2 METHODOLOGY

2.1 BASE LOAD REACTIVE POWER REQUIREMENT

The method of reactive power compensation, proposed in this research is suitable to meet the base reactive power requirement of the network. The base reactive demand of the total low voltage network will give an indication of the maximum number of fixed type capacitors that could be installed at the distribution level.

Daily load curves of primary substations in Colombo City were plotted in Annexure A based on load readings [4] taken on selected Wednesdays & Sundays in May 2006 and September 2008. Base reactive power supplied by each primary substation was identified using those load curves and the maximum number of fixed capacitors that could be installed in respective area was determined. These quantities set a benchmark for the installation program.

2.2 SELECTION OF THE PREFERRED LOCATION

2.2.1 Low cost options

Generalized installation of power capacitors at following low voltage locations of the selected sample were studied due to their low installation cost and the extended loss reduction ability in the low voltage network, which is not the case with high voltage capacitors.

1. Secondary of distribution transformers as fixed units or switching units and
2. Feeder pillars as fixed units in the low voltage network.
Above locations are to be further evaluated for the possible energy saving, cost of installation and cost recovery period for identification of the best option. The energy saving was determined by modeling typical cases of loads and part of the network involved in the proposed methods of installation. The proposed locations are indicated in Figure 4.

2.2.2 Sample installations

Figure 5 and Figure 6 illustrate sample installations made for the study. Figure 5 shows the arrangement of low voltage capacitors proposed to install at 11kV/415V
distribution transformers. Figure 6-a shows the fixing arrangement of a 30 kvar low voltage capacitor, in side of a steel enclosure, which is attached on to existing feeder pillar as in Figure 6-b.

2.2.3 Building the simulink model

a) System considered for simulation

The part of the network considered for simulation is depicted in Figure 7. It represents an 11kV/415V distribution transformer supplying two equally loaded feeder pillars. Fixed type capacitors of the model at the transformer and feeder pillar are switched as per the case of study.

![Figure 7: Part of network considered for simulation](image)

The Simulink model of the part of network considered is shown in Figure 8. The breaker shown in the model was for the simulation purpose only.

![Figure 8: Total system to represent one transformer supplying two feeders](image)
b) Simulink subsystem - Feeder pillar with fixed capacitors and the load

Subsystem to represent one feeder pillar in simulink is detailed in Figure 9. Fixed type capacitors at feeder pillars are switched on as per the case of study and the breakers are for the simulation purposes only.

![Diagram of Feeder pillar subsystem](image)

Figure 9 : Subsystem to represent one feeder pillar.

c) Simulink subsystem - Measuring module

Figure 10 shows the subsystem for measuring active and reactive power, voltage and current in the simulink model. Three phase active & reactive power and line current & voltage are displayed in the scope. This sub system can be enabled or disabled for monitoring or logging of P, Q, V & I values at nodes of the total system.

![Diagram of Measuring module subsystem](image)

Figure 10 : Subsystem for Measuring P, Q, V & I
2.2.4 Input data and assumptions made for the simulation

a) Load at feeder pillar: Actual field measurements, logged over a period of 24 hours at 15 minutes interval was used to model the load through the feeder pillar.

b) 1000kVA distribution transformer: Transformer was connected to two numbers of equally loaded feeders of which three phases were balanced.

2.3 SELECTION OF SIZE OF CAPACITOR

Once the preferred location was identified, the next step was to determine the size of the fixed type capacitor to be installed.

2.3.1 Size of capacitor for overall maximum energy saving

Simulink model was simulated for different capacitor values under the assumed load conditions over 24 hrs period. Energy saving results was tabulated to identify optimum capacitor value considering the maximum possible energy saving. Since the installation cost to include all materials, labour & transport is minimal and cost recovery period is only few months where the lifetime extends more than 20 years, the cost of capacitor has no significant influence on the selection of optimum capacitor size.

2.3.2 Size of capacitor to avoid resonance at transformer under low load conditions

Energized transformers, under no load condition draw lagging reactive power due to core magnetization. Reactive power consumption of the transformer increases with the load current due to leakage reactance of transformer windings. Fixed type capacitors can be used at the transformers to compensate reactive power consumption by the transformer itself.

However, if the connected capacitance at the transformer is higher, overvoltage would occur under no load condition and the transformer can fall into resonance due to saturation of the iron core. The recommended value [5] of fixed capacitor at a transformer is 5% of the rating of the transformer. For example, a 50 kvar fixed capacitor can be connected at the secondary of a 1000kVA transformer.
The selected capacitor size, to be used at feeder pillars, which is the second option, should not create overvoltage at the transformer under light load conditions, as there are 2 to 3 feeder pillars connected to a distribution transformer in general in the selected sample.

