Power Factor Correction Using Shunt Capacitor Bank for 33/11/0.4 kV, 10 MVA Distribution Substation

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Abstract: *A large number of distribution systems have run into problems such as poor voltage regulation, poor power factor, high losses and poor efficiency, overloading and less reliability for continuity of supply. It is necessary to improve the working of the power distribution systems to reduce the unfavourable conditions. In addition to reducing losses and improving voltage, capacitor release capacity. Improving the power factor increases the amount of real power load the circuit can supply. Using capacitors to supply reactive power reduces the amount of current in the line, so a line of a given ampacity can carry more loads. The shunt capacitors provide kVAR at leading power factor and hence the overall power factor is improved. In this paper, the appropriate rating of shunt capacitor bank is selected to correct the power factor for 33/11/0.4 kV, 10 MVA distribution substation (Maubin) in Myanmar and also show that the current reduction, voltage rise and loss reduction at 11 kV bus bar by connecting 2 MVAR shunt capacitor bank.*

Key Words*: power factor correction, shunt capacitor bank, current reduction, voltage rise, loss reduction,*

1. INTRODUCTION:

The reactive current circulating between the utility company's generator and the consumer converts electrical energy into heat in the power distribution system, and there is an additional load on generators, transformers, cabling and switchgear. Energy losses and voltage drops are incurred. If there is a high proportion of reactive current, the installed conductor cross sections cannot be fully utilized for transmitting useful power, or must be appropriately over dimensioned. From the utility company's standpoint, a poor power factor increases the investment and maintenance costs for the power distribution system, and these additional costs are passed on to those responsible, i.e. those power consumers with poor power factors.

Capacitors are static equipment without any rotating parts and require less maintenance. They are series or shunt, installed as a single unit or as a bank, is to regulate the voltage and reactive power flows at the point where they are installed. The shunt capacitor does it by changing the power factor of the load, whereas the series capacitor does it by directly offsetting the inductive reactance of the circuit to which it is applied. Therefore, the series capacitors provide for a voltage rise that increases automatically and instantaneously as the load grows and the shunt capacitors provide power factor correction applications.

Shunt capacitors, that is, capacitors connected in parallel with lines, are used extensively in distribution systems. Shunt capacitors supply the type of reactive power or current to counteract the out of-phase component of current required by an inductive load by. In a sense, shunt capacitors modify the characteristic of an inductive load by drawing a leading current that counteracts some or the entire lagging component of the inductive load current at the point of installation. Therefore, a shunt capacitor has the same effect as an overexcited synchronous condenser, generator, or motor. As shown in Fig. 1, by the application of shunt capacitor to a feeder, the magnitude of the source current can be reduced, the power factor can be improved, and consequently the voltage drop between the sending end and the load is also reduced. However, shunt capacitors do not affect current or power factor beyond their point of application. Fig. 1(a) and (c) show the single line diagram of a line and its voltage phasor diagram before the addition of the shunt capacitor, and Fig. 1(b) and (d) show them after the addition.

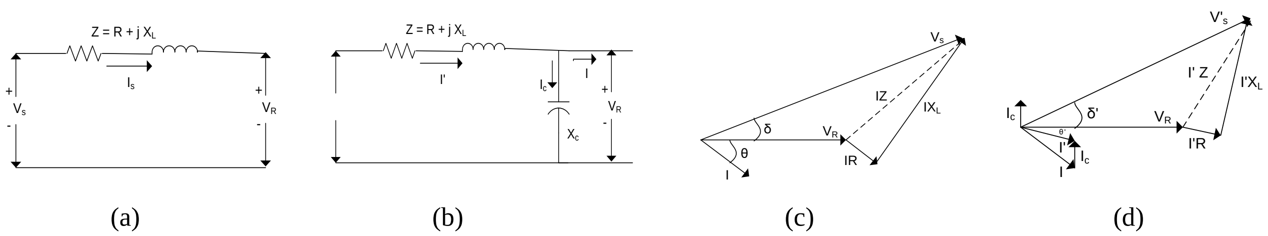


Fig.1 Voltage phasor diagrams for a feeder circuit of lagging power: (a) and (c) without and (b) and (d) with shunt capacitor

