VIABILITY OF FIXED TYPE POWER CAPACITORS FOR LOSS REDUCTION IN LOW VOLTAGE (400V) DISTRIBUTION NETWORKS OF POWER UTILITIES

A dissertation submitted to the
Department of Electrical Engineering, University of Moratuwa
in partial fulfillment of the requirements for the
degree of Master of Science

by

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February 2009

DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

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I endorse the declaration by the candidate.

Name of Supervisor: Dr. JP Karunadasa

TABLE OF CONTENTS

ABSTRACT

The viability of fixed type power capacitors for loss reduction in low voltage (400V) distribution networks of power utilities was studied. Usually, reactive power of the load is compensated at high voltage levels by utility operators, which requires high investment on equipment. This study reveals an alternative low cost reactive power compensation method, which will reduce the capacity requirements of HV reactive power installations.

Fixed type power capacitors had been used at the secondary of few of earlier 11kV/415V distribution transformers in Colombo City distribution system. Most of these units are in operation, even after 20 years of service. But the practice of having fixed capacitors at distribution transformers was not continued thereafter.

It was identified through model simulation and field measurements that installation of fixed value power capacitors at feeder pillars of the power distribution network is more economical compared to the earlier practice in Colombo City. The expected minimum energy saving is approximately 300 kWh/month with a 40kvar, 440V rated capacitor installed at the feeder pillar.

The main advantages of the proposal are low capital requirement and shorter payback period. The expected maximum payback period is 7 months. In the proposed method, the temperature of operation of capacitors was more critical. The reliability of capacitors is to ensure by adapting measures to reduce the operating temperature of capacitor units, housed in steel enclosures.

Encloses, housing capacitor units reduces the case temperature of capacitors. This arrangement was superior to the use of outdoor type capacitors without enclosures. Use of light coloured enclosure with holes for ventilation and thermal insulation will reduce the temperature of operation of capacitor unit at least by 10 ^{0}C, compared to dark green finished enclosure with louvers for ventilation and without thermal insulation on the internal surface.

Field measurements confirmed that the lifetime of capacitors are not affected due to load harmonics. The maximum harmonic current absorbed by capacitors was 50% lower than the continuous over current rating of the capacitor unit. The simulation of the model with different fixed capacitor sizes shows that there is no risk that transformers would fall into resonance along with fixed capacitors under the load harmonics due to the selected size of capacitors and level of load harmonics. The voltage rise due to fixed type capacitors at no load condition is insignificant for the sizes of capacitors proposed in this study, Hence there is no risk that the power transformers would not fall into ferroresonance due to fixed capacitors.

Practical difficulties of usage of LV fixed type capacitors were identified and solutions were recommended so that a cluster of fixed value shunt capacitors can be installed and operated effectively at low voltage distribution level for achieving greater economical benefits.

ACKNOWLEDGMENTS

I sincerely thank Dr. JP Karunadasa, Supervisor of this research study for his invaluable suggestions and guidance. I specially thank Professor JR Lucus, Dr. NK Wickramarachchi, Dr. SP Kumarawadu and Mr. WDAS Wijayapala for their constructive comments on this study . I also thank Dr. Udawatta for directing us in the proper path so that we could complete our research studies in time.

I greatly appreciate Mr. FK Mohideen, AGM (R2), Ceylon Electricity Board who guided me to study the application of fixed type power capacitors for loss reduction in Colombo city.

I also thank staff of various branches of Colombo City of Ceylon Electricity Board who helped me to implement the proposed system as a study sample. I also thank the Management of Ceylon Electricity Board for offering me the valuable opportunity of studying for my Masters Degree.

LIST OF FIGURES

LIST OF TABLES

1 RESEARCH STUDY

1.1 INTRODUCTION

Electrical network consists with generators, power transformers, transmission lines and distribution lines have resistive, inductive and capacitive effects. When the current passes through resistive elements of the network, it consumes active power, which is a loss of power. It is expressed as I^2R, where I is the current through the network and R is the resistance of network components. The efficiency of power delivery is improved if the line current could be reduced for supplying the same active power.

In most of the cases, the reactive power requirement of electrical loads is lagging, which means the load is inductive. Electricity generators shall operate to meet the active and reactive power demands of the load, which supplies through long transmission lines. Alternatively, it is possible to supply lagging reactive power with the use power capacitors, which is basically a passive device. Thus power generators can be used to supply active power, while power capacitors are supplying a major part of the lagging power requirement of the load. Power capacitors reduce the current through the electrical network as a portion of total reactive power is now supplied by capacitors, located closed to the load.

Reduction in line current, due to power capacitors reduces network losses. Therefore, power capacitors are installed at high voltage and medium voltage levels in power utilities for compensation of lagging reactive power of loads and thereby improving the efficiency of power delivery.

1.1.1 Proposed method of loss reduction & its uniqueness

Reactive power compensation with power capacitors at high or medium voltage levels could be categories as bulk power compensation. In most of the cases, the target is to achieve unity power factor of operation. Lagging reactive power is injected to the electrical system of utilities as Breaker Switch Capacitors (BSC), where the total capacitance is controlled by circuit breakers or Static Var Controllers (SVC), where the capacitance is smoothly controlled by power electronics.

Capacitors can be used in low voltage distribution network too for compensation of reactive power. The application of power capacitors in low voltage networks is not a common practice in electrical utilities due to several reasons. The low voltage network consists with many branch circuits and the level of reactive power flow is low. Therefore, it is required to connect large number of low power rated capacitors at many points for compensating reactive power of the load within the low voltage network itself. On the other hand, installation, monitoring and proper maintenance of a cluster of low voltage capacitors is a labour intensive program.

Fixed type capacitors are superior to switching type LV capacitors for a similar application as fixed capacitors can be connected at large number of points in the low voltage network and operate economically. The application of capacitors in LV networks can be identified as a distributed method of compensation. The use of fixed value low voltage capacitors could make a viable project by identifying problems specific to the proposed method and formulating solutions for same.

1.1.2 Advantages of the proposed method

The equipment configuration is simple and thus capital requirement is lower compared to switching capacitor bank. With low voltage fixed type capacitors, lagging power of the load is compensated almost at the load itself and thus the effects of reduced line current is extended almost up to the final delivery point of the utility. On contrary, with high voltage power capacitors, the line current reduces only in sections upstream from the high voltage grid substation, where capacitors are installed. It will not improve power loses in the low voltage network. The reactive power compensation at low voltage level will reduce the burden on HV or MV reactive power compensation stations improving the overall efficiency.

1.1.3 Limitations of the proposed method

In the proposed method, capacitors are installed as fixed units. The size of capacitor is selected considering the base reactive power of the load to avoid over compensation in off-peak time. Overcompensation increases the line current and thus has a negative effect on the intended purpose. The proposed method reduces distribution losses, but significant improvement of powerfactor cannot expect for all load condition as in the case of switching type capacitors.

1.2 OBJECTIVES

Some of 11kV/415V distribution transformers in Colombo city had been fitted with fixed type low voltage capacitors. This particular make of unit type distribution transformers with high voltage switching ring main unit (RMU) and low voltage distribution panel had been installed during the period from 1989 ~ 1990. The practice of having a fixed type capacitor at the secondary of distribution transformer had not been continued. Some of the capacitors installed as above are still in operation, after 20 years of service.

The power capacitors installed as above had reduced the line current and the accumulated effect of reduced power loss over the long period of their operation is immense. The main purpose of this research is to identify problems specific to the proposal and formulate valid and proven guide lines to make it more viable the application of fixed type power capacitors for loss reduction in low voltage (400V) distribution networks of power utilities.

Power capacitors, installed in an outdoor environment of a country like Sri Lanka would subject to very high temperature. Therefore the method of installation is critical for extended lifetime of capacitors. Hence suitable methodologies are to devise for determining followings.

a) Preferred location in low voltage network
b) Size of capacitor
c) Whether to install with or without enclosure
d) Enclosure selection
   Exterior colour, Use of thermal insulation & Provisions for ventilation
e) Improvements to voltage profile
f) Influence from system harmonics
g) Overvoltage under light load conditions
h) Conditions for resonance

1.3 SUBJECT OF THE ERESEARCH

The low voltage network of electricity distribution system in Colombo City was chosen as the sample for the proposed research.

1.3.1 Colombo City power distribution system

The Colombo City power distribution system consists of eight number of Primary substation with 132kV or 33kV underground cables as power incoming feeders and the power is delivered through 11kV underground cables.

11kV cables from primary substations are connected to 11kV substations, identified as ring or radial substations depending on the connectivity. The ring and radial substations feed power to large number of indoor type 11kV/415V transformer substations named as Satellite substations.

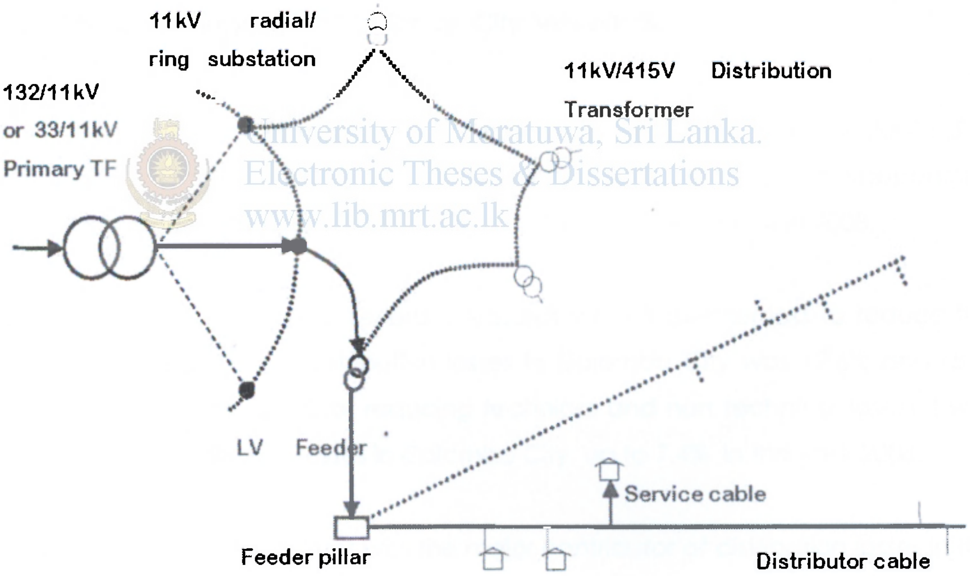


Figure 1: General arrangement of Colombo City underground distribution system

Low voltage cables from 11kV/415V transformer substations to the consumer mains are identified as Feeder cable, Distributor cable and Service cable as shown in the Figure 1.

Summary of network points of the Colombo City system is given in Table 1

Network nodes	Quantity end of 2008 (Nos.)
132/11kV primary substations	4
33/11kV primary substations	5
11kV ring/radial substations	139 [1]
11kV/415V distribution transformers	1200 [1]
Feeder pillars (Low voltage)	1500 [2]

Table 1: Statistics of 11kV & low voltage network

1.3.2 Distribution losses of the Colombo City network [3]

Electrical energy supplied to Colombo city system was 599 GWh in year 2008 up to June and the Energy sales during the same period was 555GWh. The corresponding Energy loss was 44 GWh and system losses was 7.4% for the first half in 2008.

During the recent past years, several measures were implemented to reduce the system losses. In 2002, the distribution losses in Colombo City was 12.6% and as a result of various steps taken for reducing technical and non technical losses it was able to reduce distribution losses in Colombo City up to 7.4% in the year 2008.

Prior to 2004, Non-technical loss was the major contributor of distribution losses in the Colombo City system. Non-technical losses were reduced from 6.5% (2004) up to 2.1% (Up to November 2008) due to the steps taken in the reason past by the Energy Management unit of the Colombo City. Currently technical losses had been the major contributor for the distribution losses in Colombo City. Technical and non technical losses of the Colombo City distribution system are compared in Figure 2.

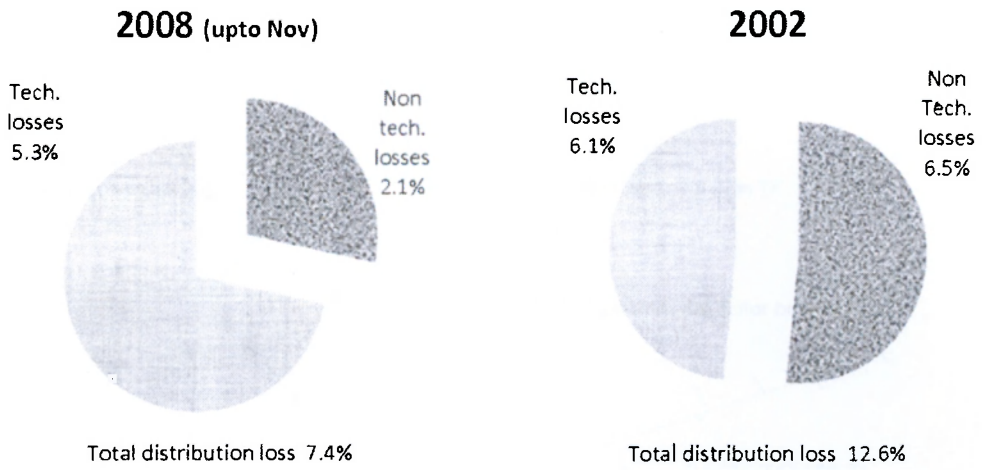


Figure 2 : Comparison of distribution losses

Further improvement to distribution losses from the current level would be critical as most of the major steps had already been taken and further improvement to technical losses from the current level of 5.3% requires proper studies of the system and higher capital investment. In this respect, it would be very remarkable if the proposed method of having power capacitors is implemented fully in the low voltage system, which is a very cost method of injecting reactive power for reducing technical losses of the network.

