Modeling, Simulation, Analysis and Optimisation of a Power System Network- Case Study

Vivek Raveendran, Sumit Tomar

Abstract—This paper deals with modeling, simulation and optimization of an existing power system network using actual data. For this purpose, Kerala state power sytem (India) has been considered and a single line diagram is modeled using Electrical Transient Analyser Programme (ETAP) software. All the physical and electrical parameters of the power system including height of towers, spacing between transmission lines, resistance and reactance values of transmission lines, transformer and generator ratings etc. are collected and coded to obtain the exact model of power system network. Then load flow study is conducted using ETAP and simulation results are studied. From the results of simulation, the buses with low voltage profiles are identified and possible solutions for improving the voltages are studied and their effectiveness is checked using the software.

Index Terms— Load flow study, Power system modeling, Improving voltage profile, Reactive power compensation, ETAP, Overloading of lines.

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1 INTRODUCTION

In power engineering, the power flow study (also known as load-flow study) is an important tool involving numerical analysis applied to a power system. Unlike traditional circuit analysis, a power flow study usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various forms of AC power (i.e. reactive, real, and apparent) rather than voltage and current. It analyzes the power systems in normal steady-state operation.

In this paper we have attempted to model an existing power system using the actual data taking care of all the parameters required for the simulation and analysis. With the help of Kerala State Electrcity Board, we have modeled 400kV, 220kV and 110kV Kerala grid using ETAP software.The algorithm used for power flow study is discussed in section 2.1 and data collection and coding required for modeling is discussed in section 3 and section 4.Load flow study is carried out using Newton Raphson method and voltage profile of buses are analysed. The simulation results are analysed in section 6.

New methods for the improvement of voltage profile are suggested and analysed using the model developed. The optimisation techiniques include power factor compensation, tap changing, upgradation of substations, upgradation of line and load shifting.These methods are analysed in section 7.

The great importance of power flow or load-flow studies is in the planning the future expansion of power systems as well as in determining the best operation of existing systems. Also the system can be analysed and simulation results can be studied before any new change in the existing system without affecting the original system.

2 POWER FLOW PROBLEM FORMULATION

The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined. Due to the nonlinear nature of this problem, numerical methods are employed to obtain a solution that is within an acceptable tolerance.

The solution to the power flow problem begins with identifying the known and unknown variables in the system. The known and unknown variables are dependent on the type of bus. A bus without any generators connected to it is called a Load Bus. With one exception, a bus with at least one generator connected to it is called a Generator Bus. The exception is one arbitrarily-selected bus that has a generator. This bus is referred to as the Slack Bus.

In the power flow problem, it is assumed that the real power PD and reactive power QD at each Load Bus are known. For this reason, Load Buses are also known as PQ Buses. For Generator Buses, it is assumed that the real power generated PG and the voltage magnitude |V| is known. For the Slack Bus, it is assumed that the voltage magnitude |V| and voltage phase Θ are known. Therefore, for each Load Bus, the voltage magnitude and angle are unknown and must be solved for; for each Generator Bus, the voltage angle must be solved for; there are no variables that must be solved for the Slack Bus. In a system with N buses and R generators, there are then 2 (N − 1) − (R − 1) unknowns.

In order to solve for the 2(N − 1) − (R − 1) unknowns, there must be 2(N − 1) − (R − 1) equations that do not introduce any new unknown variables. The possible equations to use are power balance equations, which can be written for real and reactive power for each bus. The real power balance equation is:

$$0 = -P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \tag{1}$$

where P_i is the net power injected at bus i, G_{ik} is the real part of the element in the bus admittance matrix YBUS corresponding to the ith row and kth column, B_{ik} is the imaginary part of the element in the YBUS corresponding to the ith row and kth column and θ_{ik} is the difference in voltage angle between the ith and kth buses. The reactive power balance equation is:

$$0 = -Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \qquad (2)$$

Equations included are the real and reactive power balance equations for each Load Bus and the real power balance equation for each Generator Bus. Only the real power balance equation is written for a Generator Bus because the net reactive power injected is not assumed to be known and therefore including the reactive power balance equation would result in an additional unknown variable. For similar reasons, there are no equations written for the Slack Bus.