Shunt capacitor banks can be installed in a distribution system on pole-mounted racks, substation, and at high voltage or extra-high voltage for bulkpower applications. In this substation power factor is low; therefore reactive power is delivered very large. When large reactive power is to be delivered at medium or high voltages, then shunt capacitor banks are installed in substation location. The open rack construction and exposed connection need significant protection in this substation. Such installations contain capacitor banks, cutout units with fuses, circuit breakers, surge arresters, controllers, insulator units at medium or high voltages and interconnections.

Shunt capacitor bank can be installed basically three possibilities to correct loads local or, in groups or branch. In this substation at 11 kV bus approach, the power factor correction is applied to a group of loads at one location. A group or capacitor bank installation is shown in Fig.2. This technique is suitable for utility or industrial customers with distributed load. If the entire load comes on or off together, then it is reasonable to switch the capacitor bank in this manner. If part of the load is switched on and off on a regular basis, then this type of reactive compensation is not appropriate. It is economical to have a large capacitor bank for reactive compensation rather than several smaller banks. Using shunt capacitors to supply the leading currents required by the load relieves the generator from supplying that part of the inductive current. The system benefits due to the application of shunt capacitors include; (1) Reactive power support, (2) Voltage profile improvements, (3) Line and transformer loss reductions, (4) Release of power system capacity, (5) Savings due to increased energy loss. These benefits apply for both distribution and transmission system.

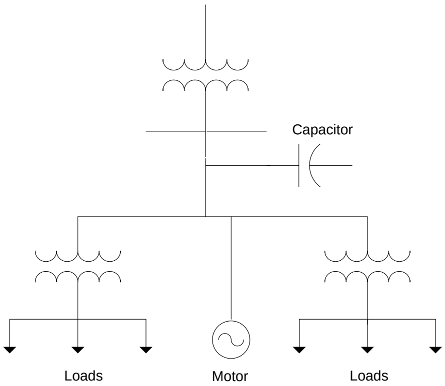


Fig. 2 Power factor correction using group or central capacitor bank technique

2. Power Factor Improvement:

A. Power Factor

The cosine of angle between voltage and current in an a.c circuit is known as power factor. In an a.c circuit, there is generally a phase difference between voltage and current. In an inductive circuit, the current lags behind the applied voltage and the power factor of the circuit is referred to as lagging. In a capacitive circuit the current leads the applied voltage and therefore, the power factor of the circuit is said to be leading. Consider an inductive circuit, which draws a current *I* from the supply mains lagging behind the supply voltage *V* by an angle Φ, known as phase angle, the phasor diagram is shown in Fig. 3.

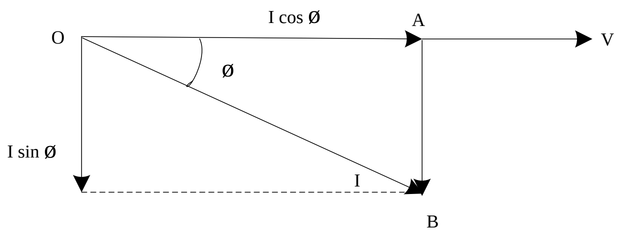


Fig. 3 Phasor diagram of the circuit

The current *I* can be resolved into two components, one along the voltage phasor and the other perpendicular to it. The component along the voltage phasor, *I* cos Φ is called the in phase or active component of current, and the on perpendicular to the voltage phasor, *I* sin Φ is called the out of phase or wattles or reactive component of current. If all these components are multiplied by voltage *V*, the product of voltage *V* and in phase component of current *I* cos Φ, i.e *VI* cos Φ will represent the true power of the circuit in watts or kW, whereas the product of voltage *V* and the quadrature component of current *I* sin Φ i.e. *V I* sin Φ will represent the reative power in VAR or kVAR and the product of voltage *V* and current *I* i.e. *VI* will represent the apparent power in volt - amperes or kVA .Thus we get a power triangle, as shown in Fig. 4 . The smaller the reactive component of power, the smaller is the phase angle and the higher is the power factor. For leading currents the triangle becomes reversed. This fact provides a key to the power factor improvement. If a device drawing leading reactive power is connected in parallel with the inductive load, then the lagging reactive power of the load will be partly neutralized, resulting in improvement of the power factor of the system.

