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Assessment of Power Grid Stability Using Continuation Power Flow Method

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***ABSTRACT*: *A power system is comprised of the generation, transmission, and distribution sections. A robust power system must have efficient primary grid system. The reason is for the system to efficiently and reliably service all required loads. It is imperative to identify the bifurcation point of the primary transmission system to avoid unnecessary system collapse and build a system that strives to satisfy load demands for greater customers' satisfaction. To achieve this aim, Nigerian 30 bus 330kV transmission network was used as a test case to implement load flows in Electrical Transient Analyzer Program (ETAP) software up to bifurcation point using Continuation Power Flow (CPF) technique. Maximum load of 3,014.08MW was drawn from a total generation of 4,000MW. From 0th through 1st to 10th loading points where CPF was used, maximum loading of 3,519.653MW representing 16.77% incremental loading was achieved at the 9th loading point. The 10th loading point was observed to be the bifurcation point where a loading factor of 0.18p.u was used and the system lost 156.893MW reducing the load to 3,362.757MW which represents 11.57% incremental loading. At this point, CPF stops suggesting that highest safe load lies between 6^{the} and 7th loading points of 3,352.075MW and 3,408.032MW which did not affect voltage stability thereby satisfying IEEE voltage stability requirements.*
KEYWORDS: *Primary transmission network, Bifurcation point, Continuation power flow, Point of collapse, Power system collapse, Voltage stability.*

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I. INTRODUCTION

It is very imperative to identify the maximum loading point of a power system to correctly manage and prevent the system from eminent voltage collapse. Doing this generally makes provision for optimal power utilization in the system. Increase in load demand and limited sources of power generation have given rise to an increasingly complex interconnected system thereby making the system to be operated closer to the limits of stability. The Guardian News Paper [1] reported that power generation dropped as Federal Government of Nigeria lost N92.28bn in 49 days. Voltage instability is described to be mainly associated with reactive power imbalance and therefore, the loadability of buses in the power system is dependent on the reactive power support that the buses receive from the system as the system tends towards the voltage collapse point or maximum loading point [2].

One major cause of voltage instability in a power system has been established to be the imbalance between the quantity of reactive power absorbed by the system and the quantity of reactive power that is available for the system. This imbalance could be due to the loss of loads, reactive power losses during transmission or reactive power generation inadequacies. Hence, efficient approach is required to keep balance between generated and consumed active and reactive powers in a power system to guarantee voltage stability [3]. Several approaches are available to ensure that optimal power utilization is achieved.

Igbogidi et al. [4] in their work maintained that continuous power flow is the best method for on-line application due to its accuracy, reliability, and fastness. Igbogidi et al. [4] in their work further stated that the Nigerian electricity grid at the present is comprised of 11 active generating stations in which there are 3 hydro and 8 thermal plants with a total installed generating capacity of 6500MW and 19 load buses with an approximation of 5000km 330kV transmission network. The hydro plants are Kainji, Jebba and Shiroro while the others are thermal. Presently, most of the generation units have broken down due to inadequate resources for the level of maintenance required.

II. RELATED WORKS

In Nigeria, the transmission system has to be continuously up-graded and expanded to accommodate the need for ever-growing power demand [5]. The transmission grid system is predominantly radial type, fragile in nature, and generally long in route length as 330kV and 132kV lines are approximated to be 11,000 km, 33kV sub-transmission line is approximated to be 24,000 km, and 11kV distribution line is approximated to be 19,000km with 22,500 substations [6]. The Nigerian 330kV transmission system is divided into North, South-East and South-West regions. While North is connected to South by a triple circuit network between Jebba and Osogbo, West is connected to the East via one transmission line from Osogbo to Benin with a double circuit network linking Ikeja to Benin [7].

Simon [8] stated that in Premium Times News Paper, Nigerians woke up on May 8, 2019 to a nationwide power outage that cut off power from very many homes and industries leading to a drastic cutdown on load allocations to the 11 distribution companies. At about 5:29 am on May 9, 2019, the grid collapsed the second time. According to Ogbikaya et al. [9], the Nigerian 330kV transmission network has so much challenges and are said to be insufficient generation and weak transmission lines that have ultimately made it not to be robust enough to wheel out the generated power in the network. The network is already vulnerable to voltage instability due to demand thereby causing bus voltage violation that would result to voltage collapse in the system. However, Ogbikaya et al. [9] stated that the large load demand placed on the transmission network may result to system insecurity and voltage collapse.

According to Lekshmi and Nagaraj [10],Artificial intelligence and machine learning provide space for qualitative and quantitative evaluation of the power system. In the same vein, Chuncha and Sureban [11] posited that ANN is good for the estimation of voltage collapse proximity in a power system. On the other hand, Gunadin et al. [12] maintained thatContinuation Power Flow (CPF) method provides maximum loading limits and the value of critical voltage on each bus in the power system. The goal of CPF is to trace the buses voltage profiles from a known initial solution which is the base case with the help of a predictor-corrector scheme to find solutions after the maximum loading point. The use of continuation power flow makes possible the availability of voltage stability margin and additional information about the voltage behavior of all the buses in the system engaged in incremental loading [13].Voltage stability indices as a method is also a good and dependable approach for the estimation of system loadability margin.

According to Rai [14], either P-V curve or Q-V curve may be adequate in estimating the highest allowable load or static voltage stability limit of the power systems. Enemuoh [15] said the commonest methods or techniques in estimating the proximity of voltage collapse point which is the highest loading point may include: Minimum Singular Value Point method, Continuation Power Flow Method, Optimization Method, and Point of Collapse Method. Enemuoh [15] further stated that continuation power flow is probably the most efficient of all the methods.

III. MATERIALS AND METHOD

3.1 Research Materials

The required data that defined the parameters for this study were taken from the National Control Centre (NCC), a substation of the Transmission Company of Nigeria (TCN) while others were calculated. Data for the study were primarily line impedance, power factor, base load, transmission line continuous current, transmission line route lengths, transformers and their ratings, and others.

