Chapter 16
Reactive Power Loss Minimization on an Interconnected Electric Power Network

Uche Chinweoke Ogbuefi, Boniface Onyemaechi Anyaka and Muncho Josephine Mbunwe

Abstract The inability of power system to maintain a proper balance of reactive power is the major cause of voltage collapse. A system can be saved from voltage collapse by reducing the reactive power load or by adding additional reactive power into the system. The electric power system is afflicted with continuous load shedding due to inadequate generation and transmission capacities. To maximize the amount of real power that can be transferred over a network, reactive power flow must be minimized. Thus, sufficient reactive power should be provided locally in the system to keep bus voltages within stipulated ranges to satisfy customers' equipment ratings. This paper presents an overview in reactive power compensation skills which remains as research challenges in this area. Newton-Raphson's solution method was used to carry out the analysis because of its fast convergence, sparsity, and simplicity attributes when compared to other solution methods, with relevant data obtained from Power Holding Company of Nigeria (PHCN). MATLAB/SIMULINK was used to carry out the simulation analysis. It is observed that the application of compensation on the unified system jointly has effect on the other buses. This is confirmed by a step-by-step application of compensation at 5% intervals. The effects were noticed in Bus (20) where voltage decreased from 0.9568 to 0.9329 p.u. about 2.39%, bus (19) from 0.998 to 1.1035 p.u. and others. These results indicate undershoot and overshoot that will cause damage to the system, and may lead to system collapse if no contingency control is installed. It is also observed that compensation should be done on weak buses only for better results. The results indicate the enhancement in voltage profile in addition to reduction in the network losses and more balanced system. Active and reactive power control greatly influence the electricity grid, thus, need adequate attention with the recent advent of integration of renewable energy into the grid.

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16.1 Introduction

The demand of electricity is increasing day-by-day and this results in an increase in per unit production cost. Again, maintaining uninterrupted power flow and providing quality power during disturbance becomes challenging. Voltage ampere reactive (VAR) compensation is the management of reactive power to improve the performance of ac power systems. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues since most power quality problems are attenuated or solved with an adequate control of reactive power [1].

In general, the problem of reactive power compensation is viewed from two aspects: load compensation and voltage support. In load compensation the objectives are to increase the value of the system voltage (power factor improvement), balance the real power drawn from the ac supply, compensate voltage regulation and eliminate current harmonics. In voltage support, the idea is for sustenance and to maintain stable voltage flow in the network. For power flow studies the frequency should remain nearly constant, because significant drop in frequency could result in high magnetizing currents in induction motors and transformers [2, 3]. The flows of active and reactive powers in a transmission network are fairly independent of each other and are influenced by different control actions. Active power control is closely related to frequency control, and reactive power control is closely related to voltage control [2, 3]. Since constancy of frequency and voltage are important factors in determining the quality of power supply, then the control of active and reactive power is vital to the satisfactory performance of a power system [3, 4].

Since electrical energy is normally generated at the power stations far away from the urban areas where consumers are located and are delivered to the ultimate consumers through a network of transmission and distribution, the terminal voltage vary substantially. Wider variation in voltage may cause erratic operation or even malfunctioning of consumers' appliances. The main cause for voltage variation is the variation in load on the supply system. With the increase in load on the supply system the voltage at the consumer premises falls due to increase in voltage drop in: (I) Alternator synchronous impedance, (ii) Transmission lines, (iii) Feeders and (iv) Distributors [5–7].

A well designed power system is one that gives good quality and reliable supply. By good quality it means the voltage levels are within reasonable limits. Naturally all the equipment on the power system are designed to operate satisfactorily only when the voltage levels in the system correspond to the rated voltage or at the most the variation are within ±5% of rated value [7]. Thus, compensation could be beneficial in in this aspect. The benefits of compensations are enormous and include the following: reactive power compensation in a transmission system improves the stability of the ac system by increasing the maximum active power that can be transmitted. It also helps to maintain a substantially flat voltage profile at all levels of power transmission if properly harnessed. It also increases transmission efficiency. It controls steady-state and temporary over-voltages and can avoid disastrous blackouts [7–10]. Objectively, reactive power loss minimization and the study of the effect of joint compensation on an interconnected network are the main issue of this work and the result obtained showed the disparity.

In an interconnected power system of n-buses the power injected into the nodes is given by a set of 2n nonlinear simultaneous equations represented in Eqs. (16.1) and (16.2).

$$P_i = \sum_{n=1}^{N} |V_i V_k Y_{ik}| \cos(\theta_{ik} + \partial_k - \partial_i) \tag{16.1}$$

$$Q_i = -\sum_{n=1}^{N} |V_i V_k Y_{ik}| \sin(\theta_{ik} + \partial_k - \partial_i) \tag{16.2}$$

Both active and reactive powers of the loads vary as a function of voltage magnitude. Compensating devices are normally added to supply or absorb reactive power and thereby control the reactive power balance in a desired form [2].

16.1.1 Reactive Power Flow on Line Voltage Drop

Voltage variation is due to imbalance in generation and consumption of reactive power in the system. If the generated reactive power is more than the consumed power, the voltage levels go up and vice versa. However, if the two are equal, then the voltage profile becomes flat and it happens only when the load is equal to the natural load. Unfortunately the reactive power in the system keeps varying because of different types of load and if the reactive power generation is simultaneously controlled, a more or less flat voltage profile could be maintained. Too wide variation of voltage causes excessive heating of distribution transformers thereby reducing the transformer capacity [2, 9].

16.2 Compensation Plans

The device commonly used for voltage and reactive power control includes: shunt reactors, shunt capacitors, synchronous generators, synchronous condensers, FACTS DEVICES etc.

Shunt Reactors are inductive current element connected between lines and neutral to compensate for inductive load/(current) from transmission lines. They are used to compensate for the effects of line capacitance, particularly to limit voltage rise on open circuit or light load [2, 6]. Shunt Capacitors supply reactive power and boost local voltages. The major advantages of shunt capacitors are their low cost and their flexibility of installation and operation [2]. They are readily applied to various points in the system, thereby contributing to efficiency of the power transmission and distribution. The disadvantage is that their reactive power output is proportional to the square of the voltage. The reactive power output is reduced at low voltages when it is likely to be needed most [2, 11, 12]. Shunt capacitors alleviate the excess loading of system and enable further active loads to be drawn from the same system. The reduction in line currents results in reduction of system losses. It is economical to carry out reactive power compensation from capacitors ideally located in the vicinity of reactive load e.g. motors and low voltage side of transformers.