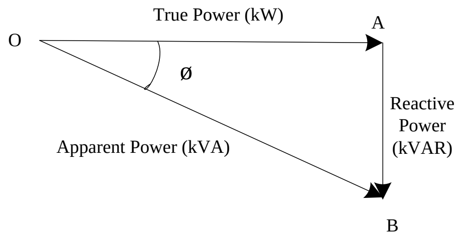


Fig. 4 Power triangle of the circuit

From power triangle *OAB* shown in Fig. 4,

OA = kW component of power

AB = kVAR component of power

$$\text{Cos } \Phi = \frac{OA}{OB} = \frac{kW}{kVA} \quad \text{(the ratio of true power and apparent power)} \tag{1}$$

Reactive power in kVAR = Apparent power x sin Φ

$$= \text{kVA sin } \Phi \tag{2}$$

$$= (\text{kVA cos } \Phi) \times \frac{\sin\Phi}{\cos\Phi}$$

$$= \text{kW tan } \Phi \tag{3}$$

$$(\text{kVA})^2 = (\text{kW})^2 + (\text{kVAR})^2 \tag{4}$$

B. Power Factor Correction

Fig. 4 shows the triangular relationship that exists between kilowatts, kilovolt amperes, and kilovars. By adding the capacitor, the reactive power component Q of the apparent power S of the load can be reduced or totally suppressed. Fig. 5 illustrates the power factor correction for a given system. As illustrated in the figure, capacitor draws leading reactive power from the source; that is, they supply lagging reactive power to the load. Assume that a load is supplied with a real power P, lagging reactive power Q_1, and apparent power S_1 at a lagging power factor of,

$$\text{P.f}_1 = \cos \Phi_1 = \frac{P}{S1} \tag{5}$$

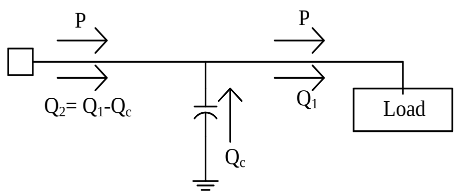
$$= \frac{P}{\sqrt{P^2+Q1^2}} \tag{6}$$

When a shunt capacitor of Q_c kVA is installed at the load, the power factor can be improved from cos Φ_1 to Φ_2, where

$$\text{P.f}_2 = \cos \Phi_2 = \frac{P}{S2} \tag{7}$$

$$= \frac{P}{\sqrt{P^2+Q2^2}} \tag{8}$$

$$= \frac{P}{\sqrt{P^2+(Q1-Qc)^2}} \tag{9}$$



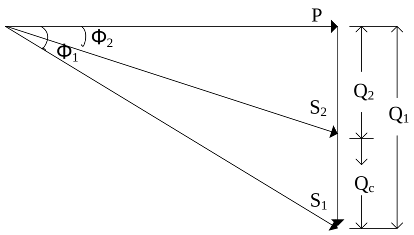


Fig. 5 Illustration of power factor correction using shunt capacitor

3. Case study of power factor correction using 2 MVAR shunt capacitor bank:

A. Analysis of Load Data at 11 kV Bus Bar

In Maubin substation, the rating of 10 MVA main transformer is applied to connect 33 kV and then step down to 11 kV distribution network. This line is radial line system as shown in Fig. 6. By adding the rating of shunt capacitor at 11 kV bus, the power factor improvement can be determined. Capacitor rating is the difference between MVAR ratings of original power factor and desired power factor. Table I shows the log sheet data of 11 kV bus, 10 MVA main transformer in Maubin substation.

