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Investigation of the Transfer Capability of the Nigerian 330 kV, 58-bus Power System Network using FACTS Devices

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Abstract: Over the years, the Nigerian power system is beset with lingering problems, which include severe power losses, as well as very low transfer capability of the transmission network to evacuate power from generating stations to the load at the distribution level. Presently, the Nigerian power industry is undergoing restructuring, especially in the generation and distribution systems. In view of the deregulation of electricity distribution and marketing, the traditional practices of the Nigerian power system are undergoing changes to address the identified problems in the existing power system. Specifically, better utilization of the existing power transmission network to improve on the system transfer capability and minimize cost is one of the key focuses of the deregulation agenda. This work deals with the enhancement of transfer capability of Nigerian 58-bus, 330kV network using FACTS (Flexible Alternating Current Transmission System) devices. FACTS devices are used for controlling transmission voltage, power flow, reducing reactive power losses, and damping of power system oscillations for high power transfer capability. Three FACTS devices; Thyristor Controlled Series Compensator (TCSC), Unified Power Flow Controller (UPFC), and Interline Power Flow Controller (IPFC) were used to investigate the transfer capability of the Nigerian 58-bus power system network. NEPLAN was employed in this work to model the Nigerian 58-bus system and optimally placed the FACTS devices at the weakest buses that were found out through the computation for available transfer capability (ATC) after continuation power flow (CPF) simulation was completed. MATLAB codes were developed and used to calculate power transfer capability of the network without and with FACTS devices. Comparing the three FACTS devices, the results obtained showed that UPFC enhanced the power transfer capability of the network than TCSC and IPFC.

Keywords: ATC, FACTS, IPFC, NEPLAN, TCSC, UPFC.

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1. INTRODUCTION

Power transfer capability of transmission system is the maximum power that can be transferred from one area to another over all transmission paths between those areas under given system conditions [1], [2]. It can be specified as either Available Transfer Capability (ATC) or Total Transfer Capability (TTC).

Essentially, ATC is a measure of the extra transmission capability above the base case power transfer for the purpose of power marketing [3], [4]. ATC value can be derived by considering various parameters relating to transfer capabilities such as total transfer capability (TTC), transmission reliability margin (TRM), and capacity benefit margin (CBM).

$$ATC = TTC - TRM - (CBM + ETC) \tag{1.1}$$

where
TTC is the summation of all the network transfers (base case and commercial transfers) including the margins for system security and reliability, and existing transmission commitments (ETC). TRM is the network margin reserved for system uncertainties, and CBM is the network margin reserved for the utilities to have access to external generation in case of emergency generation outages [2], [5], [6], [7] and [8].

Nowadays, advanced technologies paramount for the reliable and secure operations of power systems [9], based on power electronics equipment called FACTS (Flexible Alternating Current Transmission Systems), provide proven technical solutions to address the operating challenges of power system transfer capability being presented today. FACTS technologies allow for improved transmission system operation compared to the construction of new transmission lines. In [10] and [11], a solution of dynamic available transfer capability by means of stability constrained optimal power flow was computed. Also in [12], commutated voltage collapse proximity index was employed to optimally placed Thyristor Controlled Series Compensator (TCSC) and Static Synchronous

Compensator (STATCOM), modelled in the IEEE 14 bus system using Power System Analysis Toolbox (PSAT) in MATLAB for improvement in the voltage stability of the system. [13] and [14] determined the transmission reliability margin by considering uncertainties of system operating condition and transmission line outage. In [6], optimal placement of TCSC in Nigerian 330kV transmission grid to minimize real power losses using Genetic Algorithm on 35-bus system were considered. [15] investigated the effect of Contingency on available transfer capability of Nigerian 330-kV network by considering hybridized continuous-repeated power flow, (N-1) outage contingency on Nigerian 29-bus system. [16] investigated the transient stability of the multi-machine power system network through the use of SVC and STATCOM installed in the Nigerian 48-bus system using PSAT software. The synchronous generator rotor angle and speed responses without FACTS devices were compared with the system with SVC and STATCOM in the event of a three phase fault. The capability of the FACTS devices to reduce the rotor angle and speed by damping post fault oscillations showed their compensating effectiveness in restoring the system to marginal stability. Eigenvalue method of stability analysis was also employed to show the superiority of SVC over STATCOM in the enhancement of the transient stability of the multi-machine power system.. However, the author did not use NEPLAN software to validate the work. In this paper, NEPLAN software is used to model a larger Nigerian power system of 58 buses [17], comprising 22 PV generators and 36 loads buses for load flow studies with 87 transmission lines which reflect the true nature of the ever expanding power system in Nigeria. Simulation studies were carried out with the application of TCSC, UPFC and IPFC to investigate the transfer capability of the system for improved system performance.

2. NIGERIAN 330 KV, 58-BUS NETWORK

Nigerian extra-high voltage network is at 330 kV level, referred to as national grid. In NEPLAN environment, the Nigerian grid is a network of 58 buses, 87 transmission lines, 22 generators and 36 loads respectively as shown in Figure 2.1.

3. BASIC DESCRIPTION OF FACTS CONTROLLERS

3.1 TCSC

TCSC controllers use thyristor-controlled reactor (TCR) in parallel with capacitor segments of series capacitor bank. TCSC, the first generation of FACTS, can control the line impedance through the introduction of a thyristor controlled capacitor in series with the transmission line. Figure 3.1 show principle and operation of TCSC [18] and [19].

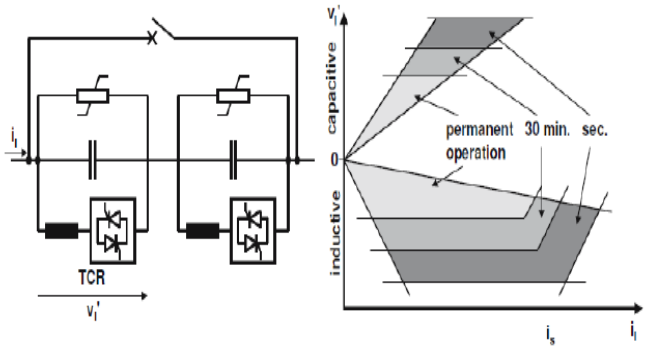

Figure 3.1. Principle and operational of (TCSC) [18], [19]

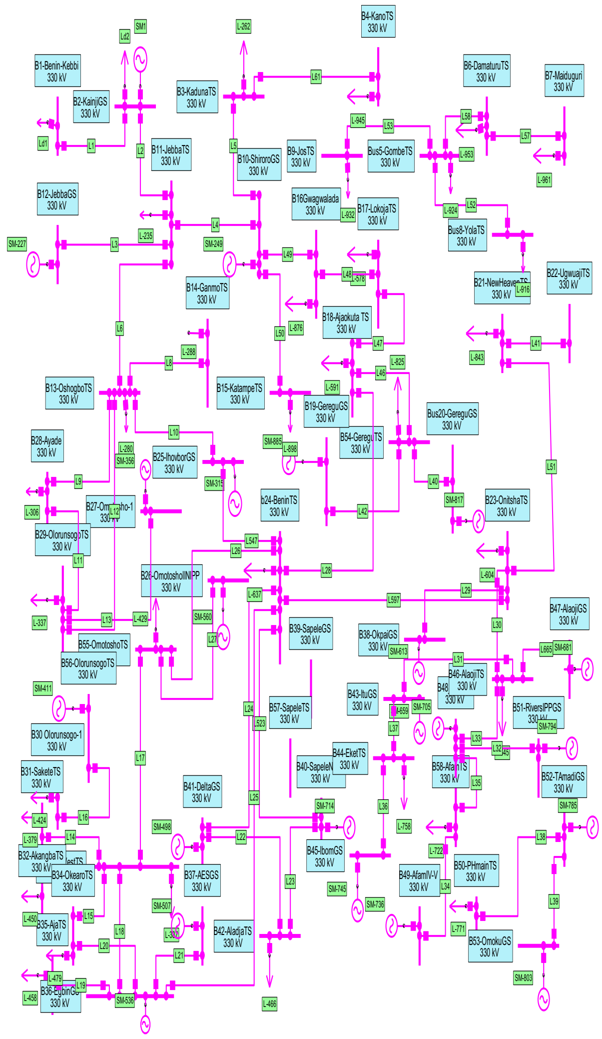

Figure 2.1. Model of Nigerian 330kV, 58 bus grid network.

