Effects of Capacitor Bank Installation in a Medium Voltage (MV) Substation

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Abstract
Several medium voltage substations, often called 33/11kV injection substations in Nigeria, are being run in electric utility companies without installing capacitor banks. Research has shown that the inclusion of capacitor bank improves system power factor and efficient running of the power system.This paper presents a brief description of the theory of power factor and its importance in achieving power system control and stability. Possible implications of substations without capacitor bank installations were also itemised. A schematic diagram of Ajangbadi 2X15MVA 33/11kV injection substation in Eko Electricity Distribution Company, Nigeria, is presented as a case study. A flowchart of the algorithm used to determine substation and network load parameters was developed and implemented. All results obtained and the necessary conclusions are presented.
Keywords: Medium voltage, Injection Substation, Capacitor Bank, Power factor, Load parameters.

1. Introduction

Electric utilities become more concerned about the quality of power delivered to customers (the end users). Electric energy is generated, distributed and utilised in sinusoidal form. For a typical voltage and current vectors in an AC circuit, the cosine of the angle between the voltage and current is called the power factor (PF) and mathematically defined as:

$$PF = Cos\emptyset \qquad (1)$$

The apparent power (KVA) in an AC circuit can be resolved into two components, the in-phase component which supplies the useful power (KW), and the wattless component (kVAr) which does no useful work. The phasor sum of the two is the KVA drawn from the supply (Chandra, A. and Agarwal, T., 2014).

Resistive loads have a power factor of unity while inductive loads have a power factor of zero. However, in practice loads in an electric circuit comprises of resistive and inductive ones. This makes the power factor of such plant or circuit to a value between zero and one. The closer the value of power factor is to 1, the less the losses in the network. Power Factor correction/compensation plays a major role towards the improvement of power system quality and efficient utilization of industrial power supply (Adesina and Ebere, 2016).

In a typical Nigerian power utility network, majority of the medium voltage (MV) power substations are without capacitor banks (CB) to minimize harmonics and stabilize system power factor to an approximate designed level. The problems related to harmonics have increased in the LV networks due to the spreading of disturbing loads (Omar, et al., 2014). Practically speaking, some of the implications of this condition are as follows: (Mazumdar, 2006):

- Voltage distortion in distribution feeders;
- Increased RMS currents, heating and line losses;
- Overheating of power transformers, which requires higher K-factor transformers;
- Derating of distribution equipment;
- Overloading of phase and neutral conductors - neutral currents in a typical commercial office building may carry more than phase RMS currents;
- Amplification of harmonic currents in the utility system due to series and parallel resonances between the utility system and nonlinear loads;
- Overloading and fuse blowing of power factor correction capacitors;
- Tripping of voltage harmonic sensitive equipment;
- Failure of control electronics, micro-processors;
- Reduced accuracy of measuring instruments (such as watt-hour meters);
- Malfunction of solid-state fuses, breakers and relays;
- Reactive power and resonance problems;
- Reduced system stability and safe operating margins.

- Power factor correction capacitors are generally installed in industrial plants and commercial buildings. Fluorescent lighting used in these facilities also normally has capacitors fitted internally to improve the individual light fitting's own power factor. The harmonic currents can interact with these capacitances and system inductances, and occasionally excite parallel resonance which can over heat, disrupt and/or damage the plant and equipment (Siemens, 2013).
- Power cables carrying harmonic loads act to introduce EMI (electromagnetic interference) in adjacent signal or control cables via conducted and radiated emissions. This "EMI noise" has a detrimental effect on telephones, televisions, radios, computers, control systems and other types of equipment. Correct procedures with regard to grounding and segregation within enclosures and in external wiring systems must be adopted to minimize EMI.
- Any telemetry, protection or other equipment which relies on conventional measurement techniques or the heating effect of current will not operate correctly in the presence of nonlinear loads. The consequences of under measure can be significant; overloaded cables may go undetected with the risk of catching fire. Bus bars and cables may prematurely age. Fuses and circuit breakers will not offer the expected level of protection. It is therefore important that only instruments based on true RMS techniques be used on power systems supplying nonlinear loads.
- There is also the possibility of both conducted and radiated interference above normal harmonic frequencies with telephone systems and other equipment due to variable speed drives and other nonlinear loads, especially at high carrier frequencies. EMI filters at the inputs may have to be installed on drives and other equipment to minimize the possibility of inference.
- Conventional meters are normally designed to read sinusoidal-based quantities. Nonlinear voltages and currents impressed on these types of meters introduce errors into the measurement circuits which result in false readings.