16.2.1 Real and Reactive Power Control

A synchronous machine that is connected to an infinite bus has fixed speed and terminal voltage. The control variables are the field current and the mechanical torque on the shaft. The variation of the field current $\left(I_f\right)$, referred to as excitation system control is applied to either a generator or a motor to supply or absorb a variable amount of reactive power. Since the synchronous machine runs at a constant speed, the only means of varying the real power is through control of the torque imposed on the shaft by either the prime mover in the case of a generator or the mechanical load in the case of a motor. The complex power delivered to the system by the generator is given in per unit as in Eqs. (16.3) and (16.4)

$$S = P + jQ = V_i I_a^* = |V_i||I_a|(\cos\theta + j\sin\theta) \tag{16.3}$$

And for real and imaginary quantities we obtain

$$P = |V_i||I_a|\cos\theta; \quad Q = |V_i||I_a|\sin\theta \tag{16.4}$$

16.2.2 Shunt Compensation—Static-Var Compensation

Shunt compensation is the use of shunt capacitor or and shunt reactors in the line to avoid or reduce voltage instability [1, 2, 8] Shunt compensators are connected in shunt either directly to a bus bar or to the tertiary winding or to the main transformer and sometimes at mid-point of the lines (in some countries) to minimize the voltage drop and the losses. Shunt compensators are installed near the local terminals in factory substations, in the receiving substations, at switching substations etc to provide leading volt ampere-reactive (MVar) and thus to reduce the line current and total kVA loading of substation transformer [4, 6, 7, 13].

16.2.3 Control of Voltage and Reactive Power

For a transmission line where X ≫ R and R is negligibly small, therefore

$$|\Delta V| = \frac{XQ_r}{X}, \quad Q_r = \frac{V_r}{X}|\Delta V| \tag{16.5}$$

This relationship shows that the reactive power Q_r is proportional to the magnitude of the voltage drop in the line. Thus voltage control and reactive power control are interrelated. The reactive power generated should be exactly equal to the reactive power consumed. Any mismatch in the reactive power balance affects the bus voltage magnitudes [1, 6, 7].

16.2.4 Reactive Power Compensation in the Nigeria 330 kV Network

VAr compensation is the management of reactive power to improve the performance of ac power systems. The concept of VAr compensation encircles a wide and diverse field of both system and customer problems, especially related with power quality issues. Most of the power quality problems can be attenuated or solved with an adequate control of reactive power.

System voltage is highly dependent on the flow of reactive power. The long transmission lines in the National Grid generate considerable reactive MVars which constitute serious problems in maintaining system voltages within statutory limits especially during light loads, system disturbances and or major switching. The Nigerian PHCN has many reactors in various locations in the country, some of which are shown in Table 16.1. Some of these reactors were incorporated in the system to carry out the compensation to control the effect of reactive Mar. The major cause of voltage variation or drop in the line is the flow of reactive power. More of over reactive currents causes I^2R losses in the system but produces no revenue.

16.2.5 Reactive Power Management in Electric Power System

An important factor in the control of voltage in a power system depends on the reactive power production or absorption. Reactive power is required to excite consumer's equipment and transmission network which consists of capacitive and inductive elements. It is important that a balance of reactive power be maintained in the operation of a system because control of voltage can be lost if this is not achieved [2, 3, 14]. The reactive power flow is minimized so as to reduce I^2R and (I^2X) losses to a practical minimum. This ensures that the transmission system operates efficiently. The rating of capacitor can be calculated with the simplified equation as;

Table 16.1 Status of reactors in Nigeria power network PHCN 330 kV system

Station	Reactor nomenclature	Rating		Remarks
		kV	MVAR	
Kaduna	3R3	330	75	Good
Jebba	2R1	„	75	Good
Kano	R1	„	75	„
Gombe	R1	„	50	„
	R2	„	50	„
Oshogbo	4R1	„	75	„
Benin	6R2	„	75	„
Ikeja-west	R1	330	75	Good
Makurdi	R1	330	75	Good
Maiduguri	2R1	330	75	Good

$$C = \frac{Q_C}{\omega V^2} \tag{16.6}$$

Equation 16.5 shows that the capacitance required to improve the system efficiency is inversely proportional to V^2. Note that at high voltages power capacitors or capacitor bank values are rated in kilo volt-ampere reactive (kvar or mvar). For three phase system, the equation for the capacitor in delta connection, where ($V_P = V_L$)

Is given by Eq. 16.7.

$$C_\Delta = \frac{Q_C}{\omega V_P^2} = \frac{Q_C}{\omega V_L^2} \tag{16.7}$$

Compensation added to the network is given by Eq. 16.8, [7, 15]

$$Q_C = \frac{P}{Pf_1} \times \sin(\cos^{-1}(pf_1)) - \frac{P}{Pf_2} \sin(\cos^{-1}(pf_2)) \tag{16.8}$$

where P = real power specified at the buses, Pf_1 = 0.85 power factor, Pf_2 = 0.95 power factor, Q_C = value of shunt capacitance to be added to the network to boost the system voltage. Hence the capacitor required per three phase in star connection is equal to three times the capacitance required per phase when the capacitors are connected in delta. Also, the capacitors for the star-connected bank have a working voltage equal to $\frac{1}{\sqrt{3}}$ times that for the delta-connected bank. For this reason, the capacitors are connected in delta in three-phase systems for improvement of the system stability. The installation of a capacitor bank can be used to avoid the need to change a transformer in the event of a load increase. System behavior is affected by the characteristics of every major element of the system. The representation of these elements by means of appropriate mathematical models is critical to the successful analysis of the system behavior [16, 17].

In an ac circuit, current ‘I’ leads voltage in a capacitive circuit and I lags voltage in an inductive circuit. A capacitor is used to generate Var and an inductor is used to reduce reactive power. In power system analysis there is a strong inter relationship between the real power and angle and also between the reactive power and the voltage magnitude which aids us in compensation analysis. These relationships below exist for real and reactive powers flow.

$$S = P + jQ,\ P = VI\mathrm{Cos}\,\theta \text{ or } P = I^2R = \frac{V^2}{R},$$
$$\text{and } Q = VI\mathrm{Sin}\,\theta \text{ or } Q = I^2X = \frac{V^2}{X}\, X_C = \frac{1}{j\omega C}$$

and with low Var in a system, the voltage becomes low and vice versa. These relationships are used for the result analysis [8, 9, 18].