3.2 Method of Analysis

Continuation Power Flow (CPF) method was used to determine the stability limit of the Nigerian 30 bus 330kV transmission network. A good numberof the data for this research were collected from the National Control Centre (NCC) while secondary data for the load flow were generated. Based on the method of continuation power flow, certain considerations were employed in Electrical Transient Analyzer software to establish the power flow limit of the Nigerian 330kV transmission network up to bifurcation point.In the course of getting the required data for the accomplishment of this research, TCN-NCC [16] maintained that generation, maximum load demand, buses, and interconnection of buses in the Nigerian 330kV transmission network are as shown in Tables 3.1-3.4while Igbogidi et al. [4] showed data consideration in software as indicated in Table 3.5.

Table 3.1: Generation Load in Nigeria, August 2019

S/N	Generators	Power (MW)
1	Kainji	470
2	Jebba	558.75
3	Olorunsogo	165
4	Egbin	341.25
5	Omotosho	271.25
6	Geregu	523.75
7	Sapele	212.5
8	Delta	327.5
9	Okpai	355
10	Afam	237.5
11	Shiroro	537.5
	Total Load	4000

Table 3.2: Maximum Load Demand in Nigeria, August 2019

S/N	Load Buses	Load (MW)
1	Birnin Kebbi	182
2	Jebba	15.5
3	Osogbo	174
4	Ayede	274
5	Ikeja-West	375.08
6	Akangba	312
7	Aja	80
8	Benin	74
9	Ajaokuta	51
10	Aladja	56
11	Onitsha	139
12	New-Haven	121
13	Alaoji	220
14	Katampe	234.5
15	kaduna	212
16	Kano	231
17	Jos	81
18	Gombe	112
19	Yola	70
	Total Load	3014.8

Table 3.3: Buses in the Nigerian 330kV Transmission Network

Bus Number	Bus Name
1	Kainji
2	Birnin-Kebbi
3	Jebba TS
4	Jebba GS
5	Osogbo
6	Ayede
7	Olorunsogo
8	Ikeja-West
9	Akamgba
10	Egbin (Slack)
11	Aja
12	Omotosho

13	Benin
14	Ajaokuta
15	Geregu
16	Sapele
17	Delta
18	Aladja
19	Onitsha
20	Okpai
21	New-Haven
22	Alaoji
23	Afam
24	Shiroro
25	Katampe
26	Kaduna
27	Kano
28	Jos
29	Gombe
30	Yola

Table 3.4: Interconnection of Buses in the Nigerian 330kV Transmission Network

S/N	Bus Name		Length (KM)
	From	To	
1	Kainji	Birnin-Kebbi	310
2	Kainji	Jebba TS	81
3	Jebba TS	Jebba GS	8
4	Jebba TS	Osogbo	157
5	Osogbo	Ayede	119
6	Ayede	Olorunsogo	60
7	Olorunsogo	Ikeja-West	30
8	Ayede	Ikeja-West	137
9	Osogbo	Ikeja-West	235
10	Ikeja-West	Akamgba	18
11	Ikeja-West	Egbin	62
12	Egbin	Aja	14
13	Egbin	Benin	218
14	Ikeja-West	Benin	280
15	Ikeja-West	Omotosho	160
16	Osogbo	Benin	251
17	Omotosho	Benin	120
18	Benin	Ajaokuta	195
19	Ajaokuta	Geregu	5
20	Benin	Sapele	50
21	Benin	Onitsha	137
22	Sapele	Aladja	63
23	Benin	Delta	107
24	Delta	Aladja	30
25	Onitsha	Okpai	56
26	Onitsha	New-Haven	96
27	Onitsha	Aladja	138
28	Alaoji	Afam	25
29	Jebba TS	Shiroro	244
30	Shiroro	Katampe	144
31	Shiroro	Kaduna	95
32	Kaduna	Kano	230
33	Kaduna	Jos	197
34	Jos	Gombe	265

35	Gombe	Yola	240

Table 3.5: Data Considerations Made in Software

S/N	Parameter/System	Dimension/Assumptions
1	330kV transmission line route length	4577km
2	Susceptance of transformer	$1.428X10^{-7}$Siemens
3	Susceptance of reactor	$1X10^{-7}$Siemens
4	Reference voltage	100%
5	Generation load	4,000MW
6	Maximum load demand	3,014.8MW
7	Firing angle range	90° - 180°
8	Susceptance of capacitor bank	$1X10^{-7}$Siemens
9	Installed generating capacity	6500MW
10	Conductor type	ACSR
11	Conductor size	$350mm^2$
12	Number of committed generators	11
13	System type	3-phase AC
14	Impedance/phase +	0.04856kΩ
15	Impedance/phase -	0.04856kΩ
16	Impedance/phase 0	0.17908kΩ
17	System frequency	50HZ
18	Base MVA	100MVA
19	System voltage	330kV
20	Conductor resistivity at 20°C	$2.83X10^{-8}$
21	Total MVA	4170MVA
22	Voltage limit: Maximum	346.5kV (+5%)
23	Voltage limit: Minimum	280.5kV (-5%)

From Tables 3.3 and 3.4, the Nigerian 30 bus 330kV transmission network is as designed and represented in Figure 3.1.