2.0 Description of case study

Ajangbadi 2 X 15MVA, 33/11kV injection substation of Eko Electricity Distribution Company, Lagos, Nigeria was selected as a case study and is proposed for a capacitor bank installation. Therefore, capacitor bank is required to minimize harmonics on the line, improve power factor, increase the stability and reliability of electric supply, improve utility revenue generation and above all meet or exceed their customers' expectations.

Figure 1 illustrates a single-line diagram of the aforementioned injection substation under study. The layout diagram comprises of two power transformers, T_1 and T_2 of 15MVA each, one 33kV bus, one 11kV bus, four 33kV circuit breakers (CB_{33}), six 11kV circuit breakers (CB_{11}), three 33kV line isolators (L_1 and L_2), one bus section/bus coupler and six outgoing 11kV feeders (F_1 to F_6):

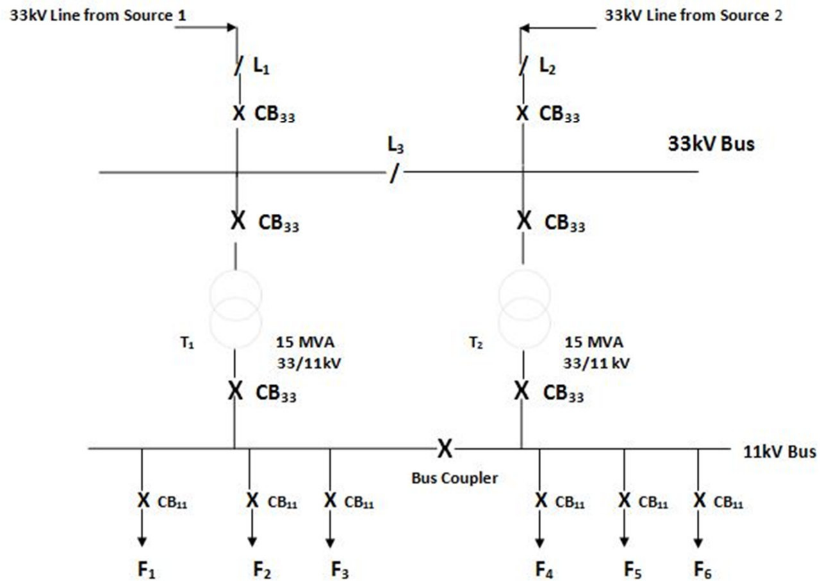

Figure 1: One Line Diagram of Ajangbadi 2 X 15 MVA, 33/11 kV Injection Substation

3.0 Substation Reactive Power and Capacitor Bank Rating Estimation

The utility substation has a total installed capacity of 30MVA and presently delivers real power at a power factor of 0.85. The research at this point is aimed at determining the MVAr capacity of the capacitor bank required to increase the power factor of the substation to a more desirable value of 0.95. The extra loads (in MW) that can be further added to the substation and still maintain this improved PF, without necessarily altering the total installed capacity of the system is calculated as follows:

First, the load parameters at pre- and post-power factor correction are required to be evaluated. Alternatively, power factor can also be redefined using equation 2 as:

$P = Scos\emptyset$ (2)

where,

P = Active Power (in MW)

S = Apparent Power (in MVA)

Cos φ = Power Factor

For pre-Power correction load parameters:

$\emptyset_1 = Cos^{-1}0.85$

$= 31.79°$

From equation 2,

$P_1 = 30 \times 0.85$

$= 25.5MW$

Therefore, the reactive power (Q_1) can be obtained using equation 3:

$Q_1 = P_1 Tan\emptyset_1$ (3)

$Q_1 = 25.5 \times Tan31.79$

$Q_1 = 15.80MVAr$

For post-PF correction load:

$\emptyset_2 = Cos^{-1}0.95$

$= 18.19°$

$Q_2 = P_2 Tan\emptyset_2$ (4)

$Q_1 = 25.5 \times Tan18.19$

$Q_2 = 8.38MVAr$

From the foregoing, it is evident that $Q_2 \ll Q_1$. Therefore, the difference between Q_1 and Q_2 as shown in equation 5 gives the rating of capacitor bank required to be installed at the substation.

