IJAREEIE

e-ISSN: 2278-8875
p-ISSN: 2320-3765

International Journal of Advanced Research

in Electrical, Electronics and Instrumentation Engineering

Volume 10, Issue 5, May 2021

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 7.122

9940 572 462 6381 907 438 ijareeie@gmail.com www.ijareeie.com

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 5, May 2021||

DOI:10.15662/IJAREEIE.2021.1005002

Enhancement of Loading Margin of Nigerian 330kV Transmission Network Using Continuation Power Flow and Static Var Compensator

Idoniboyeobu, Dikio Clifford[1], Ahiakwo, Christopher Okwuchukwu[2], Braide, Sepiribo Lucky[3] and Igbogidi, Onyebuchi Nelson[4]

Lecturers, Dept. of Electrical Engineering, Rivers State University, Port Harcourt, Nigeria[123&4]

ABSTRACT: This research was a detailed study to enhance the loading margin of Nigerian 330kV transmission network. The problem of weak loading margin of the Nigerian 330kV transmission network which was about 56MW was eliminated. Continuation Power Flow method was used to model the network in ETAP 12.6 software to determine the loading margin. Static Var Compensator was modelled in ETAP 12.6 software using shunt compensation method and yet subjected to continuation power flow to enhance the loading margin of Nigerian 330kV transmission network. The continuation power flow report showed that the highest load demand was 3519.653MW with a loading margin of 55.785MW at a loading factor of 0.18p.u but failed to run at the next load increment. The loading margin was improved from 55.785MW to 156.097MW indicating additional load demand of 100.312MW as the total load demand increased to 3619.965MW using Static Var Compensator at a loading factor of 0.22p.u but failed to run on the next load increment. The use of Static Var Compensator in the continuation power flow showed enhanced loading margin as there was additional allowable load. IEEE 519 Equation embedded in ETAP 12.6 software validates this result as it provides the Static Var Compensator support for harmonic order correction for each bus in the test system.

KEYWORDS: Loading Margin, Continuation Power Flow, Static Var Compensator, Loading Factor, Load Bus, Generator Bus.

I. INTRODUCTION

It has become obviously difficult in the recent past to build new generators and transmission facilities to accommodate the regionally increasing load demands leading to voltage instability from over utilization of the existing facilities or any contingency. One major problem plaguing the success of electric utilities is voltage instability which is essentially due to poor loading margin in the power system. Voltage collapse results when active and reactive power balance equations fail or the inability of load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation to provide the required reactive support.[1]. The lack of new generation and transmission facilities and over exploitation of the existing facilities geared by increase in load demand makes this type of problem more likely to happen in the present power systems [2].

According to a report from Energy Mix, 2019, Nigeria dropped energy consumption from an average of 3,578MW to 3,014.8MW on 19th August, 2019 representing a loading margin of about 56MW under a generation load of 4,000MW. About 75.37% system loading has been maintained either to avoid imminent voltage collapse owing to the feeling that the network has a weak loading margin [3].

In interconnected power systems, which today are very complex, there is a great need to improve utilization, while still maintaining reliability and security. While some transmission lines are charged up to the limit load, others may be overloaded, which influences the values of voltage and reduces system stability and security. For this reason, it is very important to control the power flows along transmission lines to meet transfer of power needs. The FACTS device is meant to enhance controllability as well as increase power transfer capability of the [4].

II. RELATED WORKS

It is an essential case to always ascertain the maximum loading point of every power system to avert voltage collapse [5].Whenever the voltage of a given bus in the transmission system dips below the nominal value, all substations and equipment linked to that bus practically operate at reduced efficiency and damages may occur [6]. The use of

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Continuation Power Flow method allows maximum loading limits and the value of critical voltage on each bus in the power system to be ascertained [7]. Continuation power flow as a method can be used to obtain voltage stability margin and additional information concerning the voltage behavior of the system buses with the incremental loading level [8].One of the first methods used to establish the maximum loading condition of a power system is the continuation power flow [9]. In continuation power flow, power flow begins with the initial operating point and increases load to the maximum loading point [10].

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 [11]. Continuation power flow analysis largely depends on locally parametrized continuation method which intends to avert the singularity of the Jacobian by slightly reformulating the power flow equations [12]. The reliability of continuation power flow method is high as it does not have serious convergence issues because of device limits [13].

Studies on system loadability are not only restricted on the methods and techniques to determine the secure operating region of a system. It also involves identifying suitable approaches to improve the load margin of a system. Among the popular approaches for load margin enhancement are network reconfiguration of distribution system, controlling the generation direction, installation of FACTS devices, reactive power scheduling, and load shedding [5]. In another form, loading margin of a network can be improved by any or a combination of the following: installation of new power transmission line, reconductoring of existing power transmission line, conversion of existing single circuit to double circuit, voltage upgrade, phase-shifting, and reactive power compensation.

Devoid of building a new grid, improvement of the existing lines and substations can be accomplished using FACTS which will enhance the system stability and availability, power transmission capability, power quality, load sharing between parallel circuits, improving voltage stability in the grid, reduce environmental impact, transmission losses etc [14]. The demand of Electric energy increases continuously with the increasing size and complexity of the transmission networks, the performance of the power systems decreases due to problems related to load flow, voltage stability and others, FACTS is one of the growing technologies, uses power electronics control devices for existing power system network. SVC is one of the facts devices which plays an important role in controlling the reactive and active power flow to the power network and hence both the system voltage fluctuations and transient stability.Going by the functions of SVC, capacitors generate, and reactors otherwise known as inductors absorb reactive power when connected to an AC power source. The Static Var Compensator (SVC) is a shunt device of the Flexible AC Transmission Systems [15].

III. MATERIALS AND METHODS

Bus data, transformers rating, base load, transmission lines power rating, transmission line impedance and route length, generators active power, power factor and other very important data were collected from the National Control Centre (NCC) while others were computed and used in ETAP 12.6 software. The methods and procedure adopted in this research are described accordingly.

Continuation Power Flow (CPF) method was used to model and obtain the loading margin of the Nigerian 330kV transmission network. In a second case, shunt compensation method was used to model Static Var Compensator and yet subjected the network to continuation power flow for the enhancement of the established loading margin.

Considering the equation
$P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ when load parameter λ was 1 with a loading factor of 0.02p.u, then, for 1st load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.02X182)$, $P_{Di} = 185.64MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.02\ X\ 15.5)$, $P_{Di} = 15.81MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.02\ X\ 174)$, $P_{Di} = 177.48MW$
Ayede Bus has $P_{Di} = 274 + 1(0.02\ X\ 274)$, $P_{Di} = 279.48MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.02\ X\ 375.08)$, $P_{Di} = 382.58MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.02\ X\ 312)$, $P_{Di} = 318.24MW$
Aja Bus has $P_{Di} = 80 + 1(0.02\ X\ 80)$, $P_{Di} = 81.60MW$
Benin Bus has $P_{Di} = 74 + 1(0.02\ X\ 74)$, $P_{Di} = 75.48MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.02\ X\ 51)$, $P_{Di} = 52.02MW$
Aladja Bus has $P_{Di} = 56 + 1(0.02\ X\ 56)$, $P_{Di} = 57.12MW$