3.2 UPFC

The UPFC is a combination of a static synchronous compensator and static synchronous series compensation. It acts as a shunt compensator and a phase shifting device simultaneously. The closing of switches 1 and 2 as shown in Figure 3.2 enable the two converters to exchange real power flow between the two converters. The reactive power can be either absorbed or supplied by the series connected converter [20] and [21].

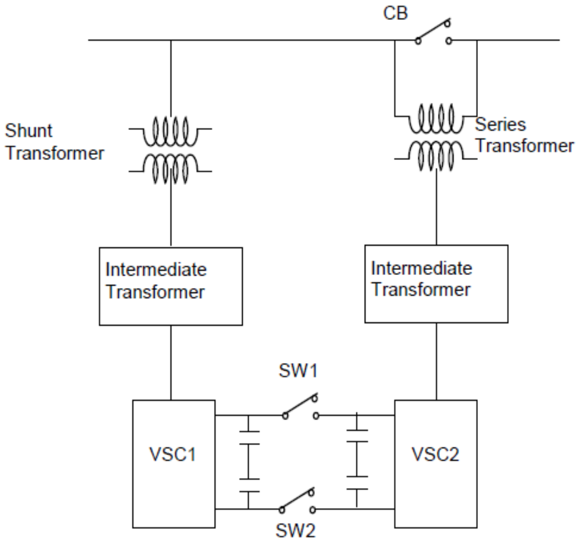

Figure 3.2. UPFC schematic and principle [20]

3.3 IPFC

This is a recent concept for the compensation and effective power flow management of multiline transmission systems. In its general form, the IPFC employs several inverters with a common DC link as shown in Figure 3.3, each to provide series compensation for a selected line of the transmission system [20].

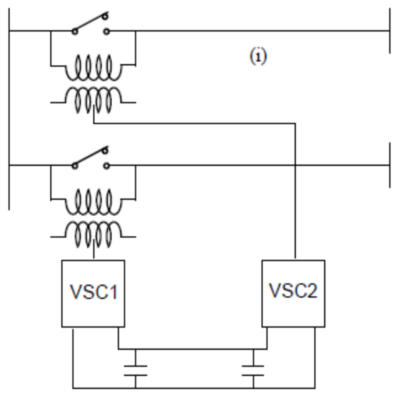

Figure 3.3. Structure of a two converter IPFC [20]

4. ATC PROBLEM FORMULATION

ATC in this paper is obtained in terms of the transmission line power flows and the key performance indicators (KPIs) which includes existing transmission commitment (ETC), capacity benefit margin (CBM), transmission reliability margin (TRM) and total transfer capability (TTC).

4.1 ATC Formulation without FACTS Devices

To calculate ATC using continuation power flow method, a loading parameter must be inserted into the power flow equations to parameterize the load-flow equation. A uniform power factor model is expressed as follows:

$$P_{Gi} - P_{Di} - Q_{Di} = 0 \tag{4.1}$$

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j| \left(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}\right) = 0 \tag{4.2}$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j| \left(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}\right) = 0 \tag{4.3}$$

$$|U_i|_{min} \le |U_i| \le |U_i|_{max} \tag{4.4}$$

$$|S_{ij}| \le |S_{ij}|_{max} \tag{4.5}$$

$$|\delta_{Gi}(t) - \delta_{Gi}(t)| \le \delta_{Gmax} \tag{4.6}$$

where:
P_D: the total real power load on all load buses
$P_{tie-lines}$: the summation of real power flow on tie lines
P_{Gi}, Q_{Gi}: the real and reactive power generation at bus i
P_{Di}, Q_{Di}: the real and reactive power at bus i
n : number of system buses
$|U_i|$: Voltage magnitude at bus i
G_{ij}, B_{ij}: real and imaginary part of the ij^{th} element of bus admittance matrix
δ_{ij} : voltage angle difference between bus i and bus j
S_{ij} : apparent power flow in line ij
$|U_i|_{min}$: lower limit of voltage magnitude at bus i
$|U_i|_{max}$: upper limit of voltage magnitude at bus i
$|S_{ij}|_{max}$: thermal limit of line ij
$\delta_{Gi}(t)$: rotor angle of generator i
δ_{Gmax} : maximum secure relative swing angle
In the process of calculation, P_{Gi}, P_{Di} and Q_{Di} are changed in following ways

$$P_{Gi} = P_{Gi}^{0}(1 + \lambda k_{Gi}) \tag{4.7}$$

$$P_{Di} = P_{Di}^{0}(1 + \lambda k_{Di}) \tag{4.8}$$

$$Q_{Di} = Q_{Di}^{0}(1 + \lambda k_{Di}) \tag{4.9}$$

where
P_{Gi}: base case power transfer at bus i
P_{Di}^0, Q_{Di}^0: base case real and reactive load at bus i
λ : increment factor in bus load and generation
k_{Gi}, k_{Di}: constants specifying the rate of change in generation and load.

According to Equations (4.7)-(4.9), we can increase the apparent load with constant power factor at each bus in the sink area and increase injected real power at each generator bus in the source area in successive steps until one or more limits are reached.

At the maximum loading parameter (λ_{max}), the ATC is calculated using Equation (4.10)

$$ATC = \sum_{i \in Sink} P_L^i(\lambda_{max}) - \sum_{i \in Sink} P_L^{io} \tag{4.10}$$

$$TTC = ATC + TRM + CBM + ETC \tag{4.11}$$

4.2 ATC Formulation with FACTS Devices

The general procedure to calculate ATC with FACTS devices is depicted in Figure 4.1.

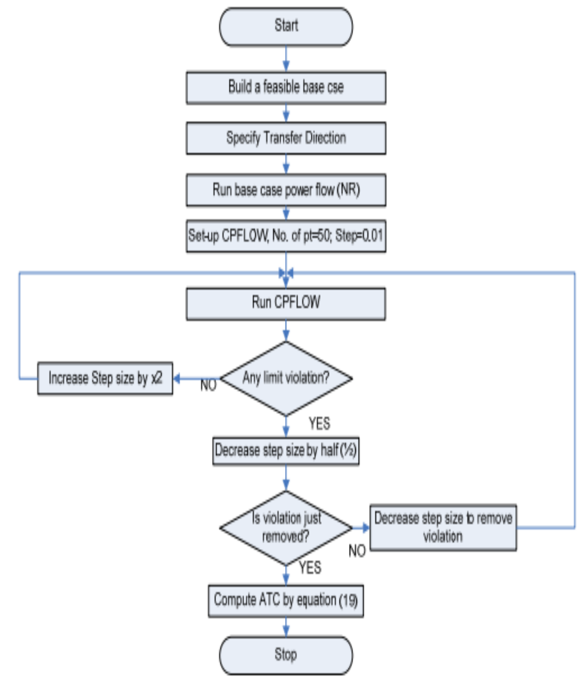

Figure 4.1. Flow chart of the ATC computation procedure

When FACTS is installed in a transmission network, the reactance of the FACTS can be adjusted. Normally the adjustment range is 0.5X to 1.5X, where X is the reactance of the original line. The formulation of ATC can be expressed as below:

$$P_{Gi} - P_{Di} - Q_{Di} = 0 \quad (4.12)$$

Subject to:

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} |U_i||U_j| \left(G_{ij-FACTS} \cos \delta_{ij} + B_{ij-FACTS} \sin \delta_{ij}\right) = 0 \quad (4.13)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} |U_i||U_j| \left(G_{ij-FACTS} \sin \delta_{ij} - B_{ij-FACT} \cos \delta_{ij}\right) = 0 \quad (4.14)$$

$$|U_i|_{min} \le |U_i| \le |U_i|_{max} \quad (4.15)$$

$$|S_{ij}| \le |S_{ij}|_{max} \quad (4.16)$$

$$0.5X \le X_{FACTS} \le 1.5X \quad (4.17)$$

$$|\delta_{Gi}(t) - \delta_{Gi}(t)| \le \delta_{Gmax} \quad (4.18)$$

where:

$G_{ij-FACTS}$, $B_{ij-FACT}$: real and imaginary part of the ijth element of bus admittance matrix when FACTS is installed.