16.3 Network Description

The Nigerian power network like many practical systems in developing countries consists of a few generating stations mostly sited in remote locations near the raw fuel sources which are usually connected to the load centers by long transmission lines.

The National Electric Power Authority (NEPA) now known as Power Holding Company of Nigeria (PHCN) has the sole statutory functions of generation, transmission, distribution and marketing of electricity, before the partial unbundling of the power sector. Nigeria national electricity grid at present consists of nine generating stations comprising of three (3) hydro and six (6) thermal plants with a total installed generating capacity of 6500 MW. The thermal stations are mainly in the southern part of the country located at Afam, Okpai, Delta (Ughelli), Egbin and Sapele. The hydroelectric power stations are in the country’s middle belt and are located at Kainji, Jebba and Shiroro. The transmission network is made up of 5000 km of 330 kV lines, 6000 km of 132 kV lines, 23 of 330/132 kV sub-stations and 91 of 132/33 kV substations [7, 9, 19].

Although, the installed capacity of the existing power stations is 6500 MW the maximum load ever recorded was 4000 MW. Presently, most of the generating units have broken down due to limited available resources to carry out the needed level of maintenance. The transmission lines are radial and overloaded. The switchgears are obsolete while power transformers have not been maintained for a long time. The present installed generating capacity in Nigeria is shown in Table 16.2. The PHCN has only once been able to generate a maximum of 4700 MW, for a country of more than 160 million people [20–22].

Table 16.2 Existing power stations

S/no.	Power station name	Location/state	Status	Capacity (MW)
1	Egbin Thermal Power Station	Lagos	Operating	1320
2	Afam Thermal PS	Rivers	Operating	969.6
3	Sapele Thermal PS	Delta	Operating	1020
4	Ijora Thermal PS	Lagos	Operating	40
5	Delta Thermal PS	Delta	Operating	912
6	Kainji Hydro PS	Niger	Operating	760
7	Jebba Hydro PS	Niger	Operating	578
8	Shiroro Hydro PS	Niger	Operating	600
9	AES Thermal PS	Lagos	Operating	300
Total capacity =				6500

16.3.1 Methodology

In this work, the method used is based on the work of [1]. The existing 330 kV, 30 bus system of Nigeria transmission network with Egbin power station as the slack bus is used, and an in-depth examination of the Nigeria Integrated Power Plant Network was carried out. The parameters of all the generators and other system components were obtained. Equations for the power flow analysis are then formulated incorporating these parameters. The algorithm for the Newton-Raphson's method was developed. The Newton-Raphson's solution method represented with Eqs. (16.9) and (16.10) was used to carry out the analysis because of its sparsity, fast convergence and simplicity attributes as compared to other solution methods using the relevant data as obtained from Power Holding Company of Nigeria (PHCN). MATLAB m-file program and SIMULINK model were developed and used for the simulation analysis.

$$\Delta \mathrm{P} = J_{11}\Delta\delta \tag{16.9}$$

$$\Delta Q = J_{22}\Delta|V| \tag{16.10}$$

16.3.1.1 Line Flows and Line Losses Model

At the end of the iterative solution of the bus voltages, the calculation of the line flows and losses for both compensated and uncompensated conditions were carried out. The following formulae are used considering a two bus system labeled 1 and 2 (or i and j, and then to nth buses). First the Line current is given as:

$$I_{12} = y(V_1 - V_2), \quad I_{21} = -I_{12} \tag{16.11}$$

$$I_{13} = y_{13}(V_1 - V_3), \quad I_{31} = -I_{13} \tag{16.12}$$

Line flows are calculated using

$$S_{12} = V_1 I_{12}^*; S_{21} = V_2 I_{21}^* \tag{16.13}$$

$$S_{13} = V_1 I_{13}^*; \quad S_{31} = V_3 I_{31}^* \tag{16.14}$$

Line losses

$$S_{L12} = S_{12} + S_{21}; \quad S_{L13} = S_{13} + S_{31} \tag{16.15}$$

16.3.2 Draft of Nigeria 330 kV Transmission Network Used as Case Study

The single-line diagram of the existing 330 kV Nigeria transmission network used as the case study is as shown in Fig. 16.1. It has 30 buses with nine generating station. The Egbin power station was chosen as the slack bus because of its capacity and location in the network.

16.3.3 Data Assembly—Line Data

The input data for the power flow analysis include the bus data, transmission line data (impedance of lines), voltages and transformer/load data obtained from Power Holding Company of Nigeria (PHCN) are as presented in Tables 16.3, 16.4 and 16.5.

The load and generation data expressed in per unit values are given as $\frac{MW+jMVAr}{base.value}$. where the Slack Bus is Egbin Generating Station. As in Table 16.4

Base value = 100 MVA

Base voltage = 330 kV, Per Unit Value $= \frac{MVA}{Base\ Voltage}$ as presented in Table 16.4.

16.3.4 Shunt Capacitor Compensation Algorithm

The flow chart in Fig. 16.2 is the procedural method applied to achieve the desired compensation results.

First, the base solution is obtained using Newton-Raphson's method. Check bus voltages range. Identify the problem buses by checking the bus voltages outside ±5% of the normal values (that is, 0.95–1.05) per unit. Calculate the capacitor values

Table 16.3 Transmission line data (of Bison, two conductors per Phase and 2 × 350 mm^2 X-section Conductor) for 330 kV lines