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Onitsha Bus has $P_{Di} = 139 + 1(0.02\,X\,139)$, $P_{Di} = 141.78MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.02\,X\,121)$, $P_{Di} = 123.42MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.02\,X\,220)$, $P_{Di} = 224.40MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.02\,X\,234.50)$, $P_{Di} = 239.19MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.02\,X\,212)$, $P_{Di} = 216.24MW$
Kano Bus has $P_{Di} = 231 + 1(0.02\,X\,231)$, $P_{Di} = 235.62MW$
Jos Bus has $P_{Di} = 81 + 1(0.02\,X\,81)$, $P_{Di} = 82.62MW$
Gombe Bus has $P_{Di} = 112 + 1(0.02\,X\,112)$, $P_{Di} = 114.24MW$
Yola Bus has $P_{Di} = 70 + 1(0.02\,X\,70)$, $P_{Di} = 71.40MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.04p.u, then, for 2nd load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.04\,X\,182)$, $P_{Di} = 189.28MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.04\,X\,15.5)$, $P_{Di} = 16.12MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.04\,X\,174)$, $P_{Di} = 180.96MW$
Ayede Bus has $P_{Di} = 274 + 1(0.04\,X\,274)$, $P_{Di} = 284.96MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.04\,X\,375.08)$, $P_{Di} = 390.08MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.04\,X\,312)$, $P_{Di} = 324.48MW$
Aja Bus has $P_{Di} = 80 + 1(0.04\,X\,80)$, $P_{Di} = 83.20MW$
Benin Bus has $P_{Di} = 74 + 1(0.04\,X\,74)$, $P_{Di} = 76.96MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.04\,X\,51)$, $P_{Di} = 53.04MW$
Aladja Bus has $P_{Di} = 56 + 1(0.04\,X\,56)$, $P_{Di} = 58.24MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.04\,X\,139)$, $P_{Di} = 144.56MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.04\,X\,121)$, $P_{Di} = 125.84MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.04\,X\,220)$, $P_{Di} = 228.80MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.04\,X\,234.50)$, $P_{Di} = 243.88MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.04\,X\,212)$, $P_{Di} = 220.48MW$
Kano Bus has $P_{Di} = 231 + 1(0.04\,X\,231)$, $P_{Di} = 240.24MW$
Jos Bus has $P_{Di} = 81 + 1(0.04\,X\,81)$, $P_{Di} = 84.24MW$
Gombe Bus has $P_{Di} = 112 + 1(0.04\,X\,112)$, $P_{Di} = 116.48MW$
Yola Bus has $P_{Di} = 70 + 1(0.04\,X\,70)$, $P_{Di} = 72.80MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.06p.u, then, for 3rd load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.06\,X\,182)$, $P_{Di} = 192..92MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.06\,X\,15.5)$, $P_{Di} = 16.443MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.06\,X\,174)$, $P_{Di} = 184.44MW$
Ayede Bus has $P_{Di} = 274 + 1(0.06\,X\,274)$, $P_{Di} = 290.44MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.06\,X\,375.08)$, $P_{Di} = 397.85MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.06\,X\,312)$, $P_{Di} = 330.72MW$
Aja Bus has $P_{Di} = 80 + 1(0.06\,X\,80)$, $P_{Di} = 84.80MW$
Benin Bus has $P_{Di} = 74 + 1(0.06\,X\,74)$, $P_{Di} = 78.44MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.06\,X\,51)$, $P_{Di} = 54.06MW$
Aladja Bus has $P_{Di} = 56 + 1(0.06\,X\,56)$, $P_{Di} = 59.36MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.06\,X\,139)$, $P_{Di} = 147.34MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.06\,X\,121)$, $P_{Di} = 128.26MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.06\,X\,220)$, $P_{Di} = 233.20MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.06\,X\,234.50)$, $P_{Di} = 248.57MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.06\,X\,212)$, $P_{Di} = 224.72MW$
Kano Bus has$P_{Di} = 231 + 1(0.06\,X\,231)$, $P_{Di} = 244.86MW$
Jos Bus has $P_{Di} = 81 + 1(0.06\,X\,81)$, $P_{Di} = 85.86MW$
Gombe Bus has $P_{Di} = 112 + 1(0.06\,X\,112)$, $P_{Di} = 118.72MW$
Yola Bus has $P_{Di} = 70 + 1(0.06\,X\,70)$, $P_{Di} = 74.40MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.08p.u, then, for 4th load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.08\,X\,182)$, $P_{Di} = 196.56MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.08\,X\,15.5)$, $P_{Di} = 16.74MW$

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 5, May 2021||

DOI:10.15662/IJAREEIE.2021.1005002

Osogbo Bus has $P_{Di} = 174 + 1(0.08\,X\ 174)$, $P_{Di} = 187.92MW$
Ayede Bus has $P_{Di} = 274 + 1(0.08\,X\,274)$, $P_{Di} = 295.92MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.08\,X\ 375.08)$, $P_{Di} = 405.09MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.08\,X\,312)$, $P_{Di} = 336.96MW$
Aja Bus has $P_{Di} = 80 + 1(0.08\,X\,80)$, $P_{Di} = 86.40MW$
Benin Bus has $P_{Di} = 74 + 1(0.08\,X\,74)$, $P_{Di} = 79.92MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.08\,X\,51)$, $P_{Di} = 55.08MW$
Aladja Bus has $P_{Di} = 56 + 1(0.08\,X\,56)$, $P_{Di} = 60.48MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.08\,X\,139)$, $P_{Di} = 150.12MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.08\,X\ 121)$, $P_{Di} = 130.68MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.08\,X\ 220)$, $P_{Di} = 237.60MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.08\,X\,234.50)$, $P_{Di} = 257.26MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.08\,X\ 212)$, $P_{Di} = 228.96MW$
Kano Bus has $P_{Di} = 231 + 1(0.08\,X\,231)$, $P_{Di} = 249.48MW$
Jos Bus has $P_{Di} = 81 + 1(0.08\,X\ 81)$, $P_{Di} = 87.48MW$
Gombe Bus has $P_{Di} = 112 + 1(0.08\,X\ 112)$, $P_{Di} = 120.96MW$
Yola Bus has $P_{Di} = 70 + 1(0.08\,X\,70)$, $P_{Di} = 75.60MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.10p.u, then, for 5th load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.10\,X\,182)$, $P_{Di} = 200.20MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.10\,X\ 15.5)$, $P_{Di} = 17.05MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.10\,X\ 174)$, $P_{Di} = 191.40MW$
Ayede Bus has $P_{Di} = 274 + 1(0.10\,X\,274)$, $P_{Di} = 301.40MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.10\,X\,375.08)$, $P_{Di} = 412.59MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.10\,X\,312)$, $P_{Di} = 343.20MW$
Aja Bus has $P_{Di} = 80 + 1(0.10\,X\ 80)$, $P_{Di} = 88.00MW$
Benin Bus has $P_{Di} = 74 + 1(0.10\,X\,74)$, $P_{Di} = 81.40MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.10\,X\,51)$, $P_{Di} = 56.10MW$
Aladja Bus has $P_{Di} = 56 + 1(0.10\,X\ 56)$, $P_{Di} = 61.60MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.10\,X\,139)$, $P_{Di} = 152.90MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.10\,X\,121)$, $P_{Di} = 133.10MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.10\,X\,220)$, $P_{Di} = 242.00MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.10\,X\ 234.50)$, $P_{Di} = 257.95MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.10\,X\,212)$, $P_{Di} = 233.20MW$
Kano Bus has $P_{Di} = 231 + 1(0.10\,X\ 231)$, $P_{Di} = 254.10MW$
Jos Bus has $P_{Di} = 81 + 1(0.10\,X\ 81)$, $P_{Di} = 89.10MW$
Gombe Bus has $P_{Di} = 112 + 1(0.10\,X\ 112)$, $P_{Di} = 123.20MW$
Yola Bus has $P_{Di} = 70 + 1(0.10\,X\ 70)$, $P_{Di} = 77.00MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.12p.u, then, for 6th load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.12\,X\,182)$, $P_{Di} = 203.84MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.12\,X\ 15.5)$, $P_{Di} = 17.36MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.12\,X\ 174)$, $P_{Di} = 194.88MW$
Ayede Bus has $P_{Di} = 274 + 1(0.12\,X\ 274)$, $P_{Di} = 306.88MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.12\,X\,375.08)$, $P_{Di} = 420.09MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.12\,X\,312)$, $P_{Di} = 349.44MW$
Aja Bus has $P_{Di} = 80 + 1(0.12\,X\,80)$, $P_{Di} = 89.60MW$
Benin Bus has $P_{Di} = 74 + 1(0.12\,X\ 74)$, $P_{Di} = 82.88MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.12\,X\,51)$, $P_{Di} = 57.12MW$
Aladja Bus has $P_{Di} = 56 + 1(0.12\,X\ 56)$, $P_{Di} = 62.72MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.12\,X\,139)$, $P_{Di} = 155.68MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.12\,X\,121)$, $P_{Di} = 135.52MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.12\,X\,220)$, $P_{Di} = 246.40MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.12\,X\ 234.50)$, $P_{Di} = 262.64MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.12\,X\,212)$, $P_{Di} = 237.44MW$

