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Power Flow Analysis of 33/11kV, 15MVA Borokiri Injection Substation

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Abstract: When an electrical power network undergoes a non-steady state condition or when been subjected to an unbalance power condition, the need for a complete electrical solution arise in which load flow analysis become a key tool. This paper examined the power flow status of Borokiri 33/11kV, 15MVA injection substation of the Port Harcourt Electricity Distribution Company to ascertain its steady state operating condition for improved performance. The Newton Raphson Load Flow Techniques was used to analyze the network in Electrical Transient Analyser Program (ETAP) Software to determine the various bus operating voltages, active and reactive power flow at generator bus and voltage phase angles at specified bus bars. It was observed from the base-case simulation that Harold Wilson 11kV feeder was overloaded and was operating under a critical under voltage condition while New Road 11kV feeder was marginally under voltage. Both cases were resolved by the application of transformer load tap changing (LTC) mechanism and the introduction of appropriate shunt capacitor bank at strategic point of Harold Wilson feeder. The Voltage profile of Harold Wilson and New Road feeder were improved from 89.22% to 95.37% and 94.49% to 99.01% respectively. However, it was recommended that bifurcation of Harold Wilson 11kV feeder should be conducted to reduce the overloading condition of the network.

Keywords: Distribution Network, Power Flow, Newton Raphson Technique, Load Tap Changing, Optimal Capacitor Placement, Voltage Profile.

1.0 INTRODUCTION

Power flow analysis also known as load flow analysis is one of the major tools of power system analysis. When a power network goes through a non-steady state condition or when it is subjected to an unbalance power condition, there is a need for a complete electrical solution in which this analysis is the key tool. Power flow analysis is a systematical mathematical approach used in the determination of various bus voltages, active and reactive power flow through different branches, phase angle, generators and loads under steady-state condition of an electric power system. Power flow calculations are very essential for power system operation, economic scheduling and planning. The results of power flow analysis are used in the studies of the normal operating condition, outage security assessment, contingency analysis and optimal dispatching and stability of power system network [1]. The main objective of the power flow analysis is to determine potential problems, such as overloading of facilities, unacceptable voltage conditions, decreasing reliability, or any failure of the transmission or distribution system to meet performance criteria. After the analysis, the Engineer or power system specialist develops alternative plans or approaches that will not only prevent the foreseen problems but also will best meet the long-term objectives of system reliability and economy. Load flow analysis is the main requirement for planning and designing a new power system. Also, extension of existing power system for increasing demand [2]. For distribution system the power flow analysis is a very important and fundamental tool. Its results play the major role in the operational stage of any power system, its control and economic schedule, as well as the design and expansion stage. The purpose of any load flow analysis is to calculate accurate steady-state voltages of all buses in the network, phase angles, the real and reactive power flows into all buses and transformer, under the assumption of known generation and load. The load flow solution also gives the initial conditions of the system when the transient behavior of the system is to be studied. In actual practice, it will be required to carry out numerous power flow solutions under a variety of conditions. A power (load) flow study is done on a power system to ensure that generation supplies the demand (load) plus losses, bus voltage magnitudes remain close to rated values, generation operates within specified real and reactive power limits and transmission lines and transformers are not overloaded [1]. The inadequate power supply and the incessant power failure from the central generating stations down to the final consumers suffers a lot of sets back; hence researchers and technologist, have resort to other means of managing this setback. In literatures, different methods have been implemented to provide an effective solution in regards to reliable power generation, transmission and delivery. In recent time, the impact of distributed generation linked to the distribution networks are on course. Distributed generation units have several benefits such as reliability, stability and economy; but it suffers some critical setbacks that may disturb these benefits as seen in [3].

Nigeria power grid network generating voltage falls within the range of 10.5kV – 16kV with operating frequency of 50Hz. It is step up to 330/132kV as primary/secondary transmission. Primary distribution voltage is 33kV to various injection substations for further distribution while secondary distribution voltage is 11kV to various consumers on point load and consumers down the road and streets through overhead lines

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and underground cables. 11/0.415kV transformers received the power from the secondary distribution network and distribute to consumers on tertiary distribution network using 3phase 4-wire system.

