STUDY OF OPTIMAL LOCATION FOR CAPACITOR INSTALLATION IN A 220/132/33 kV GRID SUBSTATION

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

Deceleration

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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Abstract

In the island wide transmission network of Ceylon Electricity Board, there are 33kV Breaker Switch Capacitor Banks at twelve locations for improving the efficiency and quality of power.

The capacitor bank installed at Pannipitiya Grid Substation, which is the highest capacity installed in a grid substation of the CEB network was failed immediately after connecting to the system. Several studies were conducted to identify reasons of the failure. However the final recommendation is still pending.

Placement of capacitor banks in a grid substation is a major factor, influencing the reliability and efficient operation of capacitor banks. Therefore, this study was focused on to determine the preferred location of installing capacitor banks in a 220/132/33 kV grid substation. The two of possible locations are at 33kV tertiary of the power transformers and at the 33 kV load bus.

Influences on capacitor banks under different fault conditions were analyzed in this study, while simulating the grid model built using Simulink in MATLAB program.

Positive and negative impacts were found in respect of the two identified locations.

- Switching stresses on capacitors of the bank is less when capacitors are installed at tertiary of the power transformers compared to the case when capacitors are at the 33 kV load busbar.

- For balance or unbalanced feeder faults, preferred location is the 33 kV load busbar, since voltage and current fluctuations are less compared to the other location.

- In case of lightning strikes at high voltage side, capacitors have less stresses when located at 33 kV load busbar.

As such, it is recommended to connect capacitor banks at tertiary of 220/132/33 kV transformers of grid substations in industrial areas such as Export processing Zones, because the capacitor banks are subjected to frequent switching due to high load variations of the industrial load.

Installation of capacitor banks at 33 kV load busbars is recommended to the grid substations where there are long power transmission lines with frequent feeder faults because such feeder faults have less influence on capacitor banks when they are located at the 33 kV load busbars.

Acknowledgement

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I specially thank Mrs. Y. M. Samarasinghe, Deputy General Manager (Western Province South), who initially put forth the idea of studying the ideal location for installation of capacitor banks in grid substations.

I highly appreciate my friends and colleagues, specially Mr. Kurrupu Dharmasiri for their help offered to collect data and information required to prepare a realistic model for the study.

Finally, I thank many individuals for making this research a success, who have not been mentioned here personally.

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Chapter 1

Introduction

1.1 Background of the research

Transmission of reactive power should be kept at a minimum level to reduce voltage drops, over voltages, transmission losses and to maximize the flow of active power. In order to minimize the flow of reactive power from the supply source, capacitors can be installed at selected places in the network close to the load. The use of Shunt Capacitor Banks (SCBs) is increasingly popular as they are relatively inexpensive, easy and quick to install and can be deployed virtually anywhere in the network. Load flow calculations will provide information on the total amount of reactive power required and the location of capacitors in the transmission network.

As reactive power requirement changes during the daily load cycle, it is necessary to switch the capacitors to match with the load. The size of the individual capacitor step must be limited to minimize voltage fluctuations. This may require large number of switching equipment. Capacitors are installed at medium voltage level to minimize the cost of switching equipment.

If the grid substation consists with auto transformers with delta tertiary, it is preferred to connect the capacitors to the tertiary because this will additionally reduce voltage fluctuations that would occur in the system.

However, electrical transients appear in the network due to network switching and faults occurrences. Network equipment, including capacitor banks are subjected to high stresses resulting from surge current and voltage..

1.1.1 Development of the CEB network

Prior to 1980s, the Ceylon Electricity Board (CEB)'s transmission system was composed of 132 kV and 66 kV lines, which had been developed in coordination with the growth in demand and development of hydroelectric power projects for delivering power to Colombo and other regions.