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 5, May 2021||

DOI:10.15662/IJAREEIE.2021.1005002

Kano Bus has $P_{Di} = 231 + 1(0.12\,X\,231)$, $P_{Di} = 258.72MW$
Jos Bus has $P_{Di} = 81 + 1(0.12\,X\,81)$, $P_{Di} = 90.72MW$
Gombe Bus has $P_{Di} = 112 + 1(0.12\,X\,112)$, $P_{Di} = 125.44MW$
Yola Bus has $P_{Di} = 70 + 1(0.12\,X\,70)$, $P_{Di} = 78.40MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.14p.u, then, for 7th load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.14\,X\,182)$, $P_{Di} = 207.48MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.14\,X\,15.5)$, $P_{Di} = 17.67MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.14\,X\,174)$, $P_{Di} = 198.36MW$
Ayede Bus has $P_{Di} = 274 + 1(0.14\,X\,274)$, $P_{Di} = 312.36MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.14\,X\,375.08)$, $P_{Di} = 427.59MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.14\,X\,312)$, $P_{Di} = 355.68MW$
Aja Bus has $P_{Di} = 80 + 1(0.14\,X\,80)$, $P_{Di} = 91.20MW$
Benin Bus has $P_{Di} = 74 + 1(0.14\,X\,74)$, $P_{Di} = 84.36MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.14\,X\,51)$, $P_{Di} = 58.14MW$
Aladja Bus has $P_{Di} = 56 + 1(0.14\,X\,56)$, $P_{Di} = 63.84MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.14\,X\,139)$, $P_{Di} = 158.46MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.14\,X\,121)$, $P_{Di} = 137.74MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.14\,X\,220)$, $P_{Di} = 250.80MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.14\,X\,234.50)$, $P_{Di} = 267.33MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.14\,X\,212)$, $P_{Di} = 241.68MW$
Kano Bus has $P_{Di} = 231 + 1(0.14\,X\,231)$, $P_{Di} = 263.34MW$
Jos Bus has $P_{Di} = 81 + 1(0.14\,X\,81)$, $P_{Di} = 92.34MW$
Gombe Bus has $P_{Di} = 112 + 1(0.14\,X\,112)$, $P_{Di} = 127.68MW$
Yola Bus has $P_{Di} = 70 + 1(0.14\,X\,70)$, $P_{Di} = 79.80MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.16p.u, then, for 8th load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.16\,X\,182)$, $P_{Di} = 211.12MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.16\,X\,15.5)$, $P_{Di} = 17.98MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.16\,X\,174)$, $P_{Di} = 201.84MW$
Ayede Bus has $P_{Di} = 274 + 1(0.16\,X\,274)$, $P_{Di} = 317.84MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.16\,X\,375.08)$, $P_{Di} = 435.09MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.16\,X\,312)$, $P_{Di} = 361.92MW$
Aja Bus has $P_{Di} = 80 + 1(0.16\,X\,80)$, $P_{Di} = 92.80MW$
Benin Bus has $P_{Di} = 74 + 1(0.16\,X\,74)$, $P_{Di} = 85.84MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.16\,X\,51)$, $P_{Di} = 59.16MW$
Aladja Bus has $P_{Di} = 56 + 1(0.16\,X\,56)$, $P_{Di} = 64.96MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.16\,X\,139)$, $P_{Di} = 161.24MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.16\,X\,121)$, $P_{Di} = 140.36MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.16\,X\,220)$, $P_{Di} = 255.20MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.16\,X\,234.50)$, $P_{Di} = 272.02MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.16\,X\,212)$, $P_{Di} = 245.92MW$
Kano Bus has $P_{Di} = 231 + 1(0.16\,X\,231)$, $P_{Di} = 267.96MW$
Jos Bus has $P_{Di} = 81 + 1(0.16\,X\,81)$, $P_{Di} = 93.96MW$
Gombe Bus has $P_{Di} = 112 + 1(0.16\,X\,112)$, $P_{Di} = 129.92MW$
Yola Bus has $P_{Di} = 70 + 1(0.16\,X\,70)$, $P_{Di} = 81.20MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.18p.u, then, for 9th load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.18\,X\,182)$, $P_{Di} = 214.76MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.18\,X\,15.5)$, $P_{Di} = 18.29MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.18\,X\,174)$, $P_{Di} = 205.32MW$
Ayede Bus has $P_{Di} = 274 + 1(0.18\,X\,274)$, $P_{Di} = 323.32MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.18\,X\,375.08)$, $P_{Di} = 442.59MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.18\,X\,312)$, $P_{Di} = 368.16MW$
Aja Bus has $P_{Di} = 80 + 1(0.18\,X\,80)$, $P_{Di} = 94.40MW$

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 5, May 2021||

DOI:10.15662/IJAREEIE.2021.1005002

Benin Bus has $P_{Di} = 74 + 1(0.18 X 74), P_{Di} = 87.32MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.18 X 51), P_{Di} = 60.18MW$
Aladja Bus has $P_{Di} = 56 + 1(0.18 X 56), P_{Di} = 66.08MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.18 X 139), P_{Di} = 164.02MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.18 X 121), P_{Di} = 142.78MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.18 X 220), P_{Di} = 259.60MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.18 X 234.50), P_{Di} = 276.71MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.18 X 212), P_{Di} = 250.16MW$
Kano Bus has $P_{Di} = 231 + 1(0.18 X 231), P_{Di} = 272.58MW$
Jos Bus has $P_{Di} = 81 + 1(0.18 X 81), P_{Di} = 95.58MW$
Gombe Bus has $P_{Di} = 112 + 1(0.18 X 112), P_{Di} = 132.16MW$
Yola Bus has $P_{Di} = 70 + 1(0.18 X 70), P_{Di} = 82.60MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.20p.u, then, for 10th load increase
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.20 X 182), P_{Di} = 218.40MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.20 X 15.5), P_{Di} = 18.60MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.20 X 174), P_{Di} = 208.80MW$
Ayede Bus has $P_{Di} = 274 + 1(0.20 X 274), P_{Di} = 328.80MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.20 X 375.08), P_{Di} = 450.10MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.20 X 312), P_{Di} = 374.40MW$
Aja Bus has $P_{Di} = 80 + 1(0.20 X 80), P_{Di} = 96.00MW$
Benin Bus has $P_{Di} = 74 + 1(0.20 X 74), P_{Di} = 88.80MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.20 X 51), P_{Di} = 61.20MW$
Aladja Bus has $P_{Di} = 56 + 1(0.20 X 56), P_{Di} = 67.20MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.20 X 139), P_{Di} = 166.80MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.20 X 121), P_{Di} = 145.20MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.20 X 220), P_{Di} = 264.00MW$
Katamkpe Bus has $P_{Di} = 234.50 + 1(0.20 X 234.50), P_{Di} = 281.40MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.20 X 212), P_{Di} = 254.40MW$
Kano Bus has $P_{Di} = 231 + 1(0.20 X 231), P_{Di} = 277.20MW$
Jos Bus has $P_{Di} = 81 + 1(0.20 X 81), P_{Di} = 97.20MW$
Gombe Bus has $P_{Di} = 112 + 1(0.20 X 112), P_{Di} = 134.40MW$
Yola Bus has $P_{Di} = 70 + 1(0.20 X 70), P_{Di} = 84.00MW$

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 the following way.

