Irish International Journal of Engineering and Applied Sciences
Irish J. Eng. A. Sci.
Volume: 7; Issue: 02,
March-April, 2023
ISSN: 2965– 3325
Impact Factor: 4.21
Advance Scholars Publication
Published by International Institute of Advance Scholars Development
https://aspjournals.org/Journals/index.php/iijeas

OPTIMAL CAPACITOR PLACEMENT AND SIZING FOR LOSS MINIMIZATION IN NIGERIAN POWER GRID USING FUZZY LOGIC TECHNIQUE

Chizindu Stanley Esobinenwu
Department of Electrical/Electronic Engineering, Faculty of Engineering, Choba, P.M.B 5323, Rivers State. Nigeria.
Email: chizindu.esobinenwu@uniport.edu.ng

Key Word: *Fuzzy Logic, Capacitor Bank, Power Loss, Transmission Line, Bus Voltage, Power Grid*

Abstract: *In this paper, the existing Nigerian 330kV grid network within the south-south geo-political region was examined. The performance of the existing transmission system must be increased in order to enhance the efficiency of the power grid. To achieve this, power loss minimization and voltage profile improvement are the two most important strategies. The network consists of seven (7) generating stations, sixteen (16) buses, and nineteen (19) transmission lines. The network was modeled in electrical transient analyzer program (ETAP19.1) to determine the voltage performance index and loss sensitivity index using Newton Raphson power flow algorithm. Also, the fuzzy logic inference system toolbox in MATLAB/Simulink environment was used to determine the capacitor suitability index (CSI). The result from the base case shows that Bus 12: 93.07% and Bus 13: 93.01% violates the statutory limit condition of 0.95-1.0 5p. u for Bus Voltage. Also, the total real and reactive power losses in the line are 47.298 MW+j 212.143 Mvar. The power loss index was calculated using loss sensitivity and normalized in the range of [0, 1]. The voltage performance index and loss sensitivity index are fed as inputs to the Fuzzy Inference System to obtain Capacitor Suitability Index (CSI) used in determining the most suitable bus for capacitor installation. Experimentally, CSI with a value greater than 0.6 are chosen for capacitor installation. The result obtained after fuzzifications of both inputs and outputs using the associated membership functions shows that the CSI values for Bus 12 and 13 are 0.604 and 0.635 and are chosen as the optimal location for capacitor bank placement. The size of the capacitor bank was determined index vector-based method. When a capacitor bank of 75Mvar was installed at Bus 12 and 13 respectively, it was noticed that the total real and reactive power loss was reduced by 28.626MW+j90.53Mvar and the voltage profile of buses 12 and 13*

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improved by 7.23% and 7.19% respectively. Hence, the installation of capacitors impacted positively on power loss reduction and voltage profile improvement.

1.0 Introduction

Power plants, which are often positioned far from load centres, provide electrical energy (Robinson 2019). In order to make use of the electricity produced, a network of circuits is needed between the power plants and the customers. In recent times, the electric power infrastructure has advanced in size and complexity. More transmission lines are added to interconnect many generating stations and load centres scattered all over the country (Odia, 2017). The extensive interconnection of the transmission circuits has altered the grid stability thereby pushing it to operate closer to its limits. A considerable proportion of power is lost as it travels through the lines. For a power network to function effectively, an accurate assessment of these power losses on the transmission system and their mitigation are essential. Reduced power supply to ultimate customers is the outcome of power losses. As a result, appropriate steps must be made to minimize power losses.

The ever-rising cost of modifying the grid network has made it imperative for the Transmission Company of Nigeria (TCN) to use different design alternatives, and effect a wholesome study of the impact on the system predicated on specific predictions under steady and transient state conditions. In order to make this an achievable possibility, artificial intelligence tools are embedded in digital to assist the system engineers and planners use large network data to solve complex power system problems. Artificial intelligence is completely integrated into the power system and can effectively solve complex network problems and also perform real-time monitoring and control of power system infrastructure (Hague,2012).

According to Rastgoufard (2018), the foremost benefits of deploying artificial intelligence tools in power systems are their speed, robustness, and relative insensitivity to missing data.

