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Load Demand Analysis of Nigerian Primary Grid System Using Continuation Power Flow Model

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ABSTRACT: The Nigerian 330kV transmission network was modelled using continuation power flow model in Electrical Transient Analyzer Program (ETAP) 12.6 software to conduct load demand analysis. The analysis showed the load growth trend on the network as well as the highest network load demand. The continuation power flow analysis further showed that from a power generation of 4000MW contributed to the grid, 3519.653MW was the highest load sustained at a loading factor of 0.18p.u and at a loading factor of 0.20p.u the continuation power flow failed. to run signifying voltage collapse. This result on load growth trend was clear evidence of the load demand pattern which was substantial enough based on the principle of continuation power flow as recognized in IEEE regulation.

KEYWORDS: Load Demand, Primary Grid System, Continuation Power Flow, Loading Factor, Voltage Collapse.

I. INTRODUCTION

According to Ogbikaya *et al.*[1], the Nigerian existing 330kV network has several drawbacks ranging from insufficient generation and weak transmission lines that are not robust enough to wheel out the generated power in the network. The Nigerian electricity grid presently consists of eleven active generating stations which include three hydro and eight thermal plants with a total installed generating capacity of 6500MW and nineteen buses [2]. The high load demand on the network makes the network vulnerable to voltage instability thereby causing bus voltage violation capable of leading to voltage collapse in the whole network. By this, the voltage has fallen below 280.5kV. The voltage problems are because of load centers being far away from generating stations and excess load on the transmission line. Consequently, the high load demand on the network may result to system insecurity and voltage collapse on the transmission network [1]. Simon [3] maintained that Nigerian's power grid had collapsed no fewer than 9 times in 2019. In January alone, the country's power grid collapsed 2 times while at least 2 major collapses were in April. Investigation shows that the 9 power grid collapses witnessed in 2019 were among at least 206 of such incidents that have been since 2010. There were also cases of Partial Grid Collapse when a section of the country was thrown into darkness for hours due to major transmission trips. Transmission Company of Nigeria traced the cause to high voltage because of multiple or several tripping on the Alaoji-Onitsha transmission line [3]. Between 2010 and 2019, Nigerian electricity users have had to contend with 206 power grid collapses, 9 of which occurred in 2019, according to the System Operator (SO), a section of TCN. A breakdown of the 206-grid collapse which often led to a power cut for an entire region or even the whole country indicates that 109 of the incidents occurred from 2010 to 2013 while 97 others occurred from 2014 to 2019. The country was in total darkness 22 times with 20 partial outages in 2010. The grid had 13 incidents of total collapse and 6 partial incidents in 2011. In 2012, 16 total and 8 partial collapses occurred. When privatization process was in top gear in 2013, 22 total power grid and 2 partial collapses occurred [3].

The post-privatization era also witnessed grid collapse though with a little improvement in 2014. There were 9 total collapses and 4 partial cases. The problem continued in 2015 with 6 total and 4 partial grid collapses. The worst was in 2016 when the grid was lost for 22 times and 6 times partial loss. Further investigations revealed that in 2017, 15 total and 9 partial collapses occurred while in 2018, 12 total and 1 partial collapse occurred. About 9 total collapses occurred in 2019 where 4 of which occurred in January. The five others were in February, April, May, June, and August [3]. Simon [3] stated that a total grid collapse on June 30, 2019 dropped the grid to 127MW and was traced to a fire outbreak at the Benin transmission substation in Edo state. On August 30, 2019, the grid had another total collapse, throwing Nigeria into darkness for at least 10 hours as the grid dropped to 20MW. Simon [3] reiterated that national grid outages were worst during some months in the rainy season and the highest was in May with 30 collapses from 2010 followed by June with 29 times. A total of 19 power outages occurred in January from 2010 till 2019. Another



trend of 17 occurrences per month occurred in April, September, and October. It slid to 16 collapses in November, 15 occurrences in July, and 14 times in March and December while in August and February 7 and 10 collapses occurred, respectively.

Simon [3] maintained that records of power generation since the privatization in 2013 to December 2018 indicate that the GenCos have more capacity to wheel power than they had before the privatization. Analysis of the historical generation data from the Association of Power Generation Companies (APGC) according to Simon [3], shows that the Generation Companies had made available at least 38,546MW generation capability since November 2013 to December 2018 while the national grid took only 20,960MW, a large amount of 17,582MW representing 45% of the total GenCos' capability was not utilized. APGC claimed the existing transmission network is insufficient, weak, and unreliable [3]. Simon [3] further declared that Transmission Company of Nigeria-System Operator has 12,910MW installed power generation capacity with the highest generation capacity of 7,652MW.

The loadability of a bus in the power system dependent on the reactive power support the bus receives from the system as the system gets closer to voltage collapse point or maximum loading point (MLP) is important [4]. Nigerian power transmission system requires continuous up-grading and expansion to cater for the need of ever-growing power demand [5]. Improvement of voltage control and reactive power support are difficult task because they are strongly influenced by random load fluctuations. There is a great need to improve utilization, while still maintaining reliability and security [6].

II. RELATED WORKS

The increase in power demand and very little or limited sources for electric power has resulted in an increasingly complex interconnected system, forced to operate closer to the boundary points or limits of stability. Voltage instability is mainly and largely associated with reactive power imbalance. Simon [3] stated that Nigerians woke up on May 8, 2019 to a nationwide power outage that cut off power from plenty homes and industries resulting to reduced load allocations to the various distribution companies.