X_{FACTS} : reactance of the FACTS

X : original reactance of the line where FACTS is installed

$$ATC = \sum_{i \in Sink} P_L^i(\lambda_{max}) - \sum_{i \in Sink} P_L^{io} \quad (4.19)$$

5. SIMULATION, RESULTS AND DISCUSSION

The performances of TCSC, UPFC, and IPFC are here presented by the outcome of the magnitude of the real and reactive power flow through the transmission lines. Newton Raphson power flow simulations were carried out on the Nigerian 58-Bus systems first without FACTS and thereafter with TCSC, UPFC, and IPFC.

Table 5.1 shows the location of 58-bus stations. The result of power flow simulation of the network model without and with FACT devices are here presented in tables and bar charts. Table 5.2 shows the result of the power flow of the test system without FACTS devices. As seen from the Table, ten weakest lines (20, 33, 40, 42, 43, 45, 58, 64, 72, 82) are highlighted where the FACTS devices will be installed.

Table 5.1. Station locations

Bus No	Location
1	Benin Kebbi TS
2	Kainji GS
3	Kaduna TS
4	Kano TS
5	Gombe TS
6	Damaturu TS
7	Maiduguri TS
8	Yola TS
9	Jos TS
10	Shiroro GS
11	Jebba TS
12	Jebba GS
13	Oshogbo TS
14	Ganmo TS
15	Katampe TS
16	Gwagwalada TS
17	Lokoja TS
18	Ajaokuta TS
19	Geregu GS
20	Geregu NIPP
21	New Heaven TS
22	Ugwuaji TS
23	Onitsha TS
24	Benin TS
25	Ihovbor NIPP
26	Omotosho II
27	Omotosho I
28	Ayede TS
29	Olorunsogo NIPP
30	Olorunsogo 1
31	Sakete TS
32	Akamgba TS
33	Ikeja west TS
34	Okearo TS
35	Aja TS
36	Egbin GS
37	AES GS
38	Okpai GS
39	Sapele GS
40	Sapele NIPP
41	Delta GS
42	Aladja TS
43	Itu TS
44	Eket TS
45	Ibom GS
46	Alaoji TS
47	Alaoji GS
48	Afam VI
49	Afam IV-V
50	PH main TS
51	Rivers IPP
52	Trans Amadi GS
53	Omoku GS
54	Geregu TS
55	Omotosho TS
56	Olorunshogo TS
57	Sapele TS
58	Afam TS

Table 5.2. Result of power flow without FACTS

Line	From Bus	To Bus	P (MW)	P loss (MW)	Q (MVA)	Q loss (MVA)
1	Bus1	Bus2	323.07	0.0294	206.28	0.6807
2	Bus3	Bus4	326.73	0.0602	266.2	0.4847
3	Bus11	Bus10	311.5	0.0497	193.95	0.7772
4	Bus11	Bus10	220.83	0.0608	236.32	0.419
5	Bus3	Bus10	242.04	0.0733	232.63	0.3816
6	Bus10	Bus16	251.6	0.0764	219.15	0.631
7	Bus3	Bus9	296.36	0.0159	236	0.1866
8	Bus9	Bus5	225.75	0.0118	232.65	0.396
9	Bus16	Bus17	301.76	0.055	180.88	0.7082
10	Bus11	Bus14	221.88	0.0083	175.57	0.4554
11	Bus13	Bus14	292.99	0.0417	267.9	0.665
12	Bus11	Bus13	272.24	0.0421	180.14	0.5824
13	Bus5	Bus8	309.28	0.0677	165.46	0.4641
14	Bus11	Bus13	300.95	0.0386	221.49	0.2012
15	Bus16	Bus15	325.48	0.0315	255.48	0.5265
16	Bus10	Bus15	323.82	0.053	232.93	0.0747
17	Bus18	Bus17	251.44	0.0584	182.19	0.4951
18	Bus50	Bus53	298.84	0.0413	201.11	0.5222
19	Bus58	Bus51	233.72	0.0279	210.84	0.5756
20	**Bus19**	**Bus54**	**211.97**	**0.0126**	**266.05**	**0.7003**
21	Bus54	Bus20	304.73	0.0464	178.58	0.7713
22	Bus18	Bus54	273	0.0213	252.69	0.606
23	Bus21	Bus23	270.39	0.0044	230.35	0.4606
24	Bus5	Bus6	325.61	0.0595	201.88	0.7294
25	Bus21	Bus22	287.28	0.0198	182.24	0.4596
26	Bus21	Bus22	288.3	0.0353	207.39	0.0232
27	Bus18	Bus24	319.73	0.0543	213.09	0.1037
28	Bus18	Bus24	312.71	0.0288	174.78	0.6786
29	Bus25	Bus24	282.97	0.0581	224.49	0.3853
30	Bus13	Bus25	231.78	0.0316	185.98	0.6648
31	Bus55	Bus26	239.19	0.054	202.77	0.1723
32	Bus27	Bus55	323.25	0.0556	223.8	0.438
33	**Bus55**	**Bus24**	**211.73**	**0.0353**	**188.69**	**0.4982**
34	Bus28	Bus13	271.69	0.0025	192.79	0.0348
35	Bus6	Bus7	229.83	0.0266	227.41	0.4864
36	Bus29	Bus56	335.23	0.0339	190.12	0.2909
37	Bus56	Bus30	300.65	0.0219	249.38	0.0484
38	Bus28	Bus56	273.06	0.0163	266.16	0.3894
39	Bus31	Bus33	269.24	0.0647	239.41	0.1592
40	**Bus56**	**Bus33**	**215.75**	**0.0343**	**198.45**	**0.1054**
41	Bus13	Bus33	296.66	0.0698	223.91	0.1693
42	**Bus55**	**Bus33**	**213.52**	**0.0313**	**173.42**	**0.1235**
43	**Bus32**	**Bus33**	**217.29**	**0.0606**	**258.07**	**0.1565**
44	Bus32	Bus33	275.81	0.0318	255.24	0.0431
45	**Bus34**	**Bus33**	**220.57**	**0.0637**	**248.68**	**0.5023**
46	Bus2	Bus11	314.36	0.0595	189.64	0.2284
47	Bus34	Bus33	314.28	0.0302	225	0.4274
48	Bus35	Bus36	301.92	0.0177	164.39	0.5488
49	Bus35	Bus36	227.48	0.0623	207.08	0.3968
50	Bus34	Bus36	293.75	0.0746	195.15	0.4252
51	Bus34	Bus36	275.42	0.0264	179.12	0.355
52	Bus33	Bus36	334.49	0.053	180.95	0.106
53	Bus24	Bus36	292.37	0.035	206.83	0.39
54	Bus36	Bus37	312.04	0.0656	171.99	0.6711
55	Bus36	Bus37	266.99	0.0606	225.44	0.6873
56	Bus24	Bus23	264.21	0.014	211.92	0.2195
57	Bus12	Bus11	315.29	0.0678	235.77	0.1716
58	**Bus24**	**Bus23**	**218.85**	**0.0777**	**236.19**	**0.4479**
59	Bus38	Bus23	225.31	0.0409	229.68	0.5062
60	Bus38	Bus23	230.54	0.0695	165.56	0.3332
61	Bus24	Bus57	258.82	0.0466	169.29	0.1696
62	Bus24	Bus57	316.08	0.013	195.88	0.7446
63	Bus24	Bus57	312.44	0.0165	218.27	0.0736
64	**Bus39**	**Bus57**	**215.86**	**0.0325**	**231.37**	**0.0919**
65	Bus57	Bus40	259.9	0.059	205.21	0.1201
66	Bus24	Bus41	276.49	0.065	248.92	0.139
67	Bus41	Bus42	262.18	0.0622	238.15	0.4912
68	Bus12	Bus11	293.39	0.0257	264.68	0.4546
69	Bus57	Bus42	289.64	0.0424	218.32	0.0504
70	Bus43	Bus44	245.96	0.008	196.47	0.7317
71	Bus44	Bus45	264.11	0.0097	173.2	0.5747
72	**Bus44**	**Bus45**	**210.01**	**0.0116**	**226.76**	**0.5818**
73	Bus43	Bus46	335.93	0.0536	244.55	0.0591
74	Bus23	Bus46	229.73	0.0394	206.89	0.6768
75	Bus46	Bus47	221.81	0.0157	171.63	0.7342
76	Bus46	Bus47	256.41	0.0394	190.25	0.7729
77	Bus48	Bus58	233.76	0.0124	178.29	0.6757
78	Bus58	Bus49	271.66	0.0053	191.79	0.6188
79	Bus2	Bus11	252.13	0.0669	208.65	0.4079
80	Bus46	Bus58	331.71	0.0444	217.88	0.1476
81	Bus46	Bus58	327.64	0.073	210.49	0.3189
82	**Bus58**	**Bus50**	**214.85**	**0.055**	**254.79**	**0.1138**
83	Bus51	Bus50	303.92	0.0462	216.91	0.0339
84	Bus52	Bus50	242.99	0.0642	262.02	0.7378
85	Bus52	Bus50	262.97	0.0691	229.6	0.2435
86	Bus52	Bus53	279.22	0.0776	263.52	0.239
87	Bus3	Bus10	330.56	0.001	187.51	0.268