2.0 Losses in Power Transmission Lines

The Nigerian electrical grid is one of the biggest dynamic system linkages in operation and, like all other power systems, it flows throughout the whole nation. Losses exist regardless of how properly the system is constructed. The energy that is wasted is due to internal or external sources, such as energy lost within a system (Nizar,2018).

These consist of losses resulting from resistance, atmospheric conditions, theft, errors in calculation, etc., as well as losses incurred among sources of supply and the load centre or consumers (Nagrath,2016).

In all human undertakings, loss quantification and mitigation are crucial. It might result in a power system operating more economically. If we are aware of the losses' causes, we can take action to restrict and reduce them. Thus, this will result in the system operating effectively and efficiently (Rao and Narasimham, 2018).

2.1 Power Loss Minimization Techniques

i. Voltage Upgrade: Increasing the nominal voltage from one level to another, such as

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upgrading from 11kV to 33kV. This type of loss minimization technique may require the construction of new lines, new substations, or upgrading the existing substations. This technique requires high capital cost and it takes a long time to plan. (Gonen, 2008).

ii. Construction of New Lines: When a transmission line's capacity for transmitting power is restricted, this is typically the first solution considered to prevent overloading by supplying extra channels for power flow. It is advantageous since the transmission system's dependability is increased. Yet, it must overcome obstacles in the areas of the economy, politics, and the environment (Navpreet, 2014)

iii. Line Upgrading: This requires a particular size of line conductor to be changed with a larger one that is capable of carrying more power if the existing line conductor is inadequate to carry expected power flows. It also involves upgrading an existing line from a single to a double circuit. This loss minimization technique greatly reduces the line impedance and increases the current-carrying capacity of the line. However, it requires high capital costs and also increases the conductor weight on the existing line structure. (Hingorani, 2015)

iv. FACT Device: This involves the integration of reactive power compensation devices to the existing power line. Depending on the line configuration and limitation the reactive power support can be either in series, shunt, or a combination of both. The power electronic device modifies the electrical impedance of the line and increases the power flows across the line. FACT device method of loss minimization among other methods is the most effective, economical, and environmentally friendly. (Keter, 2014)

3.1 Data Collection

The data for this study was obtained from the Transmission Company of Nigeria (TCN). Engineers from the Transmission Company of Nigeria (TCN) were also on-site for verbal interaction. This provided a comprehensive understanding of the current state of the grid network. The bus and line data are shown in Tables 1 and 2 below.

Table 1: Bus Data

Bus No	Bus Name	P (MW)	Q (MVar)
1	Afam	-	-
2	Sapele	160	90
3	Delta	460	250
4	Okpai	480	150
5	Alaoji	120	95
6	Odukpani	240	150
7	Ihovbor	225	110
8	Benin	270.1	130.5
9	Onitsha	135.8	63.7
10	Alaoji	253.8	118.3
11	Ikot Ekpene	135.8	63.7
12	Ugwaji	181.1	84.8
13	New Heaven	226.4	106.0
14	Asaba	71.6	35.8
15	Aladja	162.0	78.6
16	Adiabor	127.5	79.0

Source: Transmission Company of Nigeria

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Table 2: Transmission Line Data

ID	Type	R (pu)	X (pu)	km
1	1	0.0002	0.0015	5
2	2	0.0049	0.0416	137
3	3	0.0019	0.0518	52
4	1	0.0023	0.0191	63
5	1	0.0019	0.0160	53
6	1	0.0034	0.0292	96
7	2	0.0020	0.0170	56
8	1	0.0049	0.0419	138
9	2	0.0010	0.0088	28.8
10	2	0.0003	0.0021	7
11	2	0.0006	0.0054	17.7
12	2	0.0023	0.0191	63
13	2	0.0020	0.0167	55
14	4	0.0035	0.0301	99
15	1	0.0049	0.0416	137
16	1	0.0062	0.0062	20.5
17	2	0.0002	0.0015	5
18	2	0.0013	0.0112	37
19	1	0.0011	0.0097	32

Source: Transmission Company of Nigeria

3.2 Mathematical Modeling

3.2.1 Newton-Raphson Power Flow Method

The real and reactive power injected in the network is given by

$$S_i = V_i I_i^* = P_i + jQ_i \quad (1)$$

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \quad (2)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k \quad (3)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right) \quad (4)$$

$$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \left[\cos(\delta_k + \theta_{ik} - \delta_i) + j\sin(\delta_k + \theta_{ik} - \delta_i)\right] \quad (5)$$