The major hydropower stations of the Mahaweli and Laxapana Complexes are in central mountains and a number of transmission lines have been constructed towards Colombo area. Initially, 132 kV transmission lines were constructed as the major systems to transmit large power for long distance and 66 kV systems for local power transmission. In 1984 , the first 220 kV transmission line with duplex Zebra conductors (400 mm^2) , Victoria –Kotmale-Biyagama (suburb of Colombo) commenced its operation to transmit the large generated power of the newly constructed two major hydro power stations of Victoria and Kothmale (approximately 410 MW in total) to Colombo. Later, this system was extended from Victoria to Rantambe via Randenigala, and from Biyagama to Kotugoda. Two 132 kV lines, Biyagama-Kelanitissa and Biyagama-Pannipitiya, were constructed with the 220 kV design and have been operated at 132 kV voltage. From Transmission & Substation Development Project1, the 220 kV network of CEB expanded up to Pannipitiya grid substation.

In1997 NIPPON KOEI CO., Ltd of Japan conducted a master plan study for development of the transmission system of the Ceylon Electricity Board. They identified the requirement of static capacitors and shunt reactors to minimize the voltage variation of the bus voltage regardless of voltage drop or rise in long transmission lines. At that time only three static capacitors of 20 Mvar each have been installed on the 33 kV buses of the Kotugoda, Anuradhapura and Galle Grid Substations. At the Galle Grid Substation, additional static var compensators (SVC), +20 Mvar and -20 Mvar are also in operation for smooth adjustment of 132 kV system voltages.

Under the master plan study of CEB, it had identified that low power factor of the Colombo power system as a serious problem to keep the operating voltage of the 132 kV systems. Though gas turbine generators are used in the condenser mode of operation, their available capacity was not enough. The shortage of reactive power was a serious problem at that time.

Following to the Power System Analysis, it was proposed to connect 100 Mvar capacitors at Pannipitiya Grid substation by 2000 [1].

Reactive power compensating substations of the CEB network and there capacities are summarized in Table 1.

No	Location	Capacity (MVar)	Connection Location
1	Galle (SVC)	20	132 kV network
2	Anuradhapura	20	33 kV load bus
3	Habarana	10	33 kV load bus
4	Kotugoda	50	33 kV load bus
5	Kiribatkumbura	20	33 kV load bus
6	Kurunegala	10	33 kV load bus
7	Matugama	20	33 kV load bus
8	Panadura	20	33 kV load bus
9	Puttalama	20	33 kV load bus
10	Pannipitiya*	100	220/132/33 kV tertiary
11	Athurugiriya*	20	33 kV load bus
12	Thulhiriya*	10	33 kV load bus

Table 1 - Power capacitors installed locations in CEB network

* Breaker Switch Capacitors installed at Aturugiriya, Pannipitiya and Thulhiriya are not in operation due technical reasons.

1.2 Motivation of this study

Under the Transmission & Substation Development Project 1, two number of 83.33 MVA power transformers were installed at Pannipitiya Grid Substation and Pannipitiya-Biyagama transmission line voltage level was improved to 220 kV. In order to improve the voltage profile of transmission network, 100 Mvar capacitor banks were installed at Pannipitiya grid substation under the Transmission & Substation Development Project -2, based on the Transmission Development Plan.

However, Breaker Switch Capacitors at Pannipitiya GSS, which were connected to tertiary of the 220/132/33 kV power transformers were failed within the defect liability period. The reasons to failure were under investigating.

Therefore, 10 Mvar capacitor banks at Thulhiriya GSS and 20 Mvar banks at Athurugiriya GSS were kept in de-energized state even though no failures observed at those places, due to unresolved issues over this failure. Unavailability of necessary reactive power affects the CEB network in following ways.

1. Network operation is severely constrained in day to day operations due to lack of reactive power.
2. Cost incurred due to increased losses in power transmission.
3. Financial losses: Capital investment cost is around 15% of the total project cost.

