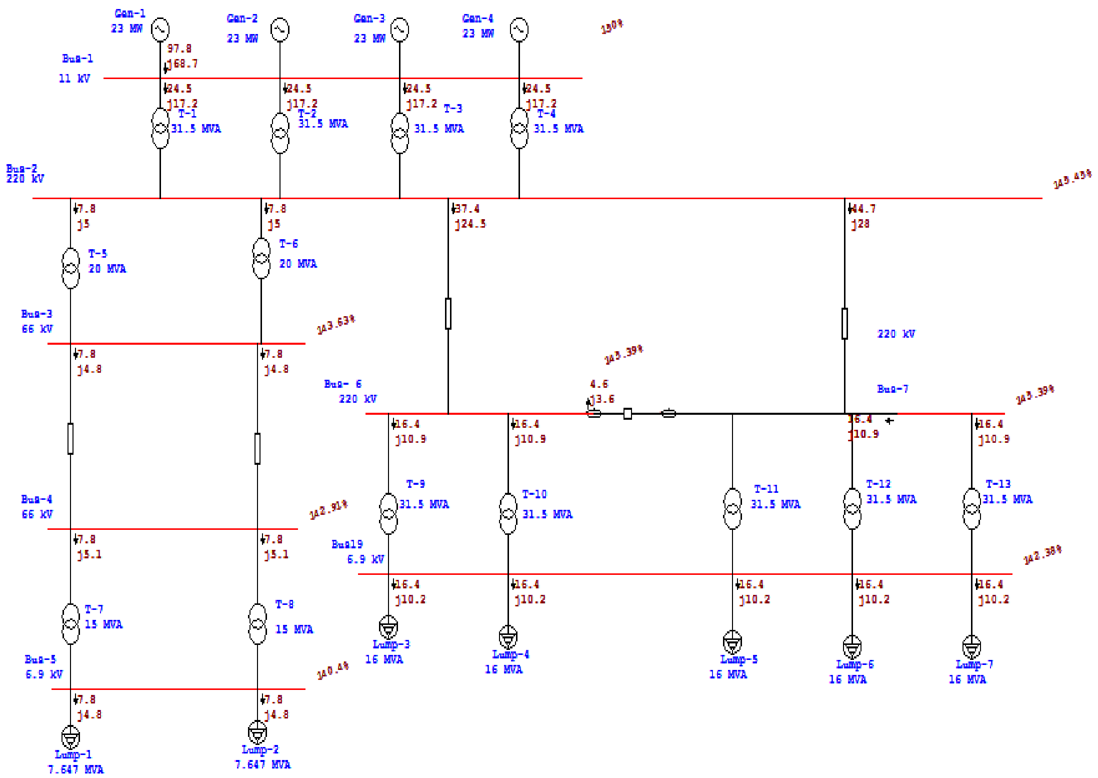


**Fig.3:** Optimal Load Flow

**Table VI:** Optimal Load Flow Data

| BUS | Voltage | | | Generation | | Load | | Load flow | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | KV | % Mag | Ang. | MW | Mvar | MW | Mvar | ID | MW | Mvar | Amp | %PF |
| **Bus-1** | 11 | 150 | 0 | 97.826 | 67.734 | 0 | 0 | Bus-2 | 24.456 | 17.183 | 1045.9 | 81.8 |
| | | | | | | | | Bus-2 | 24.456 | 16.773 | 1045.9 | 81.8 |
| | | | | | | | | Bus-2 | 24.456 | 16.773 | 1045.9 | 81.8 |
| | | | | | | | | Bus-2 | 24.456 | 16.773 | 1045.9 | 81.8 |
| **Bus-2** | 220 | 145.451 | -2.5 | 0 | 0 | 0 | 0 | Bus-6 | 37.378 | 24.502 | 80.6 | 83.6 |
| | | | | | | | | Bus-7 | 44.683 | 27.969 | 95.1 | 84.8 |
| | | | | | | | | Bus-1 | -24.421 | -15.608 | 52.3 | 84.3 |
| | | | | | | | | Bus-1 | -24.421 | -15.608 | 52.3 | 84.3 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Bus-1 | -24.421 | -15.608 | 52.3 | 84.3 |
| | | | | | | | | Bus-1 | -24.421 | -15.608 | 52.3 | 84.3 |
| | | | | | | | | Bus-3 | 7.812 | 4.981 | 16.7 | 84.3 |
| | | | | | | | | Bus-3 | 7.812 | 4.981 | 16.7 | 84.3 |
| **Bus-3** | 66 | 143.63 | -3.5 | 0 | 0 | 0 | 0 | Bus-4 | 7.802 | 4.778 | 55.7 | 85.3 |
| | | | | | | | | Bus-4 | 7.802 | 4.778 | 55.7 | 85.3 |
| | | | | | | | | Bus-2 | -7.802 | -4.778 | 55.7 | 85.3 |
| | | | | | | | | Bus-2 | -7.802 | -4.778 | 55.7 | 85.3 |