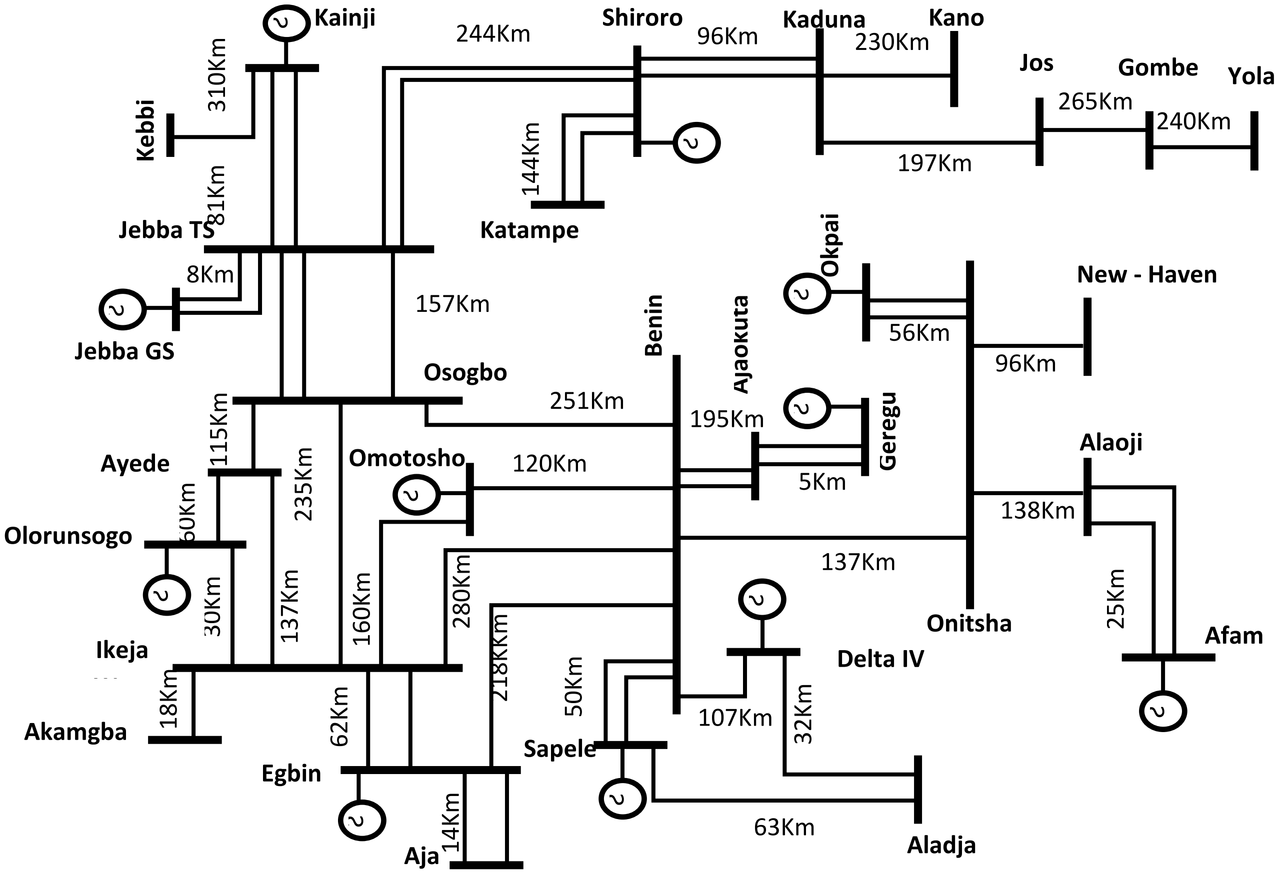

Figure 3.1: One Line Diagram of the Nigerian 30 Bus 330kV Transmission Network

3.3Network Modeling with Continuation Power Flow

In applying continuation power flow:

$P_i = \sum_{k=1}^{n} |V_i|\,|V_k| G_{ik} Cos\theta_{ik} + B_{ik} Sin\theta_{ik}$(3.1)

$Q_i = \sum_{k=1}^{n} |V_i|\,|V_k| G_{ik} Sin\theta_{ik} - B_{ik} Cos\theta_{ik}$(3.2)

We can also consider that:

$P_i = P_{Gi} - P_{Di}$(3.3)

$Q_i = Q_{Gi} - Q_{Di}$ (3.4)

Where:

G = Generation on the i^{th} bus

D = Load demand on the i^{th} bus

P_i = Injected active power at i^{th} bus

Q_i = Injected reactive power at i^{th} bus

P_{Gi} = Active power generation at i^{th} bus

Q_{Gi} = Reactive power generation at i^{th} bus

P_{Di} = Active power load at i^{th} bus

Q_{Di}= Reactive power load at i^{th} bus

Simulation of load change requires a load parameter λ to be inserted into demand powers 'P_{Di}' and 'Q_{Di}' to get:

$P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$(3.5)

$Q_{Di} = Q_{Dio} + \lambda(Q_{\Delta base})$ (3.6)

Where:

P_{Dio} and Q_{Dio} are original load demands on i^{th} bus

$P_{\Delta base}$ and $Q_{\Delta base}$ are given quantities of powers chosen to scale λ appropriately.

On a successful substitution of new demand powers in equations (3.5) and (3.6) to form equations (3.3) and (3.4), new set of equations can be generated in the following way:

$F(\theta, \quad V) = \lambda k$ (3.7)

$F(\theta, \quad V, \quad \lambda) = 0$ (3.8)

Where:

θ = Vector of bus voltage angles

V = Vector of bus voltage magnitudes

λ = Load demand parameter

The base solution for $\lambda = 0$ is generally gotten under a power flow while the continuation and parameterization processes are applied. The above nonlinear equation is then solved by specifying a value for λ in a manner that $0 \leq \lambda \leq \lambda$ critical.

3.3.1 Predictor Step

A linear approximation is generally used here to forecast the incoming solution for a change in one of the state variables with an approximate sized step in a direction that is tangential to the solution path where the derivative of both sides of equation (3.8) may become:

$F_\theta d\theta + F_V dV + F_\lambda d\lambda = 0$ (3.9)

$[F\theta \quad FV \quad F\lambda]\begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = 0$ (3.10)

For the fact that unknown variable 'λ 'is added to load flow equations, it is important to add another equation if equation (3.10) must be solved. This is always accomplished by setting one of the tangent vector components to +1 or -1 which usually represents continuation parameter. This setting imposes a non-zero value on the tangent vector making equation (3.10) to become:

$\begin{bmatrix} F\theta & FV & F\lambda \\ & e_K & \end{bmatrix}\begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix}$ (3.11)

Where:

e_K = appropriate row vector having all the elements as zero apart from the k^{th} element taken as 1.

At the initial step λ is selected as the continuation parameter. As the process continues, the state variable usually with the biggest rate of change is chosen to become the continuation parameter because of nature of parameterization. By solving equation (3.11), the tangent vector can be found and the prediction may be made in the following way:

$\begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix}^{P+1} = \begin{bmatrix} \theta \\ V \\ \lambda \end{bmatrix}^{P} + \sigma \begin{bmatrix} d\theta \\ dV \\ d\lambda \end{bmatrix}$ (3.12)

Where:

$P+^1$ = the next predicted solution

The step size σ is usually chosen in order for the predicted solution to lie within the radius of convergence of the corrector and where this fails a smaller step size is selected.