In Ceylon Electricity Board transmission network, Breaker Switch Capacitors have been connected atto the 33 kV load bus in all the locations, except at Pannipitiya GSS, where the capacitors are connected to the tertiary of 220/132/33 kV transformers. Various problems were uncounted from time to time, even the capacitor banks had been connected to the 33 kV load bus bars.

Several technical problems are to be addressed in order to guarantee the availability of installed power capacitors in CEB network. One of the problems is the selection of the location of capacitor banks in a grid substation.

1.3 Objectives

The objective of this study is to identify the most suitable location for the connection of 33kV Breaker Switch Capacitors in a 220/132/33 kV Grid substations. Those possible locations are

- Tertiary of 220/132/33 kV power transformer and
- 33 kV Load busbar.

Chapter 2

Literature Review

2.1 Applicable Standards

2.1.1 IEEE 18-2002 standard [2}

Capacitors shall be capable of continuous operation provided that none of the following limitations are exceeded.

- 110% of rated r.m.s. voltage 36.30 kV
- 120% of rated peak voltage
  i.e., 1.2 * √2* rated r.m.s. voltage 56.00 kV
  Including harmonics but excluding transients
- 135 % of nominal r.m.s. current based on rated kvar and rated voltage,
  For 5 Mvar bank 118.09 A
  For 20 Mvar bank 472.38 A

Capacitors shall be capable of withstanding switching transients having crest voltage up to two times.

- Reactive power manufacturing tolerance of up to 115% of rated reactive power.

2.1.2 IEC60871 -1: 1997 [3}

Under the routing test, capacitor should withstand ac test voltage of 2.15 times rated r.m.s voltage.

Long duration power frequency voltages are

- 100% of r.m.s. voltage for continuous operation at power frequency
- 110% of r.m.s. voltage for 12hours in every 24h
- 115% of r.m.s. voltage for 30 minute in every 24h

- 120% r.m.s. voltage for 5 minutes
- 130% r.m.s. voltage for 1 minute

Maximum permissible currents are:

- 130 % of r.m.s. current for continuous operation at rated voltage, rated current and rated frequency excluding transients.

2.2 The Capacitor Unit

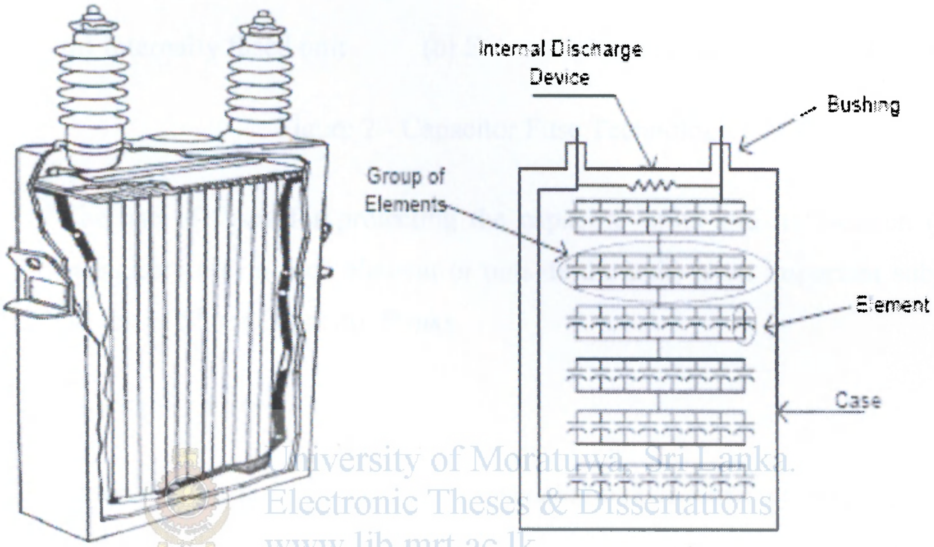
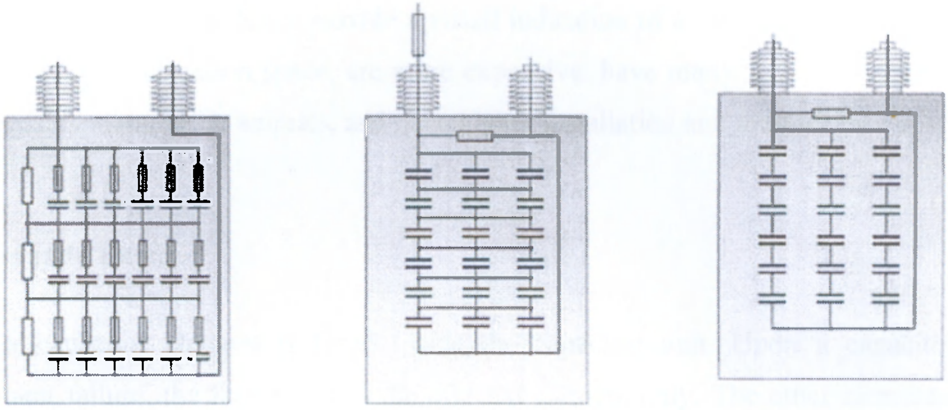