One of the first techniques used to determine the maximum loading condition of a power system is the continuation power flow (CPF) [7]. This technique consists in computing a series of power flows while increasing the overall loading level of the system. The CPF is shown to be robust even for solutions close to the collapse point, which is typically a critical point from both the physical (blackout) and numerical (singularity of equations) point of view. It can also be demonstrated that the CPF analysis, if used for determining the maximum loading condition, is a gradient reduced method [7]. The idea behind the continuation power flow is to create a predictor-corrector scheme to find a solution path [8].

The continuation power flow technique is applied to the power flow problem to enhance the simulations performance [9]. According to Vasquez & Sousa [9], the method is a mathematical path-methodology used to solve systems of nonlinear equations by adopting locally parameterized continuation method. Continuation power flow overcomes the problem of singularity at the voltage stability limit as it finds successive load flow solutions according to a load scenario [10]. The continuation algorithm starts from a known solution using a predictor-corrector scheme to find subsequent solutions at different loads [11].

Continuation power flow analysis is based on locally parametrized continuation method which intends to avoid the singularity of the Jacobian by slightly reformulating the power flow equations [12]. The Continuous Power Flow (CPF) method is the best for on-line application as it is accurate, reliable and moderately fast. The reliability is since it does not have serious convergence issues arising from device limits [13].

III. MATERIALS AND METHOD

3.1 Research Materials

Several research materials comprising of very important parameters needed for the continuation power flow to determine and effectively carry out load demand analysis of the Nigerian primary grid system (Nigerian 330kV transmission network) were collected from the National Control Centre (NCC) in Nigeria. The materials required include transmission route length, line impedance, transmission lines power rating, generators active power, bus data, power factor, transformers rating, base load, ETAP 12.6 software, etc. The method and procedure adopted in this research are described accordingly.



3.2 Method of Analysis

Continuation Power Flow method was used to model and effectively carry out the load demand analysis of the Nigerian 330kV transmission network. Equal incremental loading was conducted to ascertain the load demand of the network.

3.3 Application of Continuation Power Flow to Nigerian 330kV Transmission Network

Considering that:

$$P_i = P_{Gi} - P_{Di} \tag{1}$$

$$Q_i = Q_{Gi} - Q_{Di} \tag{2}$$

To simulate load change, a load parameter λ is inserted into demand powers ' P_{Di} ' and ' Q_{Di} ' to become:

$$P_{Di} = P_{Dio} + \lambda(P_{\Delta base}) \tag{3}$$

$$Q_{Di} = Q_{Dio} + \lambda(Q_{\Delta base}) \tag{4}$$

P_{Dio} and Q_{Dio} are original load demands on i^{th} bus whereas $P_{\Delta base}$ and $Q_{\Delta base}$ are given quantities of powers chosen to scale λ appropriately. After substituting new demand powers in equations (3) and (4) to equations (1) and (2), new set of equations can be represented as:

$$F(\theta, V) = \lambda k \tag{5}$$

Or

$$F(\theta, V, \lambda) = 0 \tag{6}$$

Where

θ = Vector of bus voltage angles

V = Vector of bus voltage magnitudes

λ = Load demand parameter

The base solution for $\lambda = 0$ is found through a power flow. Then, the continuation and parameterization processes can be applied. The nonlinear equation as given above can be solved by specifying a value for λ such that $0 \leq \lambda \leq \lambda_{critical}$.

3.3.1 Predictor Step

A linear approximation is usually employed in this step to estimate the next solution for a change in one of the state variables. It takes approximately sized step in a direction tangent to the solution path. Therefore, the derivative of both sides of equation (3.8) becomes:

$$F_{\theta}d\theta + F_VdV + F_{\lambda}d\lambda = 0 \tag{7}$$

$$\begin{bmatrix} F_{\theta} & F_V & F_{\lambda} \end{bmatrix} \begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = 0 \tag{8}$$

To solve equation (3.10), another equation is required since an unknown variable ' λ ' is added to load flow equations. This can be done by setting one of the tangent vector components to +1 or -1 which is generally known as continuation parameter. This setting imposes a non-zero value on the tangent vector making equation (8):

$$\begin{bmatrix} F_{\theta} & F_V & F_{\lambda} \\ e_k \end{bmatrix} \begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \tag{9}$$

Where

e_k = appropriate row vector with all elements equal to zero except the k^{th} element equal to 1.

At first step λ is chosen as the continuation parameter. As the process continues, the state variable having the highest rate of change is selected as continuation parameter due to nature of parameterization. By solving equation (9), the tangent vector can be found. Then the prediction can be made as follows:

$$\begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix}^{P+1} = \begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix}^P + \sigma \begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} \tag{10}$$

Where

$P + 1$ = the next predicted solution

The step size σ is chosen so that the predicted solution is within the radius of convergence of the corrector. If it is not satisfied, a smaller step size is chosen.

3.3.2 Corrector Step

In this step, the predicted solution is corrected using local parameterization where the original set of equation is increased by one equation that generally specifies the value of state variable chosen resulting in:



$$\begin{bmatrix} F(\theta, V, \lambda) \\ x_K - \eta \end{bmatrix} = [0] \quad (11)$$

Where

x_K = State variable chosen as continuation parameter

η = Predicted value of this state variable

Equation (3.11) can be solved by using a slightly modified Newton-Raphson power flow method in Electrical Transient Analyzer Program (ETAP) 12.6 software.