B/no.	Bus name		Length (km)	R_1 (p.u.)	X_1 (p.u.)	Shunt
	From	To				
1	Akamgbe	Ik-West	17	0.0006	0.0051	0.065
2	Ayede	Oshogbo	115	0.0041	0.0349	0.437
3	Ik-West	Egbin	62	0.0022	0.0172	0.257
4	Ik-West	Benin	280	0.0101	0.0799	1.162
5	Oshogbo	Jebba	249	0.0056	0.477	0.597
6	Oshogbo	Benin	251	0.0089	0.0763	0.954
7	JebbaTs	JebbaGs	8	0.003	0.0022	0.033
8	Jebba TS	Shiroro	244	0.0087	0.0742	0.927
9	Jebba TS	Kainji	81	0.0022	0.0246	0.308
10	Kainji	B.Kebbi	310	0.0111	0.942	1.178
11	Shiroro	Kaduna	96	0.0034	0.0292	0.364
12	Kaduna	Kano	320	0.0082	0.0899	0.874
13	Jos	Gombe	265	0.0095	0.081	1.01
14	Benin	Ajaokuta	195	0.007	0.056	0.745
15	Benin	Sapele	50	0.0018	0.0139	0.208
16	Benin	Onitsha	137	0.0049	0.0416	0.521
17	Onitsa	N.Heaven	96	0.0034	0.0292	0.0355
18	Onitsha	Alaoji	138	0.0049	0.0419	0.524
19	Alaoji	Afam	25	0.009	0.007	0.104
20	Sapele	Aladja	63	0.0023	0.019	0.239
21	Delta	Aladja	30	0.0011	0.0088	0.171
22	Kainji GS	Jebba TS	81	0.0022	0.0246	0.308
23	Ayede	lk West	137	0.0049	0.0416	0.521
24	Egbin TS	Aja	27.5	0.0022	0.0172	0.257
25	Egbin TS	Aja	27.5	0.0022	0.0172	0.257
26	Kaduna	Jos	197	0.007	0.0599	0.748
27	Jos	Makurdi	275	0.0029	0.0246	0
28	Oshogbo	lk West	252	0.0049	0.0341	0.521
29	Benin	Delta	107	0.0022	0.019	0.239
30	Onitsha	Okpai	80	0.009	0.007	0.104
31	Geregu	Ajokuta	5	0.0022	0.0172	0.257
32	Shiroro	Kaduna	96	0.0034	0.0292	0.364

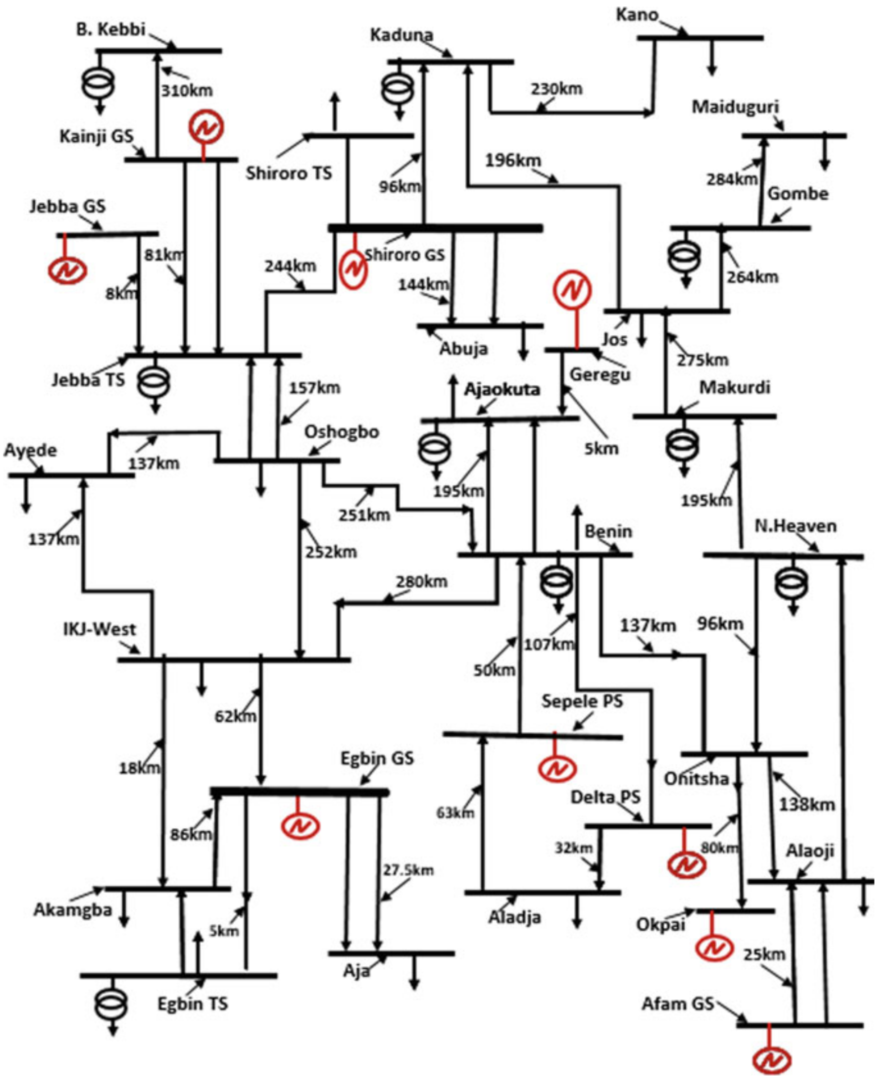


Fig. 16.1 One line diagram of the PHCN 330 kV 30 bus interconnected network

using this equation $\left(C = \frac{Q_C}{\omega V^2}\right)$ and apply compensation using this $Q_C = \frac{P}{Pf_1} \times \sin(\cos^{-1}(pf_1)) - \frac{P}{Pf_2} \sin(\cos^{-1}(pf_2))$. Where P is real power specified at the buses, Pf_1 and Pf_2 are power factors, while Q_C is value of shunt capacitance to be added to the network to boost the system voltage. Finally output result and stop. These procedures were simulated using MATLAB/SIMULINK. The results from the Newton-Raphson iterative method give the bus voltages, line flows, and power losses under normal (uncompensated) condition as shown in Table 16.7. The voltages at buses 14, 17, 18,