Figure 1 - Cross section of a Power Capacitor Unit

Figure 1 is the building block of a shunt capacitor bank. The capacitor unit is made up of individual capacitor elements, arranged in parallel/ series connected groups, within a steel enclosure. The internal discharge device is a resistor that reduces the unit residual voltage to 50V or less in 5 min. Capacitor units are available in a variety of voltage ratings (240 V to 24,940V) and sizes (2.5 kvar to about 1000 kvar) [4].

2.3 Fuse technologies

Capacitor units are available with Internal or External Fuses or Fuseless as shown in Figure 2.



(a) Internally fused unit (b) Externally fused unit (c) Fuseless unit

Figure 2 - Capacitor Fuse Technologies

The use of fuses for protecting the capacitor units and its location (inside the capacitor unit on each element or outside the unit) is an important subject in the design of Shunt Capacitor Banks.

2.3.1 Externally Fused

Externally fused SCBs are configured using one or more series groups of parallel-connected capacitor units per phase as shown in Figure 3. Advantages are

- An individual fuse typically protects each capacitor unit.
- The capacitor unit can be designed for a relatively high voltage because the external fuse is capable of interrupting a high-voltage fault.
- Use of capacitors with the highest possible voltage rating will result in a capacitive bank with the fewest number of series groups.