3.3.3 Determination of Critical Point

The continuation power flow is stopped when critical point is reached. The critical point can be viewed as the point where the loading has maximum value. After this point it starts to decrease. The tangent component of λ is zero at the critical point and negative beyond this point. On this note, the sign of $d\lambda$ indicates whether the critical point is reached.

At this juncture, continuation power flow method was applied using ETAP 12.6 software. The Nigerian 30 bus 330kV transmission network consists of 11 committed generators, 35 transmission lines and 19 loads. Bus number 10 was considered slack bus meanwhile bus numbers 1, 4, 7, 10, 12, 15, 16,17,20, 23 and 24 are PV buses while the rest 19 buses are PQ buses. The continuation power flow was run up to bifurcation point without considering generator reactive power limits.

Having gotten a total power generation of 4000MW from 11generators, a total bus load of 3014.08MW from 19 buses and all data required to model and simulate using Continuation Power Flow method to ascertain the total load demand of Nigerian 330kV transmission network with the use of ETAP 12.6 software, the data were used as input data and are shown in fig.1.

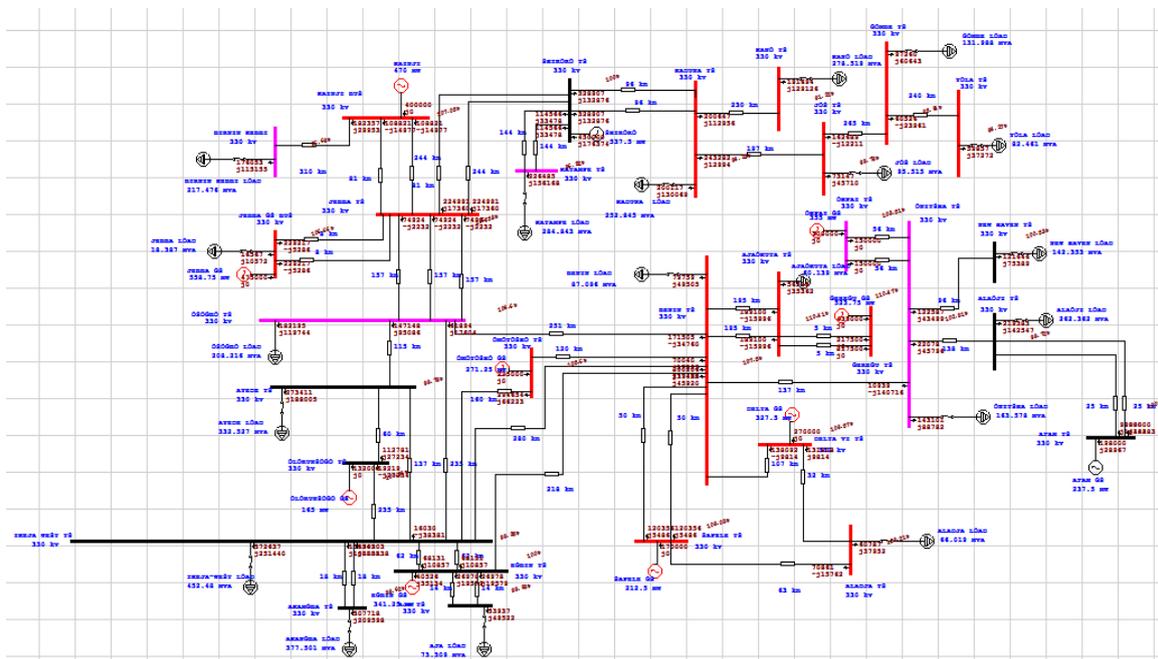


Fig. 1 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (Start-Up Load, Base Case)

Upon getting all the data required to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software, the data were used as input data and are shown in fig. 2.