Table 16.4 Bus data values

B/no.	Bus name	Generation		Load		V (volts)	Angle (degree)	Remarks
		P (MW)	Q (MVar)	P (MW)	Q (MVar)			
1	Egbin	–	–	0.0000	0.0000	1.02	0.0000	Slack
2	Delta Ps	55.000	28.160	–	–	1.0000	0.0000	PV bus
3	Okpai	220.000	112.700	–	–	1.0000	0.0000	PV bus
4	Sapele	75.000	38.420	–	–	1.0000	0.0000	PV bus
5	Afam	479.000	245.390	–	–	1.0000	0.0000	PV bus
6	Jebba	322.000	164.960	–	–	1.0000	0.0000	PV bus
7	Kainji	323.000	165.490	–	–	1.0000	0.0000	PV bus
8	Shiroro	280.000	143.440	–	–	1.0000	0.0000	PV bus
9	Geregu	200.000	102.440	–	–	1.0000	0.0000	PV bus
10	Oshogbo	–	–	120.370	61.650	1.0000	0.0000	Load bus
11	Benin	–	–	160.560	82.240	1.0000	0.0000	Load bus
12	Ikj-West	–	–	334.000	171.110	1.0000	0.0000	Load bus
13	Ayede	–	–	176.650	90.490	1.0000	0.0000	Load bus
14	Jos	–	–	82.230	42.129	1.0000	0.0000	Load bus
15	Onitsha	–	–	130.510	66.860	1.0000	0.0000	Load bus
16	Akamgbe	–	–	233.379	119.560	1.0000	0.0000	Load bus
17	Gomgbe	–	–	74.480	38.140	1.0000	0.0000	Load bus
18	Abuja (katamkpe)	–	–	200.000	102.440	1.0000	0.0000	Load bus
19	Maiduguri	–	–	10.000	5.110	1.0000	0.0000	Load bus
20	Egbin TS	–	–	0.000	0.000	1.0000	0.0000	Load bus
21	Aladja	–	–	47.997	24.589	1.0000	0.0000	Load bus
22	Kano	–	–	252.450	129.330	1.0000	0.0000	Load bus
23	Aja	–	–	119.990	61.477	1.0000	0.0000	Load bus
24	Ajaokuta	–	–	63.220	32.380	1.0000	0.0000	Load bus
25	N.Heaven	–	–	113.050	57.910	1.0000	0.0000	Load bus
26	Alaoji	–	–	163.950	83.980	1.0000	0.0000	Load bus
27	Jebba TS	–	–	7.440	3.790	1.0000	0.0000	Load bus
28	B.Kebbi	–	–	69.990	35.850	1.0000	0.0000	Load bus
29	Kaduna	–	–	149.77	76.720	1.0000	0.0000	Load bus
30	ShiroroTS	–	–	73.070	37.430	1.0000	0.0000	Load bus

19, 22, 29 and 30 are outside the limit, and in order to ensure that they are within acceptable limits shunt capacitive compensation were introduced into the buses. Based on Power Holding Company of Nigeria (PHCN) power factor of 0.85 and 0.95 for transmission lines are used. The MVAr capacities of the various capacitors required to carry out compensation of the network at the buses were determined using

$$Q_C = \frac{P}{Pf_1} \times \sin(\cos^{-1}(pf_1)) - \frac{P}{Pf_2} \sin(\cos^{-1}(pf_2))$$

Table 16.5 Line data

S/no.	Circuit (Buses)		Length (km)	Impedance Z (p.u.)	Admittance Y (p.u.)	Shunt $\frac{y}{2}$ (p.u.)
	From	To				
1	Akamgbe	Ik-West	17	0.0006 + j0.0051	22.75 − j19.32	0.065
2	Ayede	Oshogbo	115	0.0041 + jo.o349	3.333 − j38.37	0.437
3	Ik-West	Egbin	62	0.0022 + j0.0172	7.308 − j57.14	0.257
4	Ik-West	Benin	280	0.0101 + j0.0799	1.637 − j12.626	1.162
5	Oshogbo	Jebba	249	0.0056 + j0.477	0.0246 − j3.092	0.597
6	Oshogbo	Benin	251	0.0089 + j0.0763	1.508 − j12.932	0.954
7	Jebba TS	Jebba GS	8	0.003 + j0.0022	3.174 − j1.594	0.033
8	Jebba TS	Shiroro	244	0.0087 + j0.0742	1.559 − j13.297	0.927
9	Jebba TS	Kainji	81	0.0022 + j0.0246	3.607 − j40.328	0.308
10	Kainji	B.Kebbi	310	0.0111 + j0.942	1.235 − j10.478	1.178
11	Shiroro	Kaduna	96	0.0034 + j0.0292	3.935 − j3.379	0.364
12	Kaduna	Kano	320	0.0082 + j0.0899	1.657 − j14.17	0.874
13	Jos	Gombe	265	0.0095 + j0.081	1.923 − j15.456	1.01
14	Benin	Ajaokuta	195	0.007 + j0.056	1.429 − j12.180	0.745
15	Benin	Sapele	50	0.0018 + j0.0139	3.194 − j17.555	0.208
16	Benin	Onitsha	137	0.0049 + j0.0416	2.8 − j33.771	0.521
17	Onitsa	N.Heaven	96	0.0034 + j0.0292	3.935 − j3.379	0.0355
18	Onitsha	Alaoji	138	0.0049 + j0.0419	2.754 − j33.553	0.524
19	Alaoji	Afam	25	0.009 + j0.007	59.230 − j53.846	0.104
20	Sapele	Aladja	63	0.0023 + j0.019	5.284 − j51.913	0.239
21	Delta	Aladja	30	0.0011 + j0.0088	13.995 − j1.119	0.171
22	Kainji GS	Jebba TS	81	0.0022 + j0.0246	3.607 − j40.328	0.308
23	Ayede	lk West	137	0.0049 + j0.0416	2.8 − j33.771	0.521
24	Egbin TS	Aja	27.5	0.0022 + j0.0172	7.316 − j57.2036	0.257
25	Egbin TS	Aja	27.5	0.0022 + j0.0172	7.316 − j57.2036	0.257
26	Kaduna	Jos	197	0.007 + j0.0599	1.924 − j16.469	0.748
27	Jos	Makurdi	275	0.0029 + j0.0246	4.726 − j40.093	0
28	Oshogbo	lk West	252	0.0049 + j0.0341	4.128 − j28.732	0.521
29	Benin	Delta	107	0.0022 + j0.019	6.013 − j51.935	0.239
30	Onitsha	Okpai	80	0.009 + j0.007	59.230 − j53.846	0.104
31	Geregu	Ajokuta	5	0.0022 + j0.0172	7.316 − j57.203	0.257
32	Shiroro TS	Kaduna	96	0.0034 + j0.0292	3.935 − j3.379	0.364