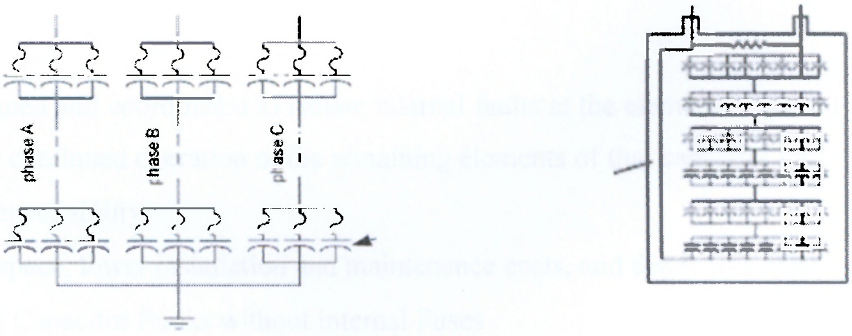


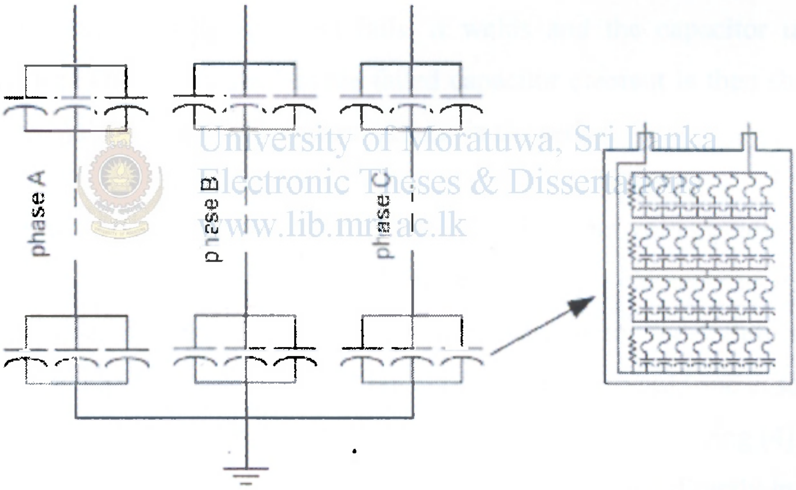
Figure 3 - Externally fused type

Although the external fuses provide a visual indication of a failure, banks tend to occupy more substation space, are more expensive, have many live parts subject to possible damage by animals, and have higher installation and maintenance costs [4].

2.3.2 Internally Fused

Each capacitor element is fused inside the capacitor unit. Upon a capacitor element failure, the fuse removes the affected element only. The other elements, connected in parallel in the same group, remain in service but with a slightly higher voltage across them.

Figure 4 illustrates a typical capacitor bank utilizing internally fused capacitor units. The capacitor units are normally large because a complete unit is not expected to fail [4].



Advantages

- Designed and coordinated to isolate internal faults at the element level and allow continued operation of the remaining elements of that capacitor unit.
- Higher reliability.
- Less space, lower installation and maintenance costs, and fewer live parts
- Shunt Capacitor Banks without internal Fuses

2.3.3 Fuseless shunt capacitor bank

To form a bank, capacitor units are connected in series strings between phase and neutral, shown in Figure 5.

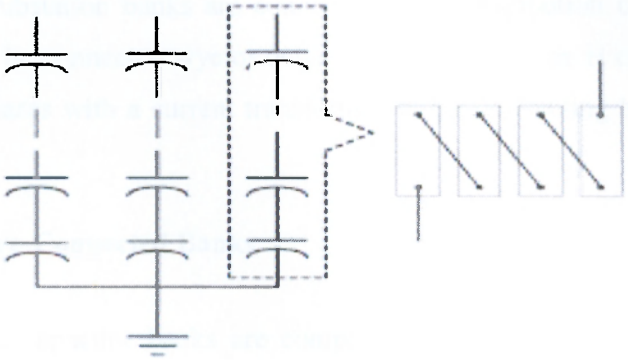


Figure 5 - Fuseless shunt capacitor bank and series string

When the capacitor element fails, it welds and the capacitor unit remains in service. The voltage across the failed capacitor element is then shared among all the remaining capacitor element groups in the series.

The fuseless design is not usually applied for system voltages less than about 34.5 kV. The reason is that there shall be more than 10 elements in series so that the bank does not have to be removed from service for the failure of one element because the voltage across the remaining elements would increase by a factor of about E (E – 1), where E is the number of elements in the string [4]. The discharge energy is small because no capacitor units are connected directly in parallel.

2.3.4 Unfused Shunt Capacitor Banks

Contrary to the fuseless configuration, where the units are connected in series, the unfused shunt capacitor bank uses a series/parallel connection of the capacitor units. The unfused approach would normally be used on banks below 34.5 kV, where series strings of capacitor units are not practical, or on higher voltage banks with modest parallel energy. This design does not require as many capacitor units in parallel as an externally fused bank [4].

2.4 Capacitor Bank Design

2.4.1 Basics of capacitor bank design and capacitor unit connections.

The optimum connection for a SCB depends on the best utilization of the available voltage ratings of capacitor units, fusing, and protective relaying. Virtually all substation banks are connected wye. Distribution capacitor banks, however, may be connected wye or delta. Some banks use an H configuration on each of the phases with a current transformer in the connecting branch to detect the unbalance.