3.3.2 Corrector Step

In the corrector step, the predicted solution is corrected through local parameterization where the original set of equation is generally incremented by one equation that usually specifies the state variable's value selected thereby appearing as:

$\begin{bmatrix} F(\theta, \quad V, \quad \lambda) \\ x_K - \eta \end{bmatrix} = [0]$ (3.13)

Where:

x_K = State variable selected as continuation parameter

η = Value of the state variable predicted

A slightly modified Newton-Raphson load flow in Electrical Transient Analyzer Program (ETAP) can be employed to solve equation (3.13).

3.3.3 Critical Point

Stop the continuation power flow at critical point. The critical point is seen as the point where the loading is maximum. There is a decrease immediately after the critical point. The tangent component of λ becomes zero at the critical point and generally negative at any point after the critical point. By this, the sign of $d\lambda$ defines the critical point.

3.4 Application of Continuation Power Flow on Nigerian 330kV Transmission Network

Continuation power flow was applied on the Nigerian 30 bus 330kV transmission network with the help of Electrical Transient Analyzer Program (ETAP) software. The Nigerian 30 bus 330kV transmission network is comprised of 11 committed generators, 35 transmission lines, and 19 loads. Bus 10 was considered a slack bus while buses 1, 4, 7, 10, 12, 15, 16,17,20, 23, and 24 are PV buses whereas the rest 19 buses are PQ buses. CPF operation was performed on the network up to bifurcation point as shown in Figures 3.3-3.12.Based on base load principle, a total generation of 4,000MW and a maximum load of 3,014.08MW in the system were used in the first case of the power flow. The operation of the load flow is as shown in Figure 3.2.

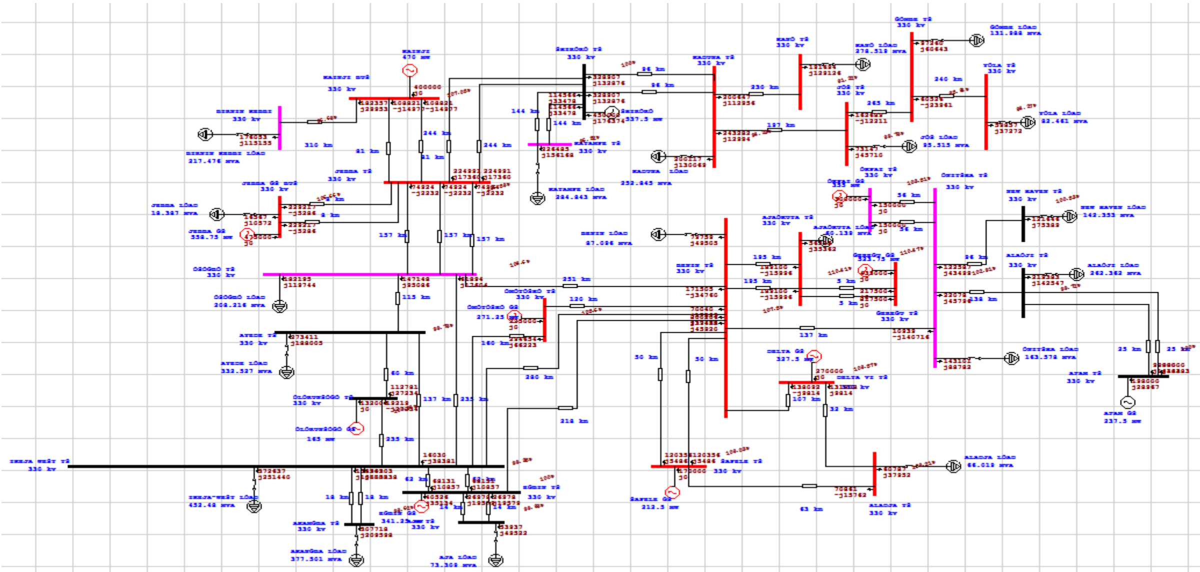

Figure 3.2: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (Start-Up Load/Base Case)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$when load parameter λ was 1 with a loading factor of 0.02p.u for 1st load increase on the 19 PQ buses.

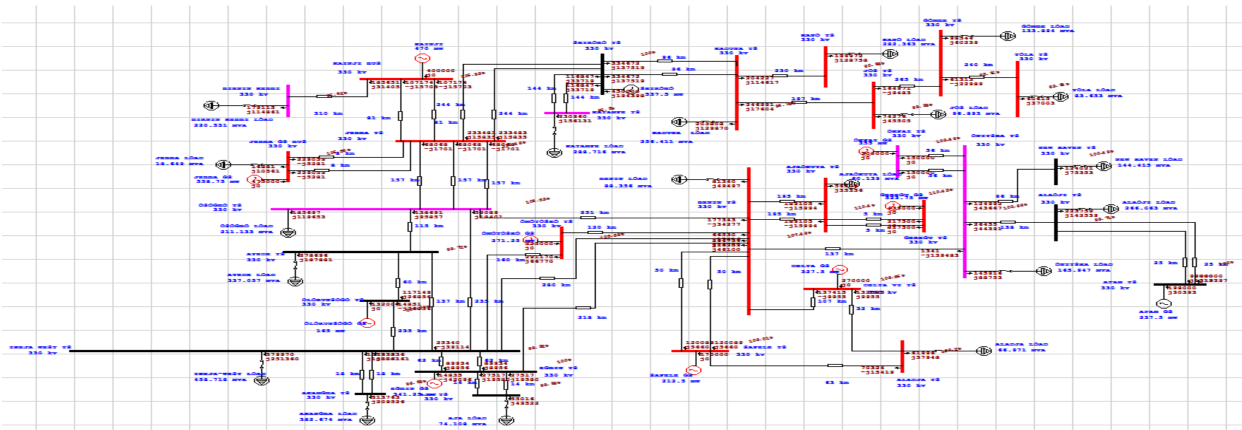

Figure 3.3: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (1st Load Increase at 0.02p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.04p.u for 2nd load increase on the 19 PQ buses.