1.4 AREA OF RESEARCH

1.4.1 Locations for installation of power capacitors

Power capacitors can be connected in the low voltage distribution system as Fixed type capacitors or Switching type capacitor banks at locations listed below and shown in Figure 3 for reducing distribution losses and improving the voltage profile of the LV network.

1. At feeder pillars as fixed type capacitors.
2. At 11/0.415kV distribution transformers as fixed type capacitors.
3. At 11/0.415kV distribution transformers as switching type capacitors.
4. At the consumer's main as fixed type capacitors.

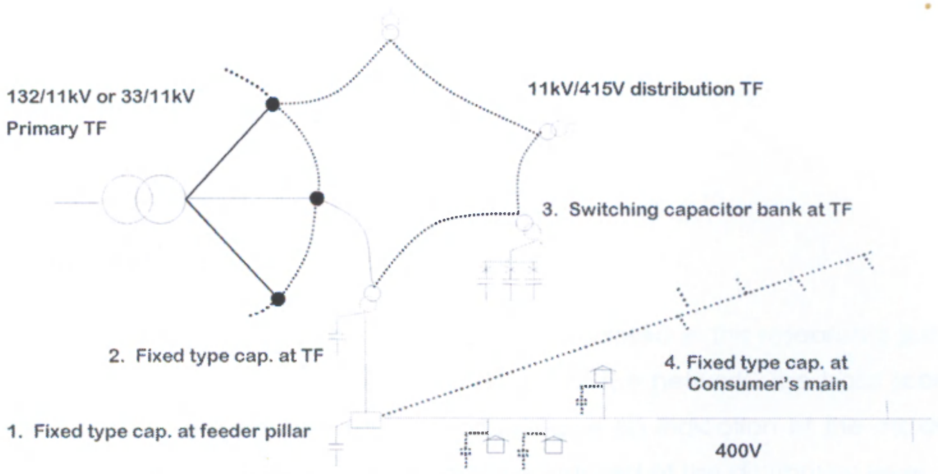


Figure 3 : Proposed locations for low voltage capacitors

The installation of switching type capacitor banks with regulators and control gears at distribution substations (above option 3) are expensive compared to fixed capacitors. Hence switching type capacitor banks cannot be used economically at most of distribution transformers of the selected sample when compared with the fixed capacitor system. The switching type capacitor banks are suitable for highly loaded distribution transformers with highly varying load patterns.

The use of capacitors at the final power delivery point of the utility, i.e. at the consumers' main (Option 4 in above Figure 3) would be the ideal location for installing capacitors for improving system losses. But such a program would be extensively labour intensive. Proper monitoring and maintenance of such a system of small capacitors would be impracticable. Therefore, above locations 1 and 2 were selected for this research study.

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.

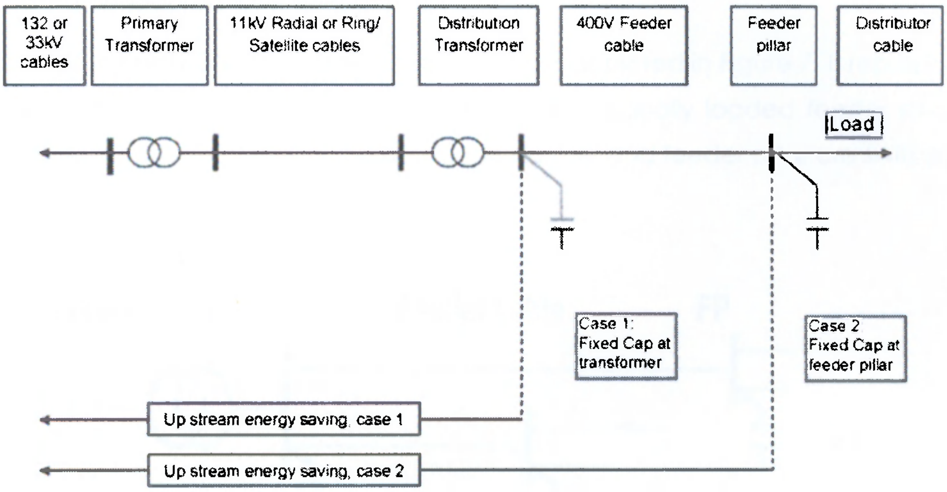


Figure 4 : Connection options of low voltage shunt capacitors

2.2.2 Sample installations

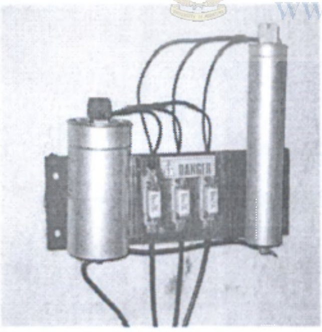
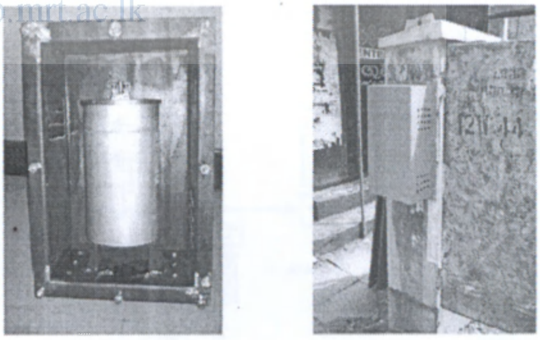


Figure 5 : Fixed type capacitors in a room of a distribution transformer



(a) (b)

Figure 6 : Fixed type capacitors at a feeder pillar

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.

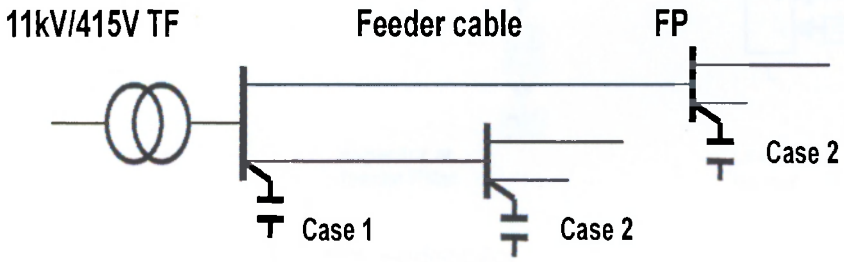


Figure 7 : Part of network considered for simulation

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.

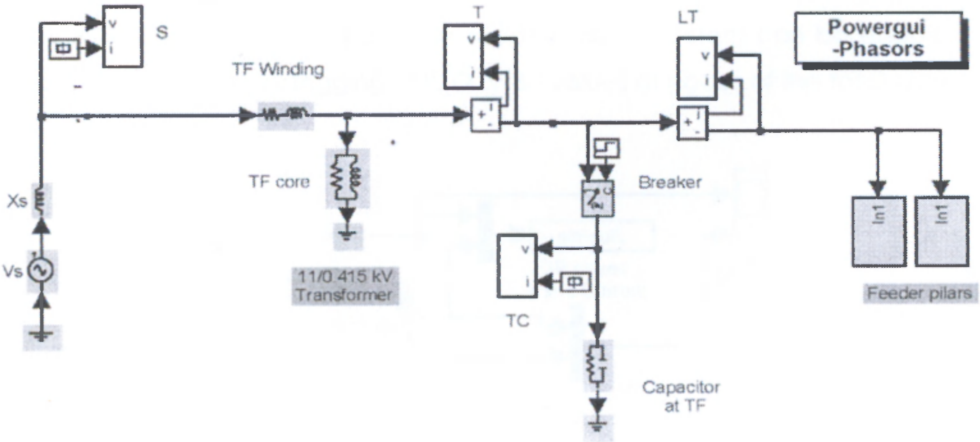


Figure 8 : Total system to represent one transformer supplying two feeders

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.

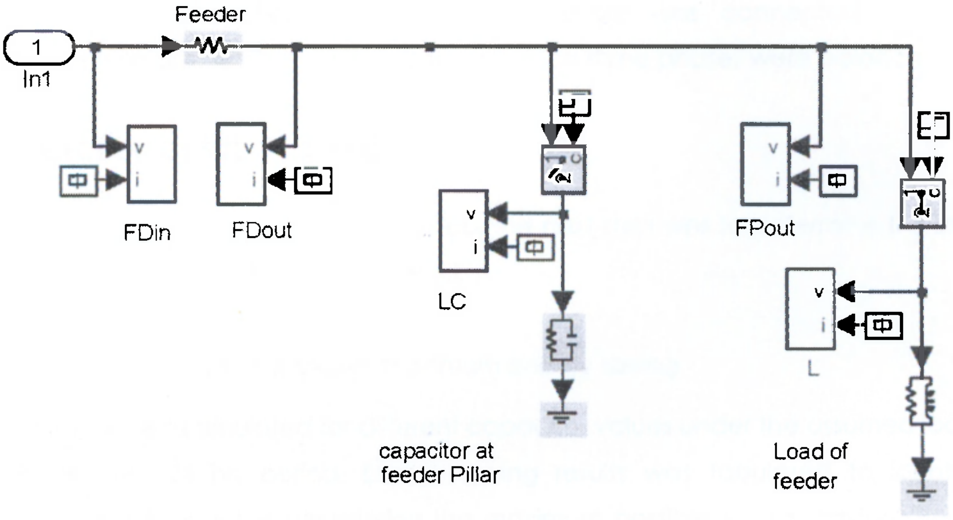


Figure 9 : Sub system to represent one feeder pillar.

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.

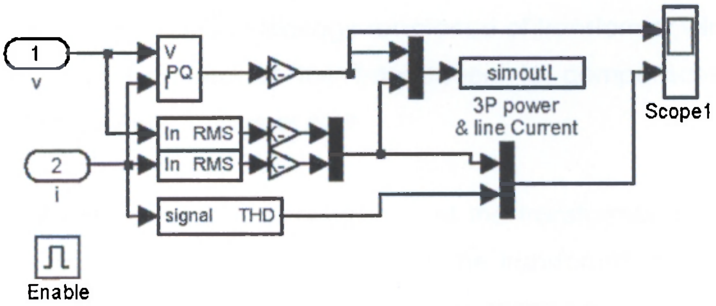


Figure 10 : Sub system for Measuring P, Q, V & I

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 th 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.

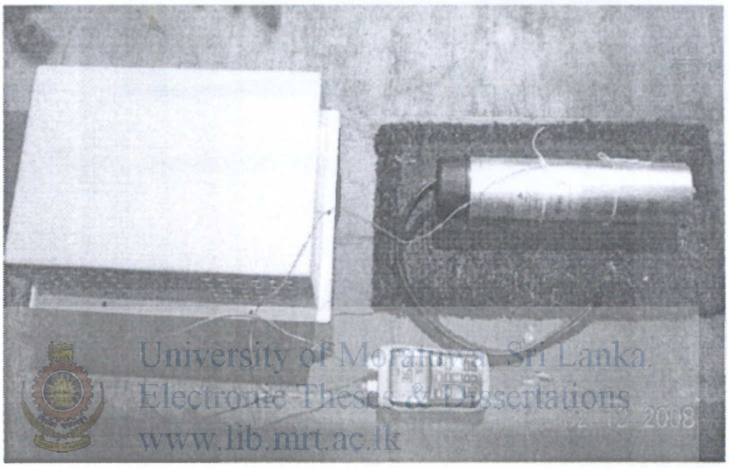


Figure 11 : Effect of enclosure

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 sun light 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.

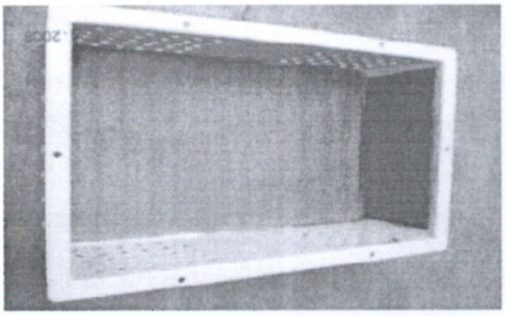
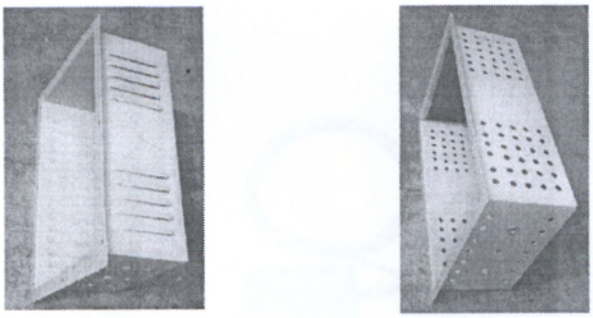


Figure 12 : Use of thermal insulation with reflective foil

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.



(a) (b)

Figure 13 : Ventilation arrangements with louvers and holes

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 [2]. 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 asses 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.

3 DATA COLLECTION AND ANALYSIS OF RESULTS

3.1 POWER FLOW THROUGH PRIMARY SUBSTATIONS

Table 2, below summarizes the daily active power flow of Primary substations in Colombo City. Total active power demand of Colombo City shows an annual growth rate of 4.3% compared to the year 2006. It was also observed that load connected to primary substation E and F had been transferred to the new primary substation I, which was energized in 2008.