2.1 Newton-Raphson solution method

There are several different methods of solving the resulting nonlinear system of equations. The most popular is known as the Newton-Raphson Method. This method begins with initial guesses of all unknown variables (voltage magnitude and angles at Load Buses and voltage angles at Generator Buses). Next, a Taylor Series is written, with the higher order terms ignored, for each of the power balance equations included in the system of equations. The result is a linear system of equations that can be expressed as:

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = -J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (3)$$

$$\Delta P_i = -P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \qquad (4)$$

$$\Delta Q_i = -Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \qquad (5)$$

$$J = \begin{bmatrix} \dfrac{\partial \Delta P}{\partial \theta} & \dfrac{\partial \Delta P}{\partial |V|} \\ \dfrac{\partial \Delta Q}{\partial \theta} & \dfrac{\partial \Delta Q}{\partial |V|} \end{bmatrix} \qquad (6)$$

where ΔP and ΔQ are called the mismatch equations and J is a matrix of partial derivatives known as a Jacobian.
The linearized system of equations is solved to determine the next guess (m + 1) of voltage magnitude and angles based on;

$$\theta^{m+1} = \theta^{m} + \Delta\theta \qquad (7)$$

$$|V|^{m+1} = |V|^{m} + \Delta|V| \qquad (8)$$

The process continues until a stopping condition is met. A common stopping condition is to terminate if the norm of the mismatch equations are below a specified tolerance.
Outline of solution of the power flow problem is:

1. Make an initial guess of all unknown voltage magnitudes and angles. It is common to use a "flat start" in which all voltage angles are set to zero and all voltage magnitudes are set to 1.0 p.u.
2. Solve the power balance equations using the most recent voltage angle and magnitude values.
3. Linearize the system around the most recent voltage angle and magnitude values
4. Solve for the change in voltage angle and magnitude
5. Update the voltage magnitude and angles

Check the stopping conditions, if met then terminate, else go to step 2.

3 LOAD FLOW REQUIRED DATA

3.1 Bus Data

Required data for load flow calculations for buses includes:

1. Nominal kV
2. %V and Angle (when Initial Condition is set to use Use Bus Voltages)
3. Load Diversity Factor (when the Loading option is set to use Diversity Factor)

3.2 Branch Data

Branch data is entered into the Branch Editors, i.e., Transformer, Transmission Line, Cable, Reactor, and Impedance editors. Required data for load flow calculations for branches includes:

1. Branch Z, R, X, or X/R values and units, tolerance, and temperature, if applicable
2. Cable and transmission line, length, and unit
3. Transformer rated kV and kVA/MVA, tap, and LTC settings
4. Impedance base kV and base kVA/MVA

3.3 Power Grid Data

Required data for load flow calculations for power grids includes:

1. Operating mode (Swing, Voltage Control, Mvar Control, or PF Control)
2. Nominal kV
3. %V and Angle for swing mode
4. %V, MW loading, and Mvar limits (Qmax & Qmin) for Voltage Control mode
5. MW and Mvar loading, and Mvar limits Mvar Control mode
6. MW loading and PF, and Mvar limits for PF Control mode

3.4 Synchronous Generator Data

Required data for load flow calculations for synchronous generators includes:

1. Operating mode (Swing, Voltage Control, or Mvar Control)
2. Rated kV
3. %V and Angle for swing mode of operation
4. %V, MW loading, and Mvar limits (Qmax and Qmin) for Voltage Control mode
5. MW and Mvar loading, and Mvar limits Mvar Control mode

6. MW loading and PF, and Mvar limits for PF Control mode

3.5 Static Load Data

Required data for load flow calculations for static loads includes:

1. Static Load ID
2. Rated kVA/MVA and kV
3. Power factor
4. % loading for desired Loading Category
5. Equipment cable data

3.6 Capacitor Data

Required data for load flow calculations for capacitors includes:

1. Capacitor ID
2. Rated kV, kvar/bank, and number of banks
3. % loading for desired Loading Category
4. Equipment cable data

3.7 Other Data

There are some study case related data, which must also be provided. This includes:

1. Method (Newton-Raphson, Fast-Decoupled, or Accelerated Gauss-Seidel)
2. Max Iteration
3. Precision
4. Acceleration Factor (when Accelerated Gauss-Seidel method is selected)
5. Loading Category
6. Initial Voltage Condition
7. Report (report format)
8. Update (for bus voltages and transformer LTCs using load flow result)

4 DATA COLLECTION FOR MODELING

All the required data for modeling are collected from Kerala State Electrcity Board (KSEB).

Data required for load flow studies have been collected from KSEB and they were sorted according to the easiness of the study.The following data was collected:

1. Single line diagram of the Kerala Power system network.
2. Details of 400kV, 220kV and 110kV substations in the network.
3. Reactances and MW rating of all generators connected to the network.
4. Impedances of all transmission and distribution lines and transformers.
5. Length and type (for eg. ACSR Wolf) of transmission lines from one substation to another.
6. Load details (MVAr and MW) of the existing network.