Table I

11 kV main 10 MVA log sheet data

11 kV Main 10 MVA Log Sheet						11 kV Main 10 MVA Log Sheet					
Time	kV	A	MVA	MW	p.f	Time	kV	A	MVA	MW	p.f
1:00	10.7	180	3.3359	2.93	0.8783	13:00	10.2	249	4.3989	3.93	0.8934
2:00	10.1	180	3.1488	2.89	0.9178	14:00	10.2	267	4.7171	4.16	0.8819
3:00	10.7	177	3.2803	2.97	0.9054	15:00	10.3	276	4.9236	4.35	0.8835
4:00	10.6	180	3.3048	3.01	0.9108	16:00	10	303	5.2482	4.61	0.8784
5:00	10.5	228	4.1466	3.7	0.8923	17:00	10.2	348	6.1478	5.45	0.8865
6:00	10.4	273	4.9177	4.36	0.8866	18:00	10.2	378	6.6788	5.85	0.8759
7:00	10.4	294	5.2958	4.61	0.8705	19:00	10	351	6.0798	5.38	0.8849
8:00	10.2	309	5.4588	4.86	0.8903	20:00	10.2	315	5.5649	4.98	0.8949
9:00	10	348	6.0273	5.26	0.8727	21:00	10.2	294	5.1939	4.58	0.8818
10:00	10.5	279	5.0742	4.58	0.9026	22:00	10.4	255	4.5936	4.08	0.8882
11:00	10.4	273	4.9179	4.43	0.9008	23:00	10.5	204	3.7099	3.29	0.8868
12:00	10.2	249	4.3989	4.01	0.9116	24:00	10.5	186	3.3827	2.99	0.8839

B. Design Calculation of Capacitor Bank Size

The following data are obtained from Maubin substation to make design calculation of appropriate capacitor bank for power factor correction.

Transformer rating = 10 MVA

Transformer reactance = 8 %

Voltage = 11 kV

Present maximum load = 5.85 MW

Present maximum MVA = 6.6788 MVA

Power factor (maximum load) = 87.59 %

Desired power factor = 95

If the power factor is raised to 95 %

$$\text{Desired MVA Demand} = \frac{\text{Present Load}}{\text{Desired Power Factor}} \quad (10)$$

$$= \frac{5.85}{0.95} = 6.158 \text{ MVA}$$

The size of the capacitor required to accomplish this isdetermined from the MVAR at the two values of power factor as follows:

$$\text{MVAR} = \sqrt{\text{MVA}^2 - \text{MW}^2} \quad (11)$$

$$\text{MVAR}_1 \text{ at } 0.8759 \text{ p.f} = \sqrt{(6.6788)^2 - (5.85)^2} = 3.222 \text{ MVAR}$$

$$\text{MVAR}_2 \text{ at } 0.95 \text{ p.f} = \sqrt{(6.158)^2 - (5.85)^2} = 1.923 \text{ MVAR}$$

$$\text{Capacitor rating} = \text{MVAR}_1(\text{uncorrected}) - \text{MVAR}_2(\text{corrected}) \quad (12)$$

$$= 3.222 - 1.923 = 1.299 \text{ MVAR}$$

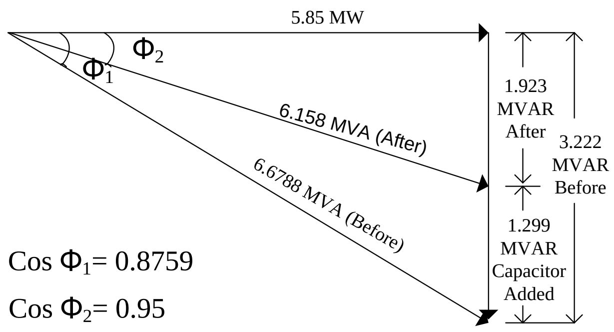


Fig. 6 The apparent power demand before and after adding capacitor

The apparent power demand before and after adding capacitor on this substation is shown in Fig.6. This figure also shows that the apparent power is reduced from 6.6788 MVA to 6.158MVA (reduction of 7.79 %) when shunt capacitor is installed to improve power factor of 95%. Theoretically, capacitors could provide 100 % of needed reactive power. In practical usage, however, power factor correction to approximately 95 % provides maximum benefit.