Year/Primary	Daily	A	B	C	D	E	F	G	H	I	Total
September 2008 (MW)	Max	33	15	19	22	53	40	27	19	25	244
	Min	8	4	8	8	14	12	10	7	6	82
	Avg-H	20	9	15	16	31	24	21	16	15	168
	Avg-L	11	5	11	11	18	14	12	11	8	100
May 2006 (MW)	Max	28	14	18	22	70	42	26	16	Not been energized	234
	Min	9	5	9	8	19	11	13	9		85
	Avg-H	18	9	15	16	43	26	20	14		161
	Avg-L	12	6	11	11	25	16	16	11		108

Note:

Max – The maximum recorded in a high demand day of the week (Wednesday)

Min - The minimum recorded in a low demand day of the week (Sunday)

Avg-H – The average value of a high demand day of the week (Wednesday)

Avg-L - The average value of a low demand day of the week (Sunday)

Table 2: Daily active power flow from Primary substations in Colombo City

Base reactive power measured at each primary substation within the year 2008 and 2006 are summarized in Table 3. It gives an indication of the quantity of fixed type capacitors that could be concentrated in area, supplied by respective primary substations.

Year/Primary	A	B	C	D	E	F	G	H	I	Total
September 2008 (MVAr)	**2.3**	**1.1**	3.1	1.2	6.3	2.6	1.5	1.8	2.4	27.0
May 2006 (MVAr)	1.5	0.7	3.1	1.2	**9.1**	**5.4**	**4.4**	**3.7**	Not been energized	**33.0**

Table 3 : Base reactive power flow from Primary substations in Colombo City

Referring to base reactive power flow in Colombo City distribution system in 2008, it is possible to have a maximum of 750 numbers of 40 kvar fixed power capacitor units. The power demand at feeder pillars was considered when deciding the actual number of installations.

3.2 COMPARISON OF COSTS AND BENEFITS

The financial benefit of the two options, considered for fixing low voltage power capacitors with minimal capital requirement was calculated as detailed below.

Part of the low voltage network to include feeder pillar, feeder cable, distribution transformer and 11kV cables up to the primary transformer was considered for evaluation of saving of losses in both the cases.

3.2.1 Determination of resistance of components of selected network:

Transformer parameters:

Capacity	$VA_{TF} = 1{,}000 \text{ kVA}$
Rated primary voltage	$V_{HV} = 11{,}000 \text{ V}$
Rated secondary voltage	$V_{LV} = 415\text{V}$
Vector group	Dyn11
Rated secondary line current	$I_{LV} = \frac{kVA_{TF}}{\sqrt{3}V_{LV}} = 1{,}391 \text{ A}$

Base impedance referred to secondary	$Z_b = \frac{V_{LV}^2}{VA_{TF}} = 0.1722\ \Omega$
Losses at Full load	$W_{FL} = 10{,}020$ W
Losses at No load	$W_{NL} = 1{,}410$ W
No load current at the rated voltage referred to secondary	$I_0 = 0.6\% = 8.49$ A
Impedance referred to secondary	$Z = 4.6\% = 0.0079224\ \Omega$
Equivalent resistance of primary & secondary windings	$R_{Cu} = \frac{W_{FL}/_3}{I_{LV}^2} = 0.00173\ \Omega$

Cable parameters:

Temperature coefficient of resistance - Al	$\alpha_{Al} = 0.00403$
Temperature coefficient of resistance - Cu	$\alpha_{Cu} = 0.00393$

Low voltage Feeder cable

Type of cable	LT/240mm²/PILC/AL/4C
Resistance @90 ⁰C to BS5467	$R_1 = 0.162$ Ω/km/phase
Operating temperature of the cable.	$\theta_2 = 70$ ⁰C
Resistance @70 ⁰C	$R_2 = R1[1 + \alpha_{Al}(\theta_2 - \theta_1)]$ $= 0.0175$ Ω/km/phase
Typical cable length	= 125m
Resistance of a typical feeder cable	$R_{Fd} = 0.02188$ Ω/phase

11kV Satellite cable

Type of cable	11kV/70mm²/PILC/Cu/3C
Resistance @20 ⁰C to BS6480	$R_1 = 0.268$ Ω/km/phase
Operating temperature of the cable.	$\theta_2 = 90$ ⁰C
Resistance @90 ⁰C	$R_2 = R1[1 + \alpha_{Cu}(\theta_2 - \theta_1)]$ $= 0.0175$ Ω/km/phase
Typical cable length	= 750m
Resistance of a typical 11kV Satellite cable	$R_{Sat} = 0.24050$ Ω/phase

11kV Radial cable

Type of cable	11kV/240mm^2/XLPE/Cu/3C
Resistance @20 ^{0}C to BS6480	$R_1 = 0.0754\ \Omega$/km/phase
Operating temperature of the cable.	$\theta_2 = 90\ ^0$C
Resistance @90 ^{0}C	$R_2 = R1[1 + \alpha_{Cu}(\theta_2 - \theta_1)]$ $= 0.090\ \Omega$/km/phase
Typical cable length	= 1500m
Resistance of a typical 11kV Radial cable	$R_{Rad} = 0.13532\ \Omega$/phase

3.2.2 Evaluation of energy and financial saving

Following assumptions were made for the calculation of monthly energy saving.

i. Peak and off-peak power demand of each section of the network including feeder pillar are 60% and 10%, respectively of the rate power through it.
ii. Duration of peak demand is 8hrs.
iii. Typical lengths of 11kV radial cable, 11kV satellite cable and low voltage feeder cable are 1500m, 550m and 125m, respectively.
iv. Unit cost of energy is Rs 10.50

Energy saving as a result of reduced I^2r losses due to capacitors was determined for each section of the network from feeder pillar up to 132kV or 33kV/11kV primary transformer for the assumed peak and off-peak load conditions of the day. Then the possible energy saving of the day was calculated by summing corresponding energy saving in each section and it was used to get the possible monthly energy saving under both the cases. Steps of the calculation are given in Table 4.

	Unit	Network section							
		LV Feeder cable		**100kVA, 415/11kV Distribution TR**		**11kV Satellite cable**		**11kV Radial cable**	
Resistance of network elements	Ω/ phase	0.02188		0.00173		0.24050		0.13532	
Rated current of network elements	A	400		1391		190		400	
Power factor (assumed)	pf	0.8		0.8		0.8		0.8	
Typical load characteristics		Peak	Off-peak	Peak	Off-peak	Peak	Off-peak	Peak	Off-peak
Load as a percentage of rated power	%	60%	10%	60%	10%	60%	10%	60%	10%
Duration of peak & off-peak loads	hrs	8	16	8	16	8	16	8	16
Line current	A	240	40	835	139	114	19	240	40
Active power flow	kW	138	23	480	80	1,738	290	3,658	610
Reactive power flow	kvar	104	17	360	60	1,303	217	2,744	457
Case 1	Fixed value capacitor at Feeder pillar (Ratings: 40kvar@440V operating at 415V)								
Reactive power flow with the capacitor at feeder pillar	kvar	68	-18	324	24	1268	182	2708	422
Line current new	A	214	41	806	116	113	18	239	39
Reduction in line current	A	26	-1	29	23	1.11	1.06	1.12	1.09
Reduction in power loss in 3 phases	W	775	-5	244	30	182	28	217	35
Energy saving per day	kWh	6	0	2	0	1	0	2	1
Total energy saving per month	kWh	**300**							
Value of the total energy saving	Rs per month	**3,150 @ 10.50 unit cost**							

Case 2		Fixed value capacitor at Distribution transformer (Ratings: 50kvar@440V, operating voltage is 415V)							
Reactive power flow with the capacitor at transformer	kvar	104	17	316	16	1259	173	2699	413
Line current new	A	240	40	799	113	113	18	239	39
Reduction in line current	A	0	0	36	26	1.39	1.30	1.39	1.36
Reduction in power loss in 3 phases	W	0	0	301	34	226	34	271	43
Energy saving per day	kWh	0	0	2	1	2	1	2	1
Total energy saving per month	kWh	**190**							
Value of the total energy saving	Rs per month	**1,995 @ 10.50 unit cost**							

Table 4 : Comparison of energy saving.

Possible energy saving, installation cost and cost recovery period, with respect to the two cases of having shunt power capacitors at feeder pillar and at the distribution transformer are compared in Figure 15.

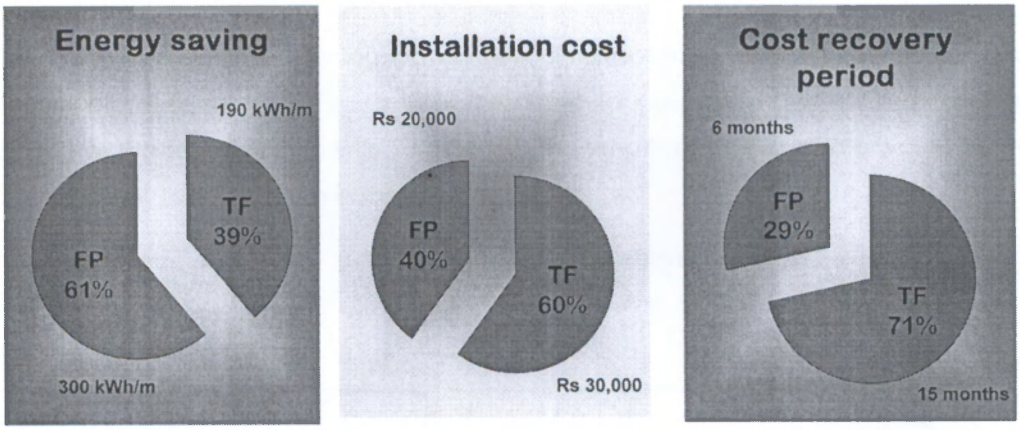


Figure 15: Comparison of benefits

As per the comparative values given in Figure 15, the installation of fixed type capacitors at the feeder pillars is more beneficial than having fixed type capacitors at the distribution transformer.

3.2.3 Verification of feeder load pattern with field measurements

Field measurements were taken to justify the assumptions made in above section 3.2.2 for calculation of financial benefit of energy saving. The resulting power flow in a typical feeder pillar is shown in Figure 16. It was observed that the typical load, supplied by the feeder pillar is having a peak duration of 10.5hrs, an average peak time power flow of 80% of its rated power and a base load of 25% of the rated power. Thus the power flow pattern assumptions made in section 3.2.2 is justifiable and it will represent the majority of feeder loads in the selected sample.

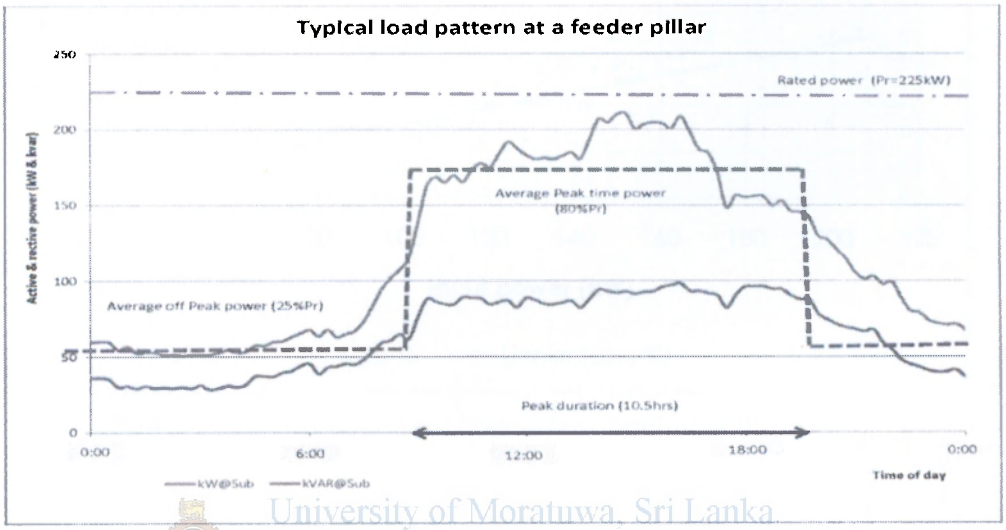


Figure 16 : Pattern of power flow through a feeder pillar

3.2.4 Assessment of monthly energy saving by field measurements

Two loggers were used to log power flow simultaneously at both the ends of a feeder cable as shown in Figure 17. In this particular case of field measurement, the length of the feeder cable was 75m, where the length of feeder cable would be in the range of 100m to 150m in the general case.

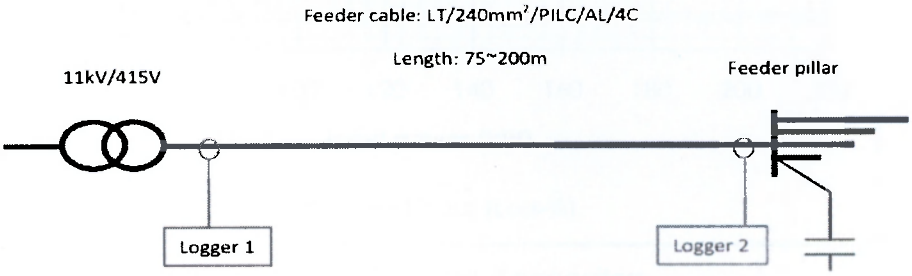


Figure 17 : Verification of energy saving in a feeder cable

Data were logged with and without capacitor at the feeder pillar over a known period of time. The power loss across the feeder cable with and without capacitor against various input power values are shown in Figure 18, Figure 19 and Figure 20.