Separating (5) into real and imaginary parts we have,

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \cos(\delta_k + \theta_{ik} - \delta_i) \quad (6)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \sin(\delta_k + \theta_{ik} - \delta_i) \quad (7)$$

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_3\\ J_2 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \quad (8)$$

Where

J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix

3.2.2 Voltage Performance Index

$$\boldsymbol{VPI = \frac{V_i}{V_{nom}} * 100} \quad (9)$$

where

V_i operating voltage

V_{nom}: nominal voltage

3.2.3 Loss Sensitivity Index

$$\boldsymbol{LSI = \frac{2 * Q_{(j)} * R_{(k)}}{V_{(j)}^2}} \quad (10)$$

where

R_k is the resistance of line k

$V_{(j)}$ is the voltage at the bus j

$Q_{(j)}$ is the reactive power loss at bus

3.2.4 Determination of Capacitor Bank Size

Index vector technique used for determining the size of the capacitor bank is given by

$$\boldsymbol{I_p = \frac{P_{kw}(Injected)}{V_{kV}}} \quad (11)$$

$$\boldsymbol{I_q = \frac{Q_{kvar}(Injected)}{V_{kV}}} \quad (12)$$

$$\boldsymbol{Index[i] = \frac{V_{kV}}{V_{base}} + \frac{I_q}{I_p} + \frac{Q_{eff\,load}[i]}{Q_{total}}} \quad (13)$$

$$\boldsymbol{Size[i] = Index[i] * Q_{Load}[i]} \quad (14)$$

Where

Ip: real component of the branch's current

Iq: reactive component of the branch's current

Vi: operating voltage in kV

Vbase : nominal or base voltage in kV

Qtotal: the reactive load of the system

Qload: local reactive load at ith bus

Qeffload: total effective load beyond ith bus (including Q at the ith bus)

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3.3 Fuzzy Logic System

The fuzzy logic system is comparable to how humans perceive and understand things. Fuzzy logic control is a range-to-point or range-to-range control contrary to the point-to-point control of the classical control method. In recent times, fuzzy logic is widely used in industrial processes due to its heuristic approach and multi-rule-based variable consideration for both linear and non-linear parameters, simplicity, and effectiveness (Mamdani and Assilion, 2017).

3.3.1 Optimal Location for Capacitor Bank Placement Using Fuzzy Logic Technique

The system is used for identifying the optimal location for capacitor placement in a transmission system with the aim of minimizing losses while bus voltages are kept within the statutory limit. Figure 1 below shows the Simulink diagram of fuzzy logic inference. it consists of two input variables namely; voltage performance index (VPI) and loss sensitivity index (LSI) and an output variable namely capacitor sensitive index (CSI). A set of multiple-antecedent fuzzy rules are established for determining the suitability of a bus for capacitor placement and nodes with the highest CSI are chosen. For this research work, nodes with CSI ≥ 0.6 are chosen for capacitor installation.

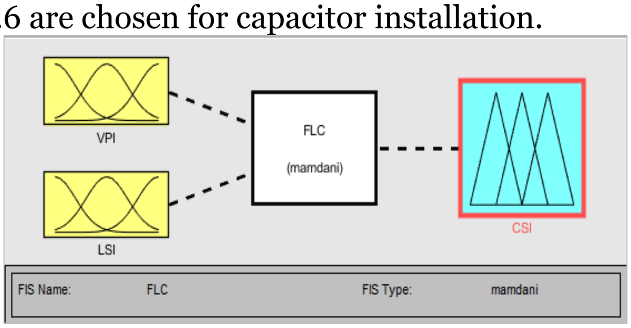

Figure 1: Simulink Block of FL System

3.3.2 Formation of Fuzzy Membership

The membership function is a technique in fuzzy logic used to define a fuzzy set. It converts numerical input variables into linguistic variables. By fuzzifying both the inputs and the outputs with the help of the corresponding membership functions, a fuzzy controller derives its output.

I. Input Variables

i. Bus Voltage Index (BVI): the value ranges from 0.9 to 1.1 with five (5) membership functions as follows CL: Critical Low, ML: Marginal Low, N: Normal, MH: Marginal High, CH: Critical High.