$Capacitor\ Bank\ Rating, Q_3 = Q_1 - Q_2$ (5)

$= 15.80 - 8.38$

$= 7.42MVAr$

The vectorial representation of substation installed capacity (MVA), Active Power (MW), Reactive Powers Q_1 and Q_2 (MVAr) and Power factor angle φ_1 and ϕ_2 (degree), is shown in figure 2.

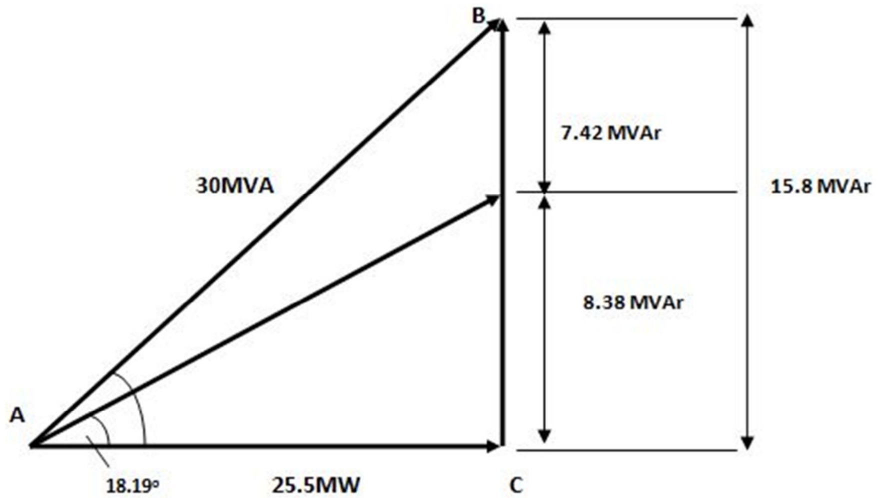

Figure 2: Vectorial Representation of Loads before and After Power Factor Correction

4.0 Expected Active Power (MW) as Allowable Extra Loads

Having improved the power factor of the electricity supply to the entire network, it is expected that a certain value of active power in Megawatts (Loads) can be added or installed in addition to the maximum active power in Megawatts, obtainable from the substation.

Let this extra load be represented by **K** MW. Figure 3 illustrates an improved vector of figure 2. Consequently, the value, **K**, can be determined using the algorithm presented in the flow chart of figure 4.

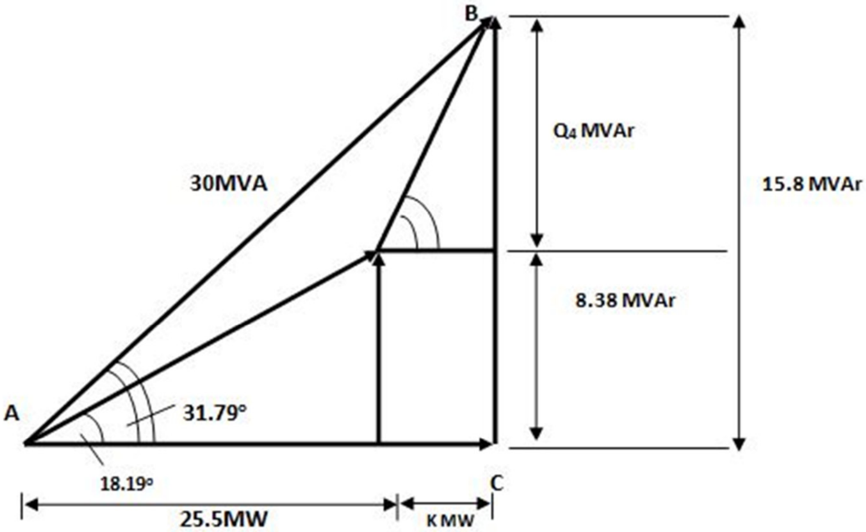

Figure 3: New Vector Diagram Showing Loading, including the Addable MW loads and the Network Reactive Power