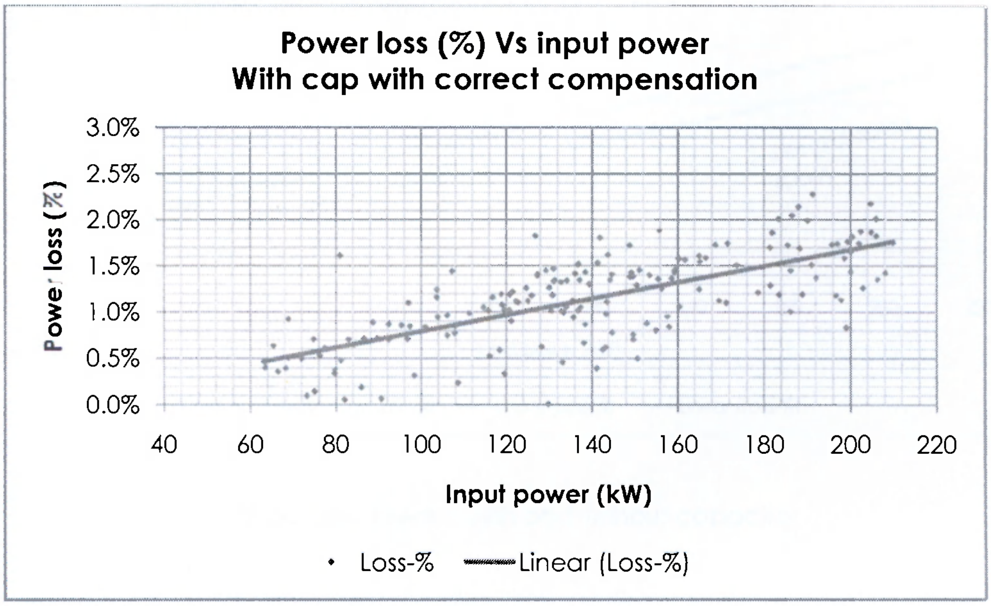


Figure 18 : Power loss across a feeder cable with capacitor at the end

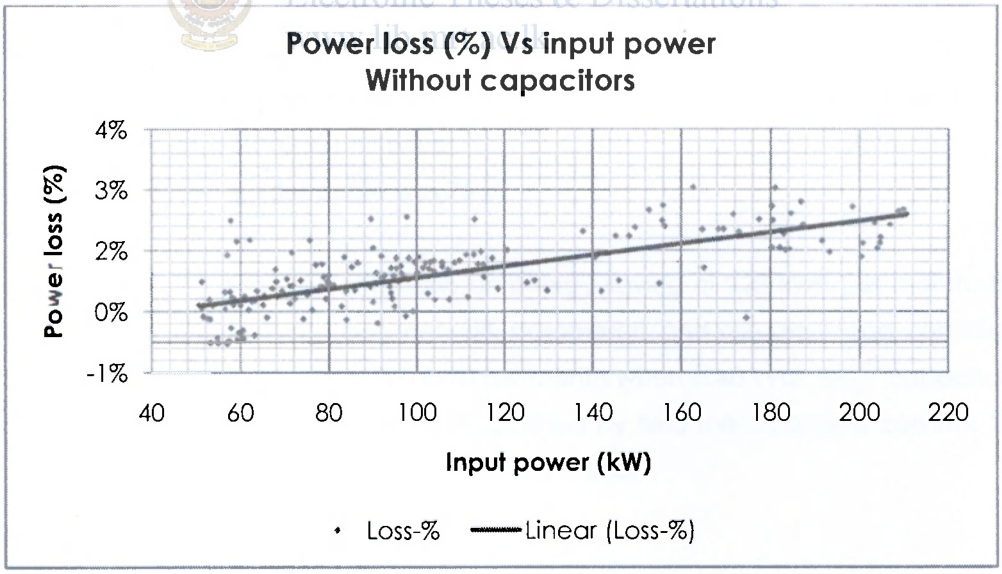


Figure 19 : Power loss across a feeder cable without capacitors

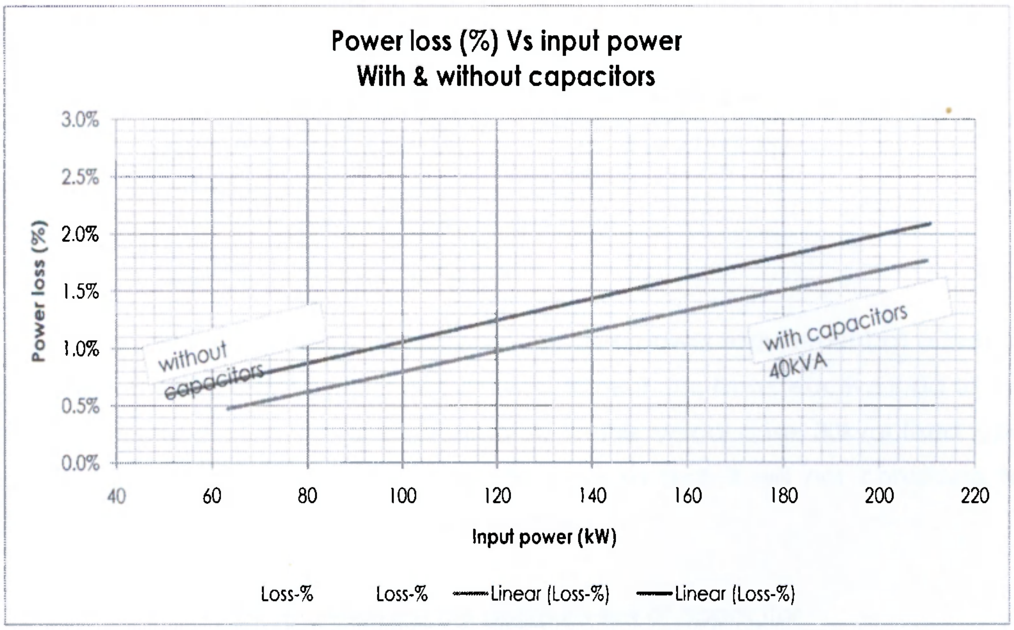


Figure 20 : Power loss across a feeder, with and without capacitor

Following results were derived with reference to Figure 20.

Total energy supplied during the period	12,324 kWh
Duration of energy monitoring	94.45 hrs
Corresponding monthly energy supply	93,946 kWh/ month
From Figure 20, the average energy saving	0.3%
Corresponding energy saving in a month	282 kWh/ month
Financial saving @ Rs 10.50 unit price	2,959 Rs/month

(The length of the feeder cable was 75m)

The above field measurement shows an energy saving of 228 kWh per month. The calculated energy saving using network parameters and assumed load conditions indicates an energy saving of 300 kWh per month when a 40 kvar, 440V capacitor is connected to feeder pillar. The result obtained by field measurement confirms the validity of calculated results and assumptions made.

3.3 SELECTION OF SIZE OF FIXED CAPACITOR

The size of fixed type capacitor to be connected at feeder pillar was determined by simulation and the results were compared with base reactive power requirement at a typical feeder pillar.

3.3.1 Base reactive load at feeder pillars

The Figure 16 in 3.2.3 depicts typical base reactive power requirement at a feeder pillar, which was plotted by taking field measurement. The base reactive load at the feeder pillar had been 30kvar approximately. In this typical case, 30kvar fixed type capacitor can be installed at the feeder pillar so that it will not contribute to increase system losses under light load conditions.

3.3.2 Use of simulink to determine the optimum size of capacitor

A typical distribution transformer in the selected sample supplies to 2 to 3 numbers of feeders. This network was modeled in Simulink and was simulated under different values for the fixed capacitor at feeder pillar and at distribution transformer for sampled load data over a period of 24 hours. The daily load pattern of the feeder pillar shown in Figure 21 was used as input variable of the modeled system. The simulation results are given in Figure 22 and Figure 23.

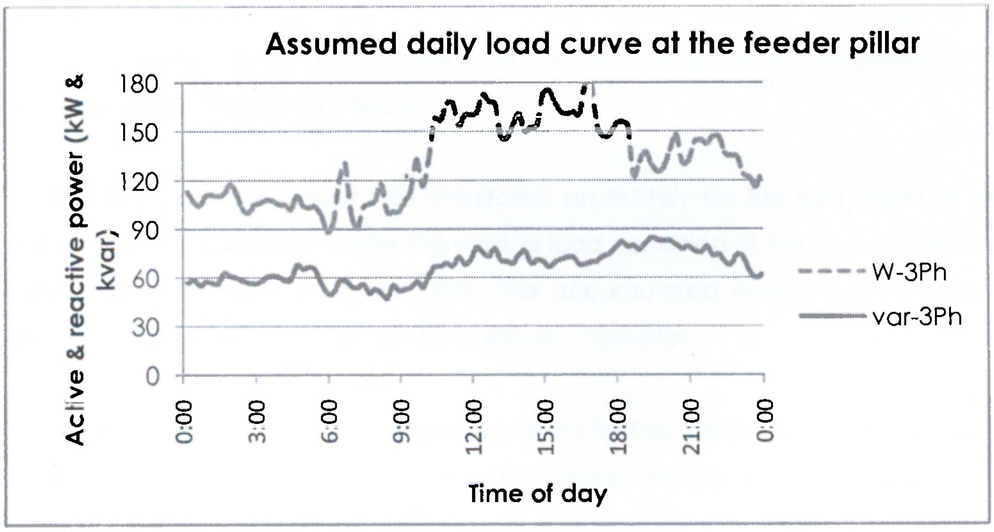


Figure 21 : Load curve at the feeder, assumed for simulation

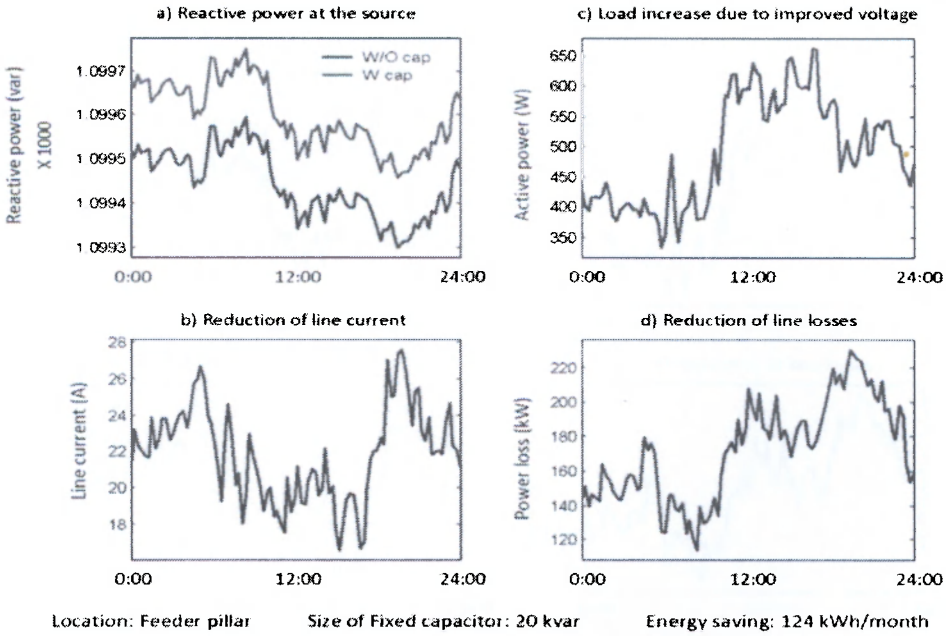


Figure 22 : Simulation results for fixed value capacitor at the feeder pillar

The Figure 22-a), above shows the reduction in reactive power, supplied from the source end due to capacitors at the load end. Figure 22-b), shows the reduction in line current with 20 kvar capacitor at the feeder pillar.

When a 20 kvar capacitor was connected to the feeder, the voltage at that point had been improved by 1 to 2V, which had slightly modified the load of the simulated model. Figure 22-C), shows the minute change in active power of the load end under the above condition.

Power loss across the feeder was monitored separately for the two cases of with and without the capacitor under the varying load condition of the day. The resulted power saving is shown in Figure 22-d). The accumulated energy saving within a period of one month was 124 kWh for a 20kvar capacitor.

Figure 23, below shows the corresponding results for the fixed value capacitor at the distribution transformer. In this case, monthly energy saving, possible with a 20 kvar capacitor was only 30 kWh.

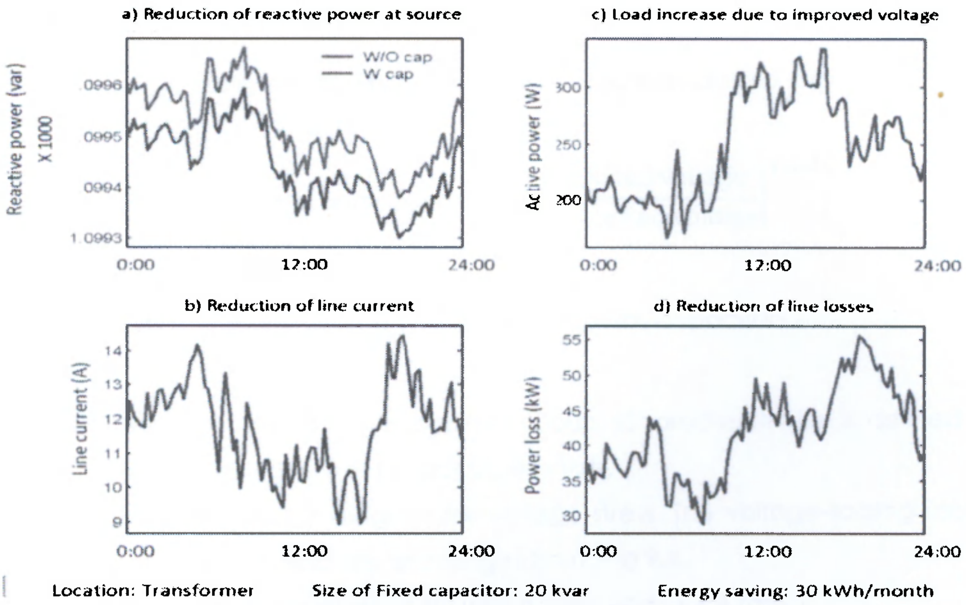


Figure 23 : Simulation results for fixed value capacitor at the transformer

Results obtained by simulation as above are compared in the Figure 24 below. It can conclude that the optimum size of capacitor for connecting at a feeder pillar is in the rage of 50 to 60 kvar and it would save 220 kWh units per month under the assumed load conditions of simulation. The corresponding optimum fixed value capacitor at the transformer is 40 kvar, approximately whereas the possible energy saving was only 60 kWh per month.