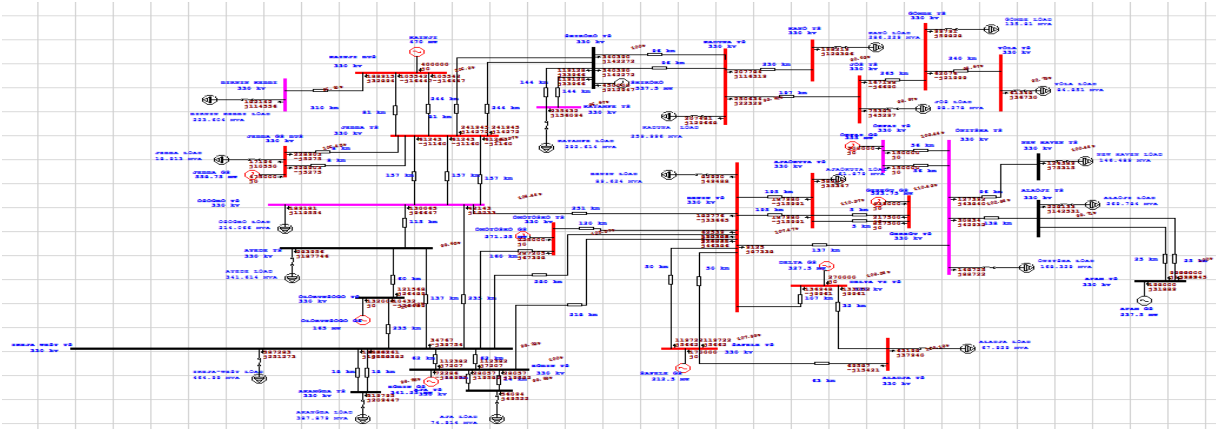

Figure 3.4: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (2nd Load Increase at 0.04p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.06p.u for 3rd load increase on the 19 PQ buses.

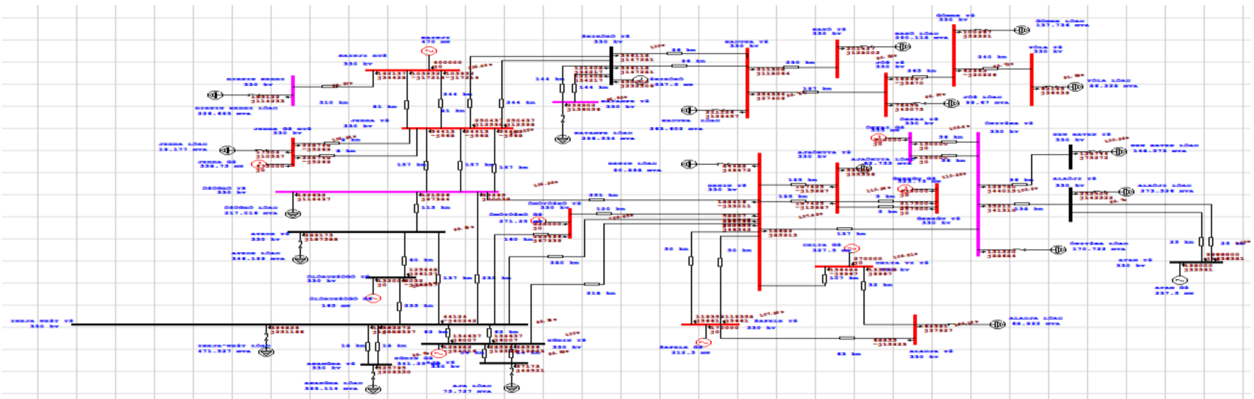

Figure 3.5: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (3rd Load Increase at 0.06p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.08p.u for 4th load increase on the 19 PQ buses.

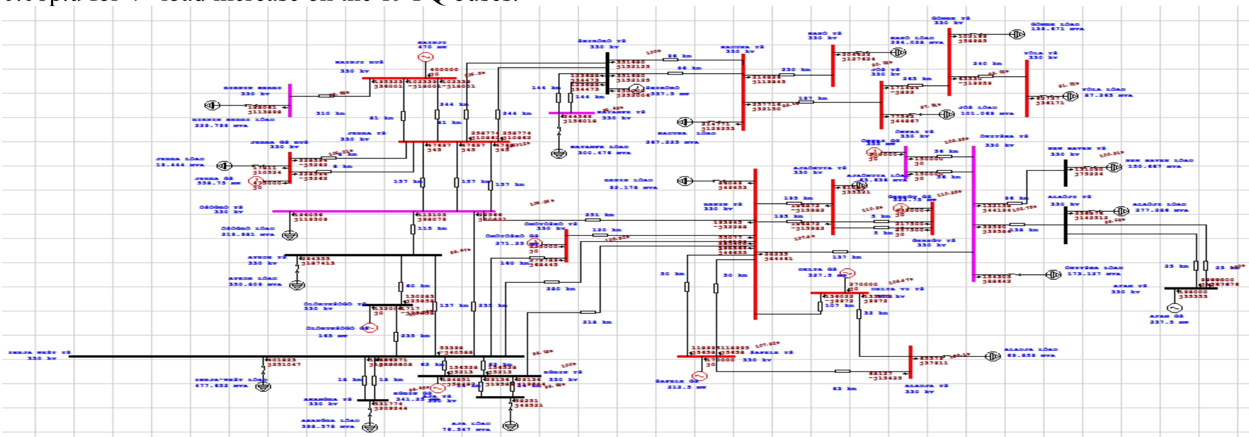

Figure 3.6: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (4th Load Increase at 0.08p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.10p.u for 5th load increase on the 19 PQ buses.