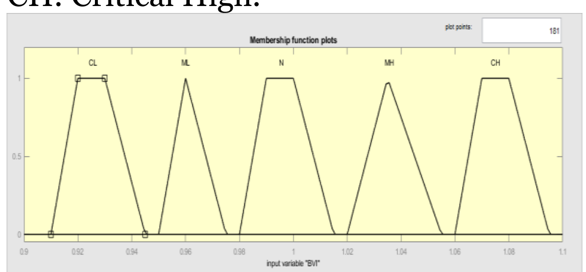

Figure 2: Membership Function for VPI

ii. Loss Sensitivity Index (LSI): the value ranges from 0 to 1 with five (5) membership functions as follows L: Low, LM: Low-Medium, M: Medium, HM: High-Medium, H: High.

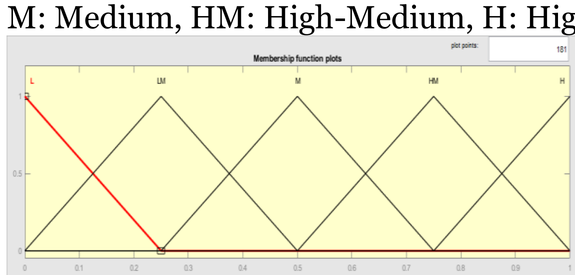

Figure 3: Membership Function for LSI

II. Output Variable

Capacitor Sensitivity Index (CSI): the value ranges from 0 to 1 with five (5) membership

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functions as follows L: Low, LM: Low-Medium, M: Medium, HM: High-Medium, H: High

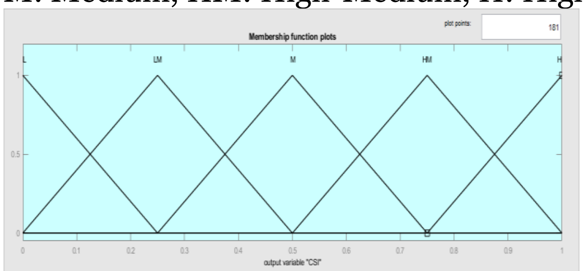

Figure 4: Membership Function for CSI

Table 3: Fuzzy Rule Decision Matrix

dD		Change in power (dP)				
		VL	***L***	***N***	***H***	***VH***
Change in voltage (dV)	***VL***	VH	VL	H	VL	VL
	L	H	H	H	VL	L
	N	H	H	N	L	L
	H	H	H	L	L	VL
	VL	H	H	L	L	VL

4. Result and Discussion

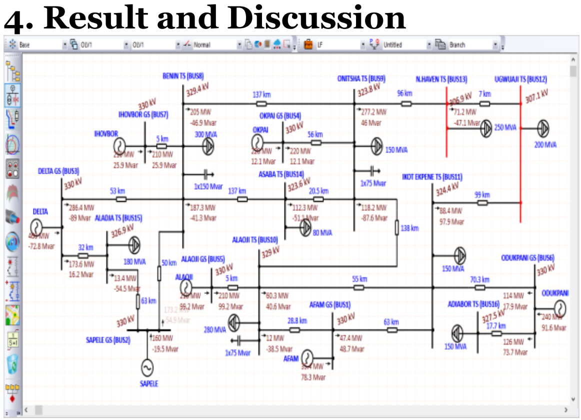

Figure5: Single Line Diagram of 16 Bus Power System Network

Table 4: Power Flow and Line Losses

From Bus	MW Flow	Mvar Flow	To Bus	MW Losses	Mvar Losses
10	59.2	55.3	**11**	0.4	15.8
8	205.8	37.9	**9**	1.4	20.5
6	112.7	40.3	**11**	1.2	18.2
11	82.6	126.8	**12**	2.9	20.2
8	187.9	33.5	**14**	6.2	24.1
1	16.6	52.7	**10**	0.1	8.8
5	209.5	172.4	**10**	0.5	0.2
1	44.4	72.3	**11**	0.5	18.1
3	172.4	22.6	**15**	1.2	6.4
3	286.3	76.0	**8**	5.8	0.0
12	73.0	55.6	**13**	7.1	1.6
6	125.5	77.8	**16**	0.5	4.1
4	216.4	53.9	**9**	3.6	6.7
2	173.3	41.1	**8**	2.0	10.0
2	13.5	54.5	**15**	0.2	19.2
9	113.8	43.3	**14**	0.4	5.0
9	267.1	35.3	**13**	10.1	1.8
9	122.1	99.3	**10**	3.9	31.0
7	209.6	165.2	**8**	0.5	0.3
				47.3	**212.1**