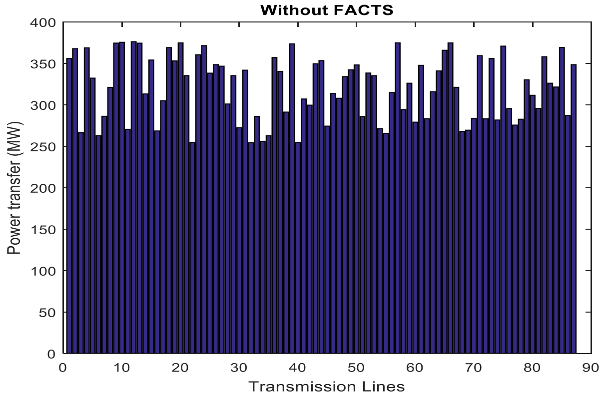

Figure 5.1. Power flow without FACTS devices

Table 5.3 summarizes the results of power flow in the weakest Lines without FACTS devices.

Table 5.3. Summary of result of power flow in the weakest lines without FACTS devices

Line	From Bus	To Bus	P (MW)	P loss (MW)	Q (MVA)	Q loss (MVA)
20	Bus 19	Bus 54	211.97	0.0126	266.05	0.7003
33	Bus 55	Bus 24	211.73	0.0353	188.69	0.4982
40	Bus 56	Bus 33	215.75	0.0343	198.45	0.1054
42	Bus 55	Bus 33	213.52	0.0313	173.42	0.1235
43	Bus 32	Bus 33	217.29	0.0606	258.07	0.1565
45	Bus 34	Bus 33	220.57	0.0637	228.68	0.5023
58	Bus 24	Bus 23	218.85	0.0777	236.19	0.4479
64	Bus 39	Bus 57	215.86	0.0325	231.73	0.0919
72	Bus 44	Bus 45	210.01	0.0116	226.76	0.5818
82	Bus 58	Bus 50	214.85	0.055	254.79	0.1138

Implementation of CPF for optimal location of TCSC, UPFC, IPFC, and the combination of the three FACTS devices on the ten weakest lines which are lines 20, 33, 40, 42, 43, 45, 58, 64, 72, and 82 enhanced power transfer capability of the system specifically as shown in the highlighted ten weakest lines of Table 5.2. The effects of the implementation of the devices are shown in Tables 5.4 – 5.7 respectively, while the power flow after application of TCSC, UPFC, and IPFC is graphically illustrated in Figures 5.2 – 5.4.

Table 5.4. Result of power flow with TCSC

Line	From Bus	To Bus	P (MW)	P loss (MW)	Q (MVA)	Q loss (MVA)
1	Bus1	Bus2	323.1	0.0082	207.06	0.6334
2	Bus3	Bus4	326.8	0.0016	266.76	0.7742
3	Bus11	Bus10	311.56	0.0338	194.84	0.0332
4	Bus11	Bus10	220.9	0.0518	236.8	0.4251