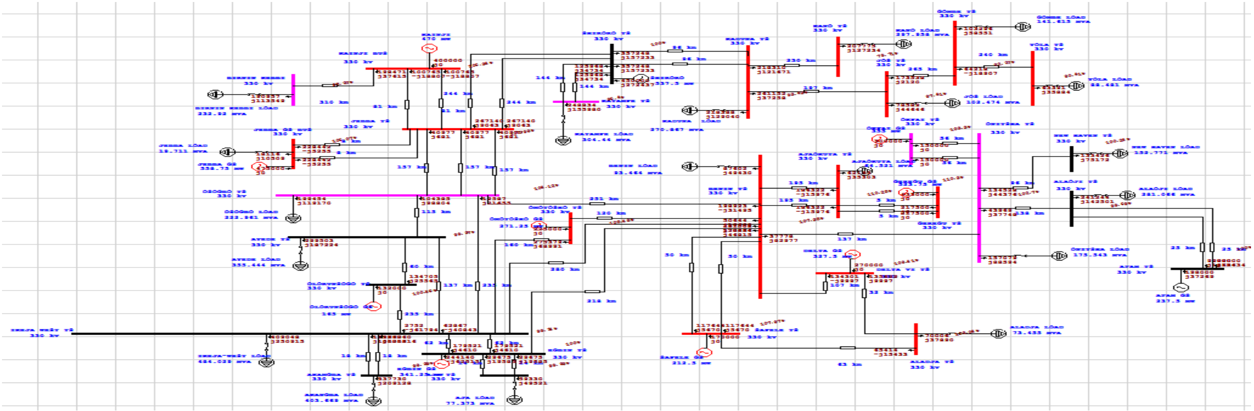

Figure 3.7: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (5th Load Increase at 0.10p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.12p.u for 6th load increase on the 19 PQ buses.

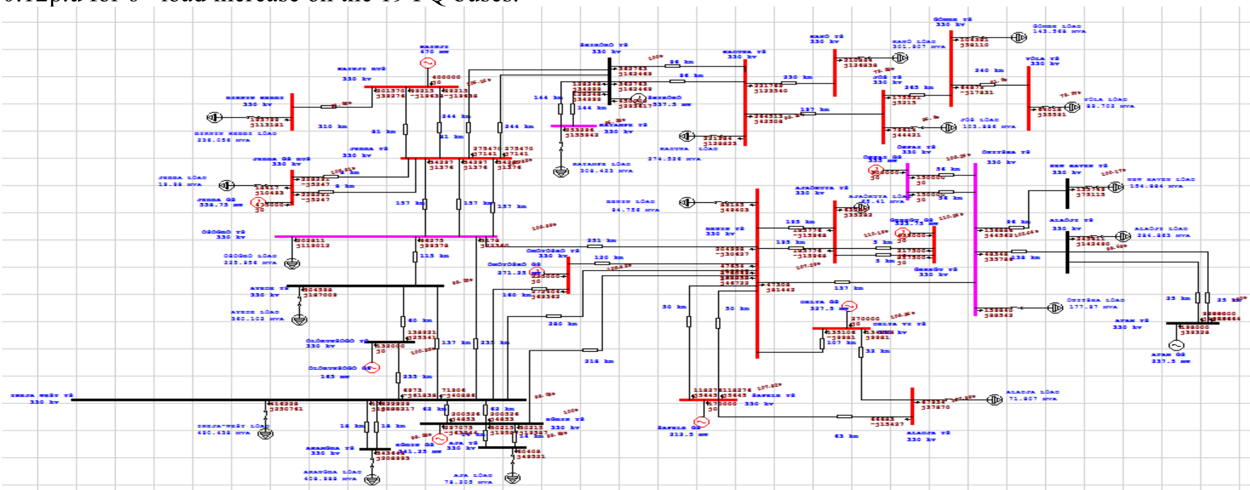

Figure 3.8: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (6th Load Increase at 0.12p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.14p.u for 7th load increase on the 19 PQ buses.

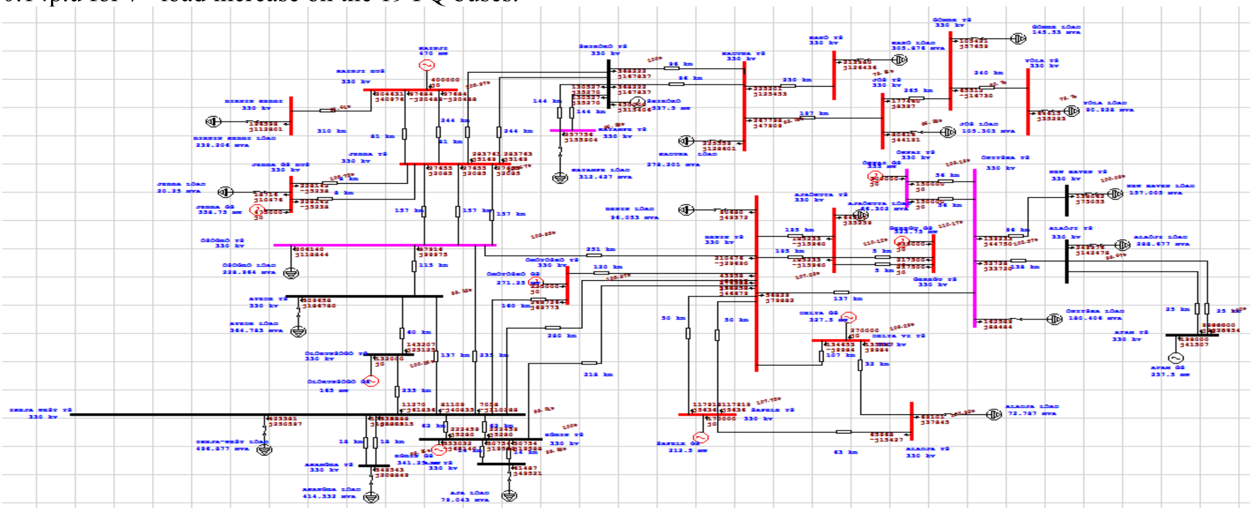

Figure 3.9: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (7th Load Increase at 0.14p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.16p.u for 8th load increase on the 19 PQ buses.