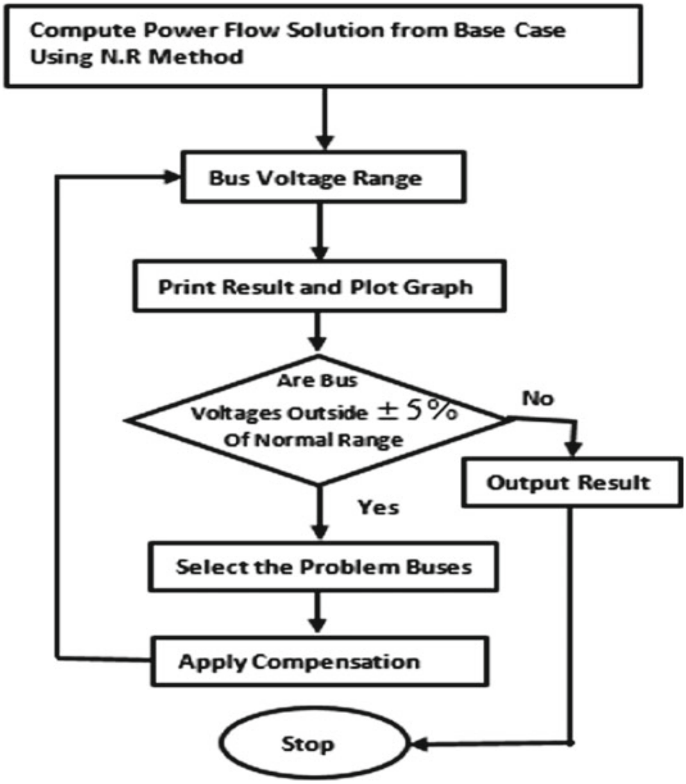


Fig. 16.2 Flow chart for the shunt capacitor compensation analysis algorithm

The following capacitor sizes were selected for the various lines. Jos bus (30 MVAr), Gombe bus (30 MVAr), Abuja bus (60 MVAr), Kano bus (40 MVAr), Kaduna bus (40 MVAr), and Makurdi bus (30 MVAr). These were introduced into the network to examine their effect on the system. The weak buses were identified as presented in Table 16.6, and the plots of the results are as shown in Figs. 16.3 and 16.4.

16.4 Results

It is also recorded during the compensation of the entire system jointly, that some buses that were normal are affected. Some buses values decreased from tolerable values while some over increased. Some of the pictorial graphs were as presented in Fig. 16.5a–f.

Table 16.6 Bus voltages for compensated and uncompensated

B/no.	Bus name	Bus vtgs. with compensation Volts (p.u.)	Without compensation Volts (p.u.)
1	Egbin-GS (Slack)	1.0000	1.0000
2	Delta-PS	1.0000	1.0000
3	Okpai-PS	1.0000	1.0000
4	SAP/PS	1.0000	1.0000
5	AFAM-GS	1.0000	1.0000
6	Jebba-GS	1.0000	1.0000
7	KAINJI-GS	1.0000	1.0000
8	Shiroro-PS	1.0000	1.0000
9	Geregu (PS)	1.0000	1.0000
10	Oshogbo	1.0035	0.9919
11	Benin	0.9998	0.9957
12	Ikeja-West	0.9969	0.993
13	Ayede	0.9967	0.9792
14	Jos	0.9823	0.8171
15	Onitsha	0.9793	0.9748
16	Akangba	0.9931	0.9859
17	Gombe	1.0242	0.8144
18	Abuja (Katampe)	0.9667	0.9402
19	Maiduguri	1.0455	0.8268
20	Egbin TS	0.9469	0.9816
21	Aladja	1.0006	0.9994
22	Kano	0.9338	0.7609
23	Aja	0.9692	0.9838
24	Ajaokuta	0.9999	0.9997
25	N.Heaven	0.9721	0.9582
26	Alaoji	0.9598	0.9564
27	Jebba-TS	0.9993	0.9988
28	B.Kebbi	1.0075	0.9873
29	Kaduna	0.9654	0.8738
30	Makurdi	0.9943	0.8247

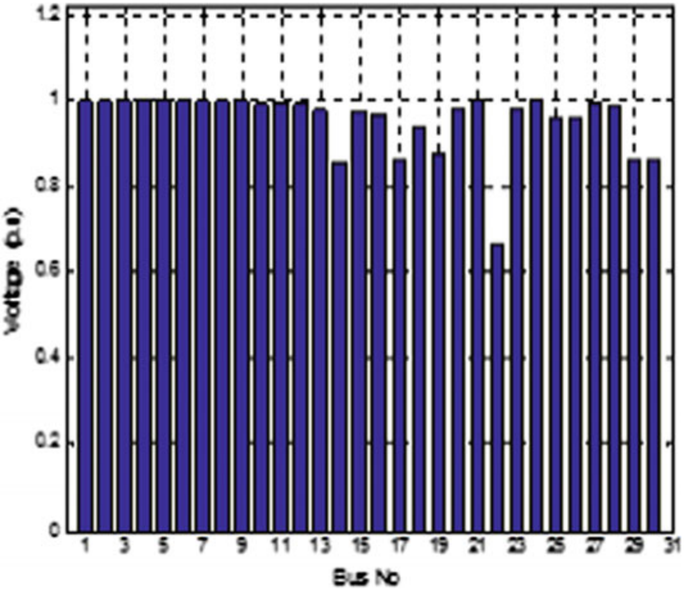


Fig. 16.3 Plot of bus voltages under normal (un compensated) condition

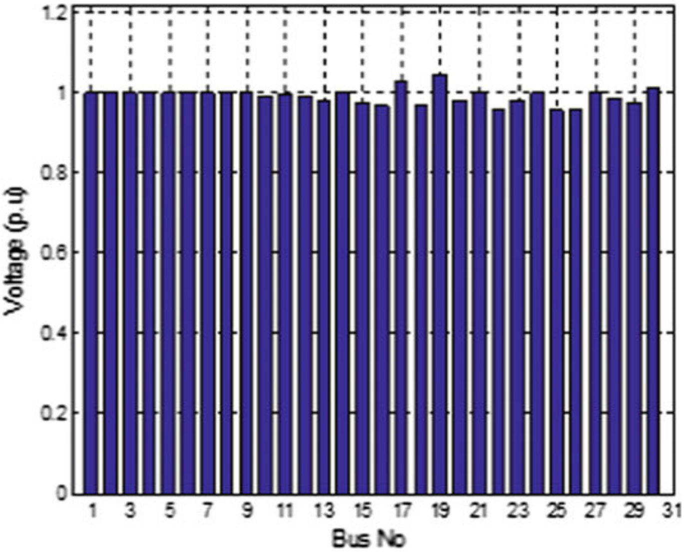
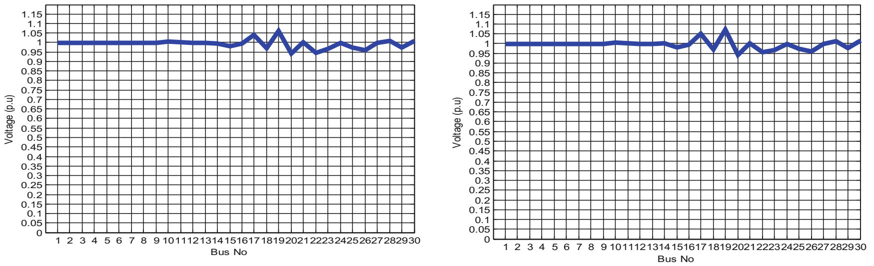
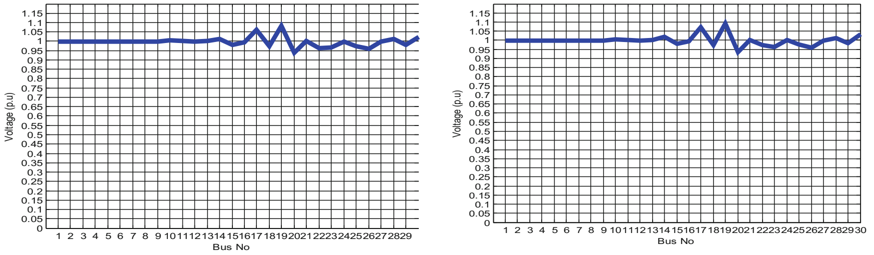