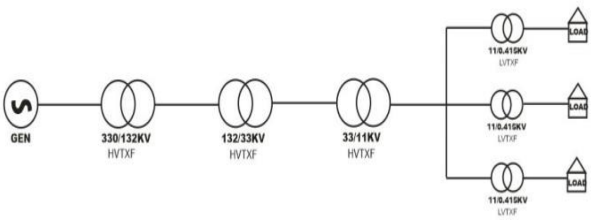

Figure 1: Schematic Diagram of Nigeria Power System

1.1 The aim of this Research Work

The aim of this research work is power flow analysis of 33/11kV, 15MVA Borokiri injection substation for improved performance.

1.2 Objectives of this Research Work

The objectives of this research work in regards to the aim are as follows:

i. Perform a load flow analysis of borokiri injection substation

ii. Improve the bus voltages margin of the distribution feeders; Harold Wilson and New Road feeder

iii. Improve the active and reactive power flow of the distribution feeders

iv. Possibly upgrade or resize overloaded grid connected transformers, etc.

1.3 Deriving the Power Flow Equations

The basic equation for power flow studies is derived from the nodal analysis equations for the power system. For example, for a 4-bus system [4]

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (1)$$

Where *Yij are the elements of the bus admittance matrices,*

Vi are the bus voltages

Ii are the currents injected at each node.

- *The node equation at bus i can be written as:*

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad (2)$$

The relationship between per-unit active and reactive power supplied to the system at bus i and the per-unit current injected into the system at that bus:

$$S_i = V_i \, I_i^* = P_i + jQ_i \quad (3)$$

Where Vi is the per-unit voltage at the bus;

I_i^* - complex conjugate of the per-unit current injected at the bus;

Pi and Qi are per-unit real and reactive powers.

Therefore,

$$I_i^* = \frac{P_i + jQ_i}{V_i} \rightarrow I_i = \frac{P_i - jQ_i}{V_i^*} \quad (4)$$

$$\Rightarrow P_i - jQ_i = V_i^* \sum_{j=1}^{n} Y_{ij} \, V_j = \sum_{j=1}^{n} Y_{ij} \, V_j \, V_i^*$$

$$Let \quad Y_{ij} = |Y_{ij}| \angle \theta_{ij} \; and \; V_i = |V_i| \angle \delta_i$$

$$Then \quad P_i - jQ_i = \sum_{j=1}^{n} |Y_{ij}| \, |V_j| \, |V_i| \angle(\theta_{ij} + \delta_j - \delta_i) \quad (5)$$

$$Hence \quad P_i = \sum_{j=1}^{n} |Y_{ij}| \, |V_j| \, |V_i| \, Cos\,(\theta_{ij} + \delta_j - \delta_i)$$

$$And \quad Q_i = -\sum_{j=1}^{n} |Y_{ij}| \, |V_j| \, |V_i| \, Sin\,(\theta_{ij} + \delta_j - \delta_i)$$

The starting point of a load flow problem is a single line diagram of the power system, from which input data for computer solutions can be obtained. Input data consist of bus data, transmission line data and transformer data. A bus is a node at which one or many lines, one or many loads and generators are connected.

In a power system each node or bus is associated with 4 quantities, such as Magnitude of voltage (V), Phage angle of voltage (δ), Active power (P) and Reactive power (Q)

In load flow problem two out of these 4 quantities are specified and remaining 2 are required to be determined through the solution of equation. In a power flow there are generally three buses they are shown on Table 1.

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Table 1: Types of Buses

Types of Bus	Voltage Magnitude (V)	Voltage Angle (δ)	Power Injection (P = Pgen - Pload)	Reactive Power Injection (Q = Qgen - Qload)
Slack Bus (Vδ-Bus) (only one of these)	Known	Known	Unknown	Unknown
(PV-Bus) (generator on AVR control)	Known	Unknown	Known	Unknown
(PQ-Bus) (load or generator not on AVR control)	Un known	Unknown	Known	Known

Source: Power World Corporation 2014 [5]

