IMPROVEMENT OF THE VOLTAGE PROFILE OF 11 kV POWER NETWORK USING CAPACITOR BANK

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Abstract: Voltage quality is an important requirement of an electrical distribution system. Deviation from the nominal voltage at the consumer end has specific ranges spelt out in technical regulations. A universal approach to voltage quality improvement is the reactive power compensation. Capacitor bank used for this purpose require optimization in sizing. This study, therefore, discusses improvement of the voltage profile of 11 kV power network using capacitor bank. Power flow in the network, Ado-Ekiti 11 kV lines, was carried out using the conventional load flow equation modeling. From the analysis of the network, rated power capacitors within the range 1.185kvar-5.644kvar is required to adequately compensate the reactive loads of the network while voltage deviation of the feeders which was within the range [(-5.9) – (-64.4)] % before the connection of the capacitor bank falls within the range [(-4.1) – (-6.8)] % after the installation of the rated power capacitor. This certainly translates to improved power quality on the network.

Keywords: Capacitor Bank, Compensation, Distribution System, Rated Power, Reactive Power, Voltage Quality

Introduction

Electricity distribution networks are continuously evolving as the human communities which they supply expand and grow. The increase in size of a network means longer feeders and more consumption points to supply. With the increase in network complexity, the voltage profile of the network will worsen. Voltage drops across feeders and bus voltage irregularity will increase, which will affect directly the security and quality of supply (Ovidiu et al., 2017). At present, with the development of power industry, power distribution network is becoming more and more complex, and the power quality has also got increasing attention, which is a challenge during the operation of the distribution network (Pilo et al., 2014; Junyong et al., 2015). In power system, voltage and frequency are two important performance indicators, which mainly depends on the operating frequency of the system active power balance, and the reactive power balance that is mainly decided to run system voltage level. Voltage affects the stability of the whole system. As the terminal of power system transmission and distribution network, the distribution network is directly connected with the power equipment so it is an important part of the power system (Venkata and Rudnik, 2007). In the light of the above, security of the distribution network and the economic operation will directly affect the users (Singh and Chandra, 1999). The researches of reactive power compensation in distribution network mainly consist of two aspects: the research of reactive power compensation optimization theory and the research of reactive power compensation device. According to certain configuration and optimization principle, the mode and capacity of reactive power compensation can be optimized, which can effectively reduce the system loss and improve the power quality of distribution network. (Yuan and Han, 2003). At present, reactive power compensation devices include shunt capacitor, static var compensator and static synchronous compensator. We could choose the appropriate reactive power compensation device to compensate the distribution network in the view of practice and economy (Ma et al., 2017). Reactive power is very important for the distribution network both on the economy and society. The equipment needs reactive power to establish field. In the process of high-speed operation of some equipment, the reactive power variation with time is quite fast. So if the reactive power consumed is not compensated in time, the security and reliability of the distribution system will be threatened. In the distribution system, the problem of voltage sag and variation could lead to the collapse of the power system (Singh and Chandra, 1999). Meanwhile, development of electrical power distribution system performance requires proper plans for increasing utilities efficiency. Different approaches are used to reduce losses such as optimal use of electrical equipment, optimal use of loading at the transformers, reconfiguration, and optimal capacitor placement, optimal placement of DG (Distributed Generation) and removal of harmonics. Amongst all, capacitor placement is comparatively lesser operating cost (Morgan et al., 1997; Kumar and Ramraj, 2015; Muselli et al., 1999). Reactive power must be compensated to guarantee an efficient delivery of active power to loads, thus releasing system capacity, reducing system losses, and improving system power factor and bus voltage profile. The achievement of these aims depends on the sizing and allocation of shunt capacitors (Antunes et al., 2009; (Levitin et al., 2000). Reactive power compensation is essential to the safe and economical operation of distribution network, related to whether the user can get the safety and quality of electric energy, the distribution network is directly connected with the load, the reactive power consumed by the line and the load must be balanced, otherwise it will affect the operation level of the voltage. So, the research on reactive compensation technology and device for power distribution systems plays a significant role in safe operation of the distribution network and the improvement of the economic benefit of the power grid. In power network which is heavily loaded the voltage level could be too low. To increase the voltage level we could apply capacitor banks. Unfortunately, installation of such devices is expensive. Therefore we should choose the best localization and the rated power for capacitor banks in the network (Agata and Robert, 2017; Dura, 1968; Kaur et al 2015). Meanwhile, the amount of compensation provided is very much linked to the placement of capacitors in the distribution system, which is essentially determination of the location, size, number and type of capacitors to be placed in the system (Hemasekhar and Harika, 2014). Capacitors are such economical devices providing required reactive power in the network. Its installation can reduce losses, improve voltage profile and freeing up the extra capacity of the generators (Grainger and Lee, 1981). The studied power network is fed from 1x15MVA & 1x7.5MVA 33/11kV distribution station through four 11kV feeders. The feeders are: Okesa, Basiri, Ajilosun and Adebayo. At the load points, 17 (50kVA), 43 (100kVA), 28 (200kVA), 32 (300kVA), 6 (315kVA), 57 (500kVA) and 1 (750kVA) distribution transformers further reduce the voltage from 11kV to 415V for customers' consumption. The service areas of the feeders of the network is as follows: Okesa feeder covers the entire Okesa street of Ado-Ekiti. It has a total route length of 17.7km with customer population of 2,755. Aluminum conductor of size 35mm^2 is used throughout its entire length. It has 59 distribution transformers (11/0.415kV) with loading of 5.4MW. Basiri feeder has customer population of 7,768, route length of 17.2km, loading of 4.7MW, 26 distribution transformers (11/0.415kV) and conductor size of 35mm^2 throughout its length. Ajilosun feeder covers Ijigbo and Ajilosun streets. Its loading is 6.3MW, total route length of 17.3km, customer population of 6,941, 65 distribution transformers (11/0.415kV) and conductor size of 35mm^2. Adebayo feeder has the lowest rated load of 4.7MW. It has customer population of 11,042, Aluminium conductor size of 100mm^2, route length of about 9.9km and 34 distribution transformers (11/0.415kV) throughout its entire length. As the distribution systems is growing large leading to higher system losses and poor voltage regulation, it must be emphasized that adequate attention should be paid to the network by subjecting it to review regularly for improvement and efficiency (Goudarzi et al., 2013; Faulkenberry and Coffer, 2008). The rest of the paper is organized as follows: Section 2 presents the methodology, section 3 captures the results and discussion while section 4 summarizes the conclusion.