4.1 Substation Details

Details of substation were obtained from Kerala State Electricity Board. It includes

1. Type of substation
2. Rating of transformers in the substation
3. A 4 letter code word for providing a unique ID in ETAP software.

4.2 Load Details

Details of static load connected to the 220 kV and 110 kV buses were collected. Load details include

1. The MVA rating
2. Power factor of operation

TABLE 1
KERALA POWER SYSTEM DETAILS

Installed Capacity -M.W.	2746.19
Maximum Demand -M.W. (System)	2998
220 K.V. Lines- Circuit- Km	2701
110 K.V. Lines- Circuit -Km	3970
No. of EHT Sub Stations	330
Connected Load -M.W.	15827.90
No. of 220 kV substations	17
No. of 110 kV substations	123

5 MODELING OF SINGLE LINE DIAGRAM

220kV and 400 kV network of Kerala Power system network was drawn as shown in Appendix A.

Then 110kV substations were drawn inside composite network. A composite network was assigned to each district and each district was interlinked to others by using the pins of composite network.Single line diagram of some of the districts are shown in the following figures.

6 SIMULATION RESULTS

Simulation was done using Newton Raphson algorithm.Buses with voltage less than 95 % were identified and necessary steps were taken for omproving the volatage profile.

TABLE 5.1

SIMULATION RESULT SHOWING UNDERVOLTAGE BUSES.

ID	Rating	Rated kV	MW
NDPM	110	93.71	22.292
CHVR	110	93.68	102.259
CLRI	110	93.18	55.286
KGLM	110	93.08	52.236
AGMY	110	93.01	8.564
VNKA	110	92.96	74.973
WSHL	110	92.95	25.657

IRTY	110	92.93	0
MTNR	110	92.93	0
KHRD	110	92.88	72.869
QLDY	110	92.79	44.448
TR-QUILANDY	110	92.79	3.874
MRBA	110	92.67	84.991
KIZY	110	92.53	40.819
PRLI	110	92.51	25.417
MAPZ	110	92.48	26.807
KPAM	110	92.43	15.378
METR-TAP	110	92.43	24.826
MPYR	110	92.39	25.722
METR	110	92.37	4.608
MUYD	110	92.27	72.515
VDKR	110	92.18	23.709
MLPM	110	92.13	83.16
MNKD	110	91.73	12.875
PINY	110	91.45	46.986
TLSY	110	90.83	36.269
PANR	110	90.46	22.094
MAHE	110	90.44	4.417
EDKD	110	90.37	64.665
TIRR	110	89.43	43.022
PONN	110	88.94	9.255
KUPM	110	88.9	13.513

7 PROPOSED OPTIMISATION TECHNIQUES

7.1 Optimisation By Reactive Power Compensation and Tap Changing

After the load flow, the results were analysed. From the analysis, voltage level between 97-100% was taken as normal voltage level. Buses with % voltage lower than 97% was declared overloaded buses. The problem of under-voltage was observed mainly in the northern part of Kerala. The following are districts which were mostly affected by the under-voltage problem:

- Kasargode
- Kannur
- Kozhikkode
- Malappuram
- Palakkad
- Thrissur

The reasons for the under-voltage were identified in each of the areas and suitable cost-effective optimization techniques were proposed. The following sections give a detailed analysis report of each of these districts and a comparison of the voltage levels of the buses before and after optimization is also shown.

7.1.1 Kasargode

The following optimization techniques were proposed for Kasargode district:

1. Addition of a 20 MVAR capacitor bank at Mylatty which is the incoming feeder to Kasargode district.
2. Addition of 20 MVAR capacitor at Kanjangad tap.

The comparison of the voltage levels of various buses at Kasargode district before and after optimization is shown by the graph in Fig. 1.

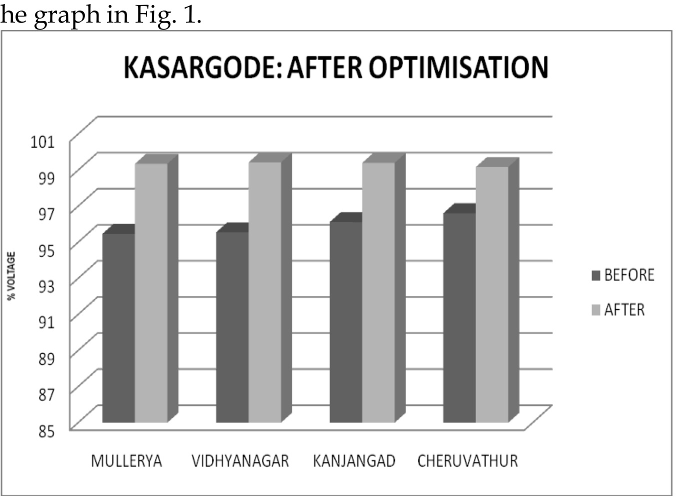


Fig. 1 Voltage profile before and after optimisation

7.1.2 Kannur

The following optimization techniques were proposed for Kannur district:

1. At Taliparamba bus a tap change of 5% was made and a 20 MVAr capacitor bank was added.
2. An addition of 10 MVAr capacitor bank was made to an existing 10 MVAr capacitor bank at Mangad and Mundayad
3. A new capacitor bank was installed at Kanjirode (40 MVAr) and Talassery (20 MVAr).