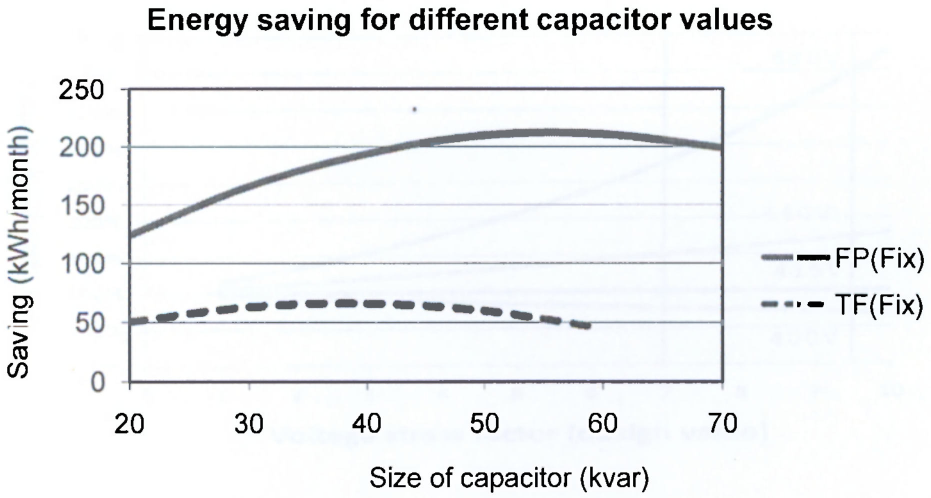


Figure 24 : Power saving under different capacitor values

3.4 SELECTION OF VOLTAGE RATING OF CAPACITORS

The characteristic lifetime of film type capacitors is mathematically expressed by Equation 1[7].

$$\theta = \text{Lifetime at name plate rating } X \left[\frac{\text{Rated voltage}}{\text{Applied voltage}}\right]^{\text{Vscale}}$$

Equation 1 : Characteristic lifetime of a.c. metalized film capacitors

θ is the characteristic life of the capacitor in hours. Characteristic life is defined as the point in time, where 63.2% of the population fails.

Vscale is the scaling factor assigned for voltage stress. The voltage-scaling factor varies by capacitor manufacture and ranges from 7 to 9.4.

Rated Temp is the case temperature for which the capacitor is rated

Variation of lifetime for different voltage ratings of capacitor is shown in Figure 25. Capacitors with rated voltage of 440V were selected for the proposed study, where the operating voltage is 415V, when connected at distribution transformers or feeder pillars. This will extend the characteristics lifetime by 50% to 75% of the lifetime at name plate rating of capacitors. This corresponds to improvement of lifetime up to 17 years to 20 years, whereas the lifetime at name plate rating of capacitors was 11 years.

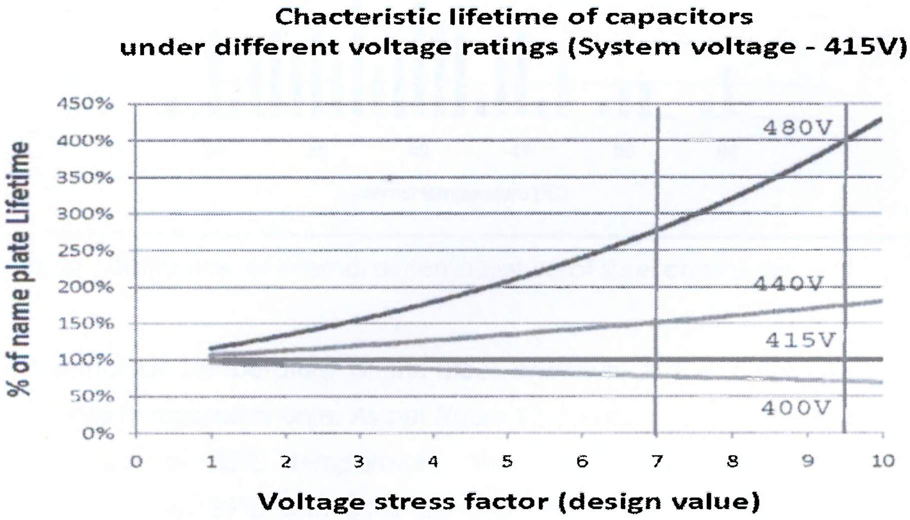


Figure 25 : Variation of lifetime under different voltage ratings of capacitors

3.5 ASSESMENT OF AMBIENT TEMPERATURE APPLICABLE TO CAPACITORS

Fixed type capacitors are housed in steel enclosures, which are attached to feeder pillars. The internal and surrounding air temperatures of those enclosures were measured using digital thermometers and mercury thermometers as shown in Figure 26. Temperature readings were taken during the period from 0900h to 1500h to cover all the capacitors, installed at feeder pillars.

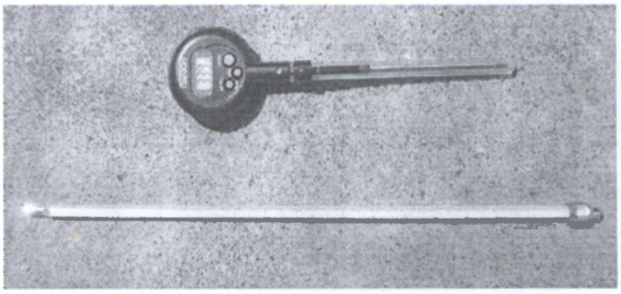


Figure 26: Thermometers used for field measurement

3.5.1 Internal air temperature of enclosures

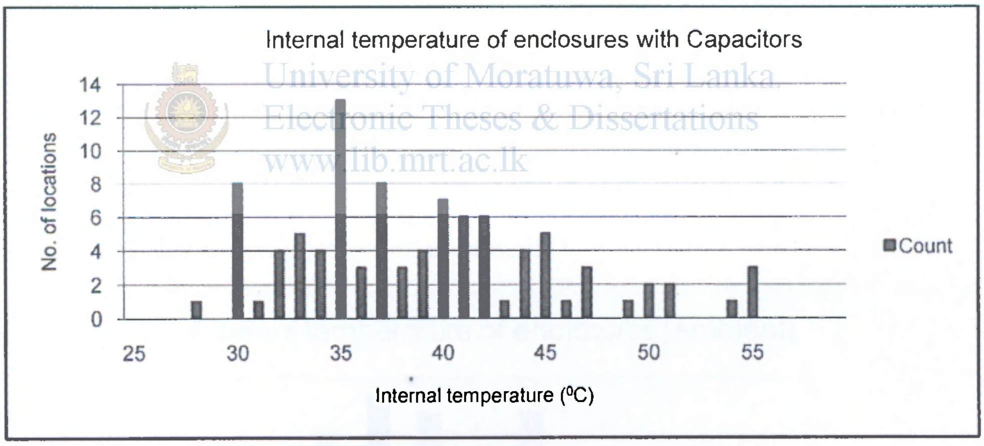


Figure 27 : Distribution of internal air temperature of steel enclosures.

The internal air temperature of the steel enclosure is the ambient temperature applicable to capacitor units. As per Figure 27, the capacitors had been subjected to maximum of 55^{0}C temperature. The average value of the internal air temperature was 39^{0}c with 6.3% standard deviation. The high temperature of operation affects the life of capacitors. Therefore, it was required to select a higher temperature rating for capacitors. And also it was necessary to identify suitable means to reduce the internal temperature of steel enclosures, wherein capacitors are installed.

3.5.2 Selection of ambient temperature category

Upper limit of the ambient temperature, applicable to capacitors for general usage is divided into four categories as detailed in Table 5 [8].

Symbol	**Ambient temperature °C**		
	Maximum	**Highest mean over any period of**	
		24 h	**1 year**
A	40	30	20
B	45	35	25
C	50	40	30
D	55	45	35

Table 5 : Upper limit of ambient temperature categories

The temperature class of capacitors was selected to be -25/D, which can withstand following ambient conditions, referring to standard IEC 60831-1.

- Maximum ambient temperature of 55 °C
- Highest mean ambient temperature over 24 hrs period of 45 °C and
- Highest mean ambient temperature over 1 year period of 35 °C

3.5.3 External air temperature of enclosures

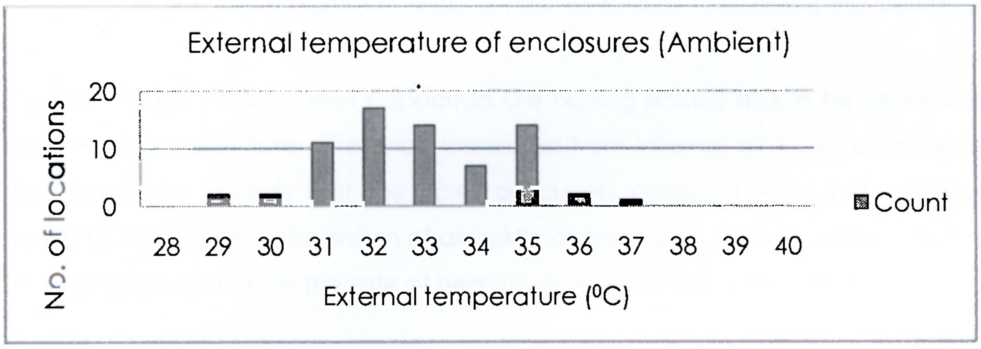


Figure 28 : Distribution of external air temperature of steel enclosures.

The external air temperature of the steel enclosure is the ambient temperature applicable to enclosures housing capacitors. The average value of the external air temperature was 33⁰c with 1.7% standard deviation. It was noted that in some cases, the external air temperature measurements had been affected due to the heat of feeder pillar itself and concreted pavements etc.

3.5.4 Internal to External temperature gradient

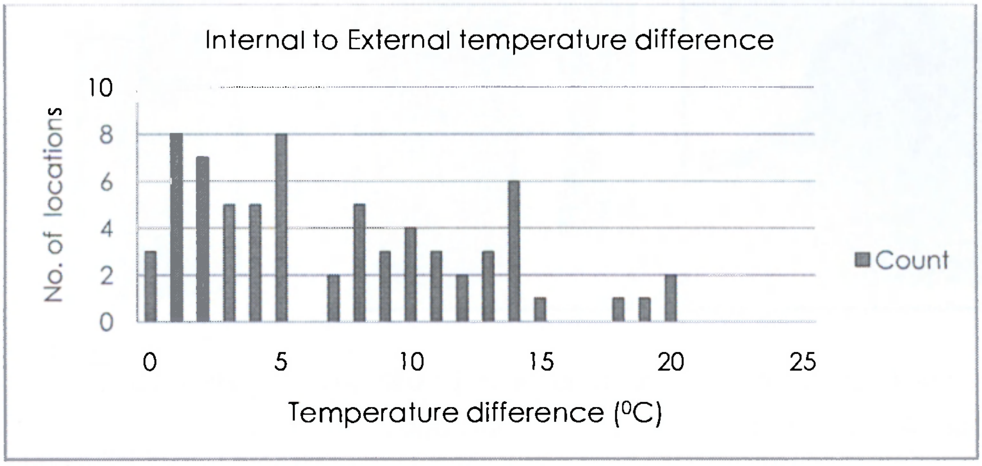


Figure 29 : Internal to external temperature difference.

The average value of internal to external air temperature gradient was 7⁰c with 5.4% standard deviation. As per Figure 29, enclosures containing capacitors had been subjected to a maximum of 20⁰C temperature difference, measured with the outside environment. It is a very high value when compared to the size of the enclosure. Thus it was required to redesign the enclosure to improve the ventilation.

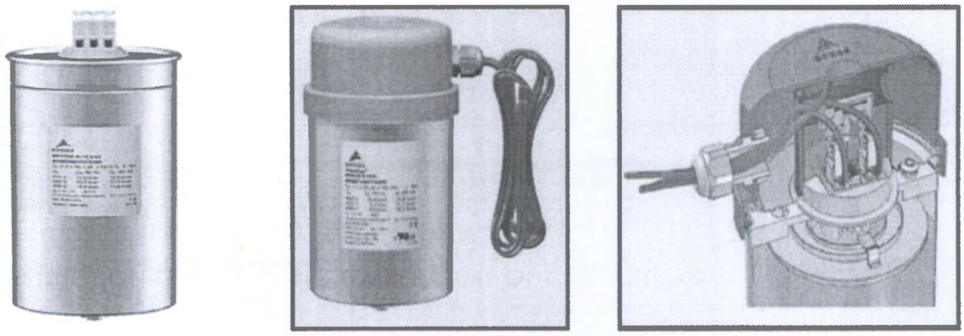
The enclosures, installed with capacitors are having limited space for heated air to trap. High temperature difference measured from internal air to surrounding air of steel enclosure reveals that the holes or louvers provided were not sufficient. It needs to improve the circulation of air inside of enclosure. Further, other means shall be employed to reduce the rate of heating of enclosure due to radiation of the sun.