5	Bus3	Bus10	242.12	0.057	233.07	0.0775
6	Bus10	Bus16	251.69	0.0422	219.88	0.6316
7	Bus3	Bus9	296.38	0.0094	236.21	0.7766
8	Bus9	Bus5	225.76	0.05	233.11	0.0619
9	Bus16	Bus17	301.82	0.0108	181.69	0.738
10	Bus11	Bus14	221.89	0.0114	176.09	0.0241
11	Bus13	Bus14	293.04	0.0086	268.66	0.54
12	Bus11	Bus13	272.29	0.014	180.81	0.6174
13	Bus5	Bus8	309.36	0.0162	165.99	0.424
14	Bus11	Bus13	300.99	0.0256	221.72	0.6962
15	Bus16	Bus15	325.52	0.0255	256.09	0.7067
16	Bus10	Bus15	323.88	0.0179	233.02	0.4951
17	Bus18	Bus17	251.51	0.0205	182.76	0.1168
18	Bus50	Bus53	298.89	0.0702	201.71	0.1788
19	Bus58	Bus51	233.75	0.0555	211.5	0.1512
20	**Bus19**	**Bus54**	**211.98**	**0.0441**	**266.86**	**0.0424**
21	Bus54	Bus20	304.78	0.0153	179.47	0.0929
22	Bus18	Bus54	273.02	0.0174	253.39	0.4877
23	Bus21	Bus23	270.4	0.007	230.88	0.7382
24	Bus5	Bus6	325.68	0.0718	202.72	0.2847
25	Bus21	Bus22	287.3	0.0558	182.77	0.3282
26	Bus21	Bus22	288.34	0.0442	207.42	0.7729
27	Bus18	Bus24	319.79	0.0253	213.21	0.7428
28	Bus18	Bus24	312.74	0.0139	175.56	0.5344
29	Bus25	Bus24	283.04	0.0492	224.93	0.7759
30	Bus13	Bus25	231.82	0.0776	186.74	0.6043
31	Bus55	Bus26	239.25	0.0142	202.97	0.2709
32	Bus27	Bus55	323.31	0.021	224.3	0.5233
33	**Bus55**	**Bus24**	**211.77**	**0.0318**	**189.26**	**0.1992**
34	Bus28	Bus13	271.69	0.0067	192.83	0.239
35	Bus6	Bus7	229.86	0.054	227.97	0.5371
36	Bus29	Bus56	335.27	0.0322	190.45	0.4191
37	Bus56	Bus30	300.68	0.0772	249.44	0.329
38	Bus28	Bus56	273.08	0.0322	266.61	0.477
39	Bus31	Bus33	269.31	0.0491	239.59	0.5917
40	**Bus56**	**Bus33**	**215.79**	**0.013**	**198.57**	**0.4622**
41	Bus13	Bus33	296.74	0.0306	224.1	0.4376
42	**Bus55**	**Bus33**	**213.56**	**0.0135**	**173.56**	**0.4623**
43	**Bus32**	**Bus33**	**217.36**	**0.0598**	**258.25**	**0.4067**
44	Bus32	Bus33	275.85	0.0685	255.29	0.074
45	**Bus34**	**Bus33**	**220.64**	**0.0282**	**249.26**	**0.5677**
46	Bus2	Bus11	314.43	0.0541	189.9	0.782
47	Bus34	Bus33	314.31	0.0238	225.49	0.2848
48	Bus35	Bus36	301.94	0.0421	165.02	0.7627
49	Bus35	Bus36	227.55	0.0655	207.54	0.2785
50	Bus34	Bus36	293.84	0.0473	195.64	0.6971
51	Bus34	Bus36	275.45	0.027	179.53	0.3624
52	Bus33	Bus36	334.55	0.0242	181.07	0.3304
53	Bus24	Bus36	292.41	0.0361	207.28	0.1787
54	Bus36	Bus37	312.12	0.0338	172.76	0.1074
55	Bus36	Bus37	267.06	0.0289	226.23	0.2494
56	Bus24	Bus23	264.23	0.0443	212.17	0.5727
57	Bus12	Bus11	315.37	0.0585	235.97	0.6167
58	**Bus24**	**Bus23**	**218.94**	**0.0339**	**236.71**	**0.5477**
59	Bus38	Bus23	225.36	0.0343	230.26	0.0176
60	Bus38	Bus23	230.62	0.0107	165.94	0.6635
61	Bus24	Bus57	258.87	0.0029	169.49	0.7248
62	Bus24	Bus57	316.09	0.0235	196.74	0.6075
63	Bus24	Bus57	312.46	0.0256	218.35	0.0431
64	**Bus39**	**Bus57**	**215.9**	**0.0517**	**231.48**	**0.3031**
65	Bus57	Bus40	259.97	0.0752	205.35	0.5559
66	Bus24	Bus41	276.56	0.0735	249.08	0.5754
67	Bus41	Bus42	262.25	0.0365	238.71	0.1838
68	Bus12	Bus11	293.42	0.0196	265.2	0.2185
69	Bus57	Bus42	289.69	0.0602	218.38	0.5316
70	Bus43	Bus44	245.97	0.0598	197.31	0.3801
71	Bus44	Bus45	264.12	0.0584	173.86	0.4934
72	**Bus44**	**Bus45**	**210.02**	**0.0586**	**227.43**	**0.1932**
73	Bus43	Bus46	335.99	0.0092	244.62	0.1473
74	Bus23	Bus46	229.78	0.0538	207.67	0.653
75	Bus46	Bus47	221.83	0.0369	172.47	0.6044
76	Bus46	Bus47	256.46	0.0174	191.14	0.7342
77	Bus48	Bus58	233.77	0.0086	179.07	0.0936
78	Bus58	Bus49	271.67	0.0648	192.5	0.1512
79	Bus2	Bus11	252.21	0.0146	209.12	0.0868
80	Bus46	Bus58	331.76	0.0137	218.05	0.3896
81	Bus46	Bus58	327.72	0.0526	210.86	0.1598
82	**Bus58**	**Bus50**	**214.91**	**0.0703**	**254.92**	**0.7043**
83	Bus51	Bus50	303.97	0.041	216.95	0.0868
84	Bus52	Bus50	243.06	0.0555	262.87	0.0442
85	Bus52	Bus50	263.05	0.0129	229.88	0.4419
86	Bus52	Bus53	279.31	0.0749	263.79	0.6087
87	Bus3	Bus10	330.56	0.0735	187.82	0.2518

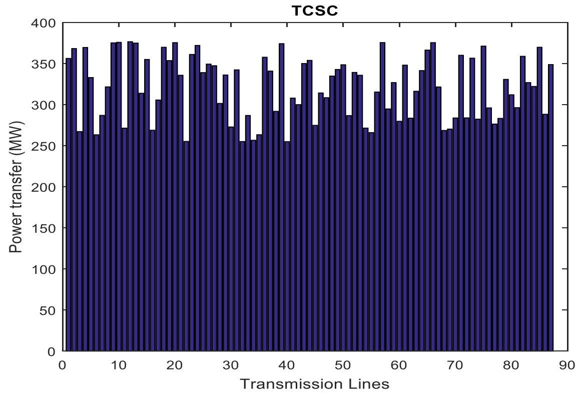

Figure 5.2. Power flow with TCSC

Table 5.5. Result of power flow with UPFC

Line	From Bus	To Bus	P (MW)	P loss (MW)	Q (MVA)	Q loss (MVA)
1	Bus1	Bus2	323.17	0.0515	207.79	0.5965
2	Bus3	Bus4	326.82	0.0189	267.65	0.3332
3	Bus11	Bus10	311.64	0.0323	194.88	0.7631
4	Bus11	Bus10	220.97	0.0105	237.29	0.7757
5	Bus3	Bus10	242.22	0.0218	233.16	0.6797
6	Bus10	Bus16	251.76	0.021	220.61	0.3114
7	Bus3	Bus9	296.42	0.0267	237.1	0.3624
8	Bus9	Bus5	225.83	0.0128	233.18	0.2012
9	Bus16	Bus17	301.86	0.028	182.54	0.6179
10	Bus11	Bus14	221.91	0.0104	176.12	0.6942
11	Bus13	Bus14	293.13	0.0695	269.28	0.7181
12	Bus11	Bus13	272.31	0.0083	181.52	0.4427
13	Bus5	Bus8	309.46	0.0731	166.48	0.4741
14	Bus11	Bus13	301.05	0.0319	222.52	0.1254
15	Bus16	Bus15	325.56	0.0047	256.9	0.7073
16	Bus10	Bus15	323.94	0.0275	233.59	0.3591
17	Bus18	Bus17	251.6	0.058	182.89	0.1694
18	Bus50	Bus53	298.91	0,0625	189 04	0.5507
19	Bus50	Bus53	298.98	0.0626	201.92	0.7072
20	**Bus58**	**Bus51**	**233.88**	**0.0432**	**211.67**	**0.601**
21	Bus19	Bus54	212.1	0.0542	266.91	0.6939
22	Bus54	Bus20	304.91	0.0703	179.58	0.2308
23	Bus18	Bus54	273.05	0.0052	253.95	0.5318
24	Bus21	Bus23	270.45	0.0245	231.73	0.5248
25	Bus5	Bus6	325.7	0.0046	203.05	0.1052
26	Bus21	Bus22	287.4	0.0161	183.15	0.3257
27	Bus21	Bus22	288.47	0.0568	208.31	0.2233
28	Bus18	Bus24	319.91	0.0569	214.06	0.5654
29	Bus18	Bus24	312.85	0.069	176.17	0.2296
30	Bus25	Bus24	283.11	0.0461	225.82	0.7046
31	Bus13	Bus25	231.89	0.0065	187.43	0.6506
32	Bus55	Bus26	239.42	0.0725	203.28	0.3123
33	**Bus27**	**Bus55**	**323.4**	**0.063**	**224.9**	**0.3959**
34	Bus55	Bus24	211.82	0.0232	189.49	0.5485
35	Bus28	Bus13	271.78	0.0431	193.1	0.6566
36	Bus6	Bus7	229.96	0.0773	228.59	0.4825
37	Bus29	Bus56	335.39	0.0565	190.93	0.4554
38	Bus56	Bus30	300.8	0.066	249.82	0.2627
39	Bus28	Bus56	273.21	0.0346	267.16	0.3637
40	**Bus31**	**Bus33**	**269.39**	**0.0375**	**240.27**	**0.5632**
41	Bus56	Bus33	215.9	0.0445	199.1	0.6954
42	**Bus13**	**Bus33**	**296.78**	**0.0219**	**224.6**	**0.5687**
43	**Bus55**	**Bus33**	**213.67**	**0.059**	**174.09**	**0.0244**
44	Bus32	Bus33	217.43	0.0401	258.72	0.533
45	**Bus32**	**Bus33**	**275.98**	**0.0511**	**255.38**	**0.3498**