1.4 The Newton Raphson Method

The Newton Raphson method is an iterative method which approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to the first approximation. It is the most iterative method used for the load flow because its convergence characteristics are relatively more powerful compared to other alternative processes and the reliability of Newton-Raphson approach is comparatively good since it can solve cases that lead to divergence with other popular processes. If the assumed value is near the solution, then the result is obtained very quickly, but if the assumed value is farther away from the solution then the method may take longer to converge. This is another iterative load flow method which is widely used for solving nonlinear equation. The admittance matrix is used to write equations for currents entering a power system. Equation (2) is expressed in a polar form, in which j includes bus i

$$I_i = \sum_{j=1}^{n} |Y_{ij}|\ |V_i| \angle(\theta_{ij} + \delta_j) \quad (6)$$

The real and reactive power at bus *i* is

$P_i - jQ_i = V_i^* I_i$

Substituting for Ii in Equation (6) from Equation (2)

$$P_i - jQ_i = |V_i| \angle - \delta_i \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle(\delta_{ij} + \delta_i) \quad (7)$$

When the real and imaginary parts are separated, we have:

$$P_i = \sum_{j=1}^{n} |Y_{ij}| |V_j|\ |V_i|\ Cos\ (\theta_{ij} + \delta_j - \delta_i) \quad (8)$$

$$Q_i = -\sum_{j=1}^{n} |Y_{ij}| |V_j|\ |V_i|\ Sin\ (\theta_{ij} + \delta_j - \delta_i) \quad (9)$$

The above Equation (8) and (9) constitute a set of non-linear algebraic equations in terms of |V| in per unit and δ in radians. Equation (8) and (9) are expanded in Taylor's series about the initial estimate and neglecting all higher order terms to obtain a set of linear equations. The element of the Jacobian matrix are obtained after partial derivatives of Equations (8) and (9) are expressed which gives linearized relationship between small changes in voltage magnitude and voltage angle. The equation can be written in matrix form as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (10)$$

J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix.
The difference between the schedule and calculated values known as power residuals for the
terms ΔPi (k) and ΔQi (k) is represented as:

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{k} \quad (11)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{k} \quad (12)$$

The new estimates for bus voltages are [1]

$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \quad (13)$$

$$|V^{(k+1)}| = |V_i^{(k)}| + \Delta\, |V_i^{(k)}| \quad (14)$$

2.0 LITERATURE REVIEW

Over the years, there have been many researchers and works on power flow analysis and improvement techniques of distribution networks. Some related works are reviewed below:
The Fast decoupled and Newton-Raphson load flow methods were used in [6] to analyze the Port Harcourt Town 33kV Distribution Network. According to authors, the main challenge encountered in this network is the frequent power outages caused by heavy losses on the line, poor power factor at load end, low voltage experienced, overloading of feeder transformers and inadequate size of line conductors. The writers recommend that reactive power needed by the network be supplied by capacitors located optimally at strategic places to improve the power factor at load end, thereby improving the voltage profile of the buses and the network at large.

The Fast-Decoupled Newton Raphson Techniques were used in [7] to analyze the electrical energy supply to Abule-Egba part of Lagos State, via Agbefa 11kV feeder. It was discovered that the voltage profile of the buses were very low and the magnitude of the active and reactive power flow were also poor. The issue was corrected by the placement of optimally sized and strategically placed capacitors close to load end to provide the system with reactive power.

In [8], a novel method for designing an electrical distribution network within Damaturu town was presented. According to the researchers, the town is supplied by two highly overloaded feeders due to expansion of the town as a result of series of development. The feeders; Alimarimi and Maiduguri road feeder are supply by 2 x 7.5MVA transformers at the injection substation. These have resulted to the epileptic power supply to the areas covered by the feeders. After series of analysis on the network, the authors recommended the use of 2 x 15MVA transformers at the injection substation to be able to feed the two feeders optimally thereby, tackling the problem of overloading and stress on the installed power transformers.

Investigations were made in [9] as to the causes and effects of voltage drops on the GMC 11kV distribution feeder in Tarkwa, Ghana. It was observed that the major causes of voltage drop on the feeder were due to Hot Spots, non-uniform conductor material, under-size conductors and overloading of the feeder. The authors proposed that a pressure test and proper fault maintenance be conducted on the feeder. They also added that, operating voltage should be increased so that power could be distributed in reduced currents to enhance the reduction of I^2R losses.