Since the capacitor is hermetically sealed and only the terminal end has to protect against the splash of water, it is possible to improve the ventilation by having more and large louvers or holes around the enclosure.

3.6 REDUCTION OF OPERATING TEMPERATURE OF CAPACITORS

3.6.1 Advantage of enclosure

Outdoor type capacitors are available for low voltage applications and these capacitors have sealed terminals to prevent ingress of moisture. Figure 30 compares the arrangements of indoor and outdoor type capacitors.



a) Indoor capacitor

b) Sealed type outdoor capacitor

c) Interal terminals are sealed with resin against moisture

Figure 30 : Indoor and outdoor type capacitors

Field measurements were taken with a dual channel temperature logger to assess the advantage of having an enclosure for reducing the operating temperature of capacitor. The measuring setup is shown Figure 31 and the results are shown in Figure 32. The enclosure had been spray painted with light gray colour and it was without any thermal insulation attached to the internal surface and louvers had been provided for ventilation.

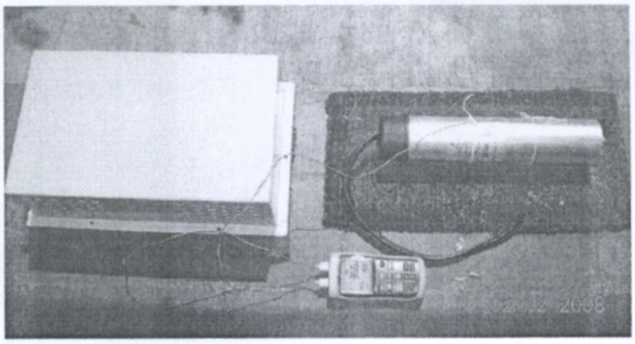


Figure 31 : Temperature logging with and without enclosure

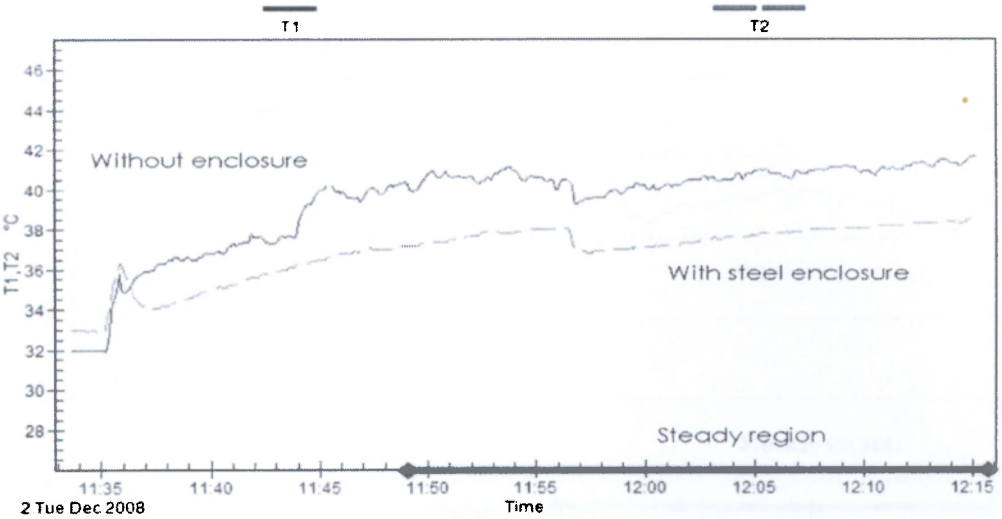


Figure 32 : Effect of enclosure

Accordingly, the case temperature of the capacitor can be reduced approximately by 2.5 ^{0}C by having an enclosure to house the capacitor unit.

3.6.2 Effect of exterior colour on heating due to sun's radiation

Internal air temperature of the steel enclosure was logged simultaneously for the two enclosure types as shown in Figure 33, using thermocouples with Fluke 54 II temperature logger. The type of louvers and dimensions of the two enclosures were the same and one enclosure had been painted with dark green colour and the other had been coloured with light gray.

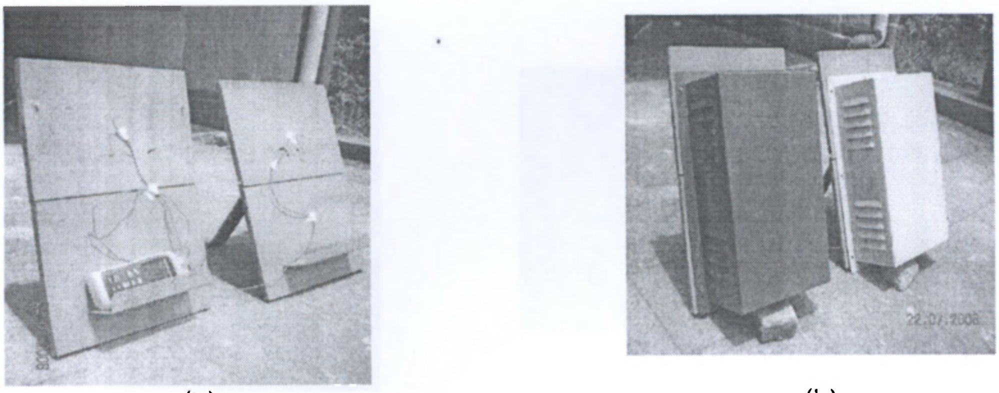

(a) (b)

Figure 33 : Temperature logging to evaluate the effect of exterior colour

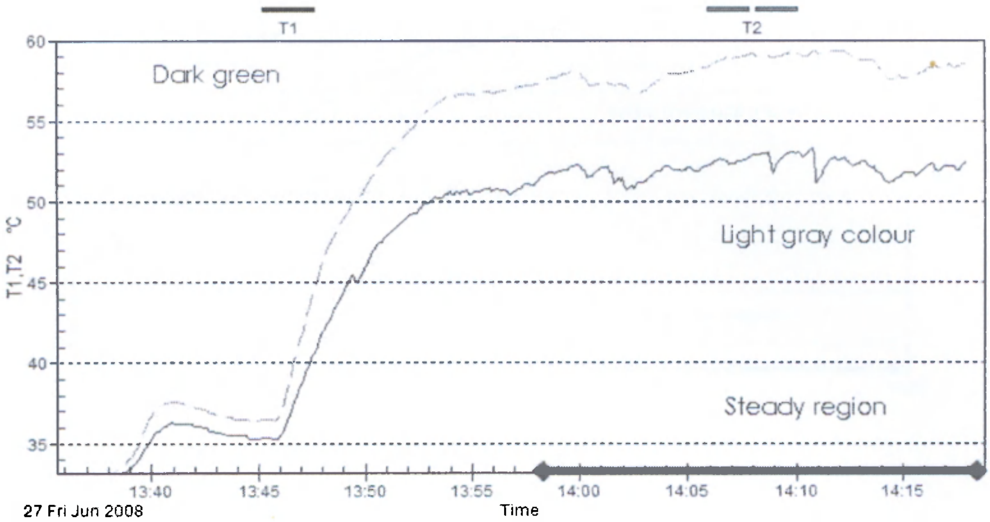


Figure 34 : Effect of colour on internal temperature

The internal air temperature of the enclosure finished with dark green colour had reached a maximum temperature of 59 ^{0}C and the light gray enclosure had reached a maximum of 52 ^{0}C. The average of difference of internal air temperature of two cases was 6 ^{0}C. Thus the exterior colour of the enclosure is significant for reducing inside air temperature of the enclosure when it is open to sunlight, directly.

3.6.3 Thermal insulation

The arrangement used for logging internal air temperature with and without thermal insulation is shown in Figure 35 and the results are shown in Figure 36.

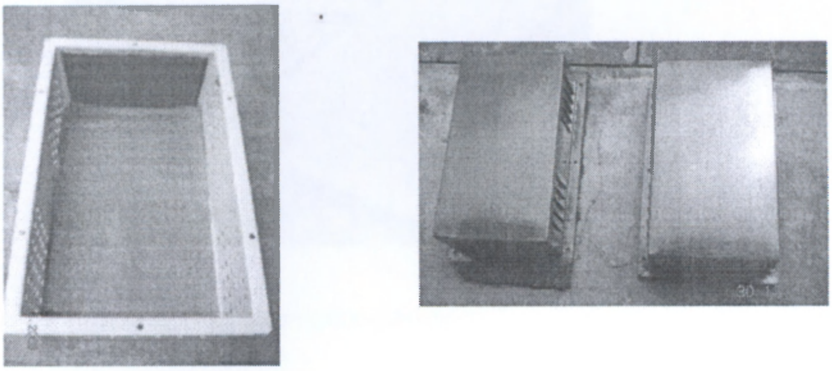


Figure 35: Use of thermal insulation and temperature measuring set up

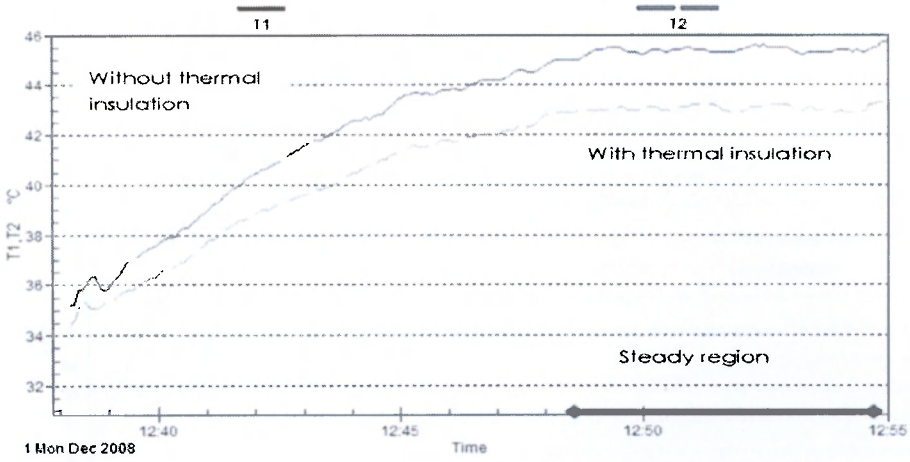


Figure 36 : Effect of thermal insulation

The thermal insulation, applied internally of the enclosure had reduced the inside air temperature by 2.5 ^{0}C, approximately.

3.6.4 Ventilation arrangement

The internal air temperature was logged simultaneously of the two enclosure types as shown Figure 37, where one enclosure had holes for ventilation and the other with louvers. The temperature was measured with Fluke 54II dual channel logger. The results are shown in Figure 38.

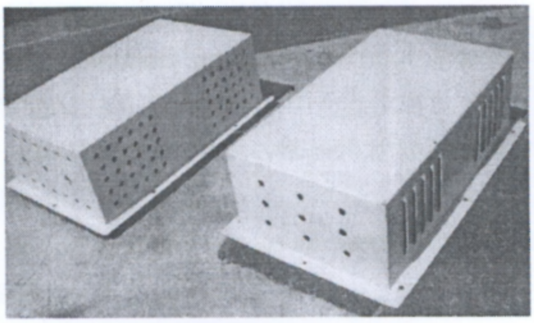


Figure 37 : Comparing ventilation arrangements

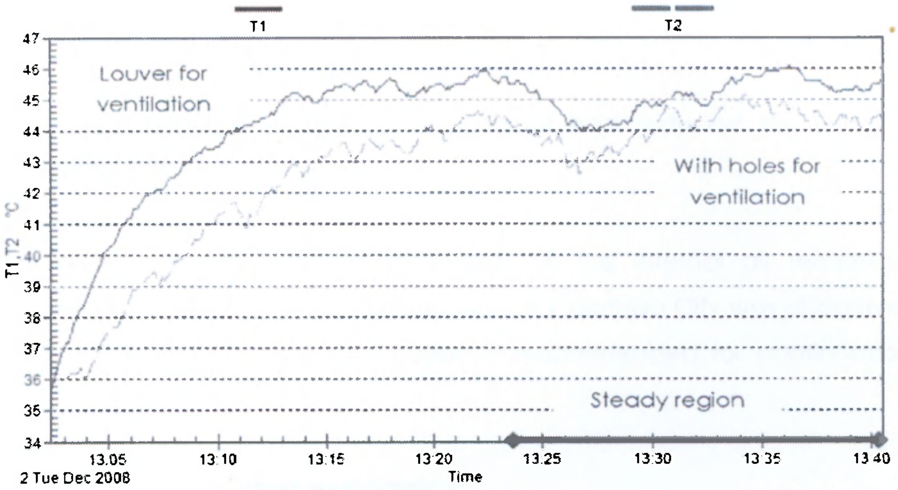


Figure 38 : Holes against louvers for ventilation

It is clear from the above figure that holes are more effective for ventilation than louvers. The internal air temperature of enclosure with holes had been lower by 1°C to 1.5 °C, approximately when compared that with louvered enclosure.

3.6.5 Selection of enclosure

Following options were considered for deciding the most suitable type of enclosure.

1. Use of capacitors without enclosures.
2. Light gray finished enclosure without thermal insulation and louvers for ventilation.
3. Light gray finished enclosure with interior thermal insulation and holes for ventilation.
4. Dark green finished enclosure without thermal insulation and louvers for ventilation.