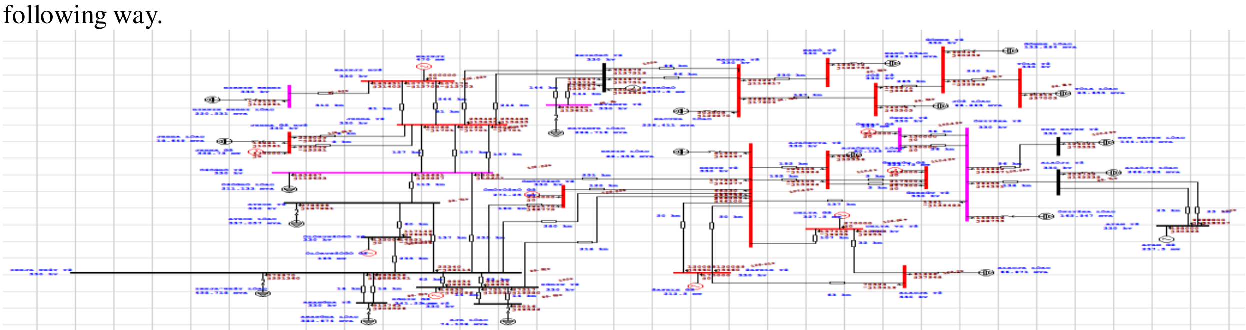

Fig. 1 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (1st Load Increase at 0.02p.u)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 5, May 2021||

DOI:10.15662/IJAREEIE.2021.1005002

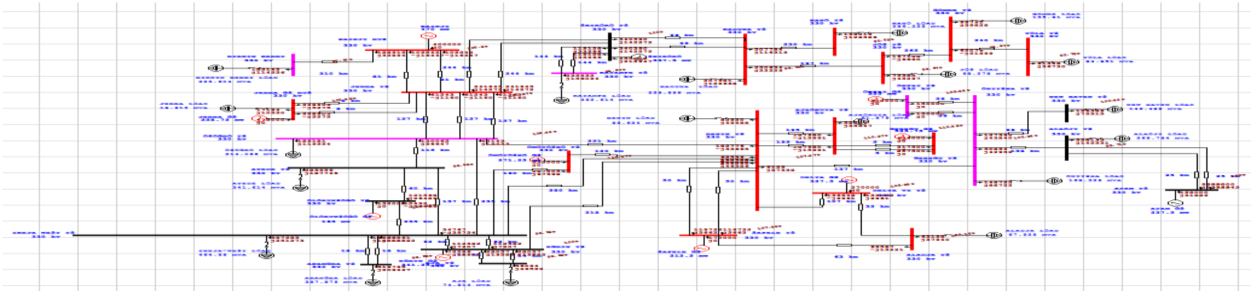

Fig. 2 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (2nd Load Increase at 0.04p.u)

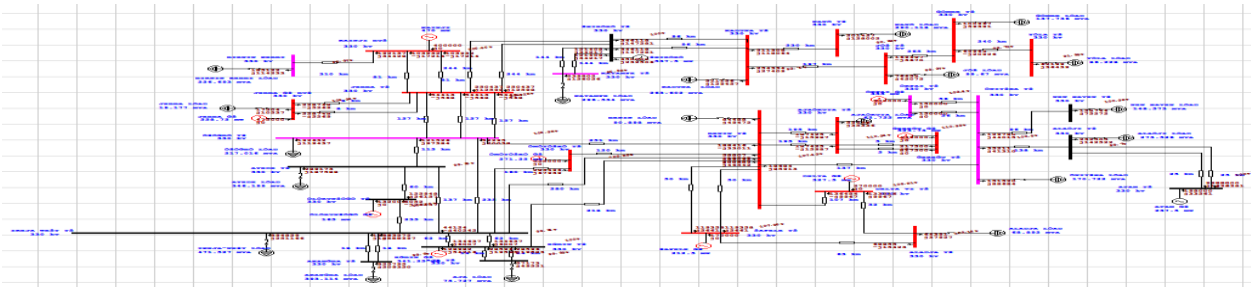

Fig. 3Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (3rd Load Increase at 0.06p.u)

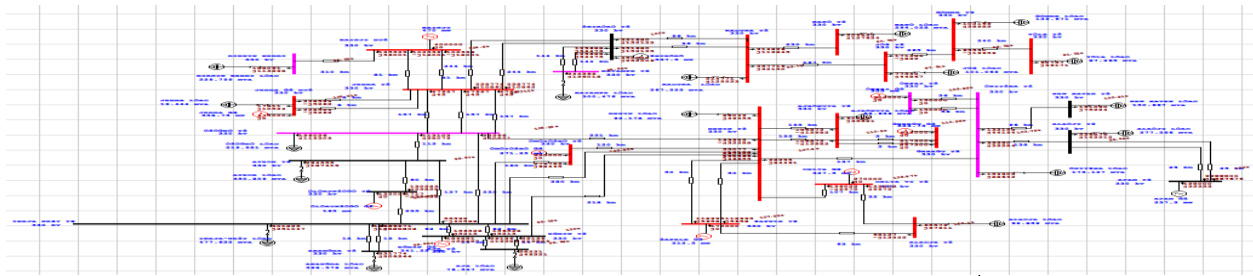

Fig. 4 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (4th Load Increase at 08p.u)

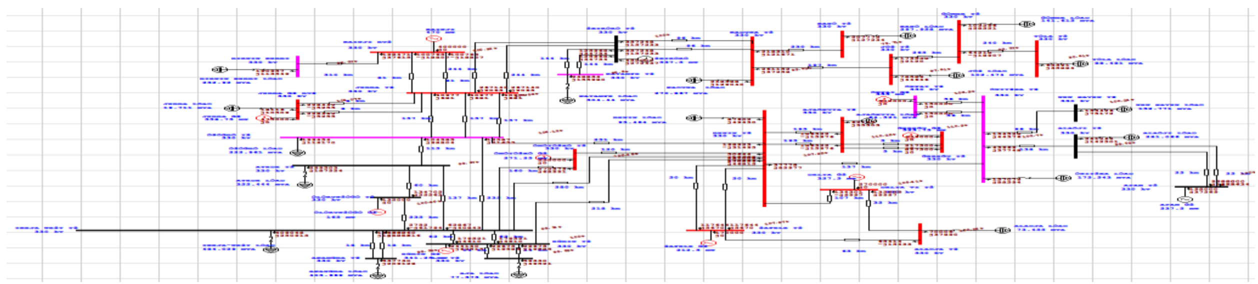

Fig. 5 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (5th Load Increase at 0.10p.u)

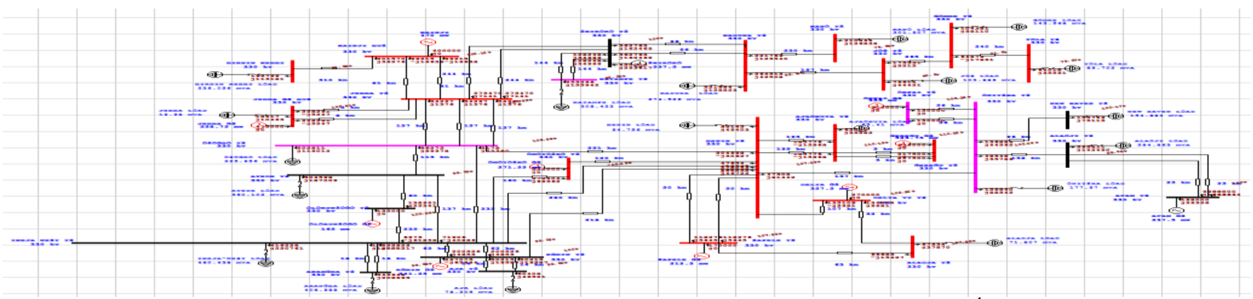

Fig. 6 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (6th Load Increase at 0.12p.u)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 5, May 2021||