Methodology

The approach adopted for the study is as follows: Collection of relevant documented information about the Ado-Ekiti distribution network. Such documents include; electrical map, loading of the feeders, feeder lengths and conductor capacity. The electrical map shows the arrangement of the feeders, connection of ring main unit (R.M.U), span of each feeder and the positions of each distribution transformers and circuit breakers. Inventory of distribution transformers gives a clear picture of names of feeders, voltage level and route length of feeders. Impedance modeling of the network using load flow computation method was carried out to ascertain the magnitude of voltage drop and deviation under two scenarios of half feeder load at the middle and half at the end of the line, and equal distribution of feeder load.

Impedance Modeling of the Feeders

The Load values of Tee offs on Okesa Feeder, using distribution transformer current ratings are:

$T_1 = 15.75 + 26.25 = 42A$

$T_2 = 26.25A$

$T_3 = 16.54 + 26.25 + 5.25 + 5.25 = 53.29A$

$T_4 = 26.25 + 26.25 + 2.62 + 2.62 = 57.74A$

$T_5 = 10.50 + 10.50 = 21.0A$

$T_6 = 15.75 + 10.50 = 26.26A$

Total current $(I) = 226.53A$

Conductor Parameters

The conductor size of Okesa, Basiri and Ajilosun Feeders is 35mm^2 while that of Adebayo Feeder is 100mm^2.

For Aluminum conductor of 35mm^2,

$$r_0 = \frac{\rho}{q} \quad (1)$$

Where r_0 is resistance per kilometer, ρ is Resistivity and q is conductor diameter. Therefore,

$r_0 = \frac{28}{33} = 0.85\Omega/km$ while x = 0.34Ω/km (from Electrical Cable Catalogue).

R (17.7km) $= 17.7 \times 0.85 = 15.05\Omega$

X (17.7km)$= 17.7 \times 0.34 = 6.02\Omega$

Where R is the line Resistance and X is the line reactance.

Voltage Drop Calculation

Voltage Drop calculation was done using the following load conditions:

(i) Half feeder load at the middle and half at the end of the line and

(ii) Equal distribution of Feeder load.

(i) Half Feeder Load at the middle and half at the end of the Line.

The total feeder load was divided to two equal parts and one half placed at the middle while the other half was placed at the end of the line. When the loads were in these positions, the voltage drop was calculated. The impedance diagram is shown in figure 1.