5.0 Development of Algorithm for Substation and Network Load Parameters Computation

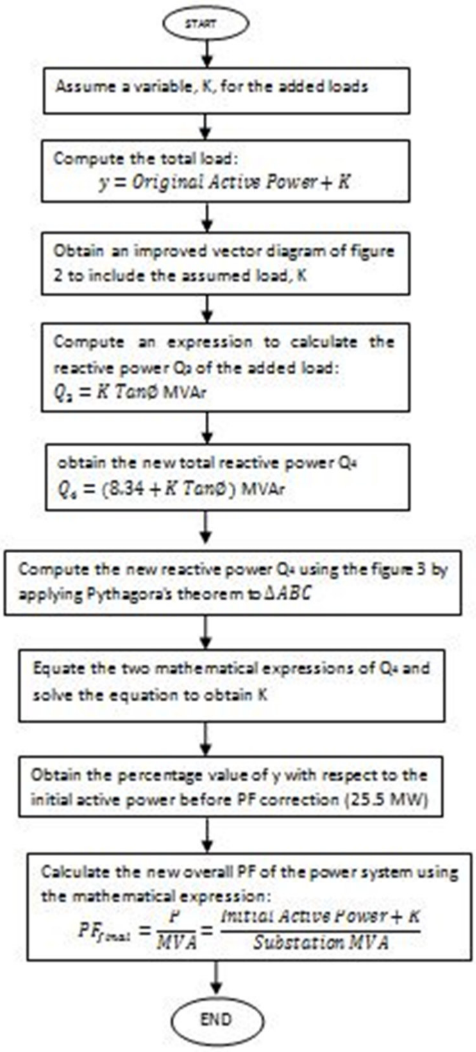

Figure 4: Flowchart of Algorithms for the Estimation of Addable Loads after Capacitor Bank Installation

From the flowchart in figure 4,
$Added\ Load = K\ MW$
Therefore, the new total load $y = 25.5 + K$
$Original\ MVA\ Capacity = 25.5/0.85 = 30MVA$
From figure 3,

$$
\begin{aligned}
Q_3 &= KTan\emptyset_1 \\
&= KTan(31.79°) \\
&= 0.6198KMVAr
\end{aligned}
$$

The expression for the new total reactive Power is given as:

$$Q_4 = (8.38 + 0.6198K)MVAr \qquad (6)$$

Also, the expression for new total reactive power Q_4, using ΔABC in figure 3, is obtained by applying Pythagora's rule:

$$Q_4 = \left(\sqrt{30^2 - (25.5 + K)^2}\right) MVAr \qquad (7)$$

Equating equations (6) and (7),

$$Q_4 = (8.38 + 0.6198K)^2 = 30^2 - (25.5 + K)^2$$

$$Q_4 = 1.38K^2 + 61.38K - 179.53 = 0 \qquad (8)$$

A value for K is obtained from the quadratic equation (8) by applying equation (9) as follows:

$$K = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \qquad (9)$$

$$K = \frac{-6.138 \pm \sqrt{6.138^2 - (4 \times 1.38 \times \{-179.53\})}}{2a}$$

$$K = 2.72\ or - 47.10$$

Therefore, the positive value of K is selected as the addable active power in MW after the installation of capacitor bank.

6.0 Determining a New Power Factor of the Power System Network

The initial substation active power value of 25.5MW and the addable active power value of 2.72MW implies that a 10.98% increase in power output from the substation into the network can be achieved.
Thus, the new power factor can be obtained as:

$$PF_{final} = \frac{M+K}{J} \qquad (10)$$

where,
M = Initial Active Power (MW) prior to capacitor bank installation
K = Addable Active Power after installation of capacitor bank
J = Installed Capacity of the substation which is 30MVA
Therefore,

$$
\begin{aligned}
PF_{final} &= \frac{25.5 + 2.72}{30} \\
&\approx 0.94
\end{aligned}
$$

7.0 Conclusion

The paper has generally presented a review of power factor importance and the value of capacitor bank specification for a typical Nigerian power substation used as a case study. In achieving this, the reactive power before and after the installation of a bank of capacitors were estimated and presented vectorially. An algorithm was developed to determine the ratings of required capacitor bank, overall new network reactive power, addable active power and the new system power factor (0.94) due to capacitor bank installation.

With the capacitor bank installed in the MV substation, the system is efficiently operated and the number of outages due to fault conditions are greatly reduced. This consequently results in improved power supply stability and reliability, increased revenue collection for the utility company and ultimately, meeting or exceeding electricity consumers' expectations.

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