DOI:10.15662/IJAREEIE.2021.1005002

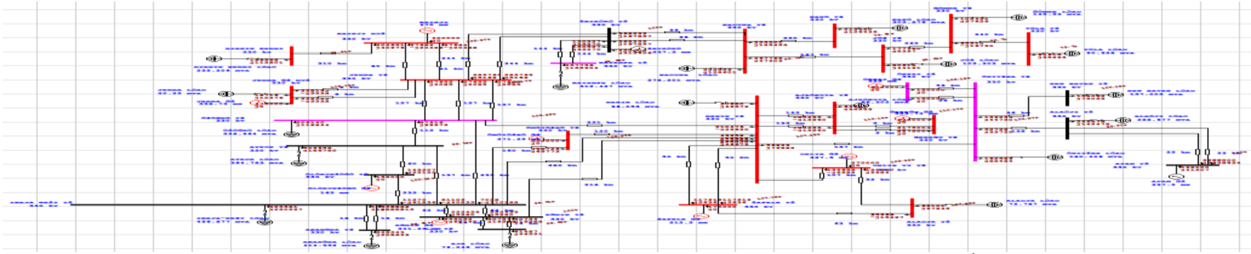

Fig. 7 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software(7th Load Increase at 0.14p.u)

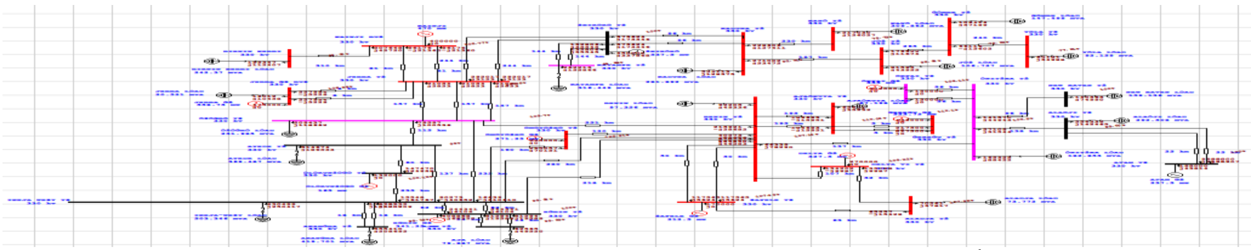

Fig. 8 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (8th Load Increase at 0.16p.u)

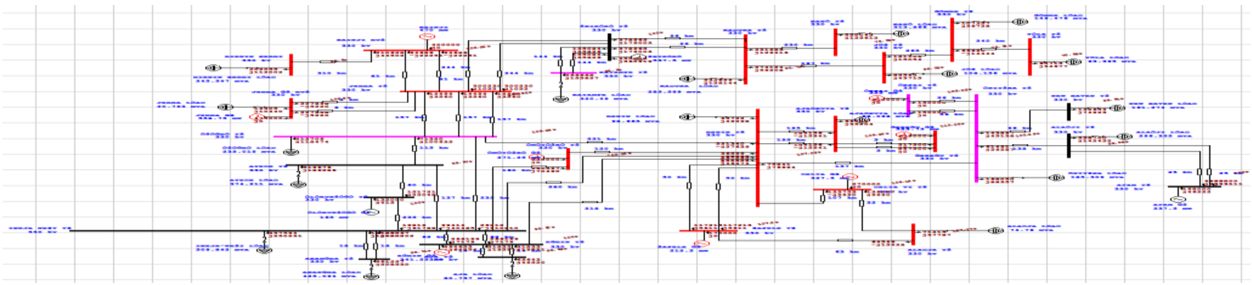

Fig. 9 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software (9th Load Increase at 0.18p.u)

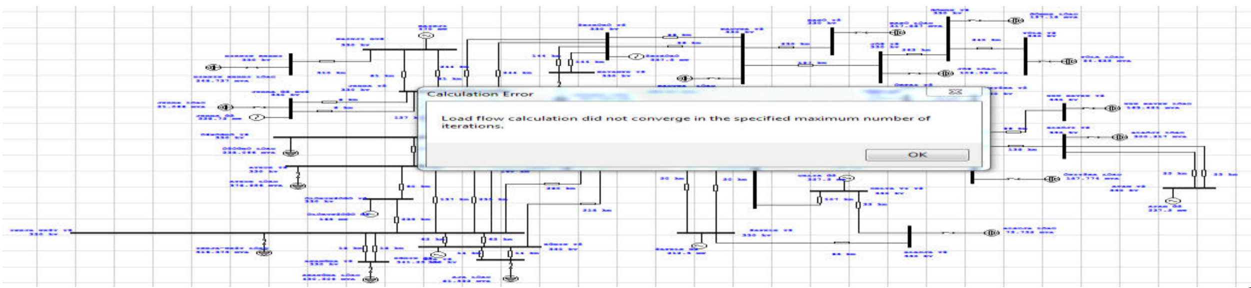

Fig. 10 Nigerian 30 Bus 330kV Transmission Network Modelled in ETAP 12.6 Software at Bifurcation Point (10th Load Increase at 0.20p.u)

Considering Static Var Compensator modelling equation

$$B_{SVC}^{Min} = \frac{B_\sigma(B_{C1} + B_{C2} + \cdots + B_{Cn} + B_L)}{B_\sigma + B_{C1} + B_{C2} + \cdots + B_{Cn} + B_L}$$

Where in this case

$B_{SVC}^{Min} = \frac{B_\sigma(B_C + B_L)}{B_\sigma + B_C + B_L}$ for every violated bus

Such that

$$B_{SVC}^{Min} = \frac{1.428X10^{-7}(1X10^{-7} + 1X10^{-7})}{1.428X10^{-7} + 1X10^{-7} + 1X10^{-7}}$$

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DOI:10.15662/IJAREEIE.2021.1005002