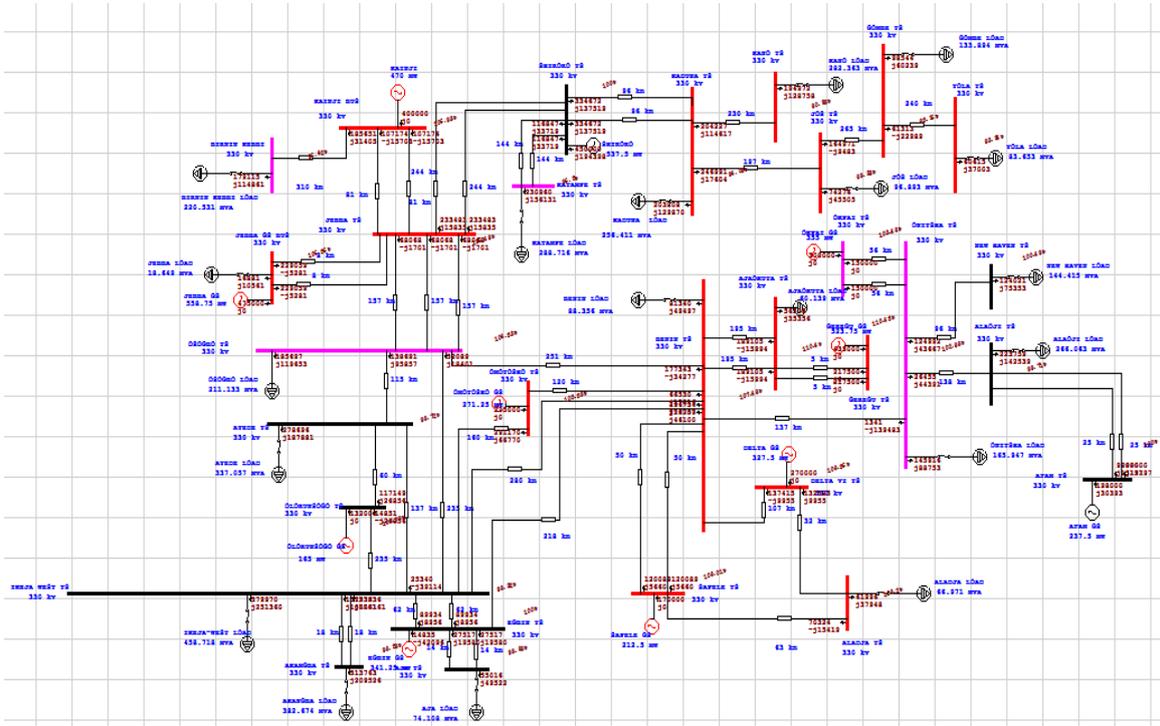


Fig. 2 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (1st Load Increase at 0.02p.u)

After realizing all the data required to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software, the data served as input data and are indicated in fig. 3.

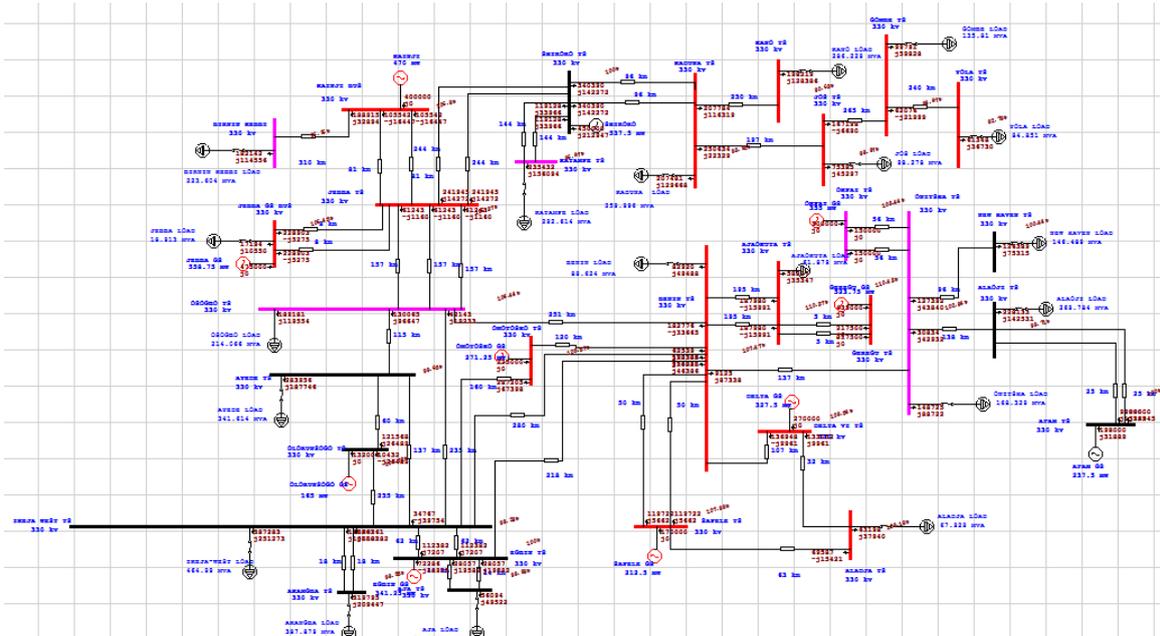


Fig. 3 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (2nd Load Increase at 0.04p.u)

Having realized all the data required to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software, the data served as input data and are indicated in fig. 4.