Table 4 shows the result of line flow and line losses obtained from load flow analysis using Newton Raphson method. The total real and reactive power losses are 47.298 MW and 212.143 Mvar. A quick look at table 4 shows that the highest real power loss occurred between Bus 9 to Bus 13 and the highest reactive power loss occurred between Bus 9 to Bus 10.

Table 5: Optimal Capacitor Placement

Bus No	(%)	LSI	CSI
1	100.00	0.00	0.08
2	100.00	0.00	0.08
3	100.00	0.00	0.08
4	100.00	0.00	0.08
5	100.00	0.00	0.08
6	100.00	0.00	0.08
7	100.00	0.00	0.08
8	99.82	1.00	0.50

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9	98.12	0.11	0.24
10	99.69	0.05	0.16
11	98.29	0.06	0.23
12	93.07	0.34	0.60
13	93.01	0.37	0.64
14	98.05	0.20	0.24
15	99.07	0.61	0.36
16	99.23	0.77	0.50

Table 5 shows the result of the capacitor sensitivity index obtained from the fuzzy implementation of two inputs variables VPI and LSI. The CSI value is obtained by selecting the values of VPI and LSI with respect to their bus number. A quick look at table 5 shows that the CSI values for Bus 12 and 13 are 0.60 and 0.64 respectively. Therefore, Bus 12 and 13 are chosen as candidate buses for capacitor placement.

Table 6: Capacitor Bank size

Bus No	Calculated	Available
12	71.3 Mvar	75 Mvar
13	73.2 Mvar	75 Mvar

Table 6 shows the optimal buses and size of for capacitor bank calculated using the index vector-based method described by (11), (12), (13), and (14) respectively. A cursory look at table 6 shows that the calculated capacitor sizes are Bus 12: 71.3Mvar and Bus 13: 73.2Mvar but the nearest available capacitor size selected is 75Mvar. These selected capacitors are thus placed at optimal buses 12 and 13 respectively. The capacitor bank when placed at an optimal location generates reactive power that improves the voltage profile and reduces the total power losses.

Table 7 Power Loss Reduction

Existing System		Improved System	
MW	**Mvar**	**MW**	**Mvar**
47.3	212.1	18.7	121.6

Table 7 shows the total real and reactive power losses in the existing system. when no capacitor bank was not installed was 47.3MW + j212.1Mvar. However, when a capacitor bank of 75Mvar was installed at bus 12 and 13 respectively in the improved system, the total real and reactive power loss was reduced to 18.7MW+ j121.6Mvar.

Table 8: Voltage Profile Improvement

Bus No	Existing System (%)	Improved System (%)
12	93.07	98.7
13	93.01	98.5

Table 8 shows voltage violation at Bus 12: 93.07% and Bus 13: 93.01% in the existing system when no capacitor bank was not installed was installed. However, when a capacitor bank of 75Mvar was installed at bus 12 and 13 respectively in the improved system, a significant improvement was recorded at Bus 12: 98.7% and Bus13: 98.5% which is an indication that the proposed techniques impacted positively.

Conclusion

The study examined the existing Nigerian 330kV grid network within the Benin regional control centre. The network consists of seven (7) generating stations, sixteen (16) buses, and nineteen (19) transmission lines. The network was modeled in the Electrical Transient analyzer program (ETAP19.1) to determine the voltage performance index and loss sensitivity index. A fuzzy logic inference system toolbox in MATLAB/Simulink environment was used to determine the capacitor suitability index (CSI). Buses with a CSI value greater than 0.6 is considered are chosen as candidate buses for capacitor placement. The size of the capacitor

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bank was determined using the index vector-based method. When a capacitor bank of 75Mvar was installed at Bus 12 and 13 respectively, It was noticed that the total real and reactive power loss was reduced by 28.626MW+j90.53Mvar and the voltage profile of buses 12 and 13 improved by 7.23% and 7.19% respectively.

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