$B_{SVC}^{Min} = \frac{2.856X10^{-14}}{3.428X10^{-7}}$
$B_{SVC}^{Min} = 8.33X10^{-8}$Siemens
Since the reactive power that can be exchanged to the system estimated to be 991.5MVAr is:
$Q_{SVC}^{Max} = -V_{Max}^2 B_{SVC}^{Min}$ for shunt compensation
$Q_{SVC}^{Max} = (-346.5X10^3)^2 \, X \, 8.33X10^{-8}$
$Q_{SVC}^{Max} = 10001.18543Var$
$Q_{SVC}^{Max} = 0.01Mvar$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.20p.u, then, for 10th load increase with SVC
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.20\,X\,182)$, $P_{Di} = 218.40MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.20\,X\,15.5)$, $P_{Di} = 18.60MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.20\,X\,174)$, $P_{Di} = 208.80MW$
Ayede Bus has $P_{Di} = 274 + 1(0.20\,X\,274)$, $P_{Di} = 328.80MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.20\,X\,375.08)$, $P_{Di} = 450.10MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.20\,X\,312)$, $P_{Di} = 374.40MW$
Aja Bus has $P_{Di} = 80 + 1(0.20\,X\,80)$, $P_{Di} = 96.00MW$
Benin Bus has $P_{Di} = 74 + 1(0.20\,X\,74)$, $P_{Di} = 88.80MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.20\,X\,51)$, $P_{Di} = 61.20MW$
Aladja Bus has $P_{Di} = 56 + 1(0.20\,X\,56)$, $P_{Di} = 67.20MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.20\,X\,139)$, $P_{Di} = 166.80MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.20\,X\,121)$, $P_{Di} = 145.20MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.20\,X\,220)$, $P_{Di} = 264.00MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.20\,X\,234.50)$, $P_{Di} = 281.40MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.20\,X\,212)$, $P_{Di} = 254.40MW$
Kano Bus has $P_{Di} = 231 + 1(0.20\,X\,231)$, $P_{Di} = 277.20MW$
Jos Bus has $P_{Di} = 81 + 1(0.20\,X\,81)$, $P_{Di} = 97.20MW$
Gombe Bus has $P_{Di} = 112 + 1(0.20\,X\,112)$, $P_{Di} = 134.40MW$
Yola Bus has $P_{Di} = 70 + 1(0.20\,X\,70)$, $P_{Di} = 84.00MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.22p.u, then, for 11th load increase with SVC
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.22\,X\,182)$, $P_{Di} = 222.04MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.22\,X\,15.5)$, $P_{Di} = 18.91MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.22\,X\,174)$, $P_{Di} = 212.28MW$
Ayede Bus has $P_{Di} = 274 + 1(0.22\,X\,274)$, $P_{Di} = 334.28MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.22\,X\,375.08)$, $P_{Di} = 457.60MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.22\,X\,312)$, $P_{Di} = 380.64MW$
Aja Bus has $P_{Di} = 80 + 1(0.22\,X\,80)$, $P_{Di} = 97.60MW$
Benin Bus has $P_{Di} = 74 + 1(0.22\,X\,74)$, $P_{Di} = 90.28MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.22\,X\,51)$, $P_{Di} = 62.22MW$
Aladja Bus has $P_{Di} = 56 + 1(0.22\,X\,56)$, $P_{Di} = 68.32MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.22\,X\,139)$, $P_{Di} = 169.58MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.22\,X\,121)$, $P_{Di} = 147.62MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.22\,X\,220)$, $P_{Di} = 268.40MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.22\,X\,234.50)$, $P_{Di} = 286.09MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.22\,X\,212)$, $P_{Di} = 258.64MW$
Kano Bus has $P_{Di} = 231 + 1(0.22\,X\,231)$, $P_{Di} = 281.82MW$
Jos Bus has $P_{Di} = 81 + 1(0.22\,X\,81)$, $P_{Di} = 98.82MW$
Gombe Bus has $P_{Di} = 112 + 1(0.22\,X\,112)$, $P_{Di} = 136.64MW$
Yola Bus has $P_{Di} = 70 + 1(0.22\,X\,70)$, $P_{Di} = 85.40MW$

From $P_{Di} = P_{Dio} + \lambda(P_{\Delta base})$ with a loading factor of 0.24p.u, then, for 12th load increase with SVC
Birnin Kebbi Bus has $P_{Di} = 182 + 1(0.24\,X\,182)$, $P_{Di} = 225.68MW$
Jebba Bus has $P_{Di} = 15.5 + 1(0.24\,X\,15.5)$, $P_{Di} = 19.22MW$
Osogbo Bus has $P_{Di} = 174 + 1(0.24\,X\,174)$, $P_{Di} = 215.76MW$

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

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DOI:10.15662/IJAREEIE.2021.1005002

Ayede Bus has $P_{Di} = 274 + 1(0.24\,X\ 274), P_{Di} = 339.76MW$
Ikeja-West has $P_{Di} = 375.08 + 1(0.24\,X\,375.08), P_{Di} = 465.10MW$
Akamgba Bus has $P_{Di} = 312 + 1(0.24\,X\,312), P_{Di} = 386.88MW$
Aja Bus has $P_{Di} = 80 + 1(0.24\,X\ 80), P_{Di} = 99.20MW$
Benin Bus has $P_{Di} = 74 + 1(0.24\,X\ 74), P_{Di} = 91.76MW$
Ajaokuta Bus has $P_{Di} = 51 + 1(0.24\,X\ 51), P_{Di} = 63.24MW$
Aladja Bus has $P_{Di} = 56 + 1(0.24\,X\ 56), P_{Di} = 69.44MW$
Onitsha Bus has $P_{Di} = 139 + 1(0.24\,X\,139), P_{Di} = 172.36MW$
New-Haven Bus has $P_{Di} = 121 + 1(0.24\,X\ 121), P_{Di} = 150.04MW$
Alaoji Bus has $P_{Di} = 220 + 1(0.24\,X\,220), P_{Di} = 272.80MW$
Katampe Bus has $P_{Di} = 234.50 + 1(0.24\,X\,234.50), P_{Di} = 290.78MW$
Kaduna Bus has $P_{Di} = 212 + 1(0.24\,X\ 212), P_{Di} = 262.88MW$
Kano Bus has $P_{Di} = 231 + 1(0.24\,X\,231), P_{Di} = 286.44MW$
Jos Bus has $P_{Di} = 81 + 1(0.24\,X\ 81), P_{Di} = 100.44MW$
Gombe Bus has $P_{Di} = 112 + 1(0.24\,X\,112), P_{Di} = 138.88MW$
Yola Bus has $P_{Di} = 70 + 1(0.24\,X\,70), P_{Di} = 86.80MW$

The modelled Static Var Compensators were located at every voltage violated bus in ETAP 12.6 software environment to enhance the loading margin of the Nigerian 330kV transmission network as shown.

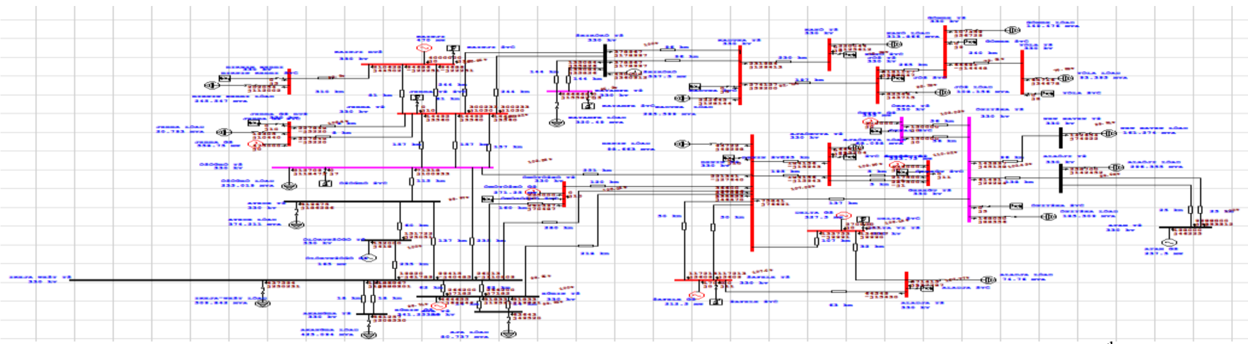

Fig. 11 Nigerian 30 Bus 330kV Transmission Network Modelled with SVC in ETAP 12.6 Software (9th Load Increase at 0.18p.u, Start-Up Load)

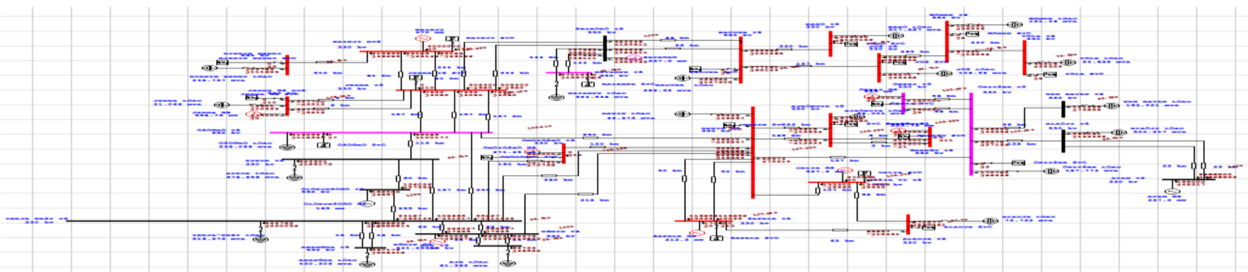

Fig. 12 Nigerian 30 Bus 330kV Transmission Network Modelled with SVC in ETAP 12.6 Software (10th Load Increase at 0.20p.u)