The second option had lowered the body temperature of capacitor units by 2.5 °C, when compared with option 1, above.

The third option had lowered the internal air temperature, which is the ambient temperature applicable to capacitor units by 4 ⁰C when compared with option 2, above.

The third option, when compared with option 4 had reduced the internal air temperature by 10⁰C.

The dark green colour had a major impact on the internal air temperature. Therefore the use of dark green for feeder pillars in Colombo City was discontinued. Referring to above results, the third option is recommended for continuation of capacitor installation works.

3.7 INFLUENCE FROM SYSTEM HARMONICS

3.7.1 Current harmonics absorbed by capacitors

Currents Harmonics absorbed by a 40 kvar and a 30 kvar capacitor are shown in Figure 39. Quadruple harmonics had not been absorbed by the capacitor, as it was connected in Delta.

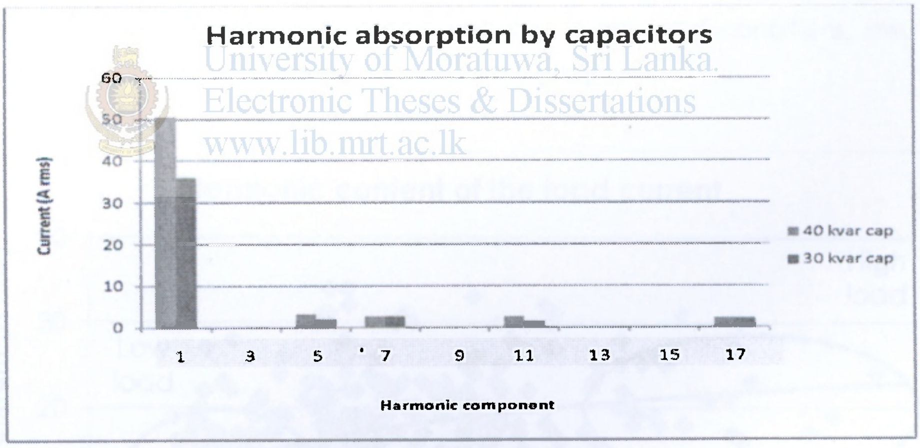


Figure 39 : Current harmonics absorbed by capacitors

3.7.2 Harmonics presence of the load at feeder level

Current harmonics of the load were measured at feeder pillars using LEM Q70 power quality analyzer. Sample readings taken under high and low load conditions are shown in Figure 40.

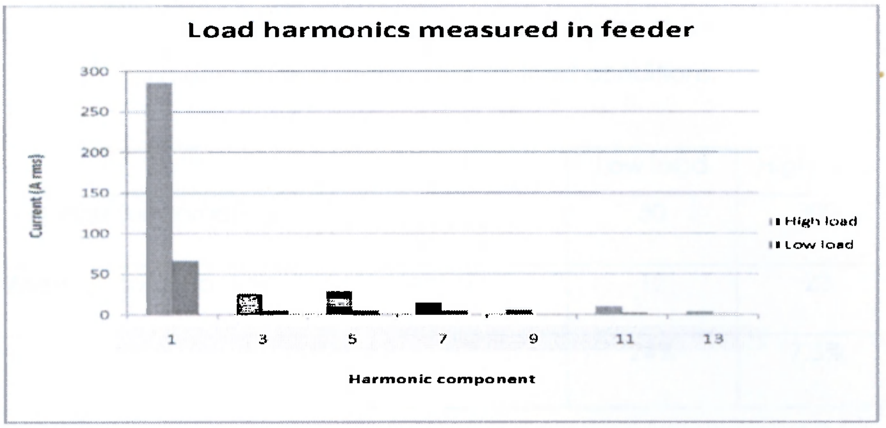


Figure 40 : Current harmonics at a feeder pillar

Harmonics of the order of 3rd, 5th, 7th and 11th were significant. Total harmonic distortion (THD) level of the load current during the peak time was 5%. The corresponding THD level in off-peak time was 23%.

3.7.3 THD levels in peak & off-peak duration

Current harmonics of load measured at the feeder pillars are shown in Figure 41. When comparing severity of harmonic under different load conditions, the THD figure would not express the correct status of the problem.

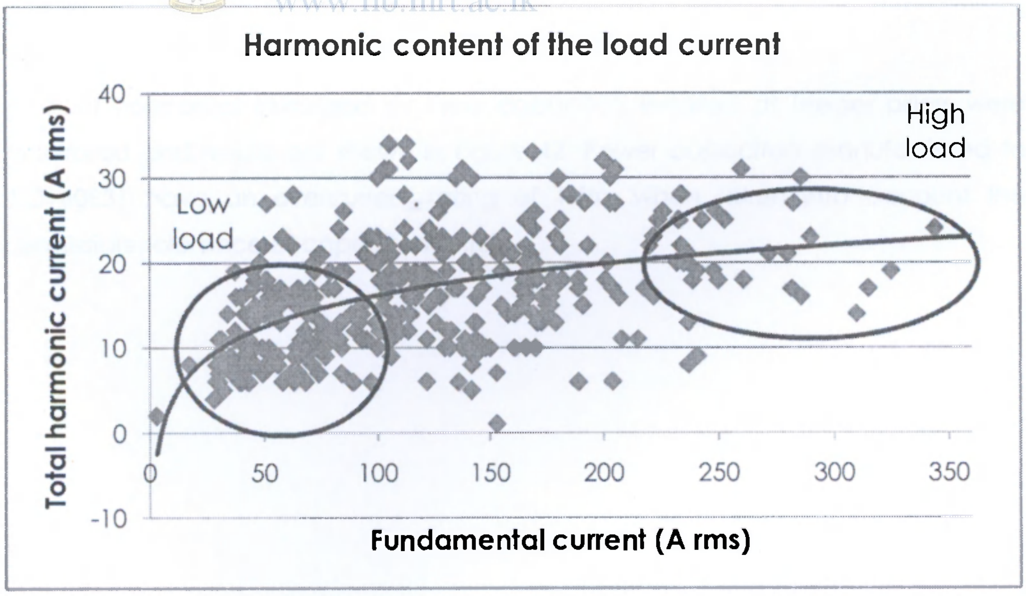


Figure 41 : Load harmonics

Following results in Table 6 were derived referring to Figure 41 for comparison of THD values with the harmonic current under different load conditions.

	Low load	High load
Average fundamental current (A rms)	50	300
Average total harmonic current (Arms)	12	22
THD value	24%	7.3%

Table 6 : Comparison of harmonic current and THD values

The THD value was higher (24%) under low load condition, where the total harmonic current was only 12A compared with corresponding values under high load conditions, which were 7.3% and 22A, respectively.

Therefore, harmonic current in rms shall be recorded of different harmonic orders for assessing the harmonic problem, correctly. Then, the total harmonic current shall be compared against the allowable over current rating of capacitors for assessing the influence of harmonics on capacitors than mere comparison of THD values.

3.7.4 Influence from system harmonics on capacitors

Current harmonics absorbed by fixed capacitors installed at feeder pillars were monitored and results are shown in Figure 42. Power capacitors manufactured to IEC 60831 have an overcurrent rating of 1.5In, when taken into account the permissible tolerance of capacitance [6].

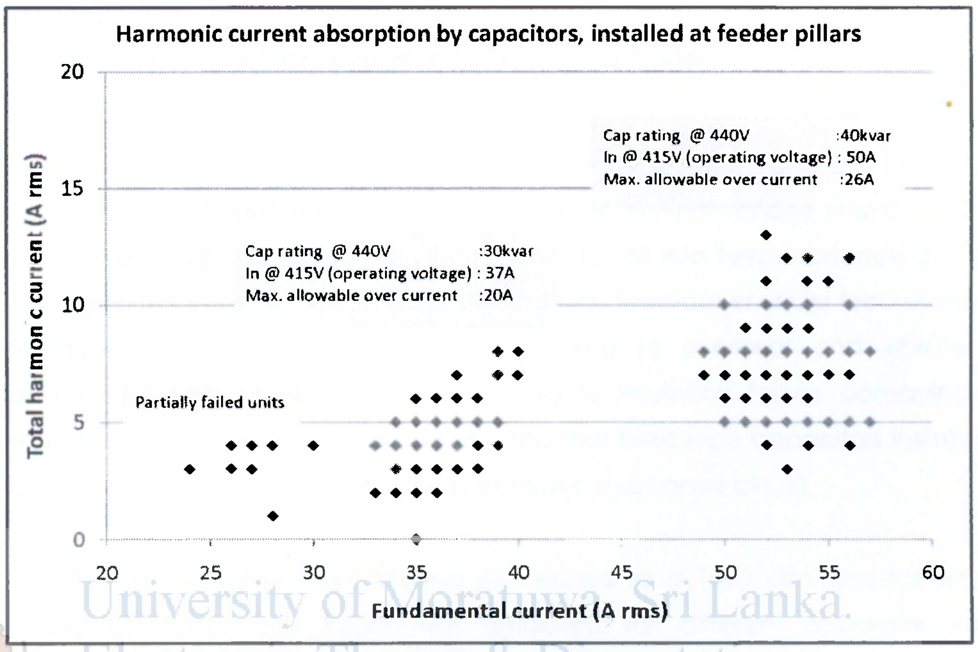


Figure 42 : Level of current harmonics absorbed by capacitors

Figure 42 shows three separate regions. When compared with nominal current of capacitors that were used in the sample system, those regions represent partially failed capacitor units, 30 kvar healthy units and 40 kvar healthy units in the given order. The vertical axis shows the harmonic current absorbed by each capacitor units. According to the allowable overcorrect rating of capacitors (1.5In), 30 kvar and 40 kvar capacitors have overcurrent ratings of 20 A and 26 A, respectively. According to field measurements depicted in Figure 42, the maximum current drawn by 30 kvar and 40 kvar capacitors, over their rated current is less than the corresponding allowable overcurrent ratings. Thus it can conclude that fixed capacitors, installed in the selected sample have no influence from load harmonics.

It is clear from the above figure that capacitors had absorbed certain components of current harmonics of the system. Thus the capacitors installed as a cluster in the distribution system has contribute to improve the quality of power to a certain degree.

3.7.5 Frequency domain analysis of the simplified model

Fixed capacitor along with inductances of the transformer and line reactances would create a resonance condition. Transformer terminal voltage would rise under resonance conditons causing the transformer to fall into ferroresonance condtion damaging the transformer and other switchgears. Transformer under ferroresonance condition operates at high flux levels causing to overheat and vibrate the laminated sheets of the Iron core leading to insulation failure damaging the transformer [9-12]. Thus it should be ensured that fixed type capacitors installed at feeder pillars or at transformers would not form a resonance circuit.

The model representing two feeders connected to a 1000 kVA transformer was considered here. The model was simulated for different capacitor values connected to feeder pillar and transformer, separately under no load condition.

The model given in Figure 43 was used to analyze the frequency response when capacitors are connected at feeder pillars. The low voltage capacitor would form a resonance circuit with saturable core inductance of transformer. Simulink model was used to study the resonance conditions that would occur at the transformer.

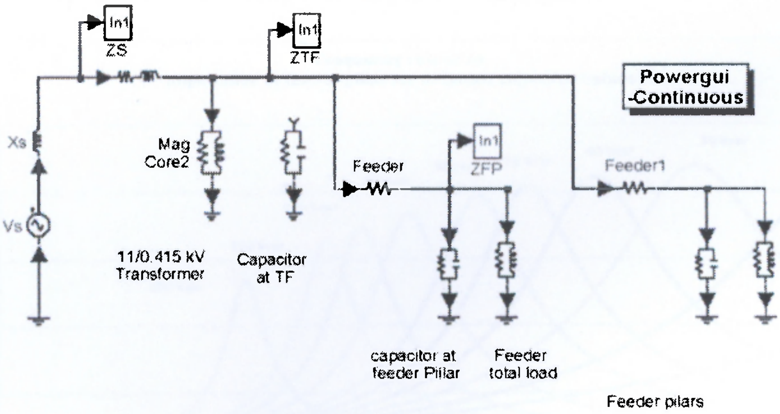


Figure 43 : Model for analyzing the frequency response

The result obtained when a 200 kvar capacitor was connected at feeder pillars is shown in Figure 44 as an example. It depicts that a parallel resonance would occur for harmonic of the order of 7th.

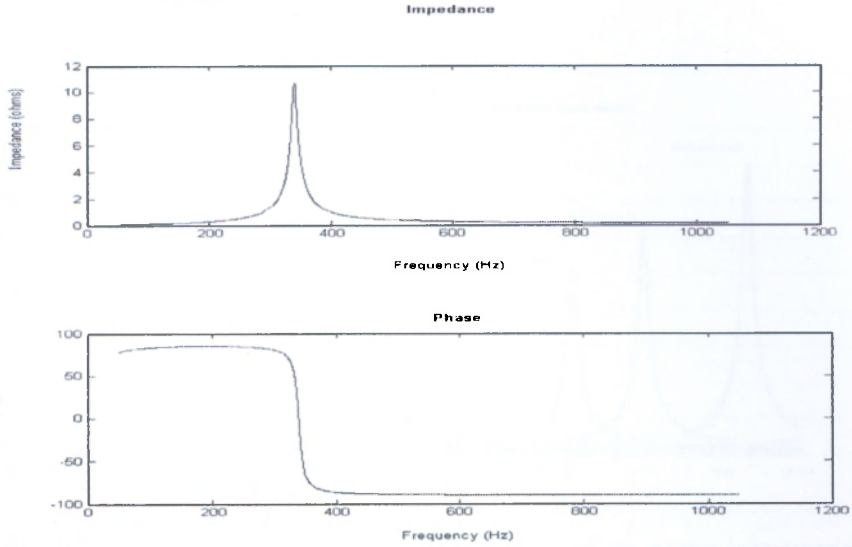


Figure 44 : Frequency response at a feeder pillar

Summary of results corresponds to various capacitor values at the feeder pillar are shown in Figure 45. The frequency of resonances for capacitor values lower than 20 kvar is higher than the 21st harmonic. On the other hand, the presence of harmonics of the order higher than 21st in the low network is negligible.