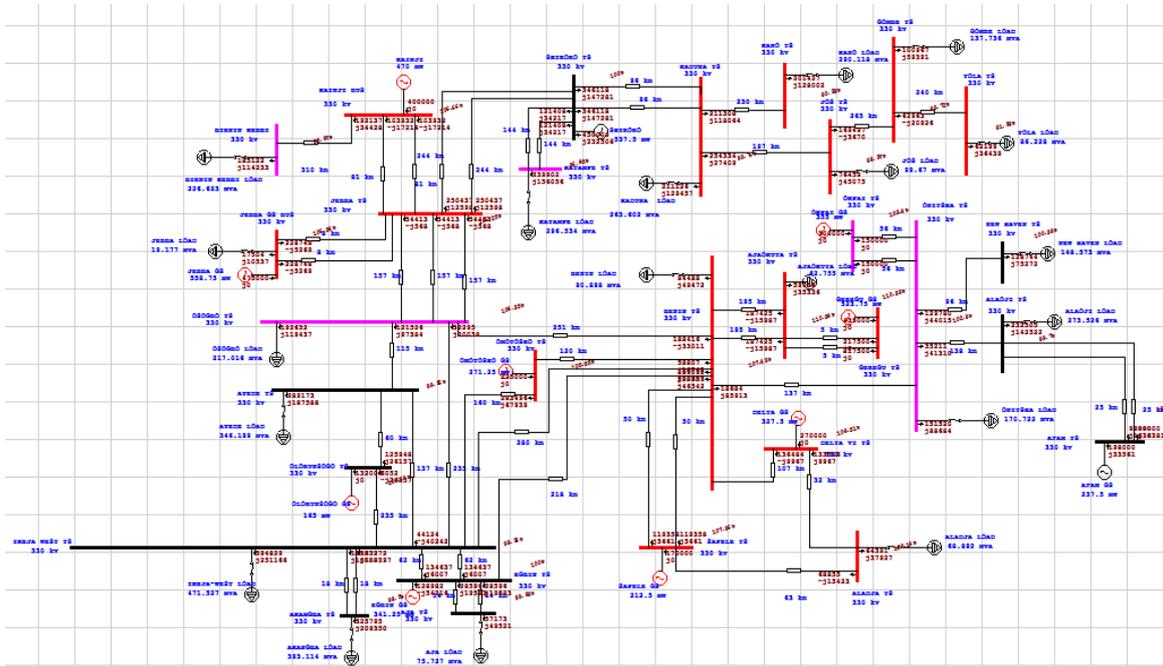


Fig. 4 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (3rd Load Increase at 0.06p.u)

All the data realized after the calculation to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software served as input data and are indicated in fig. 5.

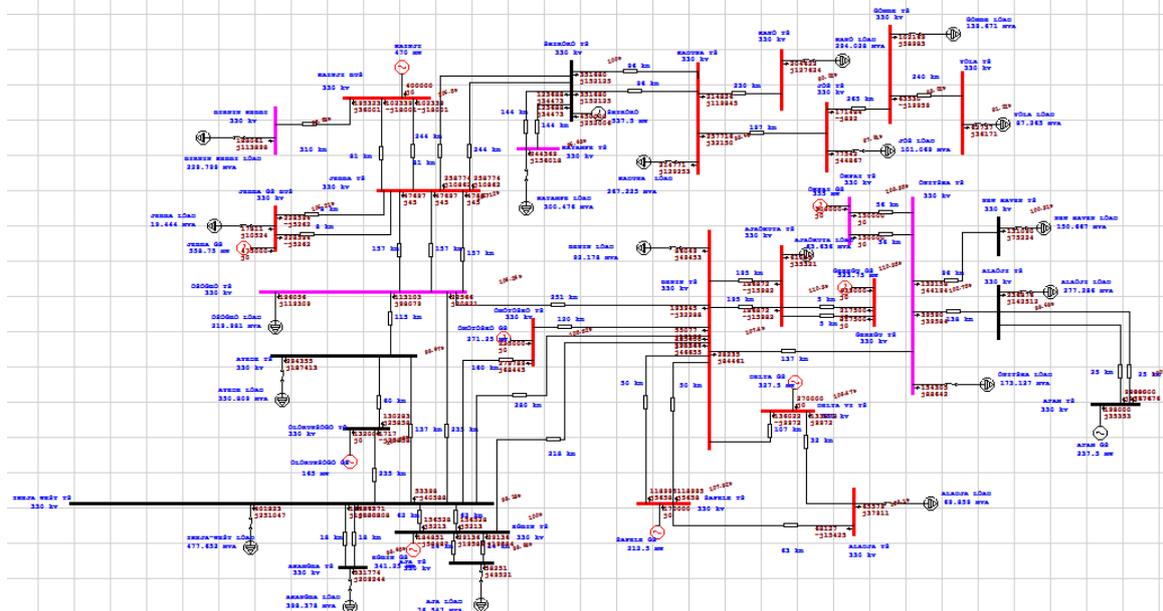


Fig. 5 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (4th Load Increase at 0.8p.u)

After realizing all the needed data to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software, the data served as input data and are indicated in fig. 6.

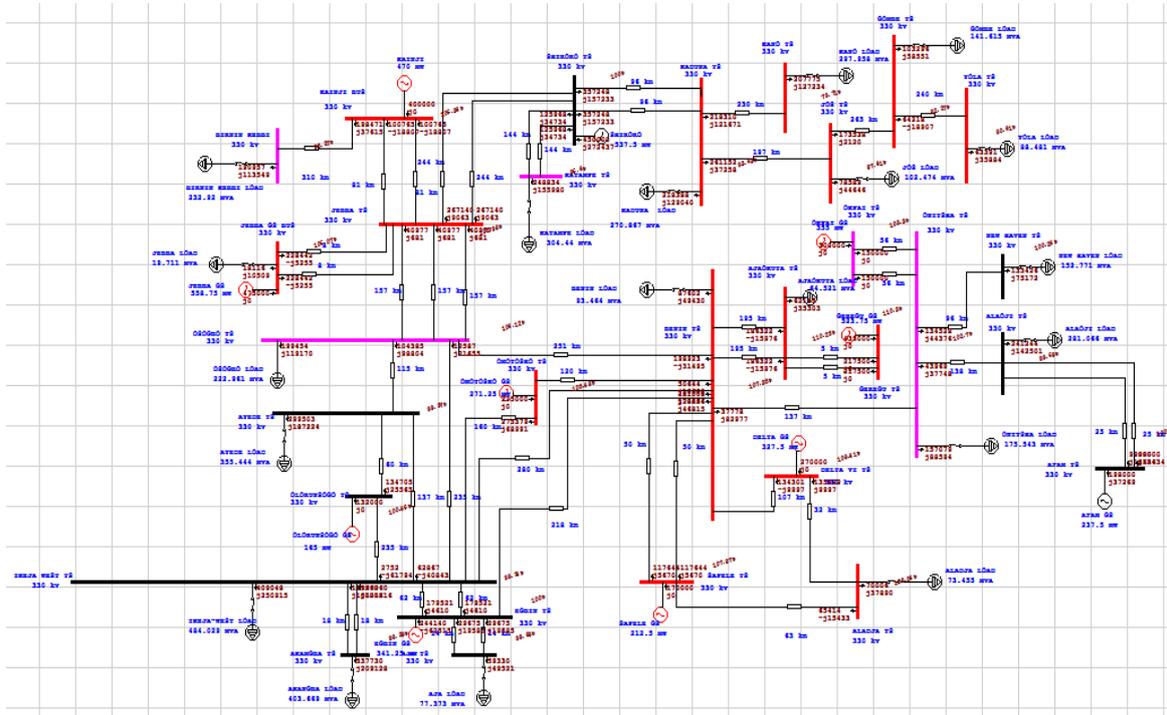


Fig. 6 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (5th Load Increase at 0.10p.u)