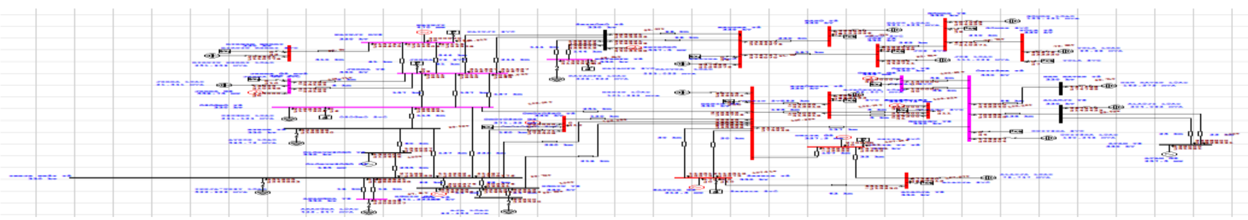

Fig. 13 Nigerian 30 Bus 330kV Transmission Network Modelled with SVC in ETAP 12.6Software (11th Load Increase at 0.22p.u)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

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DOI:10.15662/IJAREEIE.2021.1005002

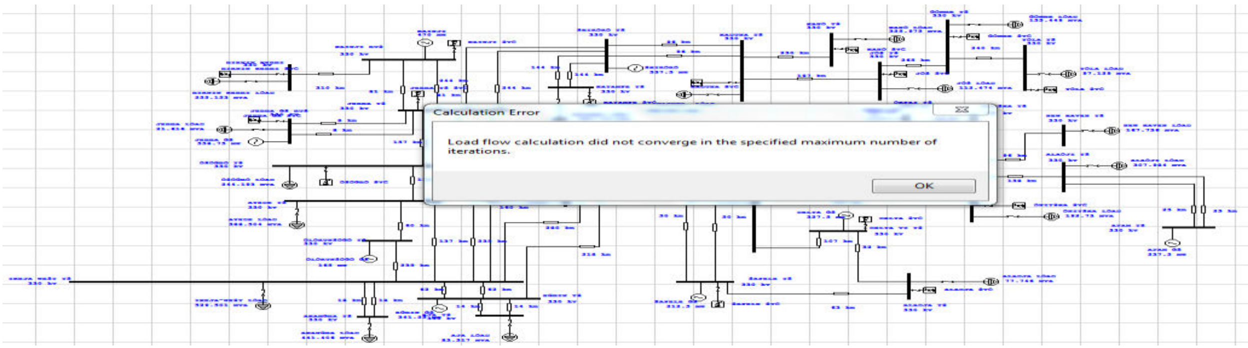

Fig. 14 Nigerian 30 Bus 330kV Transmission Network Modelled with SVC in ETAP 12.6 Software at bifurcation Point (12th Load Increase at 0.24p.u)

IV. RESULTS AND DISCUSSION

The results obtained from the continuation power flow without SVC and continuation power flow with SVC are shown in tables 1to 4 and figs.15to 18 respectively.

Table 1 Summary of Load Demand Using CPF without SVC

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

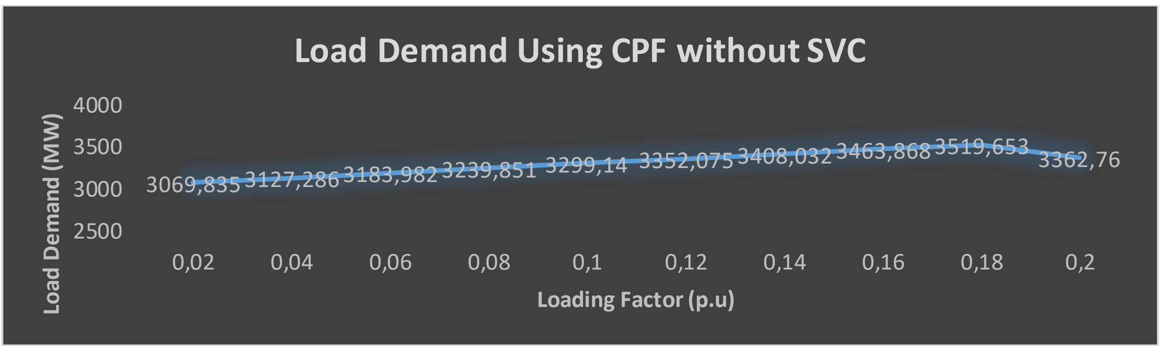

Fig. 15 Graph Showing Load Demand Using CPF without SVC

Table 2 Summary of Load Demand Using CPF with SVC

Loading Factor (P.U)	Total Load Demand (MW)
0.18	3519.655
0.20	3576.049
0.22	3619.965
0.24	3544.464

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DOI:10.15662/IJAREEIE.2021.1005002

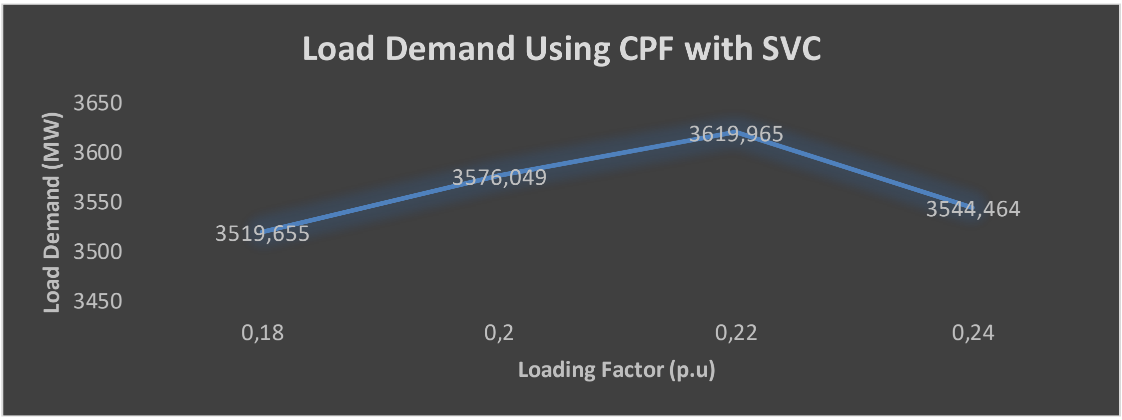

Fig. 16 Graph Showing Load Demand Using CPF with SVC

Table 3 Comparing Load Demand, CPF without SVC and CPF with SVC

Loading Factor (P.U)	Load in MW for CPF without SVC	Load in MW for CPF with SVC
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	3519.655
0.20	3362.760	3576.049
0.22	-	3619.965
0.24	-	3544.464