The comparison before and after optimization is shown in Fig.2.

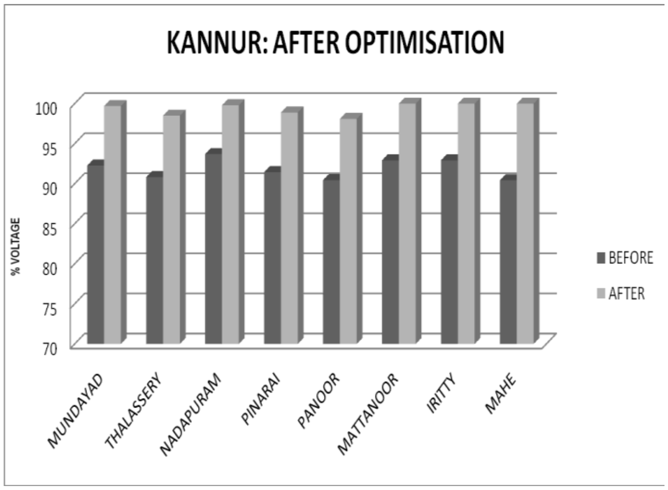


Fig. 2 Voltage profile before and after optimisation

7.1.3 Kozhikkode

The following optimization measures were taken at

Kozhikkode for the improvement of the voltage profile:

1. Installation of 15 MVAr capacitor bank at Quilandi.
2. Installation of 20 MVAr capacitor bank at Kunnamangalam.
3. Installation of 10 MVAr capacitor bank at Vadakara.

The graph showing the voltage profile comparison at various buses at Kozhikkode is shown in Fig. 3.

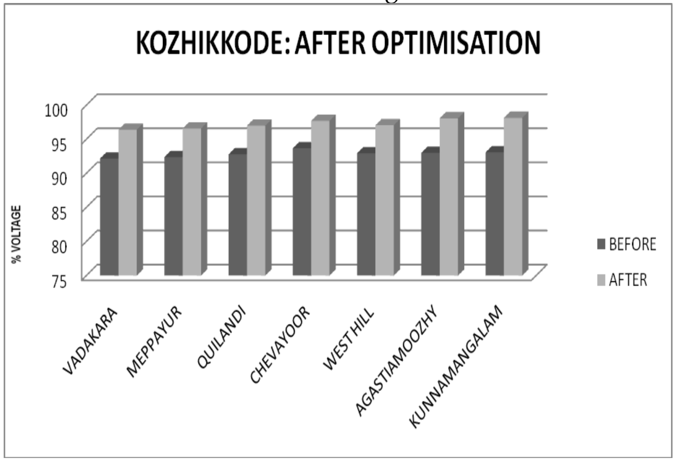


Fig. 3 Voltage profile before and after optimisation

7.1.4 Malappuram

As a part of the optimization measures, capacitor banks were installed at the following places:

1. Keezhissery – 20 MVAr Capacitor Bank
2. Malappuram – 15 MVAr Capacitor Bank
3. Tirur- 20 MVAr Capacitor Bank
4. Edappal – 20 MVAr Capacitor Bank

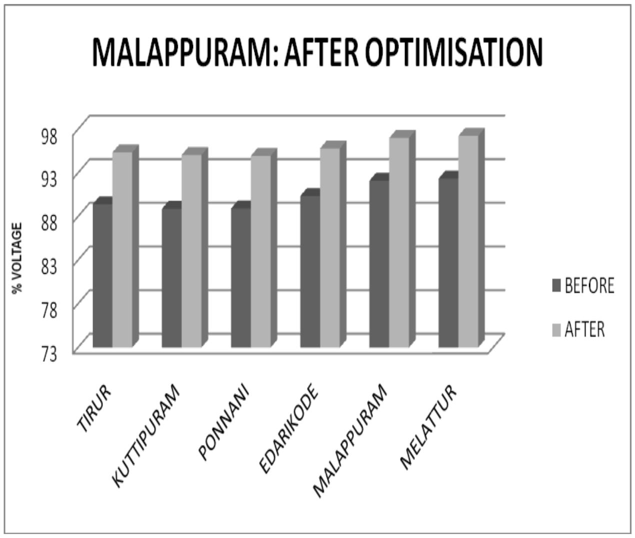


Fig. 4 Voltage profile before and after optimisation

7.1.5 Palakkad

As a part of the optimization techniques employed at Palakkad, the following places were installed with a new capacitor bank:

1. Shornur - 25 MVAr Capacitor Bank
2. Palakkad -60 MVAr Capacitor Bank
3. Vennakara -20 MVAr Capacitor Bank

The voltage profile comparison before and after optimization is shown in Fig.5.