Having gotten all the data required to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software, the data served as input data and are indicated in fig. 7.

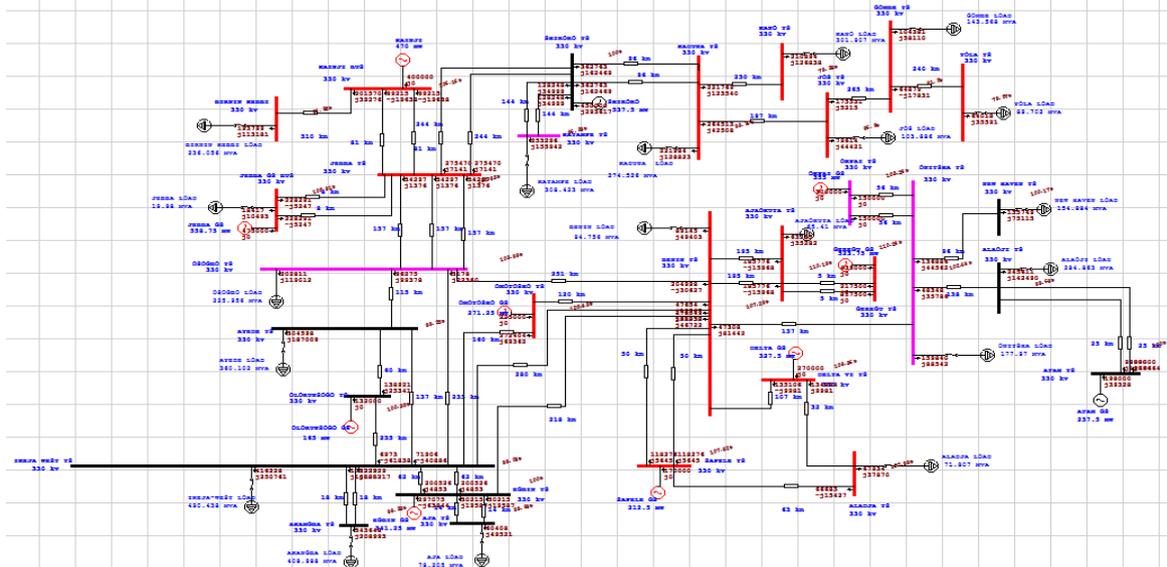


Fig. 7 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (6th Load Increase at 0.12p.u)

Data realized to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software served as input data and are indicated in fig. 8.

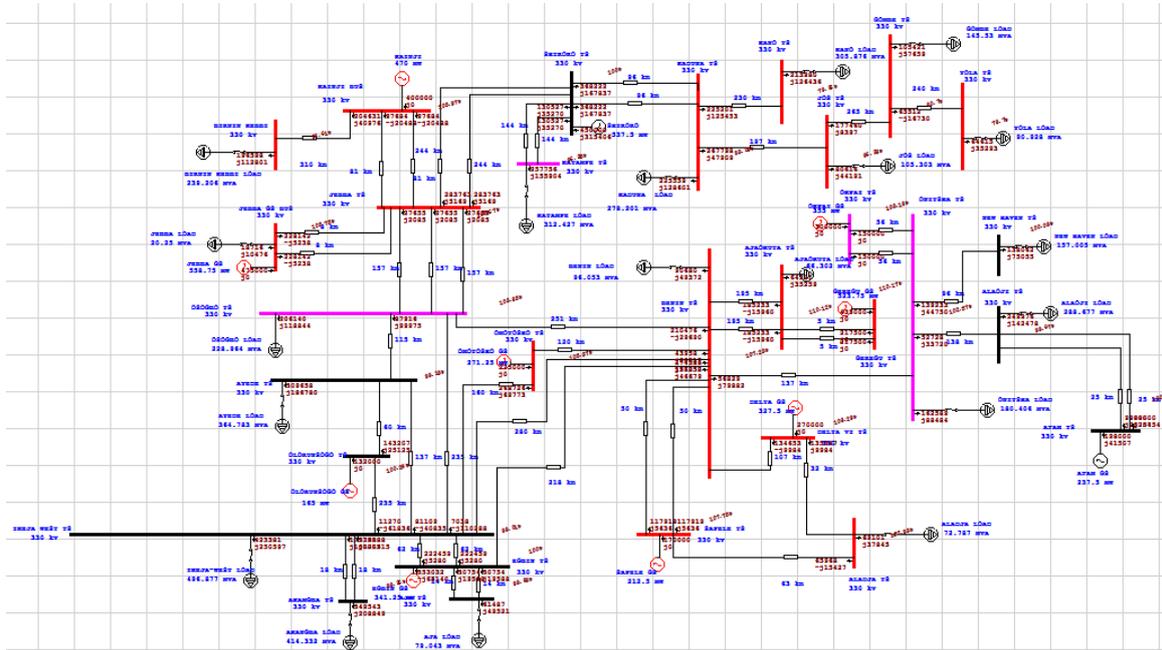


Fig. 8 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (7th Load Increase at 0.14p.u)

All the data required as realized to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software served as input data and are indicated in fig. 9.