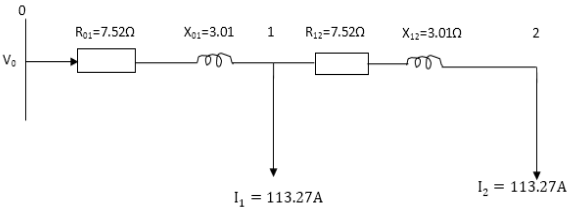

Figure 1: Impedance diagram of Okesa Feeder when half feeder load is at the middle and the other half is at the end of the line

$R_{01} = R_{12} = 8.85 \times 0.85 = 7.52\Omega$

$X_{01} = X_{12} = 8.85 \times 0.34 = 3.01\Omega$

$$\Delta V_{01} = I_{01}[R_{01} + jX_{01}] \quad (2)$$

$= 113.27[7.52 + j3.01]$

$= 851.79 + j340.94$

$= 917.49\angle 21.8$

$= 0.917kV$

$V_1 = V_0 - \Delta V_{01}$

$= 11.55 - 0.917 = 10.63kV$

$\Delta V_{12} = I_{12}[R_{12} + jX_{12}] = 113.27[7.5 + j3.01]$

$= 0.917kV$

$V_2 = 10.63 - 0.917$

$V_2 = 9.71kV$

$$\delta V = \frac{V - V_{NOM}}{V_{NOM}} \quad (3)$$

$\delta V = \frac{9.71 - 11.55}{11.55} = \frac{-1.84}{11.55}$

$= -0.1593 = -16\%.$

where V_0 is the sending end Voltage.

(i) Equal Distribution of Feeder Load

The total feeder load was distributed equally as shown in Figure 2 and the voltage drop and voltage deviation (δV) is calculated as shown below;

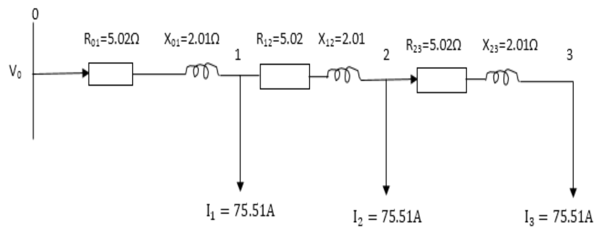

Figure 2: Impedance diagram of Okesa feeder when the load is distributed equally

$R_{01} = R_{12} = R_{23} = 5.9 \times 0.85$

$= 5.02\Omega$

$X_{01} = X_{12} = X_{23} = 5.9 \times 0.34$

$= 2.01\Omega$

$\Delta V_{01} = I_{01}(R_{01} + jX_{01})$

$= 75.51(5.02 + j2.01)$

$= 379.06 + j151.78$

$= 408.32\angle 21.8 = 0.41kV$

$V_1 = V_0 - \Delta V_{01}$

$= 11.55 - 0.41 = 11.14kV$

$\Delta V_{12} = I_{12}[R_{12} + jX_{12}] = 0.41kV$

$V_2 = 11.14 - 0.41 = 10.73\text{kV}$
Likewise, $\Delta V_{23} = I_{23}[R_{23} + jX_{23}]$
$= 0.41\text{kV}$
$V_3 = 10.73 - 0.41 = 10.32\text{kV}$
$\delta V = \frac{10.32-11.55}{11.55}$
$\frac{-1.23}{11.55} = -0.1065 = -10.7\%.$

The Okesa feeder modeling approach shown above was used for the three other feeders and the result is shown in table 1

Table 1: Result of Voltage Deviation percentage computation under the loading conditions

Loading Conditions	Voltage Deviation (%)			
	Okesa	Basiri	Ajilosun	Adebayo
Half Feeder Load at the middle and half	-16.0	-18.7	-64.4	-9.0
Equal Distribution of Feeder Load	-10.7	-12.5	-42.8	-5.9

Line capacitance

The capacitance of the distribution lines of the network is calculated using equation (4)

$$C_0 = \frac{0.0556}{ln\frac{GMD}{r}}\left(\frac{\mu F}{km}\right) \quad (4)$$

where GMD is the Geometric Mean Distance of the conductor and r is the conductor radius.

Okesa Feeder

Figure 3 shows the proposed positions of the compensating capacitors required to compensate the reactive load on the feeder.