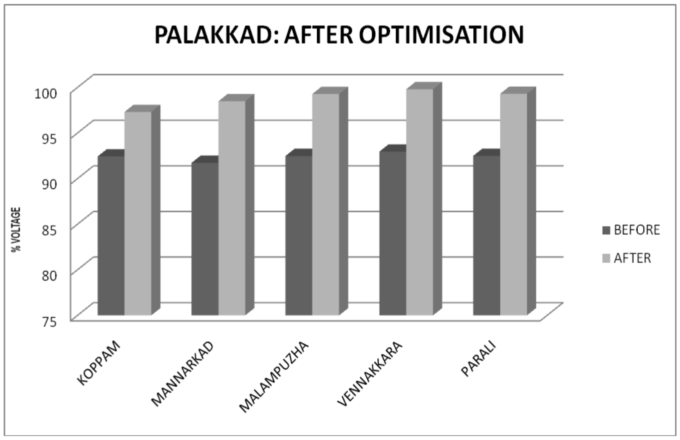


Fig. 5 Voltage profile before and after optimisation

7.1.6 Thrissur

The voltage profile at Thrissur district was improved by using the following optimization methods:

1. Installation of a 35 MVAr capacitor bank at Chalakkudy
2. 5% tap change at the 220/110 kV substation at Madakkathara.

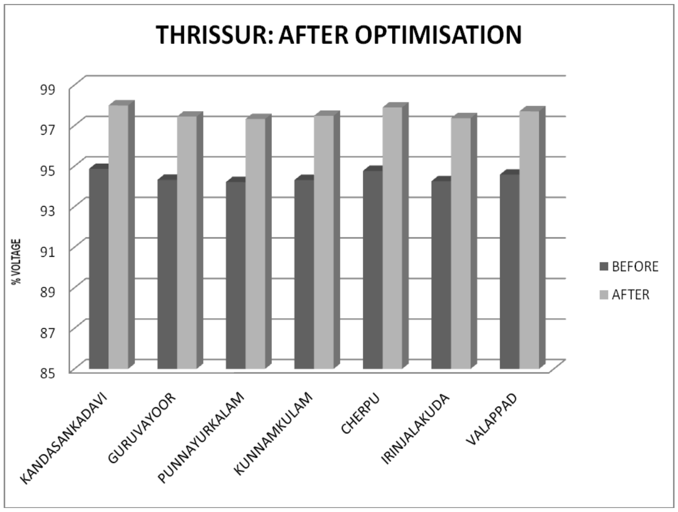


Fig. 6 Voltage profile before and after optimisation

7.2 Upgradation of Substations

In addition to the optimization techniques discussed in the previous sections, up gradation of substations and transmission lines were found to be an effective method for improving the voltage profile and to reduce line losses.

The following substation up gradations were proposed:

- Malappuram 110kV substation to 220kV.
- Kattakada 110kV substation to 220kV.

The graphs for Thiruvananthapuram and Malappuram districts before and after the proposed substation up gradation are shown in Fig.7 and Fig. 8.