Fig. 16.4 Bar plot of bus voltages with compensation



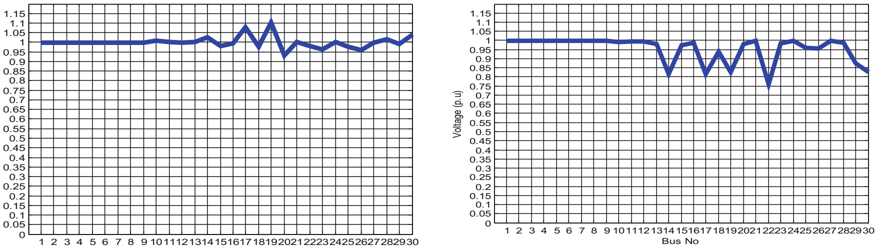
(a) 60%

(b) 70%



(c) 80%

(d) 90%



(e) 100%

(f) Uncompensated

Fig. 16.5 a–f Graph of voltage versus bus nos. at different levels of percentage compensation

16.4.1 Discussions

The analysis of Nigeria 330 kV 30 bus network using Newton-Raphson's power flow solution algorithm with MATLAB/SIMULINK software was effectively completed. The results obtained revealed the weak buses with values outside the standard limit of 0.95 p.u. (313.5 kV) and 1.05 p.u. (346.kV). The recorded results are; Bus 14 (Jos) with value 0.8171 p.u., bus 17 (Gombe) 0.8144 p.u bus 18 (Abuja) 0.9402 p.u., bus 19 (Maiduguri) 0.8268 p.u., bus 22 (Kano) 0.7609 p.u., bus 29 (Kaduna) 0.8738 p.u., and bus 30 (Makurdi) 0.8247 p.u. under normal uncompensated condition as presented in Fig. 16.4.

The compensation was carried out on the weak buses. At 45% capacitive shunt compensation on those buses indicated improved performance, Kano and Jos were still at the weak positions due to their distances in the national grid. With sixty (60) per cent compensation a better result was recorded as buses 14 (Jos) improved to 0.9823 and 22 (Kano) 0.9338. The compensated results are as displayed in Fig. 16.5a–f. It was observed that the application of compensation on the entire system jointly has negative effect on the other buses—which is part of the main aim of this work. This was verified by a step-by-step application of compensation at 5% intervals. **It was observed that compensating the whole network jointly affects some of the other buses that were within the tolerable range**. For instance, at Bus (20) the value decreased from 0.9568–0.9329 p.u. about 2.39% decrease. This can cause damage to the "**system's equipment and consumers' appliance**" if no proper security for contingency analysis control was installed. Also, bus (17) increased from 0.9786 to 1.0799 p.u. and bus (19) from 0.998 to **1.1035** p.u. and so on, which show undershoot and overshoot respectively which may lead to system collapse if not monitored. System efficiency was improved from 65% (uncompensated) to 85% after compensation.

16.5 Conclusion

In this work compensation of interconnected electric power network was studied using Shunt capacitive compensation. Shunt capacitive compensation is widely recognized as one of the prevailing methods to combat the problems of voltage drops, power losses, and voltage flicker in power system networks. Though each compensating technique has its area of proficiency and limit of application, but shunt capacitor compensation method was used because of its outstanding performance especially in long transmission lines and its control of reactive power flow. Though they associated with high cost implication but control voltage *directly* and also control temporary over voltage fast. **It was observed also that application of compensation on the interconnected system jointly has side effect on the other buses**. The results indicated that control of active and reactive power has high influence on the Nigeria network, hence adequate attention must be placed on it. Also with innovation/advent of renewable energy integration into the grid, if adequate control measure of reac-

Table 16.7 Bus voltages at various compensation levels for the compensated buses

B/no.	50%	65%	75%	90%
14	0.964547	0.976966	0.984707	0.995664
17	0.995396	1.009312	1.017975	1.030226
18	0.954925	0.954925	0.954925	0.954925
19	1.014868	1.029198	1.038118	1.05073
22	0.810757	0.834761	0.849712	0.945864
29	0.928746	0.93879	0.945069	0.953981
30	0.975601	0.98823	0.9961	1.007241

Table 16.8 Line current, line flow, and line losses (uncompensated)