46	Bus34	Bus33	220.75	0.0249	249.91	0.3493
47	Bus2	Bus11	314.47	0.0118	190.8	0.1007
48	Bus34	Bus33	314.41	0.0379	225.82	0.6414
49	Bus35	Bus36	302	0.0291	165.9	0.2618
50	Bus35	Bus36	227.67	0.0621	207.86	0.2008
51	Bus34	Bus36	293.99	0.0615	196.44	0.2756
52	Bus34	Bus36	275.56	0.0528	179.95	0.3012
53	Bus33	Bus36	334.59	0.0113	181.45	0.4336
54	Bus24	Bus36	292.44	0.0027	207.49	0.4455
55	Bus36	Bus37	312.21	0.0444	172.88	0.3168
56	Bus36	Bus37	267.13	0.0243	226.52	0.3186
57	Bus24	Bus23	264.34	0.0738	212.83	0.4094
58	**Bus12**	**Bus11**	**315.51**	**0.077**	**236.68**	**0.5196**
59	Bus24	Bus23	219.04	0.0232	237.34	0.747
60	Bus38	Bus23	225.47	0.0631	230.28	0.5698
61	Bus38	Bus23	230.74	0.0704	166.7	0.3201
62	Bus24	Bus57	258.93	0.0473	170.32	0.6547
63	Bus24	Bus57	316.17	0.0695	197.44	0.1141
64	**Bus24**	**Bus57**	**312.58**	**0.0741**	**218.4**	**0.0569**
65	Bus39	Bus57	215.98	0.0436	231.83	0.0753
66	Bus57	Bus40	260.1	0.0574	205.99	0.137
67	Bus24	Bus41	276.7	0.0457	249.74	0.2613
68	Bus41	Bus42	262.33	0.003	238.92	0.2438
69	Bus12	Bus11	293.5	0.0356	265.45	0.0191
70	Bus57	Bus42	289.77	0.0511	218.99	0.4284
71	Bus43	Bus44	246.09	0.0414	197.75	0.0839
72	**Bus44**	**Bus45**	**264.22**	**0.0299**	**174.43**	**0.1235**
73	Bus44	Bus45	210.17	0.0736	227.65	0.4991
74	Bus43	Bus46	336.14	0.0653	244.79	0.676
75	Bus23	Bus46	229.87	0.0668	208.42	0.765
76	Bus46	Bus47	221.92	0.0299	173.17	0.4524
77	Bus46	Bus47	256.55	0.047	191.98	0.7826
78	Bus48	Bus58	233.87	0.0686	179.18	0.439
79	Bus58	Bus49	271.76	0.0733	192.67	0.4095
80	Bus2	Bus11	252.34	0.0528	209.22	0.2663
81	Bus46	Bus58	331.8	0.017	218.5	0.3433
82	**Bus46**	**Bus58**	**327.8**	**0.0517**	**211.04**	**0.3911**
83	Bus58	Bus50	214.98	0.0066	255.73	0.0651
84	Bus51	Bus50	304.09	0.0325	217.05	0.698
85	Bus52	Bus50	243.17	0.0527	262.92	0.0601
86	Bus52	Bus50	263.19	0.0734	230.39	0.348
87	Bus52	Bus53	279.39	0.0638	264.49	0.6506

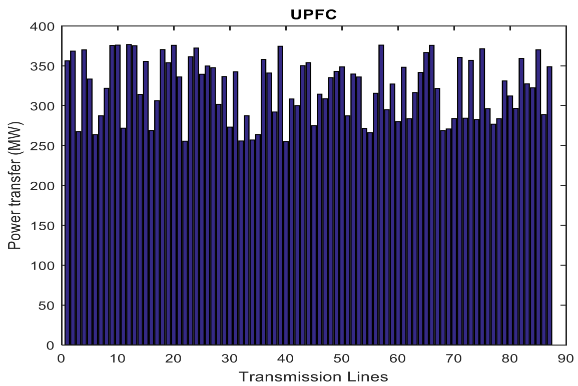

Figure 5.3. Power flow with UPFC

Table 5.6. Result of power flow with IPFC

Line	From Bus	To Bus	P (MW)	P loss (MW)	Q (MVA)	Q loss (MVA)
1	Bus1	Bus2	323.17	0.0351	208.48	0.323
2	Bus3	Bus4	326.82	0.074	268.03	0.4351
3	Bus11	Bus10	311.64	0.0518	195.76	0.0478
4	Bus11	Bus10	220.97	0.036	238.18	0.4384
5	Bus3	Bus10	242.22	0.0661	233.94	0.223
6	Bus10	Bus16	251.76	0.0423	220.97	0.1972
7	Bus3	Bus9	296.42	0.0439	237.52	0.1984
8	Bus9	Bus5	225.83	0.0537	233.41	0.1295
9	Bus16	Bus17	301.86	0.0295	183.25	0.7512
10	Bus11	Bus14	221.91	0.0195	176.92	0.7351
11	Bus13	Bus14	293.13	0.0459	270.11	0.6445
12	Bus11	Bus13	272.31	0.0682	182.03	0.5744
13	Bus5	Bus8	309.46	0.0325	167.03	0.1463
14	Bus11	Bus13	301.05	0.0097	222.66	0.2893
15	Bus16	Bus15	325.56	0.0354	257.71	0.1563
16	Bus10	Bus15	323.94	0.0243	234	0.0109
17	Bus18	Bus17	251.6	0.0321	183.08	0.2552
18	Bus50	Bus53	298.98	0.0656	202.73	0.5522
19	Bus58	Bus51	233.88	0.0323	212.36	0.4946
20	**Bus19**	**Bus54**	**212.1**	**0.0312**	**267.71**	**0.4309**
21	Bus54	Bus20	304.91	0.0289	179.85	0.3503
22	Bus18	Bus54	273.05	0.0119	254.56	0.2328
23	Bus21	Bus23	270.45	0.0212	232.33	0.3988
24	Bus5	Bus6	325.7	0.0077	203.17	0.6002
25	Bus21	Bus22	287.4	0.0343	183.52	0.6009
26	Bus21	Bus22	288.47	0.0209	208.57	0.4564
27	Bus18	Bus24	319.91	0.0241	214.71	0.5894
28	Bus18	Bus24	312.85	0.0339	176.43	0.5103
29	Bus25	Bus24	283.11	0.0102	226.63	0.1055
30	Bus13	Bus25	231.89	0.0394	188.18	0.4009
31	Bus55	Bus26	239.42	0.0557	203.64	0.2791
32	Bus27	Bus55	323.4	0.0199	225.36	0.0814
33	**Bus55**	**Bus24**	**211.82**	**0.0618**	**190.12**	**0.1246**
34	Bus28	Bus13	271.78	0.0067	193.86	0.1636
35	Bus6	Bus7	229.96	0.0315	229.14	0.531
36	Bus29	Bus56	335.39	0.0013	191.45	0.3444
37	Bus56	Bus30	300.8	0.0181	250.12	0.5482
38	Bus28	Bus56	273.21	0.0011	267.58	0.209
39	Bus31	Bus33	269.39	0.0157	240.92	0.0176
40	**Bus56**	**Bus33**	**215.9**	**0.012**	**199.9**	**0.4225**
41	Bus13	Bus33	296.78	0.0218	225.25	0.2265
42	**Bus55**	**Bus33**	**213.67**	**0.0146**	**174.12**	**0.7433**
43	**Bus32**	**Bus33**	**217.43**	**0.0117**	**259.33**	**0.7125**
44	Bus32	Bus33	275.98	0.0474	255.78	0.3143
45	**Bus34**	**Bus33**	**220.75**	**0.0708**	**250.31**	**0.0293**
46	Bus2	Bus11	314.47	0.0738	190.92	0.5304
47	Bus34	Bus33	314.41	0.0181	226.56	0.6588
48	Bus35	Bus36	302	0.0384	166.2	0.7629
49	Bus35	Bus36	227.67	0.0301	208.09	0.0541
50	Bus34	Bus36	293.99	0.0416	196.76	0.359
51	Bus34	Bus36	275.56	0.0215	180.3	0.4614
52	Bus33	Bus36	334.59	0.0063	181.95	0.5421
53	Bus24	Bus36	292.44	0.0348	208	0.5676
54	Bus36	Bus37	312.21	0.0145	173.24	0.5138
55	Bus36	Bus37	267.13	0.003	226.89	0.5734
56	Bus24	Bus23	264.34	0.075	213.3	0.2997
57	Bus12	Bus11	315.51	0.0344	237.28	0.4607
58	**Bus24**	**Bus23**	**219.04**	**0.0755**	**238.2**	**0.1**
59	Bus38	Bus23	225.47	0.0601	230.94	0.0547
60	Bus38	Bus23	230.74	0.0016	167.07	0.7693
61	Bus24	Bus57	258.93	0.0537	171.07	0.2307
62	Bus24	Bus57	316.17	0.0557	197.57	0.4711
63	Bus24	Bus57	312.58	0.051	218.47	0.7557
64	**Bus39**	**Bus57**	**215.98**	**0.0438**	**231.92**	**0.154**
65	Bus57	Bus40	260.1	0.0179	206.15	0.1596
66	Bus24	Bus41	276.7	0.0609	250.04	0.2748
67	Bus41	Bus42	262.33	0.0187	239.2	0.733
68	Bus12	Bus11	293.5	0.0297	265.47	0.3128
69	Bus57	Bus42	289.77	0.07	219.48	0.2217
70	Bus43	Bus44	246.09	0.0674	197.85	0.1278
71	Bus44	Bus45	264.22	0.0322	174.57	0.3178
72	**Bus44**	**Bus45**	**210.17**	**0.0256**	**228.22**	**0.3004**
73	Bus43	Bus46	336.14	0.0482	245.57	0.1116
74	Bus23	Bus46	229.87	0.0715	209.3	0.3472
75	Bus46	Bus47	221.92	0.0715	173.69	0.0809
76	Bus46	Bus47	256.55	0.0468	192.88	0.4863
77	Bus48	Bus58	233.87	0.0268	179.68	0.0185
78	Bus58	Bus49	271.76	0.0671	193.14	0.4543
79	Bus2	Bus11	252.34	0.0353	209.53	0.622
80	Bus46	Bus58	331.8	0.0711	218.89	0.1924
81	Bus46	Bus58	327.8	0.0036	211.49	0.3572
82	**Bus58**	**Bus50**	**214.98**	**0.0423**	**255.8**	**0.4513**
83	Bus51	Bus50	304.09	0.0565	217.85	0.0576
84	Bus52	Bus50	243.17	0.0149	262.99	0.3946
85	Bus52	Bus50	263.19	0.0271	230.79	0.5078
86	Bus52	Bus53	279.39	0.0155	265.24	0.1815