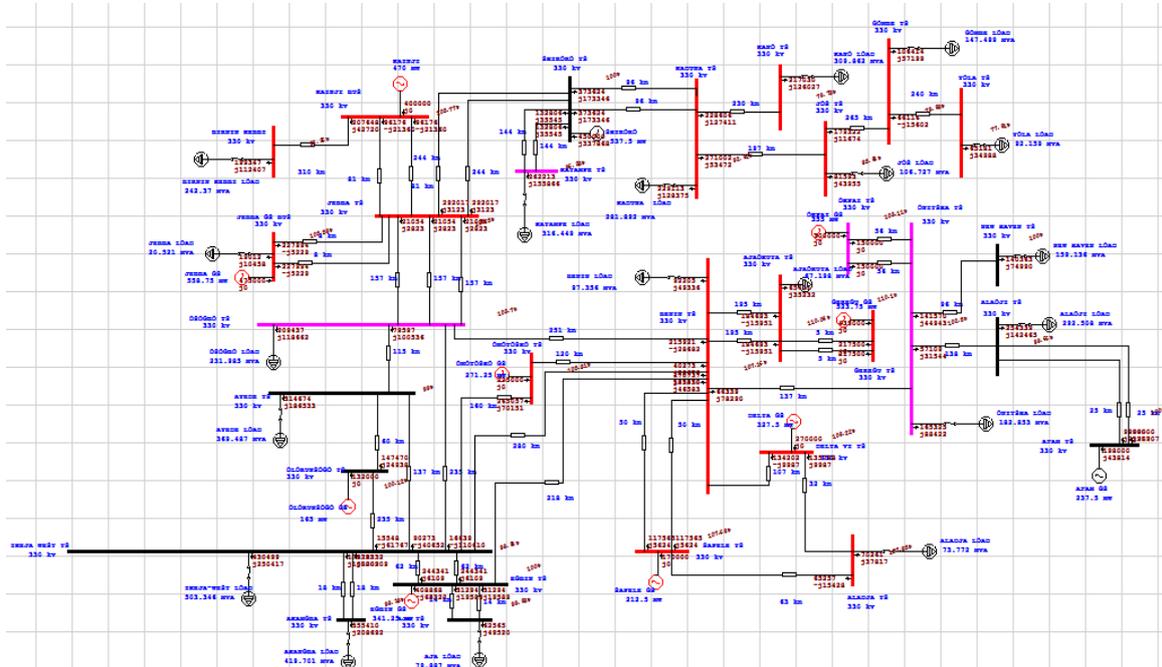


Fig. 9 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (8th Load Increase at 0.16p.u)

All the data needed to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software were realized. They became the input data and are indicated in fig. 10.

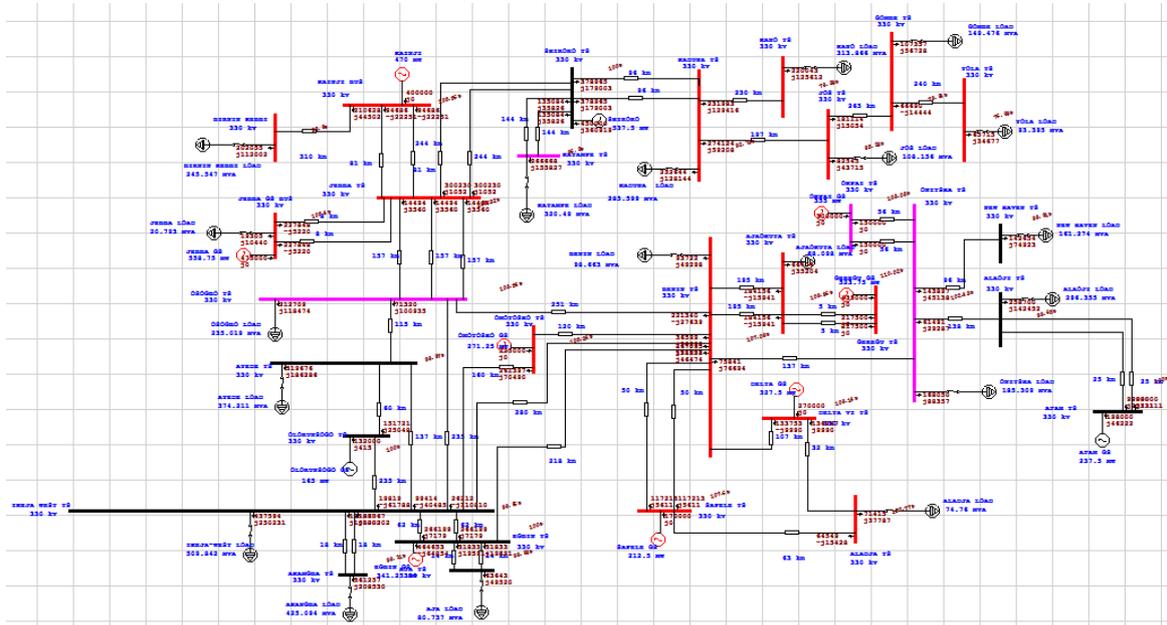


Fig. 10 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (9th Load Increase at 0.18p.u)

Upon getting all the data required to model and simulate to establish the loading margin of Nigerian 330kV transmission network with the use of ETAP 12.6 software, the data served as input data and are indicated in fig. 11.