The researchers in [10] in their research carried out on Dumez 11kV distribution feeder network using DIsilent Power Factory 2016 and ETAP 7.0. stated that the Nigeria electrical power distribution network is constantly challenged by the ever-increasing load demand. This increase in load demand could be checked by performing a load flow analysis on the existing distribution network to ascertain the true performance of the network with its steady state operational values. According to authors, most distribution substation's irregular supply and under-voltage in the system are due to the weak and obsolete nature of the system infrastructures and thus, experiences high energy losses. This resulted to increase in rate of load shedding by the utility company as a way of controlling the challenge. The network were improved by the used of Distributed Generation (DG) technique.

3.0 METHODOLOGY

3.1 Data Source

The data source for this research work is Port Harcourt Electricity Distribution Company (PHEDC). The data gathered are: installed capacity of injection sub-station, single line diagram of substation, examined feeders, total number and power rating of distribution transformer. Newton Raphson Method will be used for computing bus voltages and the simulation on each of the feeders will be carried out using ETAP software.

3.2 Description of Substation

This study was carried out using 1x15MVA, 33/11kV Borokiri Injection Substation. Borokiri injection substation is one of the distribution substations of Port Harcourt Electricity Distribution Company located at Borokiri, Port Harcourt Local Government Area of Rivers State. It lies at latitude 4.742° N and longitude 7.035° E. The substation has its 33kV source from Port Harcourt Town Transmission Station. It has two 11kV outgoing feeders namely; Harold Wilson and New Road Feeder with 5.5MW and 2.4MW load at peak respectively.

Table 2: Feeders Details

Feeders	**Route Length (km)**	**Conductor Size (mm2)**	**Conductor Type**	**No. of Distribution Transformer (KVA)**				
				500	**300**	**200**	**100**	**50**
Harold Wilson	16.7	150	Aluminium	26	4	-	-	-
New Road	6.5	150	Aluminium	11	-	1	-	-

Source: Port Harcourt Electricity Distribution Company (PHEDC) [11]

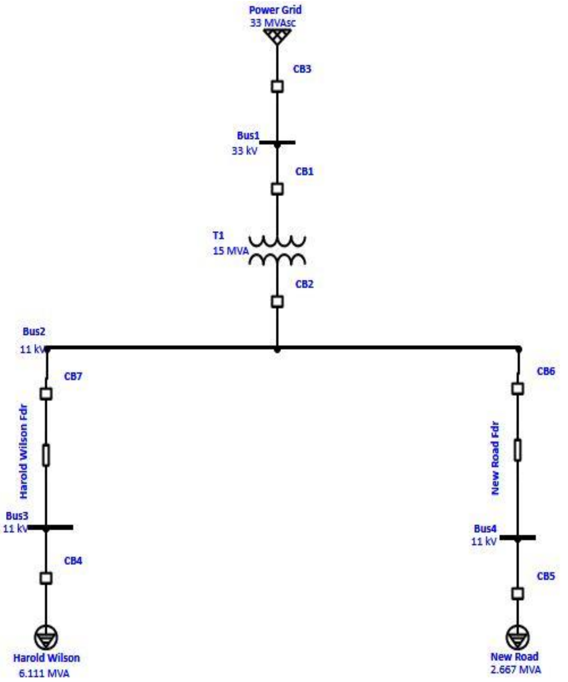

Fig. 2: Single Line Diagram of Borokiri Injection Substation

4.0 RESULTS AND DISCUSSIONS

The network parameters of the Borokiri injection substation were used to carry out a base case simulation to ascertain the existing state of the networks in ETAP 19.0 Software and the results are shown in Figure 3. The ETAP simulation produced three distinct color codes across all parameters, inferring to meanings. Red zone (bus 3) implies that critical attention is needed as it is operating under an under voltage condition, the system is considered to be on the verge of breakdown at this point. Purple zone (bus 4) means this is a marginally operational zone, though not too good but can be managed, areas with this code needs moderate attention but not immediate. Such systems could become Red (critical) at any time if not worked on. Black zone (bus 2) is a perfect working zone; the system is accepted to be optimally functional at this point. Our goal is to make the entire system operate within the Black zone. To do that we introduce Transformer Load Tap Changing (LTC) on the power transformer so as to increase the voltage of the upstream buses at the substation. After then, shunt capacitors were installed on the 11kV bus 3 at load end to raise the network power factor, which then improved the voltage profile of the network and reduced losses from the network. The comparative result of the Voltage profile of Borokiri Injection Substation before and after improvement is shown in figure 6.