87	Bus3	Bus10	330.69	0.0259	188.47	0.6587

Table 5.7. Result of power flow with TCSC, UPFC, and IPFC

Line	From Bus	To Bus	P (MW)	P loss (MW)	Q (MVA)	Q loss (MVA)
1	Bus1	Bus2	323.11	0.0515	207.79	0.5965
2	Bus3	Bus4	326.8	0.0189	267.65	0.3332
3	Bus11	Bus10	311.6	0.0323	194.88	0.7631
4	Bus11	Bus10	220.96	0.0105	237.29	0.7757
5	Bus3	Bus10	242.19	0.0218	233.16	0.6797
6	Bus10	Bus16	251.74	0.021	220.61	0.3114
7	Bus3	Bus9	296.39	0.0267	237.1	0.3624
8	Bus9	Bus5	225.82	0.0128	233.18	0.2012
9	Bus16	Bus17	301.83	0.028	182.54	0.6179
10	Bus11	Bus14	221.9	0.0104	176.12	0.6942
11	Bus13	Bus14	293.05	0.0695	269.28	0.7181
12	Bus11	Bus13	272.3	0.0083	181.52	0.4427
13	Bus5	Bus8	309.38	0.0731	166.48	0.4741
14	Bus11	Bus13	301.01	0.0319	222.52	0.1254
15	Bus16	Bus15	325.55	0.0047	256.9	0.7073
16	Bus10	Bus15	323.91	0.0275	233.59	0.3591
17	Bus18	Bus17	251.53	0.058	182.89	0.1694
18	Bus50	Bus53	298.91	0.0626	201.92	0.7072
19	Bus58	Bus51	233.83	0.0432	211.67	0.601
20	**Bus19**	**Bus54**	**212.04**	**0.0542**	**266.91**	**0.6939**
21	Bus54	Bus20	304.83	0.0703	179.58	0.2308
22	Bus18	Bus54	273.04	0.0052	253.95	0.5318
23	Bus21	Bus23	270.42	0.0245	231.73	0.5248
24	Bus5	Bus6	325.69	0.0046	203.05	0.1052
25	Bus21	Bus22	287.38	0.0161	183.15	0.3257
26	Bus21	Bus22	288.4	0.0568	208.31	0.2233
27	Bus18	Bus24	319.84	0.0569	214.06	0.5654
28	Bus18	Bus24	312.77	0.069	176.17	0.2296
29	Bus25	Bus24	283.06	0.0461	225.82	0.7046
30	Bus13	Bus25	231.88	0.0065	187.43	0.6506
31	Bus55	Bus26	239.34	0.0725	203.28	0.3123
32	Bus27	Bus55	323.33	0.063	224.9	0.3959
33	**Bus55**	**Bus24**	**211.79**	**0.0232**	**189.49**	**0.5485**
34	Bus28	Bus13	271.73	0.0431	193.1	0.6566
35	Bus6	Bus7	229.87	0.0773	228.59	0.4825
36	Bus29	Bus56	335.33	0.0565	190.93	0.4554
37	Bus56	Bus30	300.72	0.066	249.82	0.2627
38	Bus28	Bus56	273.17	0.0346	267.16	0.3637
39	Bus31	Bus33	269.35	0.0375	240.27	0.5632
40	**Bus56**	**Bus33**	**215.85**	**0.0445**	**199.1**	**0.6954**
41	Bus13	Bus33	296.75	0.0219	224.6	0.5687
42	**Bus55**	**Bus33**	**213.6**	**0.059**	**174.09**	**0.0244**
43	**Bus32**	**Bus33**	**217.38**	**0.0401**	**258.72**	**0.533**
44	Bus32	Bus33	275.92	0.0511	255.38	0.3498
45	**Bus34**	**Bus33**	**220.72**	**0.0249**	**249.91**	**0.3493**
46	Bus2	Bus11	314.46	0.0118	190.8	0.1007
47	Bus34	Bus33	314.37	0.0379	225.82	0.6414
48	Bus35	Bus36	301.97	0.0291	165.9	0.2618
49	Bus35	Bus36	227.6	0.0621	207.86	0.2008
50	Bus34	Bus36	293.92	0.0615	196.44	0.2756
51	Bus34	Bus36	275.5	0.0528	179.95	0.3012
52	Bus33	Bus36	334.58	0.0113	181.45	0.4336
53	Bus24	Bus36	292.44	0.0027	207.49	0.4455
54	Bus36	Bus37	312.16	0.0444	172.88	0.3168
55	Bus36	Bus37	267.1	0.0243	226.52	0.3186
56	Bus24	Bus23	264.26	0.0738	212.83	0.4094
57	Bus12	Bus11	315.42	0.077	236.68	0.5196
58	**Bus24**	**Bus23**	**219.01**	**0.0232**	**237.34**	**0.747**
59	Bus38	Bus23	225.4	0.0631	230.28	0.5698
60	Bus38	Bus23	230.66	0.0704	166.7	0.3201
61	Bus24	Bus57	258.88	0.0473	170.32	0.6547
62	Bus24	Bus57	316.09	0.0695	197.44	0.1141
63	Bus24	Bus57	312.49	0.0741	218.4	0.0569
64	**Bus39**	**Bus57**	**215.93**	**0.0436**	**231.83**	**0.0753**
65	Bus57	Bus40	260.03	0.0574	205.99	0.137
66	Bus24	Bus41	276.65	0.0457	249.74	0.2613
67	Bus41	Bus42	262.33	0.003	238.92	0.2438
68	Bus12	Bus11	293.46	0.0356	265.45	0.0191
69	Bus57	Bus42	289.71	0.0511	218.99	0.4284
70	Bus43	Bus44	246.04	0.0414	197.75	0.0839
71	Bus44	Bus45	264.19	0.0299	174.43	0.1235
72	**Bus44**	**Bus45**	**210.09**	**0.0736**	**227.65**	**0.4991**
73	Bus43	Bus46	336.06	0.0653	244.79	0.676
74	Bus23	Bus46	229.79	0.0668	208.42	0.765
75	Bus46	Bus47	221.89	0.0299	173.17	0.4524
76	Bus46	Bus47	256.5	0.047	191.98	0.7826
77	Bus48	Bus58	233.79	0.0686	179.18	0.439
78	Bus58	Bus49	271.68	0.0733	192.67	0.4095
79	Bus2	Bus11	252.28	0.0528	209.22	0.2663
80	Bus46	Bus58	331.78	0.017	218.5	0.3433
81	Bus46	Bus58	327.74	0.0517	211.04	0.3911
82	**Bus58**	**Bus50**	**214.97**	**0.0066**	**255.73**	**0.0651**
83	Bus51	Bus50	304.05	0.0325	217.05	0.698
84	Bus52	Bus50	243.11	0.0527	262.92	0.0601
85	Bus52	Bus50	263.11	0.0734	230.39	0.348
86	Bus52	Bus53	279.32	0.0638	264.49	0.6506
87	Bus3	Bus10	330.65	0.0386	188.11	0.1007