Multiplying factor = 0.238

$$\text{Capacitor Rating} = \text{Multiplying Factor} \times \text{MW Demand} \tag{13}$$
$$= 0.238 \times 5.85$$
$$= 1.3923 \approx 2 \text{ MVAR}$$

In this substation, the power factor is corrected from 87.59 %. According to the above calculated results, to achieve desired power factor of 95% while providing the same productive power of 5.85 MW, the rating of 2 MVAR shunt capacitor bank is appropriated to install at 11 kV bus in this substation.

C. Check for power factor improvement after installation of capacitor bank

For maximum load condition,

$$\text{MVAR}_2\text{(corrected)} = \text{MVAR}_1\text{(uncorrected)} - \text{Capacitor rating}$$
$$= 3.222 - 2$$
$$= 1.222 \text{ MVAR}$$

$$\text{MVA}_2 = \sqrt{(\text{MW})^2 + (\text{MVAR})^2} \tag{14}$$
$$= \sqrt{(5.85)^2 + (1.222)^2}$$
$$= 5.9763 \text{ MVA}$$

$$\text{Power Factor} = \frac{\text{Present Load}}{\text{MVA Demand}}$$
$$= \frac{5.85}{5.9763} = 0.9789$$

D. Check for voltage rise after installation of capacitor bank

The percent of voltage rise and improved voltage after installation of capacitor bank at a transformer secondary bus 11 kV are calculated by using the following equations:

$$\%\text{ Voltage rise} = \frac{\text{Capacitor MVAR x Transformer reactance \%}}{\text{Transformer MVA}} \tag{15}$$

$$\text{Improved voltage} = \text{original kV} + \frac{\text{original kV x volt rise \%}}{100} \tag{16}$$

$$\%\text{ Voltage rise} = \frac{2\ x\ 8}{10} = 1.6\ \%$$

The voltage regulation of a system from no-load to fullload is practically unaffected by the amount of capacitors, unless the capacitors are switch. However, the addition of capacitors can raise the voltage level. The voltage rise due to capacitors in most industrial plants with modern power distribution system and a single transformation is rarely more than a few percent.

For maximum load condition,

$$\text{Improved voltage} = 10.2 + \frac{10.2 \ x \ 1.6}{100} = 10.363 \text{ kV}$$

E. Check for line current reduction after installation of capacitor bank

The percent line current reduction and reduced current after installation of capacitor bank are calculated by using the following equations:

$$\%\text{ current reduction} = 100\text{x}[1 - \frac{\text{Present Power Factor}}{\text{Improved Power Factor}}] \quad (17)$$

$$\text{Reduced current} = \text{original(I)-} \frac{\text{original (I)x current reduction \%}}{100} \quad (18)$$

For maximum load condition,

$$\%\text{ current reduction} = 100 \text{ x } [1- \frac{0.8759}{0.9789}] = 10.522 \%$$

$$\text{Reduced current} = 378 - \frac{378 \text{ x } 10.522}{100} = 338.226 \text{ A}$$

F. Check for lower losses after installation of capacitor bank

The percent power loss and loss reduction are calculated by using the following equations;

$$\%\text{ Power Loss} = 100 \text{ x } [\frac{\text{Present Power Factor}}{\text{Improved Power Factor}}]^2 \quad (19)$$

$$\%\text{ Loss reduction} = 100 \text{ x } [1-[\frac{\text{Present Power Factor}}{\text{Improved Power Factor}}]^2] \quad (20)$$

$$\%\text{ Loss reduction} = 100 \text{ x } [1- [\frac{0.8759}{0.95}]^2] = 14.99 \%$$

There is 14.99 % reduction in power losses for 33/11/0.4 kV, 10 MVA substation.