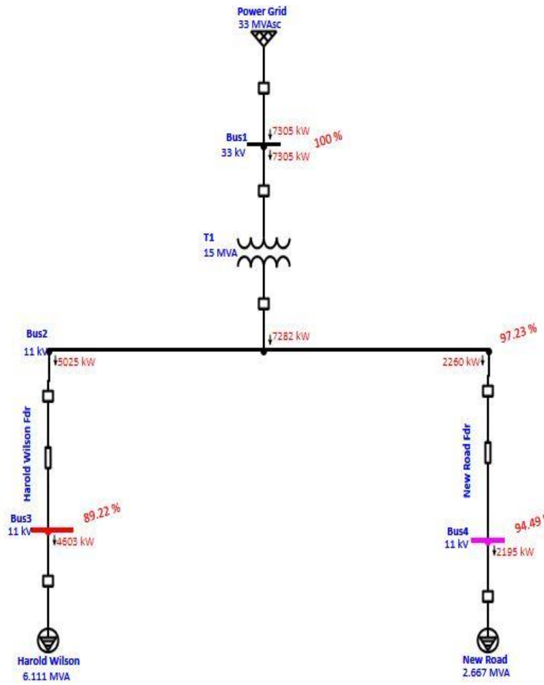

Fig 3: Load Flow Results of Borokiri Injection Substation

4.1 Transformer Load Tap Changing (LTC)

The principle of transformer tap changing is based on changing the number of primary or secondary turns of the transformer. A single step = $\pm 2.5\%$ of the nominal rating. On the power transformer, tap position based on operating condition = Step 1 Percentage increase = 2.5% Voltage rise. The tapping (-2.5%) was done on the high voltage winding of the transformer, it improve the voltage level of bus 4 which was marginally under voltage (94.49%) to a perfect working condition (99.01%). A decrease in primary turns causes an increase in e.m.f per turn thereby causing corresponding increase in the secondary output voltage.

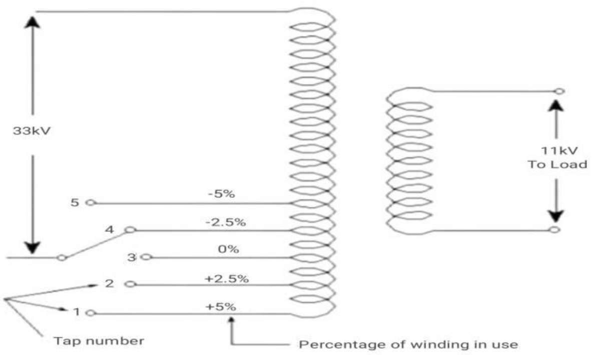

Fig. 4: Transformer tapping diagram

4.2 Shunt Capacitor Bank

Capacitor bank help to improve the voltage profile of a network by supplying reactive power to the load or line. ETAP does that by also considering the economic factor. Capacitor bank by improving the voltage also improves the power factor of the system.

$Shunt\ capaitor\ bank\ 12 \times 300Kvar$ were used on bus 3 to improve the voltage from 89.22% (critically under voltage) to 95.37% (Perfect working voltage). This was obtained from the simulation result on Optimal Capacitor Placement Module in ETAP 19.0.