Field measurements were carried out to identify the minimum load conditions at transformers and feeder pillars.

2.4 SELECTION OF VOLTAGE RATING OF CAPACITORS

Lifetime of capacitors depends on its operating voltage, ambient temperature and the maximum rms current through the capacitors, which is decided by the harmonics presence in the network.

Standard shunt power capacitors have a voltage rating of 1.1Un for 8hrs in every 24h and the continuous admissible voltage is Un, where Un is the rated voltage [6]. Lifetime of capacitors can be extended by selecting a higher value for its rated voltage than the actual operating voltage.

2.5 SELECTION OF AMBIENT TEMPERATURE CATEGORY

Steel enclosures were used to attach and protect fixed capacitors installed at feeder pillars. Although enclosures had provisions for ventilation, the ambient temperature applicable to capacitor could be much higher than the outside ambient air temperature. This was assessed with field measurements and the selection of ambient temperature category of capacitor units was confirmed with the results.

2.6 REDUCTION OF OPERATING TEMPERATURE OF CAPACITORS

Fixed type capacitors, to be installed at feeder pillar are proposed to house in a steel enclosure with provisions for better ventilation. Since enclosures are opened to direct sunlight every possible means shall be employed to reduce the heating of steel enclosure due to radiation of the sun. Followings matters were studied for
identifying methods for reducing operating temperature of capacitors, which will prolong the lifetime of capacitor units.

2.6.1 Use of enclosures

The temperature rise of the capacitor container was monitored on two capacitor units, while one capacitor was kept inside of a ventilated steel enclosure and the other was without an enclosure. Both the specimens were exposed to sunlight, during the measurement as indicated in Figure 11. The purpose of this measurement was to establish the effectiveness of enclosures for reducing the heating of outdoor capacitor unit.

![Figure 11: Effect of enclosure](image)

2.6.2 Exterior colour of enclosure

Feeder pillars of the Colombo City distribution system had been painted with light gray colour for a longer period. But in the recent pass, the colour of feeder pillar had been changed to dark green, mainly considering the aesthetic view. Then the steel enclosures housing capacitors also had to be matched with the feeder pillar colour.

The effect of exterior colour of steel enclosure was evaluated by simultaneously logging internal air temperature of the two cases, where one enclosure was painted with silver colour and the other with dark green colour.
2.6.3 Use of thermal insulation

Effectiveness of reflective foil for reducing the heat due to sun's radiation was monitored. Thermal insulation can be affixed on to three internal surfaces of outdoor enclosures, especially on the front side, which is the largest area on which the sunlight falls directly. One side of the thermal insulation has a laminated aluminum foil, which is very effective in reflecting the sun's radiation out of the enclosure.

![Figure 12: Use of thermal insulation with reflective foil](image)

2.6.4 Provisions for ventilation

Ventilation arrangements are provided on three sides of the steel enclosure as shown in Figure 13. There are two possible arrangements for ventilation as louvers and holes. The use of ventilation louvers or holes on the front surface is not suitable as the sunlight could directly fall on to the internal capacitor unit and it could be covered by posters with the time.

![Figure 13: Ventilation arrangements with louvers and holes](image)
2.7 INFLUENCE OF HARMONICS

When a capacitor bank is added to a power system, it is effectively connected in parallel with the system's impedance, which is primarily inductive. As far as the harmonic source is concerned, it sees a capacitor in parallel with an inductor. There is a frequency at which these two parameters will be equal. This frequency is called the system's natural resonant frequency. At this frequency, the system's impedance appears to the harmonic source to be very large. Therefore, a harmonic current at the resonant frequency flowing through this impedance will result in a very large harmonic voltage. Therefore frequency response of fixed capacitors in low voltage system was studied to identify resonance conditions.

2.7.1 Frequency response of fixed capacitors in the system.

The two possible locations for connecting low voltage capacitors were considered for the analysis in frequency domain to evaluate possible resonance conditions. Those locations are fixed value capacitor at the feeder pillar and at the distribution transformer. The power network was modeled using simulink for the above two cases and the frequency response was studied to identify resonance condition for various capacitor values.

2.7.2 Current & voltage harmonics in low voltage network.

Harmonics levels of feeder loads and that of the capacitor current were monitored using LEM make single phase power quality analyzer, illustrated in Figure 14. These readings were taken routinely at 120 numbers of feeder pillars, at which capacitors were installed.

Figure 14 : Power quality analyzer with flexible current transformer
2.8 OVERVOLTAGE DUE TO FIXED CAPACITORS

The model without the load was simulated for various capacitor values to assess overvoltage possibilities due to fixed value capacitors. The voltage rise at the respective points of the network was monitored for the two cases, where the fixed type capacitor is connected at feeder pillar and transformer respectively.