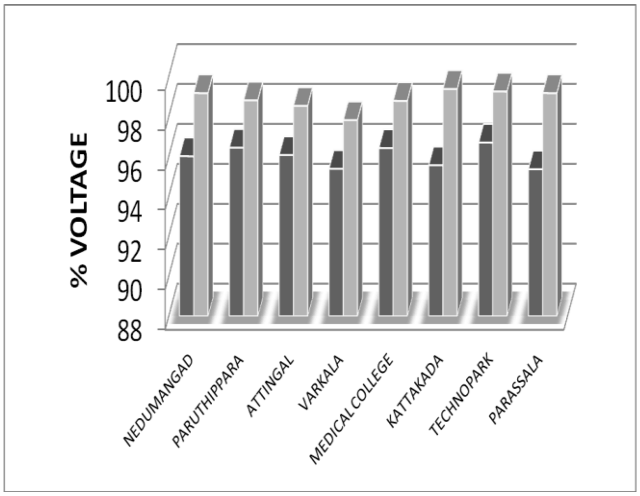


Fig. 7 Voltage profile before and after optimization of Trivandrum district

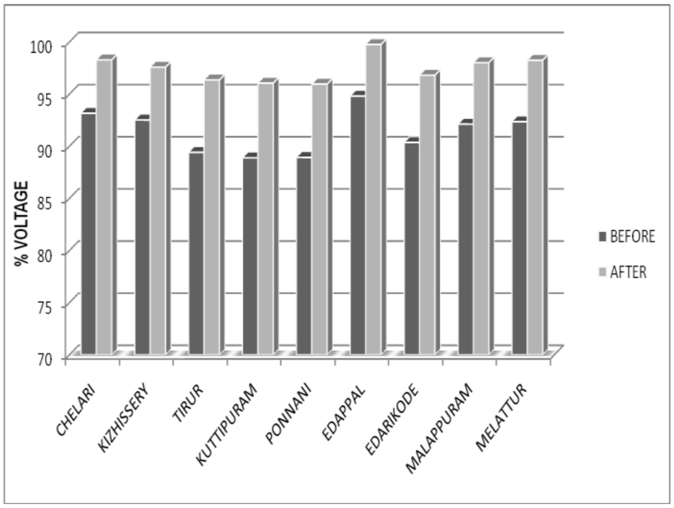


Fig. 8 Voltage profile before and after optimization of Malappuram district

7.3 Upgradation of Transmission Lines

The Areakode-Kaniyampetta line was upgraded from single circuit to double criciut.The following improvements were seen in the load flow results of this region:

- Line losses reduced from 5.14 MW to 3.52 MW
- Overall voltage profile increased in the northern Kerala.

A screen shot of the load flow results before and after the line up gradation is shown in Appendix B

CONCLUSION

Load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line.

Load Flow Analysis was conducted on all 400kV, 220kV and 110kV substations in the Kerala Power System Network using ETAP.Overloaded buses are identified and suitable measures for reducing the overloading are suggested. Upgradation of substations, Tap changing of transformers, Static capacitor banks for reactive power compensation, Capacitor Bank Shifting techniques, replacing single circuit lines by double circuit lines are found to be effective in improving the voltage profiles.