B/sequence		Line current (p.u.)		Line flows (p.u.)		Line losses (p.u.)	
From	To	Real	Imaginary	Real	Imaginary	Real	Imaginary
16	12	0.1842	−1.4405	0.1783	−1.3941	−0.0046	0.0363
12	1	0.0514	−0.4023	0.05109	−0.3994	0.0511	−0.3995
12	11	0.0047	−0.0364	0.0047	−0.0361	−0.00001	0.0001
12	13	−0.0386	0.3280	−0.0384	0.3257	−0.0005	0.0045
13	10	0.0423	−0.3605	0.0415	−0.3530	−0.0005	0.0046
10	11	0.0059	−0.0512	0.0059	−0.0507	−0.00002	0.0002
10	27	0.0166	−0.1417	0.0165	−0.1406	−0.0001	0.0009
12	6	1.5244	−1.1179	1.5137	−1.1101	−0.011	0.0078
27	8	0.0016	−0.0177	0.0017	−0.0177	−0.0000	0.00002
27	7	0.0059	−0.0504	0.0059	−0.0503	−0.0000	0.00006
7	28	−0.0156	0.1328	−0.0156	0.1328	−0.0002	0.0017
8	29	−0.5455	4.6854	−0.5456	4.6854	−0.0756	0.6497
29	22	−0.3214	2.7405	−0.2769	2.3605	−0.0624	0.5322
14	17	0.0054	−0.0462	0.0046	−0.0396	−0.00002	0.0002
11	24	0.0085	−0.0678	0.0084	−0.0676	−0.00003	0.0003
11	4	0.0380	−0.2938	0.0378	−0.2926	−0.0002	0.0012
11	15	−0.0587	0.4984	−0.0584	0.4963	−0.0012	0.0105
15	25	−0.0579	0.5641	−0.0565	0.5498	−0.0009	0.0094
15	26	−0.0508	0.4346	−0.0496	0.4237	−0.0009	0.0080
26	5	3.0208	−2.3495	2.8890	−2.2470	−0.1318	0.1025
4	21	−0.0039	0.0327	−0.00396	0.0327	−0.0000	0.00002
2	21	−0.0039	0.0327	−0.0039	0.0327	−0.0000	0.00002
1	23	−0.1185	0.9261	−0.1184	0.9261	−0.0019	0.0149
29	14	−0.0094	0.0807	−0.0081	0.0695	−0.0000	0.0004
14	30	0.0137	−0.1170	0.0117	−0.1002	−0.0001	0.0009
10	12	0.0030	−0.0256	0.0029	−0.0254	−0.0000	0.0000
11	2	0.0261	−0.2173	0.0259	−0.2145	−0.0001	0.0009
15	3	1.7427	−1.356	1.6988	−1.3213	−0.0439	0.0341
8	18	−0.1486	0.6769	−0.1486	1.3112	−0.00890	0.0784
9	24	−0.0567	0.2838	−0.0566	0.2833	−0.00002	0.0001
19	17	−0.0408	0.2265	−0.0357	0.1432	−0.0006	0.0023
20	23	0.0158	−0.1236	0.0155	−0.1214	−0.0000	0.0003
27	26	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

tive power is not put in place there will be no much success. **Thus, it is advised that concentrating the compensation on the problem buses gives best result like buses** 14, 17, 18, 19, 22, 29, 30, at 65% recorded 0.976966, 1.009312, 0.954925. 1.029198, 0.834761, 0.93879 and 0.98823 and others as shown in Table 16.7. This reduces cost as well. Losses in the system were minimized as can be seen through Tables 16.8, 16.9, 16.10 and 16.11.

Table 16.9 Summary of total loss (uncompensated)

Line current (p.u.)		Line flows (p.u.)		Line losses (p.u.)	
Real	Imaginary	Real	Imaginary	Real	Imaginary
5.2816	3.4557	5.1362	3.2760b	−0.2427	0.6670

Table 16.10 Line current, line flows, and line losses (compensated)

B/sequence		Line current (p.u.)		Line flows (p.u.)		Line losses (p.u.)	
From	To	Real (I)	Imagi (I)	Real (P)	Imag (P)	Real (L)	Imag (L)
16	12	0.0859	−0.7304	0.0853	−0.7254	−0.0003	0.0028
12	1	0.0226	−0.1768	0.0225	−0.1762	0.0225	−0.1762
12	11	0.0047	−0.036	0.0047	−0.0359	0.000	1E−04
12	13	−0.0006	0.0048	−0.0006	0.0048	0.0000	0.0000
13	10	0.0224	−0.1908	0.0223	−0.1901	−0.0002	0.0013
10	11	−0.0056	0.0477	−0.0056	0.0479	0.0000	0.0002
10	27	−0.01	0.085	−0.010	0.0853	0.0000	0.0003
12	6	0.6698	−0.4912	0.6677	−0.4897	−0.0021	0.0015
27	8	0.0009	−0.0093	0.0009	−0.0093	0.0000	0.0000
27	7	0.0031	−0.0263	0.0031	−0.0263	0.0000	0.0000
7	28	0.0093	−0.079	0.0093	−0.079	−1E−04	0.0006
8	29	−0.1362	1.1695	−0.1362	1.1695	−0.0047	0.0405
29	22	−0.0522	0.4453	−0.0504	0.4299	−0.0016	0.014
14	17	0.0599	−0.5103	0.0588	−0.5013	−0.0025	0.0214
11	24	0.0004	−0.0031	0.0004	−0.0031	0.0000	0.0000
11	4	0.0022	−0.0167	0.0022	−0.0167	0.0000	0.0000
11	15	−0.0571	0.4845	−0.0571	0.4844	−0.0012	0.0099
15	25	−0.0252	0.2455	−0.0247	0.2405	−0.0002	0.0018
15	26	−0.0539	0.4605	−0.0527	0.451	−0.0011	0.009
26	5	2.785	−2.1661	2.673	−2.079	-0.112	0.0871
4	21	0.0037	−0.0305	0.0037	−0.0305	0.0000	0.0000
2	21	0.0037	−0.0305	0.0037	−0.0305	0.0000	0.0000
1	23	−0.2254	1.7619	−0.2254	1.7619	−0.0069	0.0543
29	14	0.0326	−0.2792	0.0315	−0.2695	−0.0006	0.0047
14	30	0.0198	−0.1691	0.0195	−0.1661	−0.0002	0.0020
10	12	−0.0183	0.1552	−0.0183	0.1557	−1E−04	0.0010
11	2	0.0015	−0.0123	0.0015	−0.0123	0.0000	0.0000
15	3	1.431	−1.113	1.4014	−1.09	−0.0296	0.023
8	18	−0.0827	0.7296	−0.0827	0.7296	−0.0027	0.0243
9	24	−0.0117	0.0586	−0.0117	0.0586	0.0000	0.0000
19	17	−0.0623	0.2498	-0.0651	0.2612	−0.0013	0.0053
20	23	0.1632	−1.2761	0.1546	−1.2083	−0.0036	0.0285
27	26	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 16.11 Summary of total loss (compensated)

Line current (p.u.)		Line flows (p.u.)		Line losses (p.u.)	
Real	Imaginary	Real	Imaginary	Real	Imaginary
4.5805	−1.4488	4.4256	−1.2589	−0.1485	0.1574

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