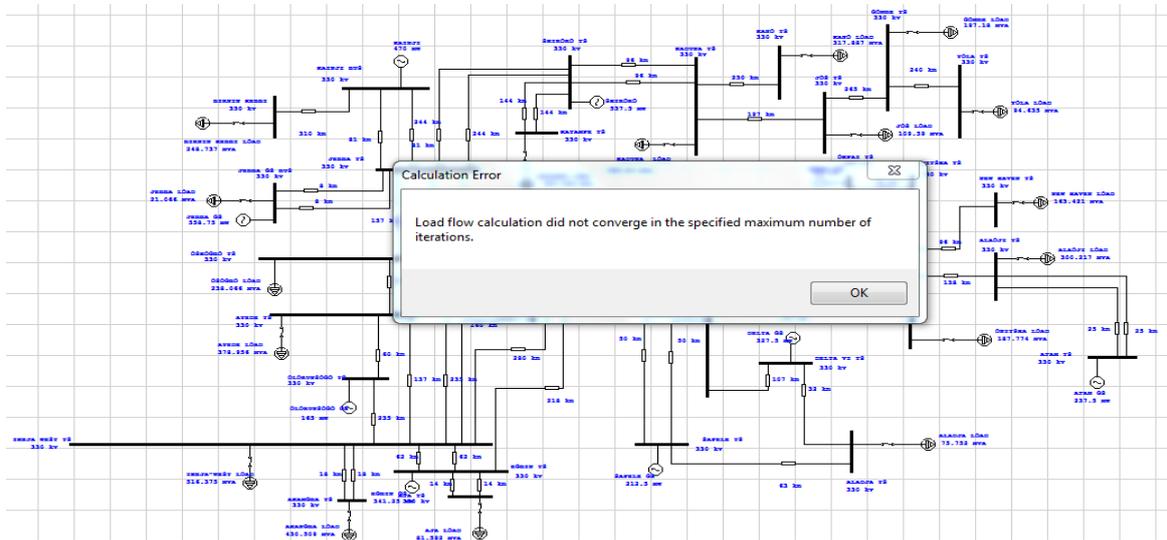


Fig. 11 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software at Bifurcation Point (10th Load Increase at 0.20p.u)



IV. RESULTS AND DISCUSSION

The results obtained from the continuation power flow are shown in table 1 and fig. 12 respectively.

Table 1 Summary of Load Demand Using Continuation Power Flow

Loading Factor (P.U)	Total Load Demand (MW)
0.02	3069.835
0.04	3127.286
0.06	3183.982
0.08	3239.851
0.10	3299.140
0.12	3352.075
0.14	3408.032
0.16	3463.868
0.18	3519.653
0.20	3362.760

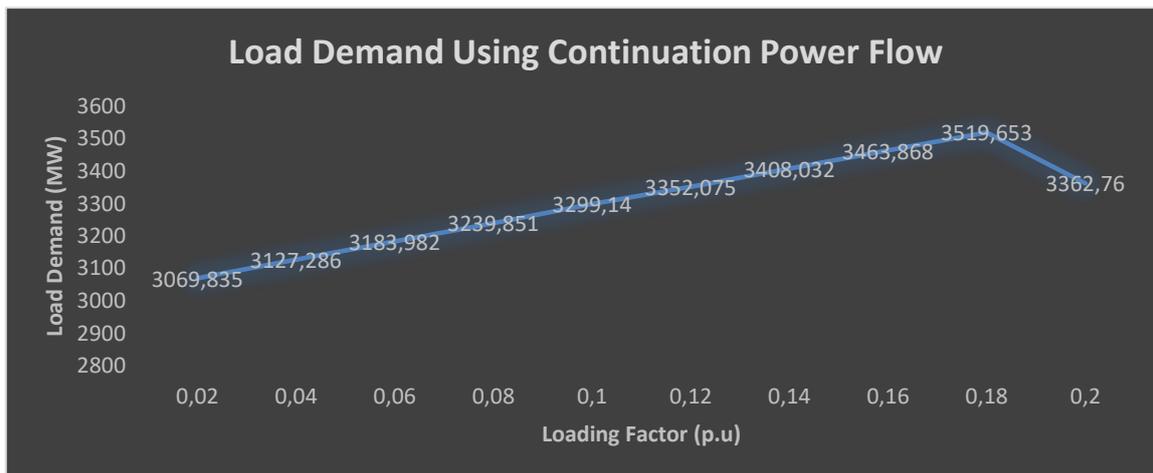


Fig. 12 Graph Showing Load Demand Using Continuation Power Flow

V. CONCLUSION

This research has highlighted the relevance of a comprehensive load demand analysis of Nigerian primary grid system. Continuation Power Flow method was used to model the Nigerian 330kV transmission network in ETAP 12.6 software environment to determine load growth trend on the network as well as the highest network load demand.

The continuation power flow analysis showed that from a power generation of 4000MW contributed to the grid, 3519.653MW was the highest load sustained at a loading factor of 0.18p.u. The analysis also showed that at a loading factor of 0.20p.u the continuation power flow failed to run signifying voltage collapse and if continued, system collapse may occur.

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