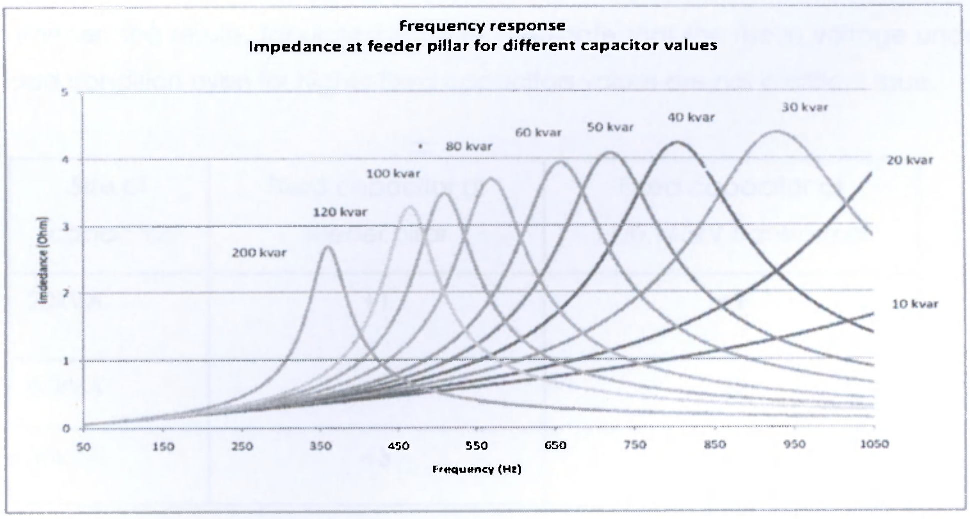


Figure 45 : Frequency response for various capacitor values at the feeder pillar

Summary of results obtained for different capacitor values at the feeder pillar are shown in Figure 46. The frequency of resonances for capacitor values lower than 60 kvar is higher than the 21st harmonic, where the presence of harmonics of the order higher than 21st is negligible.

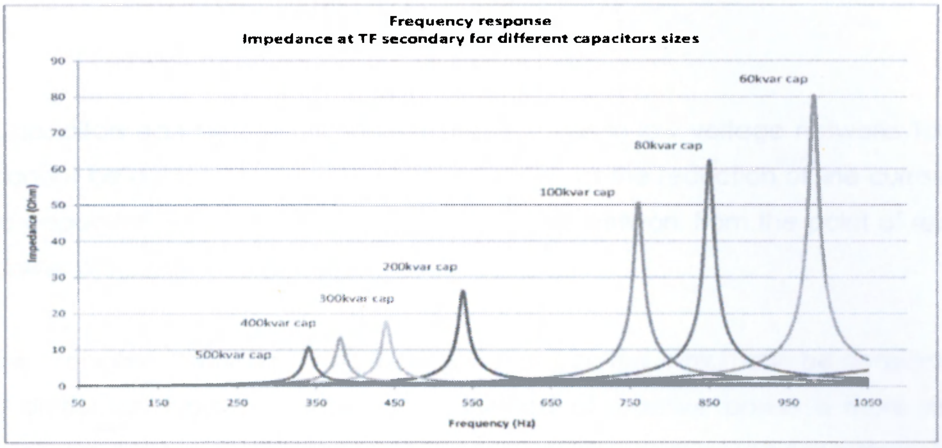


Figure 46 : Frequency response for various capacitor values at the transformer

3.8 OVERVOLTAGE DUE TO FIXED CAPACITORS UNDER LOW LOAD CONDITIONS

The model was simulated for various capacitor values with no load connected to feeder pillars. The voltage rise at respective points of the network was monitored for the two cases that the fixed type capacitor is connected at feeder pillar and transformer. The results, tabulated in Table 7 indicate that the rise in voltage under no load condition even for higher fixed capacitors values are not a critical issue.

Size of capacitor	Fixed capacitor at feeder pillar	Fixed capacitor at 11/0.145kV transformer
20kVA	**+1**	**+1**
60kVA	**+2**	**+2**
80kVA	**+3**	**+3**

Table 7 : Voltage rise under no load condition

4 CONCLUSION AND RECOMMENDATIONS

Capacitors can be used to reduce system losses in low voltage networks too. This cannot be achieved with HV or MV capacitors as the reduction of line current due to capacitors is only in upstream sections of the network from the point of reactive power injection.

The proposed method of using fixed power capacitors, which can be considered as a distributed type of compensation method of reactive power is more reliable compared to bulk reactive power compensation techniques used at higher voltage levels. Failure of HV shunt power capacitor system would affect a major load.

Fixed type power capacitors, which require only minimal accessories, are highly effective and very economical in reducing system losses of the low voltage distribution network. The payback period of the proposed method is only 6 months.

Followings are recommended when implementing a cluster of Fixed type capacitors for loss reduction purposes in a LV distribution system. All possible means shall be employed to reduce the operating temperature of capacitors, which was found to be the major reason to reduce the lifetime of capacitor units.

- Use capacitors close to the final distribution point of the low voltage network. In the selected sample of underground system having fixed type low voltage capacitors at feeder pillars is more effective than having them at distribution transformers.

- When capacitors are installed outside and exposed to direct sunlight used enclosures. Enclosures will reduce temperature of the capacitor tank at least by 2.5 ^{0}C.

- The exterior colour of enclosures shall be a light colour. For example the internal air temperature of a light gray coloured enclosure is lower by 7 ^{0}C compared to that of Dark green finished enclosure.

- Thermal insulators with reflective foil shall be affixed on to internal surfaces. Internal air temperature of enclosures could be reduced by 2.5 ^{0}C by thermal insulators at least on top and the front sides of the enclosure.

- Provision of sufficient number of holes for ventilation of enclosures is more effective than having louvers. Louvers do not allow air flow in all directions with the flow surrounding natural air. It is possible to achieve a temperature difference of 1~1.5^{0}C of internal air inside of the enclosure by using holes instead of louvers.

- Cluster of low voltage capacitors installed in the distribution system shall be monitored periodically after installation.

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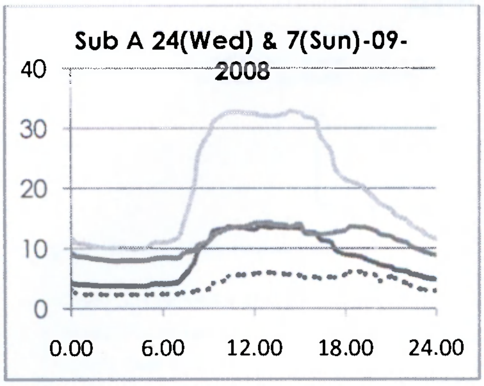
APPENDIX A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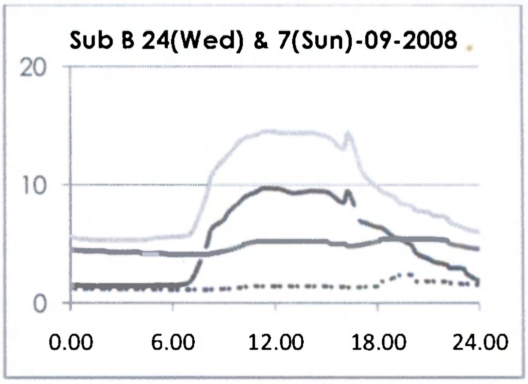
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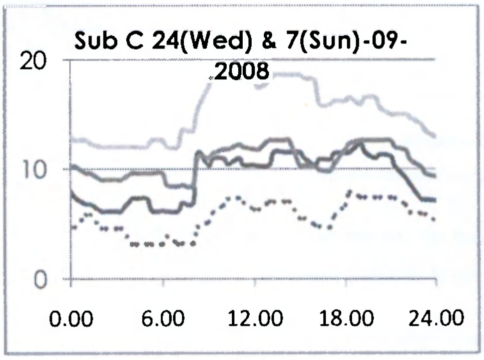
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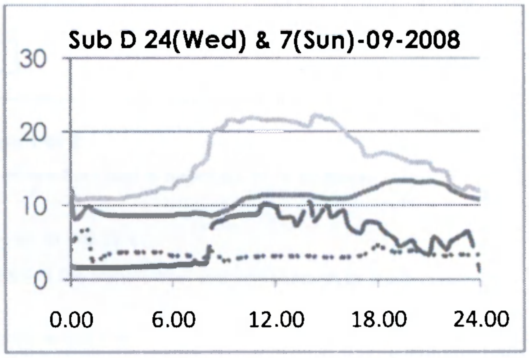
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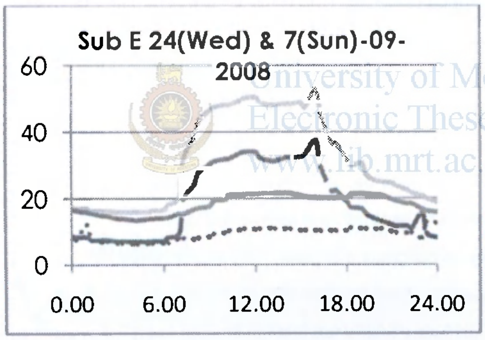
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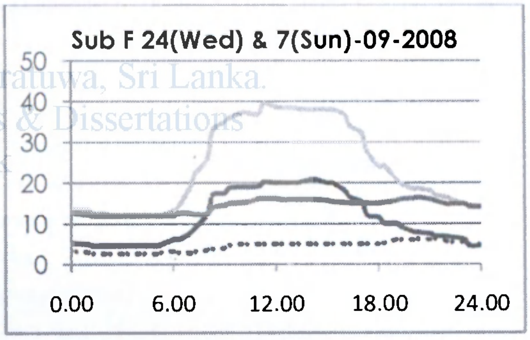
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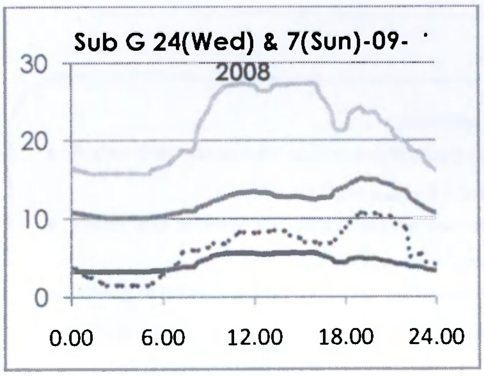
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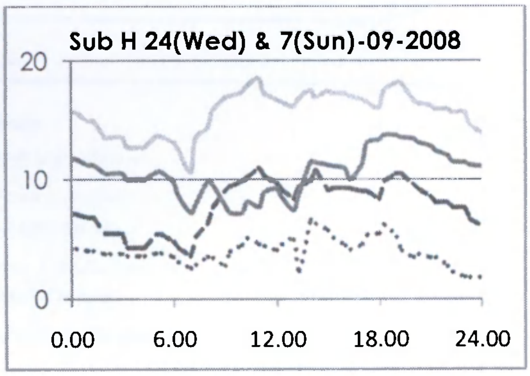
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▬	Mvar_H (On a high demand day)	– – ·	MW_H
••••••••	Mvar_L (On a low demand day)	▬	MW_L

APPENDIX B

STEPS OF MATLAB PROGRAM

Initialize model parameters

Import Load data (P & Q)

⇩

Case of simulation ?

Case1: Fix capacitor at 400V feeder pillar (20kVA @ 2xFP)

Case2: Fix capacitor at 11/0.415kV transformer (40kVA @ 1xTF)

Caee3: Switching capacitors at 11/0.415kV transformer (40kVAx5 steps (@ 1xTF)

⇩

Steps – Case 1 or 2

- System is simulated for the imported load data, where the Load is switched on in all three feeder pillars at t=0 s.
- P, Q, V & I at the source and the load are measured at t=0.25 s.
- Fix capacitors at three feeder pillars or fix capacitor at the transformer are switched on at t=0.3 s, depending on the case.
- P, Q, V & I at the source and the load are measured at t=0.5 s.

Steps – Case 3

- System is simulated for the imported load data, where the Load is switched on in all three feeder pillars at t=0 s
- Q flow at Transformer secondary is measured at t=0.25 s
- No. of possible capacitor to switch is calculated to compensate above Q.
- System is again simulated for the imported load data as before
- P, Q, V & I at the source and the load are measured at t=0.25 s.
- All required capacitor steps are switched on at t=3 s.
- P, Q, V & I at the source and the load are measured at t=0.5 s.

⇩

Calculated results

- Power loss between the source and the load without capacitor as

  $[\text{Source}_{\text{Power}} - 3 \times \text{Load}_{\text{Power}}]_{\text{with capacitor}}$

- Power loss between the source and the load with capacitor as

  $[\text{Source}_{\text{Power}} - 3 \times \text{Load}_{\text{Power}}]_{\text{without capacitor}}$

- Saving of loses is calculated as the difference of above results
- Energy saving over a period of one month is calculated by integrating above results