| **BUS** | | **Voltage** | | **Generation** | | **Load** | | **Load flow** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | **KV** | **% Mag** | **Ang.** | **MW** | **Mvar** | **MW** | **Mvar** | **ID** | **MW** | **Mvar** | **Amp** | **%PF** |
| **Bus-4** | 66 | 142.91 | -3.7 | 0 | 0 | 0 | 0 | Bus-3 | -7.777 | -5.093 | 56.9 | 83.7 |
| | | | | | | | | Bus-3 | -7.777 | -5.093 | 56.9 | 83.7 |
| | | | | | | | | Bus-5 | -7.777 | -5.093 | 56.9 | 83.7 |
| | | | | | | | | Bus-5 | -7.777 | -5.093 | 56.9 | 83.7 |
| **Bus-5** | 6.9 | 140.4 | -5.1 | 0 | 0 | 15.525 | 3.269 | Bus-4 | -7.763 | -4.811 | 544.3 | 85 |
| | | | | | | | | Bus-4 | -7.763 | -4.811 | 544.3 | 85 |
| **Bus-6** | 220 | 145.385 | -2.5 | 0 | 0 | 0 | 0 | Bus-2 | -37.374 | -25.415 | 81.6 | 82.7 |
| | | | | | | | | Bus-9 | 16.41 | 10.888 | 35.5 | 83.3 |
| | | | | | | | | Bus-9 | 16.41 | 10.888 | 35.5 | 83.3 |
| | | | | | | | | Bus-7 | 4.553 | 3.639 | 10.5 | 78.1 |
| **Bus-7** | 220 | 145.385 | -2.5 | 0 | 0 | 0 | 0 | Bus-2 | -44.678 | -29.026 | 96.2 | 83.9 |
| | | | | | | | | Bus-9 | 16.41 | 10.888 | 35.5 | 83.3 |
| | | | | | | | | Bus-9 | 16.41 | 10.888 | 35.5 | 83.3 |
| | | | | | | | | Bus-9 | 16.41 | 10.888 | 35.5 | 83.3 |
| | | | | | | | | Bus-6 | -4.553 | -3.639 | 10.5 | 78.1 |
| **Bus-9** | 6.9 | 142.383 | -4.3 | 0 | 0 | 81.971 | 16.63 | Bus-6 | -16.394 | -10.16 | 1133.5 | 85 |
| | | | | | | | | Bus-6 | -16.394 | -10.16 | 1133.5 | 85 |
| | | | | | | | | Bus-7 | -16.394 | -10.16 | 1133.5 | 85 |
| | | | | | | | | Bus-7 | -16.394 | -10.16 | 1133.5 | 85 |
| | | | | | | | | Bus-7 | -16.394 | -10.16 | 1133.5 | 85 |

**Table VII:** Loss summary

| **ID** | **MW** | **Mvar** | **MVA** |
|---|---|---|---|
| Source | 97.826 | 68.734 | 119.558 |
| Total Demand | 97.496 | 57.664 | 113.273 |
| Total line charging | 0 | -2.759 | |
| **Apparent Losses** | **0.329** | **11.069** | **6.285** |

## V. Conclusion

Optimal Load Flow analysis provides suitable changes in network parameters. In order to meet demand generation has been increased such that reactive power can be compensated. It can be observed from table V and table VII that active and reactive power losses have been reduced by 23% and 10%.respectively. This optimal load flow suggests suitable measures to be taken in order to maintain system voltage stability.

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