Appendix A

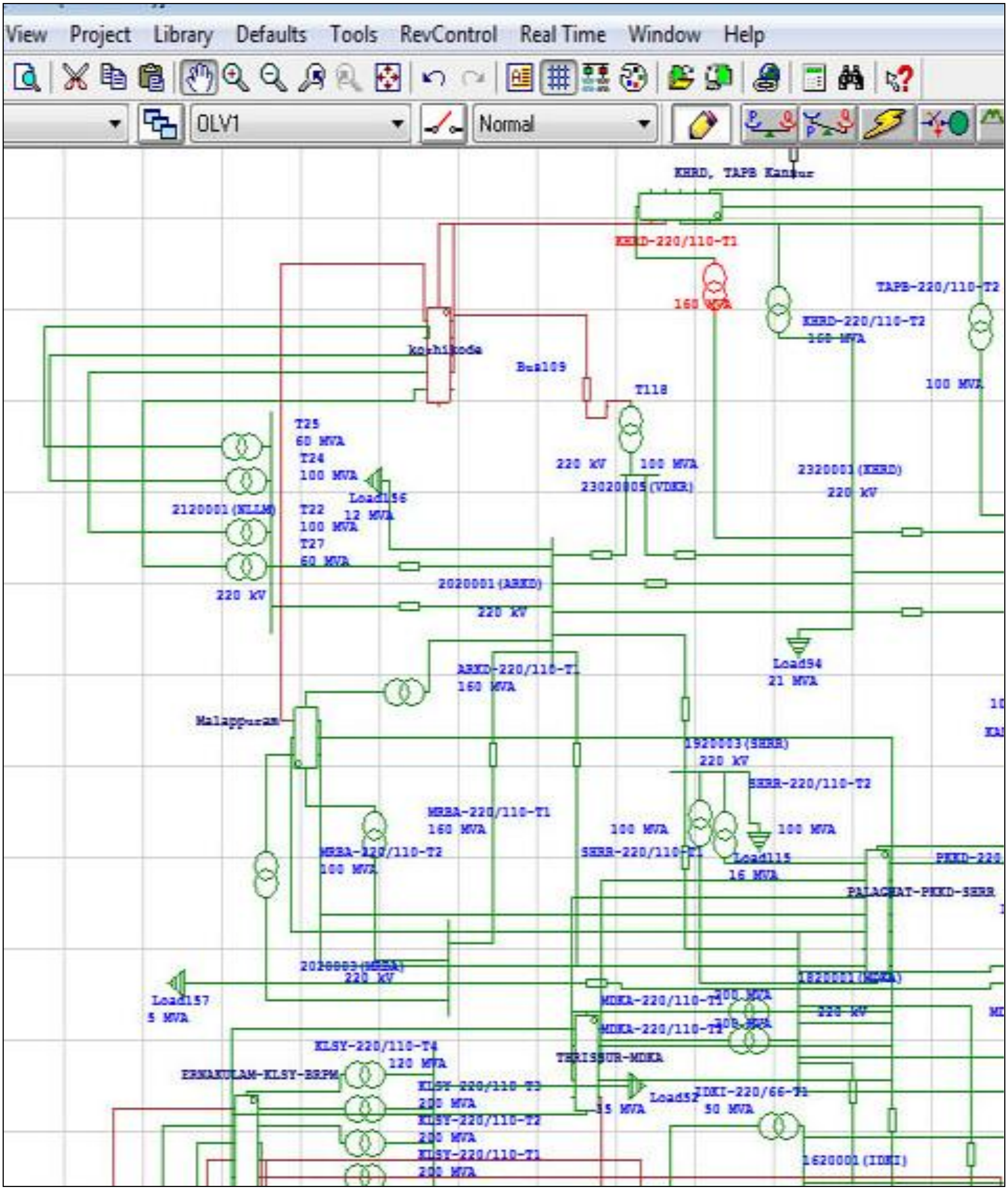


Fig. 9 Single line diagram of 220kV & 400 kV lines developed using ETAP software

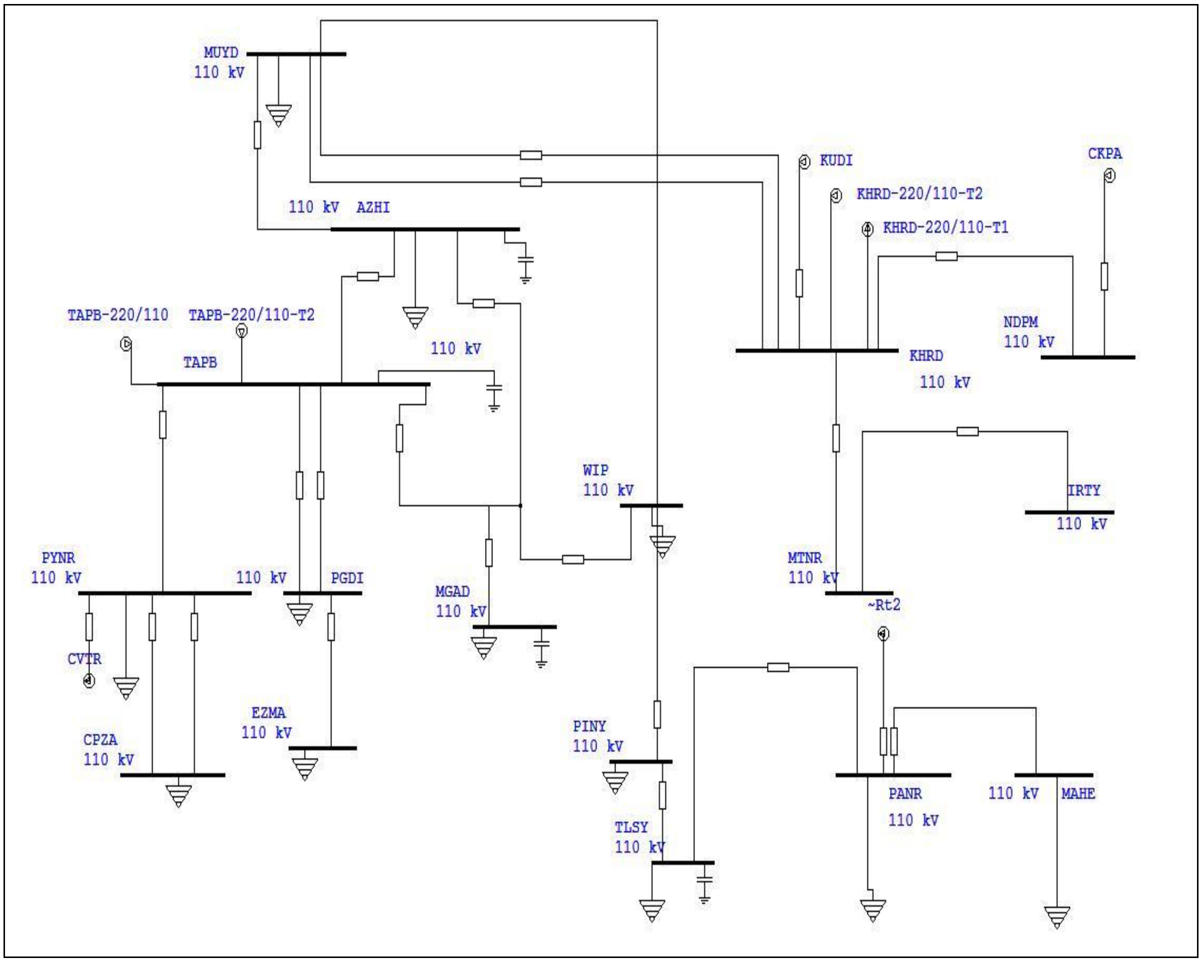
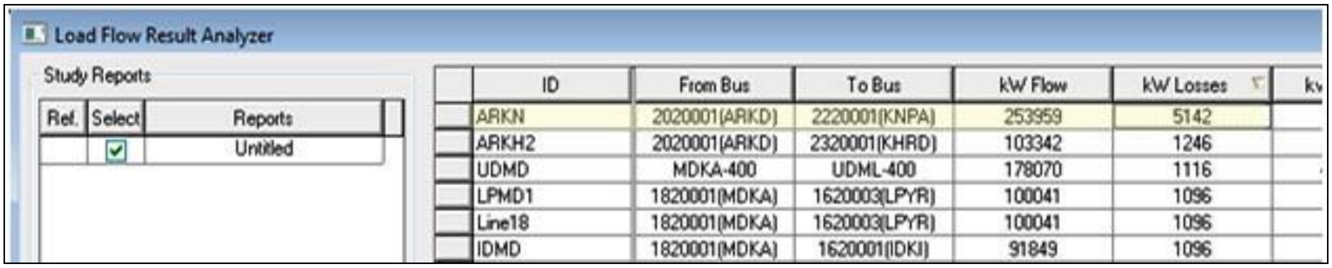