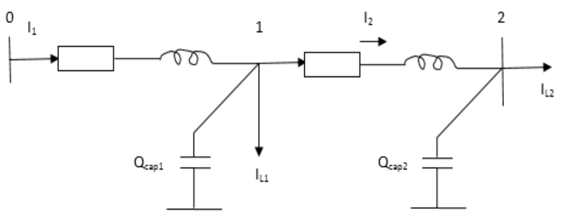

Figure 3: Impedance diagram of Okesa feeder with the proposed positions of compensating capacitors.

$$A = \pi r^2 = 35\text{mm}^2 \quad (5)$$

where A is the conductor cross sectional area and π = 3.142

$$\text{GMD} = \sqrt[3]{D_{AB} \times D_{BC} \times D_{AC}} \quad (6)$$

$\sqrt[3]{1000 \times 1000 \times 2000}$
$\sqrt[3]{2000{,}000{,}000} = 1259.9\text{mm}$
$r = 3.34\text{mm and GMD} = 1259.9\text{mm}$

$$C_0 = \frac{0.0556}{\ln\frac{GMR}{r}} = \frac{0.0556}{\ln\frac{1259.9}{3.34}} = 0.00937\frac{\mu F}{km}$$

$$x_0 = \frac{1}{2\pi f C_0} \quad (7)$$

$$x_0 = \frac{1}{2\pi f C_0} = \frac{1}{2 \times 3.142 \times 50 \times 0.00937} = 0.3397 \times 10^{-6}$$

but $b_0 = \frac{1}{x_0}$ (8)

Where b_0 is the line Susceptance
Therefore,

$$b_0 = \frac{1}{x_0} = \frac{1}{0.3397} = 2.944 \times 10^{-6}\text{S/km}$$

$$Q_c = U^2 b_0 l \quad (9)$$

Where U is Nominal Voltage and l is Feeder lenght

$Q_c = 11^2 \times 2.944 \times 10^{-6} \times 17.7$
$= 0.0063\text{kvar}$

Basiri Feeder

Similar computation was done for Basiri and Ajilosun feeders and the results are as follows:
Feeder length is 17.20km, $r = 3.34\text{mm and GMD} = 1259.9\text{mm}$
Using Equation (9);
$Q_c = 11^2 \times 2.944 \times 10^{-6} \times 17.2$
$= 0.0061 kvar$

Ajilosun feeder
Feeder length is 17.33km,
$r = 3.34\text{mm and GMD} = 1259.9\text{mm}$
Using Equation (9);
$Q_c = 11^2 \times 2.944 \times 10^{-6} \times 17.33$
$= 0.0062 kvar$

Adebayo Feeder

Feeder length is 9.85km, Conductor Cross Sectional Area is 100mm while π is 3.142.

$A = \pi r^2 = 100mm$

$r^2 = \frac{100}{3.142} = \sqrt{\frac{100}{3.142}} = 5.64\text{mm}$

Using Equation (6), GMD = 1259.9mm.

$C_0 = \frac{0.0556}{ln\frac{GMD}{r}}\left(\frac{\mu F}{km}\right)$

$C_0 = \frac{0.0556}{ln\frac{GMR}{r}}$

$= \frac{0.0556}{ln\frac{1259.9}{5.64}} = 0.01027\frac{\mu F}{km}$

$x_0 = \frac{1}{2\pi f C_0} = \frac{1}{2\times3.142\times50\times0.01027\times10^{-6}} = 0.3099 \times 10^6$

$Susceptance(\,b_0) = \frac{1}{x_0} = \frac{1}{0.3099 \times 10^6}$

$= 3.2268 \times 10^{-6}\frac{\text{S}}{\text{km}}$

Applying Equation (9):
$Q_c = 11^2 \times 3.2268 \times 10^{-6} \times 9.85$
$= 0.0038\text{kvar}.$

The result of the computation above formed the basis of the rated power of the device for reactive power compensation of the network. The nominal voltage (U), the useful power (P_1) and the current were kept constant while the reactance of the distribution lines was resolved into its components (Inductive and Capacitive). A factor (alpha) was introduced to vary the reactive power (Q_1) to a point when the capacitance of the required capacitor bank (Qcap) will be equal to the reactive power on the line. I_{effect} is the emerging useful current, U_1 is the resulting voltage at the end of the line while U_{dev} is the voltage deviation. The result of Okesa feeder is shown in Table 2.