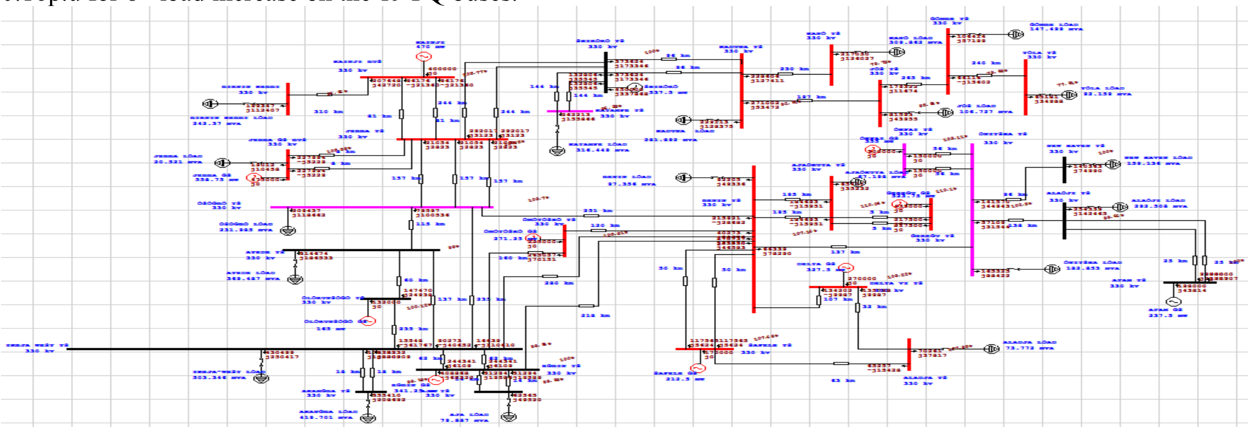

Figure 3.10: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (8th Load Increase at 0.16p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.18p.u for 9th load increase on the 19 PQ buses.

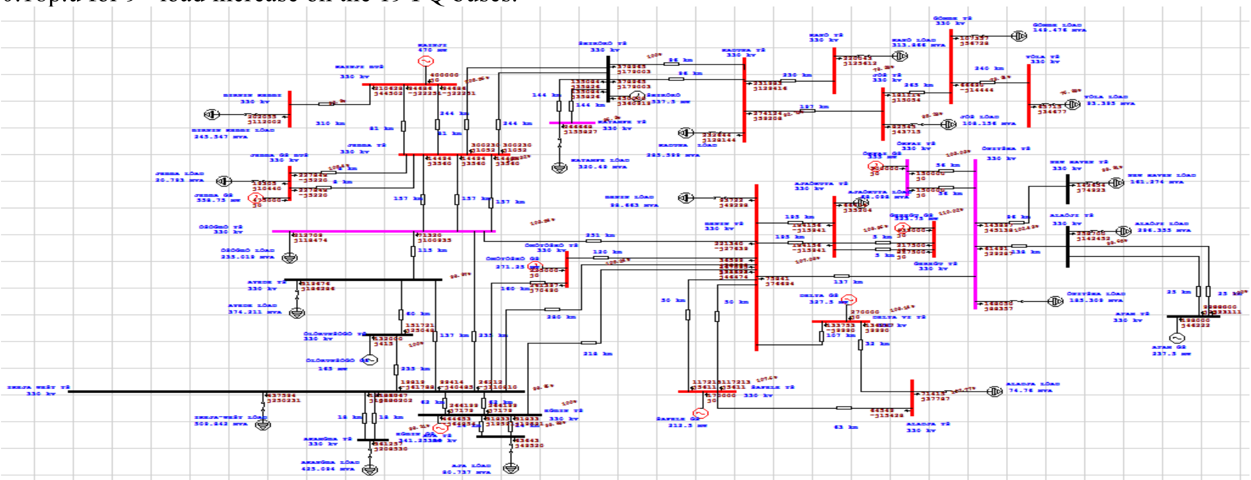

Figure 3.11: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software (9th Load Increase at 0.18p.u)

The equation considered was $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.20p.u for 10th load increase on the 19 PQ buses.

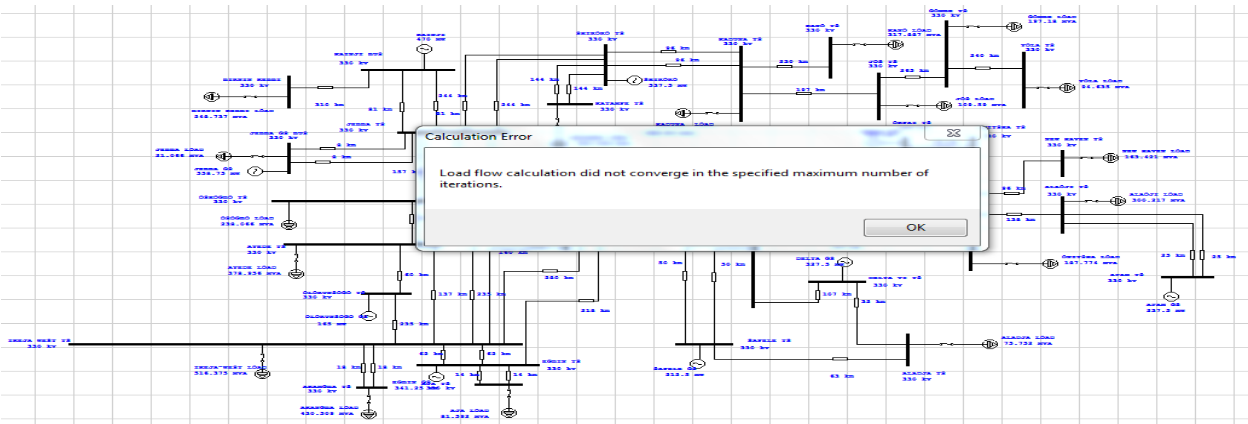

Figure 3.12: Nigerian 30 Bus 330kV Transmission Network Modeled in ETAP 12.6 Software at Bifurcation Point (10th Load Increase at 0.20p.u)

IV. RESULTS AND DISCUSSION

4.1 Network Loading Result Summary

The results realized in the course of conducting Continuation Power Flows (CPFs) on the Nigerian 30 bus 330kV transmission network are shown in Table 4.1 and Figures 4.1-4.3. Table 4.1 contains base load and continuation power flow loads. Figure 4.1 contains trend of power flow using continuation power flow method. Figure 4.2 contains incremental loading and loading factor while Figure 4.3 shows continuation power flow and bifurcation point.