G. Result Data after installation of capacitor bank

Table II shows the result data; these are calculated results after installing 2 MVAR shunt capacitor banks at 11 kV bus, the secondary side of 10 MVA transformer to achieve the desired power factor (0.95) while providing the same productive power of 5.85 MW. Table III shows the proposed 2 MVAR shunt capacitor bank data for this substation. Single Line Diagram of 33/11/0.4 kV Maubin distribution substation is shown in Fig. 7.

TABLE II

Result data after adding 2 MVAR shunt capacitor bank at 11 kV main 10 MVA transformer

Time	kV	A	MVA	MW	p.f	Time	kV	A	MVA	MW	p.f
1:00	10.9	159	2.9579	2.93	0.9906	13:00	10.4	222	3.9301	3.93	0.9999
2:00	10.3	170	2.9857	2.89	0.9679	14:00	10.4	235	4.1660	4.16	0.9986
3:00	10.9	163	3.0314	2.97	0.9797	15:00	10.5	244	4.3608	4.35	0.9975
4:00	10.8	167	3.0764	3.01	0.9784	16:00	10.2	267	4.6379	4.61	0.9939
5:00	10.7	203	3.7022	3.7	0.9994	17:00	10.4	312	5.5151	5.45	0.9882
6:00	10.6	242	4.3686	4.36	0.9980	18:00	10.4	338	5.9764	5.85	0.9789
7:00	10.6	258	4.6497	4.61	0.9914	19:00	10.2	311	5.4439	5.38	0.9883
8:00	10.4	280	4.9469	4.86	0.9824	20:00	10.4	283	5.0034	4.98	0.9953
9:00	10.2	308	5.3438	5.26	0.9843	21:00	10.4	260	4.6020	4.58	0.9952
10:00	10.7	252	4.5837	4.58	0.9992	22:00	10.6	226	4.0815	4.08	0.9996
11:00	10.6	246	4.4321	4.43	0.9995	23:00	10.7	181	3.3024	3.29	0.9963
12:00	10.4	227	4.0146	4.01	0.9989	24:00	10.7	165	3.0190	2.99	0.9904