2.5 Grounded Wye-Connected Banks

Grounded wye capacitor banks are composed of series and parallel-connected capacitor units per phase and provide a low impedance path to ground. Figure 6 shows typical bank arrangements.

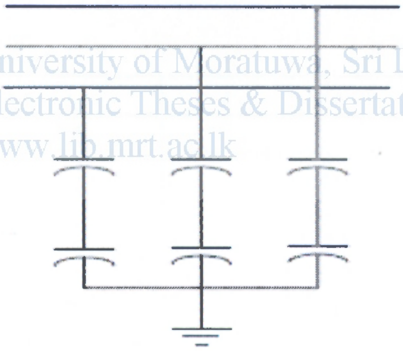


Figure 6 - Multiple units grounded single Wye

Advantages of the grounded capacitor banks include:

- Its low-impedance path to ground provides inherent self-protection for lightning surge currents and give some protection from surge voltages. Banks can be operated without surge arresters taking advantage of the capability of the capacitors to absorb the surge.
- Offer a low impedance path for high frequency currents and so they can be used as filters in systems with high harmonic content. However, caution

shall be taken to avoid resonance between the SCB and the system.

- Reduced transient recovery voltages for circuit breakers and other switching equipment.
- Some drawbacks for grounded wye SCB are:
- Increased interference on telecom circuits due to harmonic circulation.
- Phase series reactors are required to reduce voltages appearing on the CT secondary due to the effect of high frequency, high amplitude currents.

2.6 Multiple Units in Series Phase to Ground – Double Wye

When a capacitor bank becomes too large, making the parallel energy of a series group too great (above 4650 kvar) for the capacitor units or fuses, the bank may be split into two wye sections. Figure 7 shows typical bank arrangement for multiple units grounded double wye capacitor bank [4].

The characteristics of the grounded double wye are similar to a grounded single wye bank.

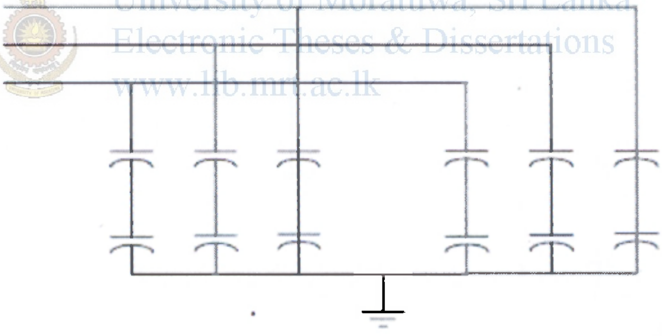


Figure 7 - Multiple units grounded double Wye

2.7 Ungrounded Wye-Connected Banks

Ungrounded wye banks do not permit

- Zero sequence currents,
- Third harmonic currents, or
- Large capacitor discharge currents during system ground faults to flow.
- Over voltages appearing at the CT secondaries are not as high as in the case of grounded banks.

However, the neutral should be insulated for full line voltage because it is momentarily at phase potential when the bank is switched or when one capacitor unit fails in a bank configured with a single group of units. Figure 8 shows multiple units ungrounded single wye capacitor bank. For banks above 15kV this may be expensive [4].