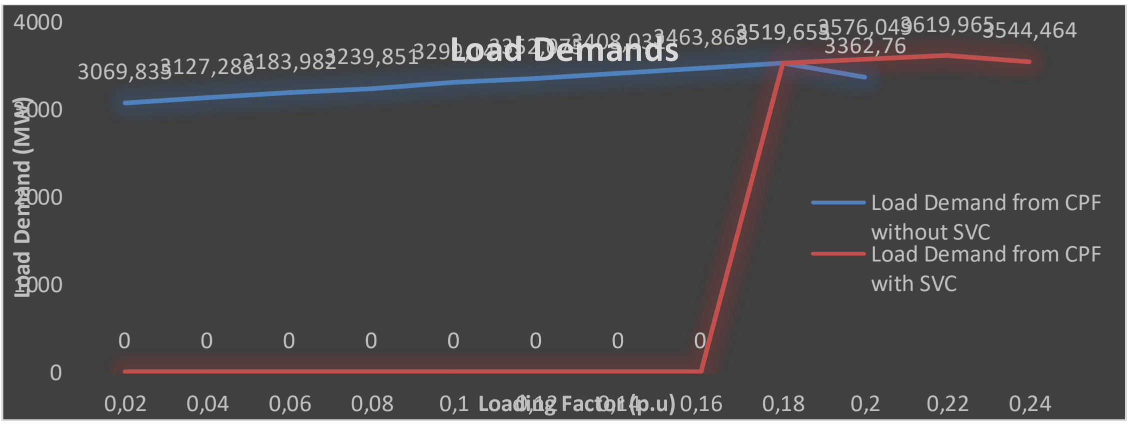

Fig. 17 Graph Comparing Load Demand, CPF without SVC and CPF with SVC

Table 4 Allowable Load Increment Before Voltage Collapse (Loading Margin)

Loading Condition	Without SVC	With SVC
Loading Factor (P.U)	0.18	0.22
Total Load Demand (MW)	3519.653	3619.965
Loading Margins (MW)	55.785	100.312
Actual Loading Margin (MW)	156.097	

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

||Volume 10, Issue 5, May 2021||

DOI:10.15662/IJAREEIE.2021.1005002

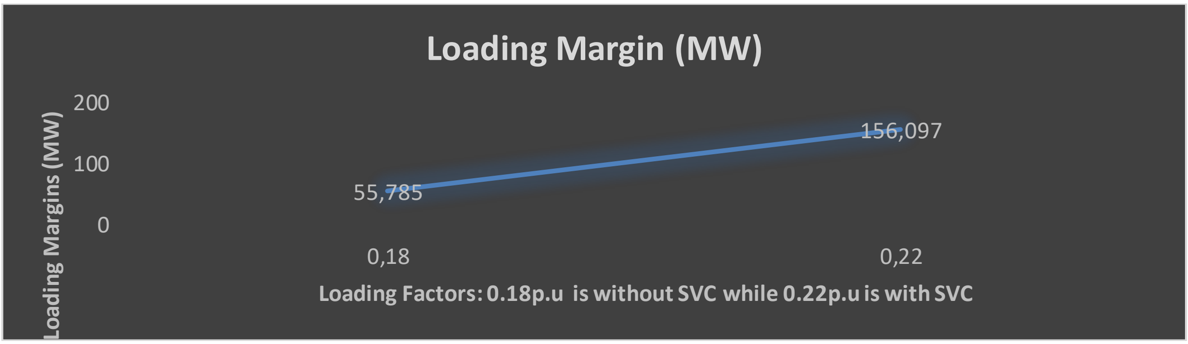

Fig. 18 Graph Showing Loading Margin

V. CONCLUSION

Continuation Power Flow method was used to run load flow analysis in ETAP 12.6 software environment on a generation load of 4000MW and it was noted that 3519.653MW was the highest load sustained at a loading factor of 0.18p.u. The analysis showed that at a loading factor of 0.20p.u the continuation power flow failed to run.

Still at 0.18 p.u loading factor, a new case of load flow analysis was conducted using Continuation Power Flow method with Static Var Compensators modelled using shunt compensation method and placed on voltage violated buses to enhance the loading margin of Nigerian 330kV transmission network. The continuation power flow analysis showed that from a generation of 4000MW, 3619.965MW was the highest load sustained at a loading factor of 0.22p.u. It further showed that at a loading factor of 0.24p.u the continuation power flow failed to run.

Comparatively, the continuation power flow without SVC allowed a maximum load of 3519.653MW with 55.785MW loading margin while continuation power flow with SVC allowed a maximum load of 3619.965MW in the system with 156.097MW loading margin. Generally, additional 100.312MW was made possible in the system using Static Var Compensator.

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| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 7.122|

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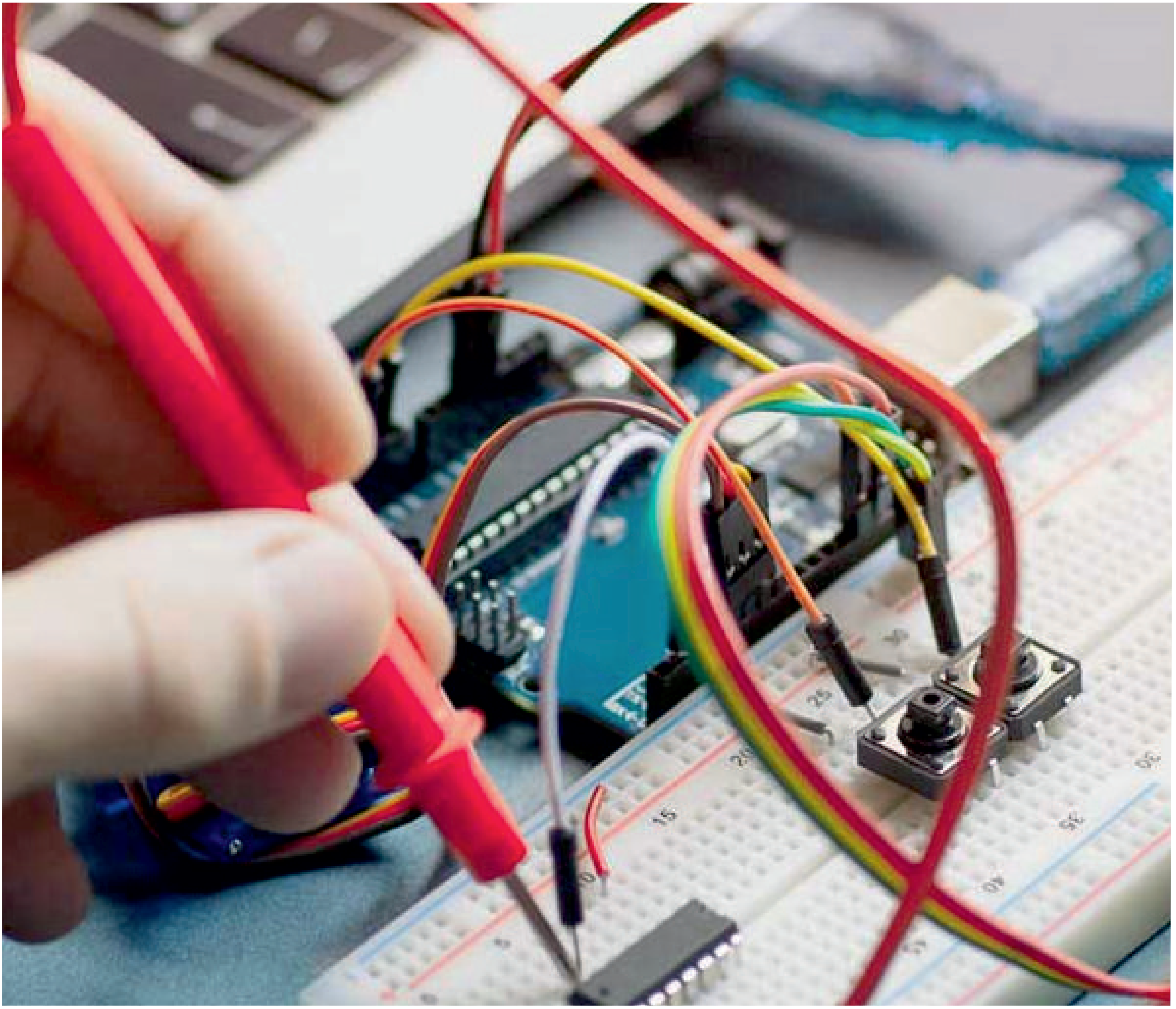

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