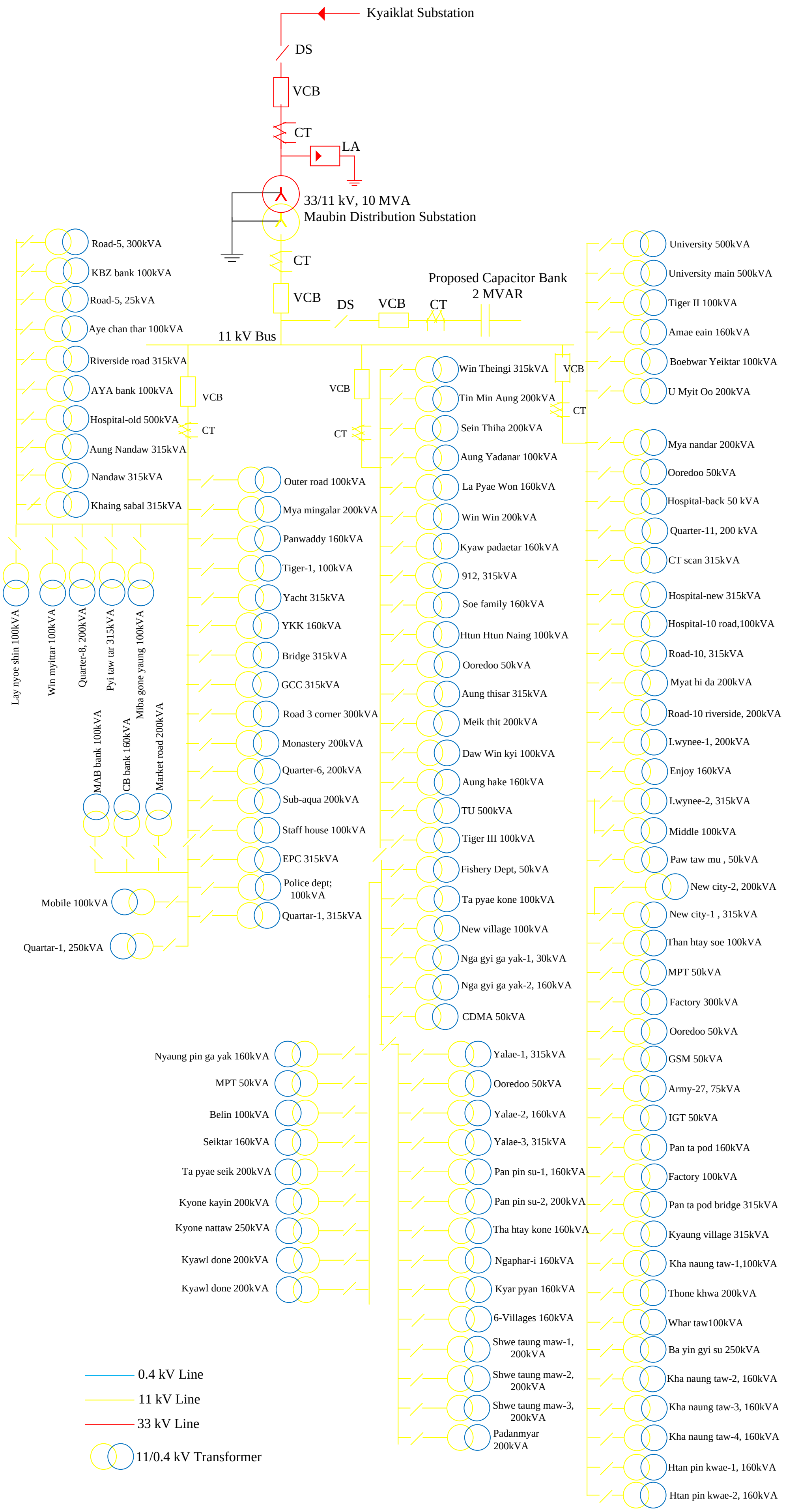


Fig. 7 Single Line Diagram of Maubin Distribution Substation

Table III

The proposed 2 MVAR shunt capacitor bank data

No.	Principal Parameter	Value
1	Nominal system voltage	11 kV
2	KVAR capacity	2000 KVAR (min)
3	No. of phase	3 phase
4	Rated voltage	12.65 kV
5	Frequency	50 Hz
6	Rated output	2640 KVAR
7	Rating of capacitor unit in KVAR with internal fuses	220 KVAR 2 bushings
8	Connection of capacitor bank	Double Star with internal fuses
9	No. of units/bank	6+6 = 12 Nos /units
10	Power loss	Not to exceed 0.2 watt/KVAR
11	Permissible over load	Reference to voltage,current and reactive output shall conform to IS13925/1998
12	Type of grounding	Ungrounded neutral
13	Capacitor impregnant	Non PCB
14	Type of protection	Internal fuse
15	Type of discharge	Internally through resistor provided
16	Capacity to receive in rush current	Not less than 100 times rated current

4. CONCLUSION:

Power factor correction is given to restore the power factor to as close to unity as is economically viable. This is normally achieved by the addition of capacitors to the electrical network which compensate for the reactive power demand of the inductive load and thus reduce the burden on the supply. The use of shunt capacitor has increased because they are relatively inexpensive, easy and quick to install and can be deployed virtually anywhere in the network. This paper described 2 MVAR shunt capacitor bank is an appropriate device to install at 11 kV bus, the secondary voltage of 10 MVA transformer to provide capacitive reactive compensation or power factor correction. Its installation show that other beneficial effects on the system such as: improvement of the voltage profile, reduction in line current, reduction of power loss and release of power system capacity in distribution substation. In this case study, the power factor correction is applied to a group of loads at one location. This technique is suitable for utility or industrial customers with distributed load and is also economical to have a large capacitor bank for reactive compensation rather than several smaller banks for the entire distribution system.

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