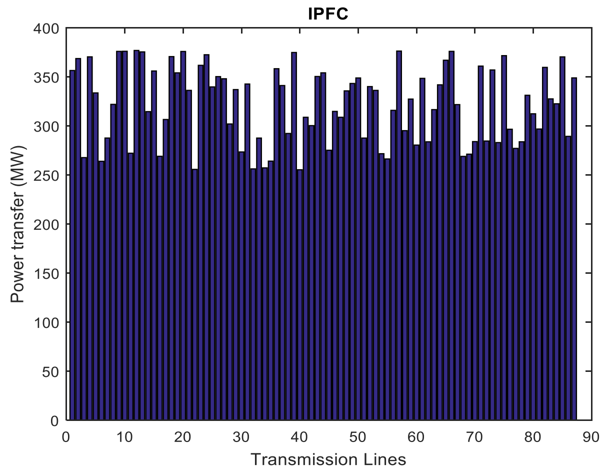

Figure 5.4. Power flow with IPFC

6. POWER TRANSFER CAPABILITY ENHANCEMENT

After optimal placement of FACTS devices in the 58-bus network system, the power transfer capability of the identified weakest buses were improved. Table 6.1 shows the summary of performance of TCSC, UPFC, and IPFC in the network system.

Table 6.1 Result of power flow with FACTS devices on the weakest lines

Line	From Bus	To Bus	P(MW) without FACTS	P(MW) with TCSC	P(MW) with IPFC	P(MW) with UPFC	P(MW) with TCSC, UPFC and IPFC
20	Bus 19	Bus 54	211.79	211.98	212.1	233.88	212.04
33	Bus 55	Bus 24	211.73	211.77	211.82	323.4	211.79
40	Bus 56	Bus 33	215.75	215.79	215.9	269.39	215.85
42	Bus 55	Bus 33	213.52	213.56	213.67	296.78	213.6
43	Bus 32	Bus 33	217.29	217.36	217.43	213.67	217.38
45	Bus 34	Bus 33	220.57	220.64	220.75	275.98	220.72
58	Bus 24	Bus 23	218.85	218.94	219.04	315.51	219.01
64	Bus 39	Bus 57	215.86	215.9	215.98	312.58	125.93
72	Bus 44	Bus 45	210.01	210.02	210.17	264.22	210.09
82	Bus 58	Bus 50	214.85	214.91	214.98	327.80	214.97

6.1 ATC Results

Results obtained from CPF in conjunction with network data collected from the case study were used to calculate the transfer capability and other performance key indicators (KPIs) of the network system. Results of the computed ATC are as presented in Table 6.2 and Figures 6.1 and 6.2.

Table 6.2. Result of computed ATC of Nigerian 58-bus network

Parameter	Without FACTS	TCSC	IPFC	TCSC, UPFC, And IPFC	UPFC
ATC	407.93	1,115.7	2,166.9	3,900.4	7,277.7
CBM	150.01	150.01	150.01	150.01	150.01
ETC	775.1	775.1	775.1	775.1	775.1
TRM	480	480	480	480	480
TTC	1,813	2,520.8	3,572	5,305.5	8,682.8

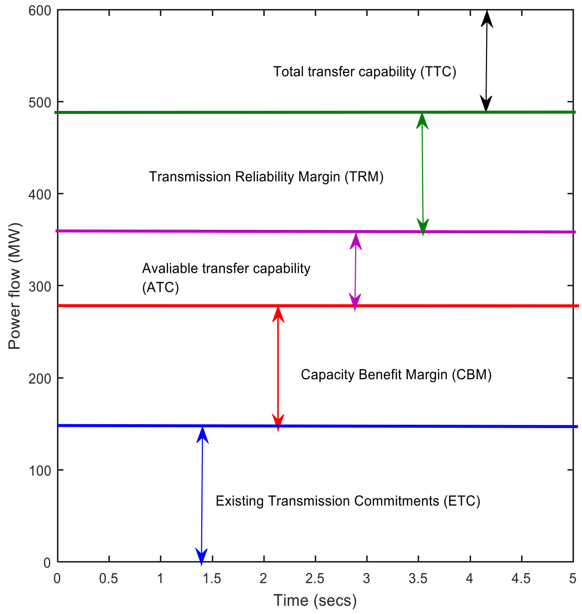

Figure 6.1. ATC limitations and related parameters

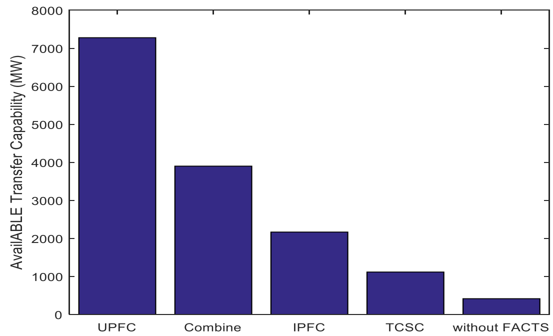

Figure 6.2 ATC Summary of Nigerian 58-Bus Network

7. CONCLUSION

The power transfer capability of the Nigerian 58-bus system has been thoroughly investigated using TCSC, UPFC, and IPFC. The parameters of the system modelled using NEPLAN without FACTS devices is compared with the system with TCSC, UPFC, IPFC and the combination of the three FACTS devices. The FACTS devices performed creditably by enhancing transfer capability of the system. Of the three devices, UPFC was observed to give best compensation for effective power transfer capability of the Nigerian 58-Bus system compared to TCSC and IPFC.

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