2.8 Multiple Units in Series Phase to Neutral - Single Wye

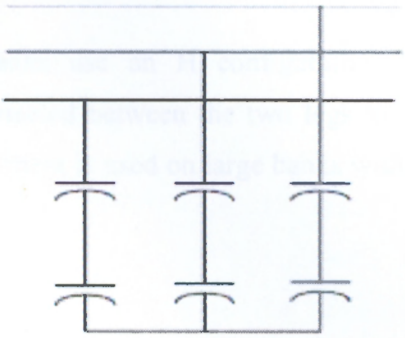


Figure 8 - Multiple units ungrounded single Wye

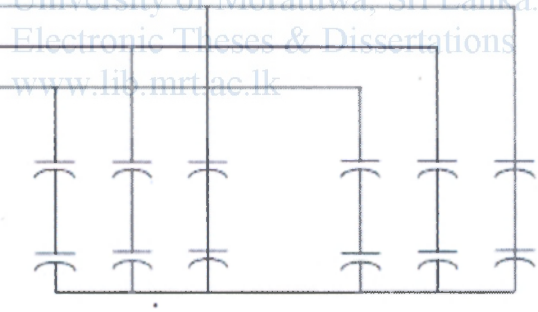


Figure 9 - Multiple units ungrounded double Wye

When a capacitor bank becomes too large for the maximum 4650 kvar per group the bank may be split into two wye sections as shown in Figure 9. As for any ungrounded why bank, the neutral instrument transformers should be insulated from ground for full line-to-ground voltage, as should the phase terminals [4].

2.9 Delta-connected Banks

Delta-connected banks are generally used only at distributions voltages and are configured with a single series group of capacitors rated at line-to-line voltage. With only one series group of units no overvoltage occurs across the remaining capacitor units from the isolation of a faulted capacitor unit [4].

2.10 H Configuration

Some larger banks use an H configuration in each phase with a current transformer connected between the two legs to compare the current down each leg. This arrangement is used on large banks with many capacitor units in parallel [4].

Chapter 3

Methodology

3.1 Introduction

Transient disturbances in power systems may damage key equipment, potentially having a great impact on system reliability. These transients may be introduced during normal switching operations, interruption, short circuit faults, lightning strikes, or due to equipment failures. Capacitor banks installed in a grid substation would have great stresses from excessive currents and voltages due to such type of transients. Different fault conditions, which could develop in the power supply network were simulated to determine the most suitable location of capacitor banks to be installed in a grid substation and the simulated results were used for the analysis of voltage and current stress on capacitors and switchgears.

3.2 Software for transient analysis

Dynamic analysis model was to select for the analysis of transient voltages and currents in the network during different switching conditions due to frequency dependency the system.

The ATP-EMTP software (Alternative Transients Program - Electromagnetic Transients Program) is mostly used world-wide to compute electromagnetic transients in electrical power systems.

PSSE software is available in CEB to analysis the network transient. Currently, the PSSE software is used for the steady state analysis only. Therefore it requires to modify all the data files for dynamic analysis of the system. Due to time limitation, it was difficult to use PSSE for this study.

Considering convenience and the complexity of the study model MATLAB simulation software was used for this study.

3.2.1 Selection of Model for Study

Pannipitiya Grid Substation was selected as the model to study the optimal location for installation of capacitor in a 220/132/33kV Grid Substation. An equivalent model of Pannipitiya GSS was developed to include both the proposed options in the same model as depicted in Figure 9 . The switchgear arrangement of th ePannipitiys gris substation is given in annexure 1.

The options studied for connecting shunt capacitors are

- Capacitor banks connected to tertiary of 220/132/33kV transformers.
- Capacitor banks connected to 33 kV load bus.