Table 2: Required Reactive Power for Compensating Reactive Load and corresponding Node Voltage Profile for Okesa Feeder

I	U, kV	I_1, A	cosφ	sinφ	alpha	Irl	Ixl	$P_1=\sqrt{3}$Ir1U, kW	$Q_1=\sqrt{3}$Ix1U, kvar	Qcap1	I_{effect}(1),%	R	X	Z	U_1	U_{dev}(1)
	11.6	113.3	0.8	0.60	1	90.62	67.96	1812.8	1359.6	0.0	113.3	7.65	3.25	8.31	10.07	-8.46
					0.9	90.62	61.17	1812.8	1223.6	136.0	109.3				10.12	-8.00
					0.8	90.62	54.37	1812.8	1087.7	271.9	105.7				10.17	-7.57
35mm^2					0.7	90.62	47.57	1812.8	951.7	407.9	102.3				10.21	-7.18
17.7km					0.6	90.62	40.78	1812.8	815.8	543.8	99.4				10.25	-6.83
					0.5	90.62	33.98	1812.8	679.8	679.8	96.8				10.28	-6.53
					0.4	90.62	27.18	1812.8	543.8	815.8	94.6				10.31	-6.27
					0.3	90.62	20.39	1812.8	407.9	951.7	92.9				10.33	-6.07
					0.2	90.62	13.59	1812.8	271.9	1087.7	91.6				10.35	-5.92
					0.1	90.62	6.80	1812.8	136.0	1223.6	90.9				10.36	-5.83
					0	90.62	0.00	1812.8	0.0	1359.6	90.6				10.36	-5.80

I_2, A	cosφ	sinφ	alpha	Ir2	Ix2	$P_2=\sqrt{3}$Ir1U, kW	$Q_2=\sqrt{3}$Ix1U, kvar	Qcap2	I_{effect}(2),%	R	X	Z	U_2	U_{dev}(2)
113.3	0.8	0.60	1	90.62	67.96	1580.4	1185.3	0.0	113.3	7.65	3.25	8.31	8.59	-21.89
			0.9	90.62	61.17	1580.4	1066.8	118.5	109.3				8.69	-20.97
			0.8	90.62	54.37	1580.4	948.2	237.1	105.7				8.79	-20.12
			0.7	90.62	47.57	1580.4	829.7	355.6	102.3				8.87	-19.34
			0.6	90.62	40.78	1580.4	711.2	474.1	99.4				8.95	-18.64
			0.5	90.62	33.98	1580.4	592.7	592.7	96.8				9.02	-18.03
			0.4	90.62	27.18	1580.4	474.1	711.2	94.6				9.07	-17.52
			0.3	90.62	20.39	1580.4	355.6	829.7	92.9				9.12	-17.12
			0.2	90.62	13.59	1580.4	237.1	948.2	91.6				9.15	-16.83
			0.1	90.62	6.80	1580.4	118.5	1066.8	90.9				9.17	-16.65
			0	90.62	0.00	1580.4	0.0	1185.3	90.6				9.18	-16.59

Results and Discussion

Compensation of reactive load of the network to improve the voltage quality and the overall efficiency of the entire system requires installation of capacitor bank as follows; for Okesa feeder, 1.359kvar and 1.185kvar, Basiri feeder, 1.931kvar and 1.598kvar, Ajilosun feeder, 5.644kvar and 2.990kvar, Adebayo feeder, 3.297kvar and 3.119kvar capacitor banks are required at the middle and end of the lines respectively. Results of the modelling and comparism of tables 1 and 2 shows that Okesa feeder voltage deviation which is -16.0% before compensation will be -5.8% after the installation of the capacitor bank. On Basiri feeder, the voltage deviation of -18.7% will be reduced to -5.5% after the installation of the recommended power capacitor. Ajilosun feeder voltage deviation which stands at -42.8% will drastically reduce to -6.8% while that of Adebayo feeder will be reduced to -4.1% from -9.0%. In essence, when these capacitor banks are installed, the reactive loads of the network will be compensated and the voltage profile kept within permissible limits of ±5% of the nominal value.

Conclusion

Improvement of the voltage profile of 11 kV power network using capacitor bank was carried out. Power flow in the network, Ado-Ekiti 11kV lines, was carried out using the conventional load flow equation modeling. From the analysis of the network, rated power capacitors within the range 1.185kvar to 5.644kvar is required to adequately compensate the reactive loads of the network. Voltage deviation of the feeders which was within the range [(-5.9) – (-64.4)] % before the connection of the capacitor bank falls within the range [(-4.1) – (-6.8)] % after the installation of the rated power capacitor. This certainly translates to improved power quality on the network.

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