Manually, it can be calculated using equation (15)

$$cKvar = KW\ (tan\theta_1 - tan\theta_2) \qquad (15)$$

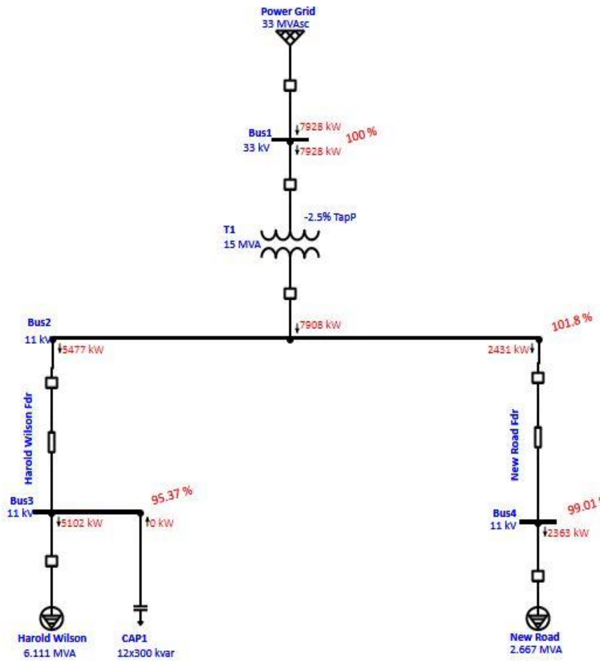

Fig 5: Load flow results after tap changing and introduction of capacitor bank

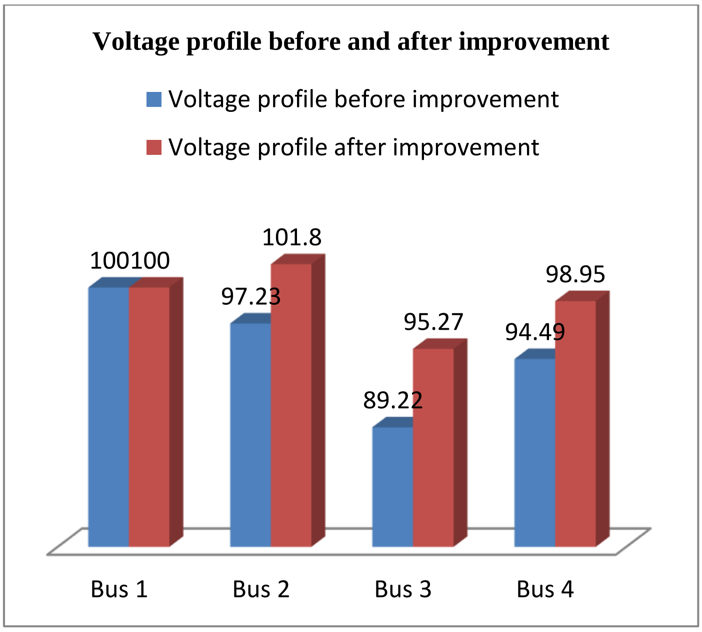

Fig 6: Voltage profile of Borokiri Injection Substation before and after improvement

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Load flow analysis is the backbone of any electrical power network. The important information obtained from this study are essentially the magnitudes and phase angles of load bus voltages, active and reactive powers at generator bus, real power flow on the lines and voltage phase angles at specified bus bars. The information obtained from the above analysis are mainly used in continuous monitoring of the present state of the system and for analyzing the effectiveness, security constraints and economic considerations of alternative plans for future system expansion in order to achieve the increased demand of load. Load flow solution is the primary requirement for designing a new power system and for planning an extension of the existing one for increasing demand. In this work the simulation and analysis of 33/11 kV Borokiri injection substation has been done with the help of the Electrical Transient Analyzer Program (ETAP) software. Harold Wilson feeder was found to be critically overloaded but was improved by optimally placing shunt capacitor bank. ETAP is an outstanding tool for the engineers that can provide the solution for the loss of the transmission line, load, transformer or the generator.

5.2 Recommendation

From the results of the analysis carried out on the Borokiri Injection Substation, the following recommendations become imperatives:

- Bifurcation of Harold Wilson 11kV feeder should be done.
- Appropriately sized capacitors should be kept at strategic points mostly on the Harold Wilson feeder.
- Harold Wilson feeder should be re-conducted with larger sizes and reduced length.
- Pressure testing should be done on feeders to correct any form of hot spots.

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