Table 4.1: Base Load and Continuation Power Flow Loads

Loading Factor (P.U)	Loading Point	Base Load (MW)	Continuation Power Flow Load (MW)	Incremental Loading (MW)
0.00	0th	3014.08	3014.080	0.00
0.02	1st	0.00	3069.835	55.755
0.04	2nd	0.00	3127.286	57.451
0.06	3rd	0.00	3183.982	56.696
0.08	4th	0.00	3239.851	55.869
0.10	5th	0.00	3299.140	59.289
0.12	6th	0.00	3352.075	52.935
0.14	7th	0.00	3408.032	55.957
0.16	8th	0.00	3463.868	55.836
0.18	9th	0.00	3519.653	55.785
0.20	10th	0.00	3362.760	-156.893

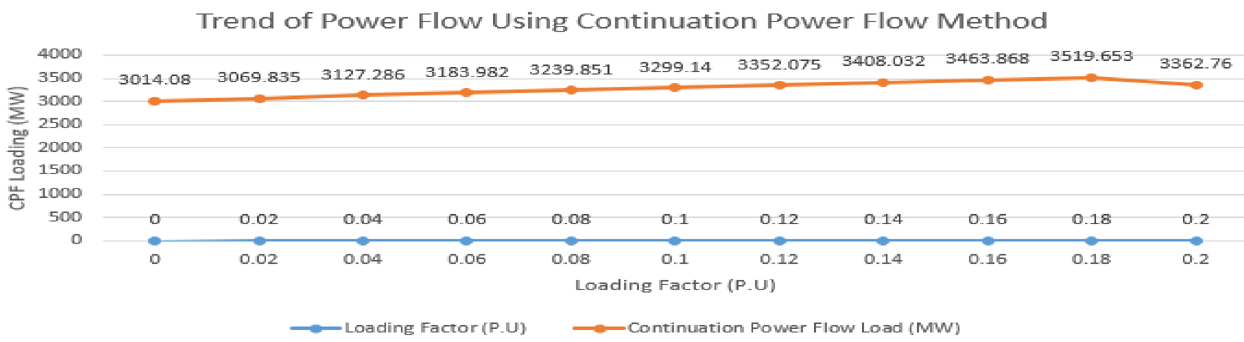

Figure 4.1: Graph Showing Trend of Power Flow Using Continuation Power Flow Method

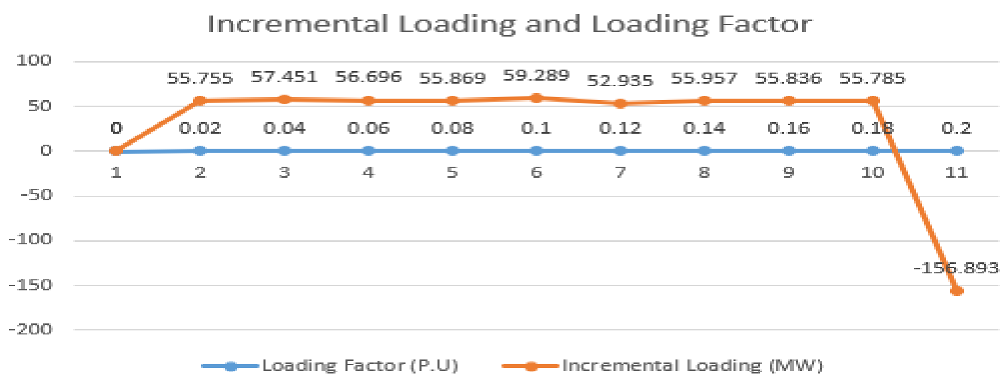

Figure 4.2: Graph Showing Incremental Loading and Loading Factor

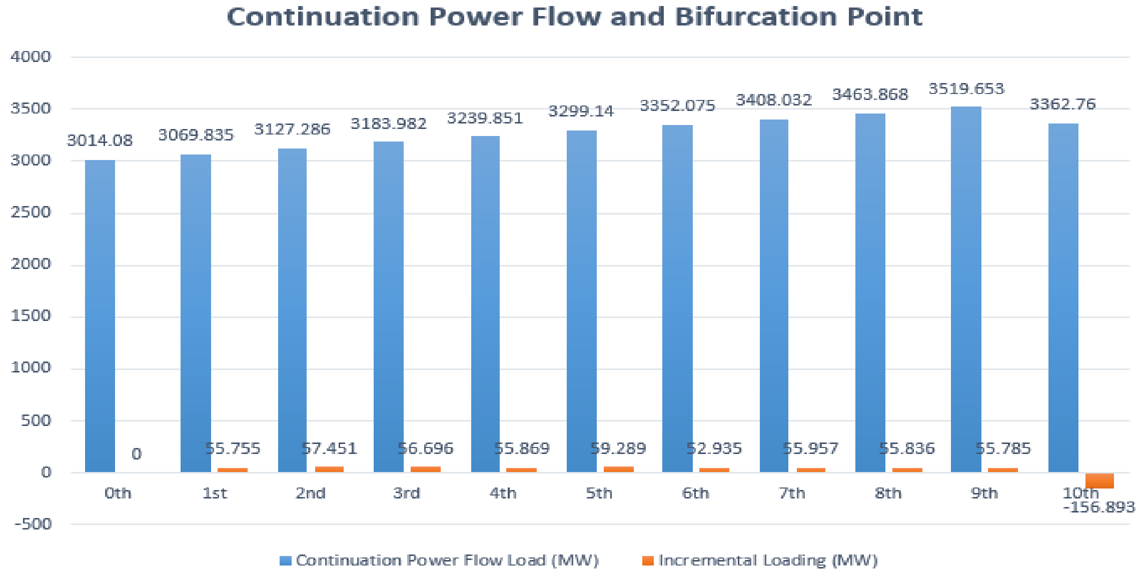

Figure 4.3: Graph Showing Continuation Power Flow and Bifurcation Point

V. CONCLUSION

5.1 Conclusion

This research has shown that more loads can be drawn from a total generation of 4,000MW and not to 3,014.08MW as maximum load. The Nigerian 30 bus 330kV transmission network by way of load stressing, it is evident that Continuation Power Flow (CPF) has shown that the primary grid system is large and robust enough to accommodate additional load up to 3,519.653MW.

Another indicator shows that loading the network beyond 3,519.653MW will amount to loss of part of the system as load reduced from 3,519.653MW to 3,362.760MW indicating a load loss of 156.893MW. In essence, partial system collapse occurred on the 10th incremental loading signifying bifurcation point (critical point). This research has proven that maximum safe loading is between 3,352.075MW and 3408.032MW which occurred between 6th and 7th incremental loading periods.

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