Fig. 10 Single line diagram on 110kV network of a district inside compsosite network in ETAP software

Appendix B



Ref.	Select	Reports
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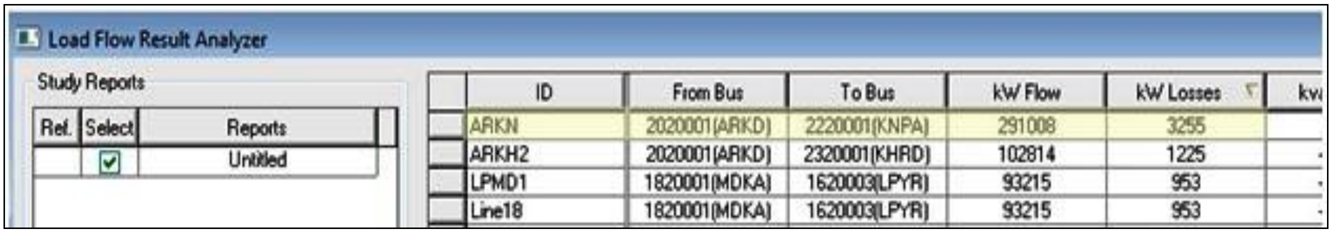
ID	From Bus	To Bus	kW Flow	kW Losses
ARKN	2020001(ARKD)	2220001(KNPA)	253959	5142
ARKH2	2020001(ARKD)	2320001(KHRD)	103342	1246
UDMD	MDKA-400	UDML-400	178070	1116
LPMD1	1820001(MDKA)	1620003(LPYR)	100041	1096
Line18	1820001(MDKA)	1620003(LPYR)	100041	1096
IDMD	1820001(MDKA)	1620001(IDKI)	91849	1096

Fig. 11 Before transmission line upgradation



Ref.	Select	Reports
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ID	From Bus	To Bus	kW Flow	kW Losses
ARKN	2020001(ARKD)	2220001(KNPA)	291008	3255
ARKH2	2020001(ARKD)	2320001(KHRD)	102814	1225
LPMD1	1820001(MDKA)	1620003(LPYR)	93215	953
Line18	1820001(MDKA)	1620003(LPYR)	93215	953

Fig. 12 After upgradation of line to double circuit

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BIBLOGRAPHY

Mr. Vivek Raveendran has completed his graduation in Electrical and Electronics Engineering from College of Engineerig Trivandrum in 2011. He is currently working in Oil and Gas field.
E-mail: vivekr.1212@gmail.com

Mr. Sumit Tomar has completed his graduation in Electrical Engineering from Thapar University in 2011. He is currently working in Oil and Gas field.
E-mail: mr.sumit.tomar@gmail.com