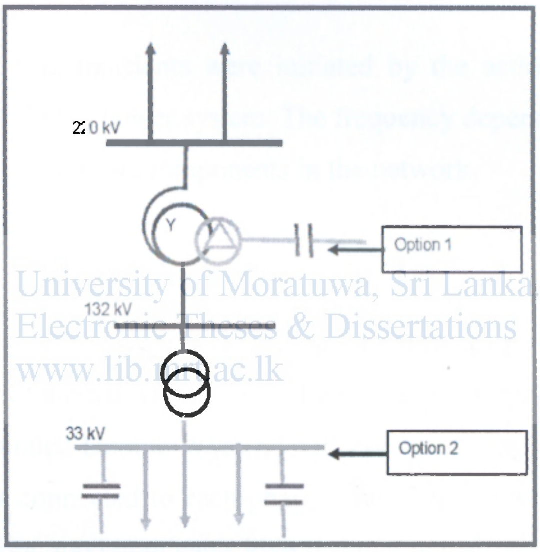


Figure 10 - Two options considered for the Study

3.3 Development of the Software Model

The model consist of following equipment,

<u>220 kV Switch Yard</u>

02 Nos.:	220/132/33 kV, 83.33 MVA auto transformers
02 Nos.:	220 kV Line Feeder Bays
01 No. :	220 kV Bus section bay

132 kV Switch Yard

02 Nos: 132/33 kV, 31.5 MVA Power transformers
04 Nos.: 132 kV Line Feeder Bays
01 No.: 132 kV Bus section bay
02 Nos.: 200 kVA earthing transformers

33 kV Switch Yard

04 Nos.: 33 kV Feeder Bays
01 No.: 132 kV Bus section bay
02 Nos.: 50 Mvar Capacitor banks are connected to 33 kV tertiary of each auto transformers or either side of the 33 kV bus section depend on study option.

Power System switching transients were initiated by the actions of the circuit breakers and by faults in the power system. The frequency dependent models were selected to represent the various components in the network.

3.3.1 Grounding System

220 kV and 132 kV systems were solidly grounded through power transformers. 33 kV system was grounded via earthing transformers. Capacitor banks were configured as ungrounded Double Wye (STAR) connected capacitor units with a fault limiting reactor connected to each phase. Transformers were not in parallel operation and therefore maximum capacitive reactive power on one 33 kV busbar was 50 Mvar.

Power Transformers

Transformers were modeled using name plate data and commissioning test data. For transient studies transformer parameters such as percentage impedances, winding resistances, capacitances core losses and hysteresis loss were considered [5].

83.3 MVA, 220/132/33 kV Auto Transformer

Winding	Percentage impedances	Percentage resistance	Percentage inductance
HV-LV	14.18	0.01562	0.04514
HV-TV	16.67	0.01376	0.03826
LV-TV	12.02	0.02343	0.05306

Table 2 - 83.33MVA Transformer Data

Selected base values were 83.33 MVA, 220 kV voltages and 220 kV on respective levels.

Winding resistances

1U-2U	0.1225 Ω
2U-N	0.2654 Ω
3U-3V	0.09351 Ω

Source of supply

The fault level at 220kV busbar was taken as 25 kA. 220 kV system was replaced with the thevenin equivalent at 220 kV supply point based on short circuit current value.

31.5 MVA, 132/33 kV Transformer [6]

Winding	Percentage impedances	Percentage Resistance	Percentage inductances
HV-LV	10.60	0.00055083	0.08922

Table 3 - 31.5 MVA Transformer Data

200 kVA Earthing Zig Zag Earthing Transformer

Winding	Zero sequence impedance (%)	Percentage Resistance	Percentage inductances
HV	9.57%	24.67	12550

Table 4 - 200 kVA Earthing Transformer Data

Transmission Lines

Due to the frequency dependence of transient surges 132 kV transmission lines and 33 kV distribution feeders were modeled using PI–sections. Cascaded pi-sections were selected to obtain accurate transients. Actual line parameters were used [7].

Line description	Length (km)	R/cct (pu)	X/cct (pu)	Y/cct (pu)
Pannipitiya – Ratmalana 132 kV Transmission Line	6.9	0.00705	0.01588	0.00336
Pannipitiya – Panadura 132 kV Transmission Line	12.3	0.00629	0.02734	0.00631
33 kV lines	4.7	0.0048	0.01082	0.00229

Table 5 - Transmission and Distribution Line Data

Switch Gear - Circuit Breakers

Circuit breakers were modeled with introducing small contact resistance, high snubber resistances and capacitances. External control switch was used to control the breaker activities.

Loads and Reactors

132 kV and 33 kV loads were modeled using parallel RLC elements.

Breaker Switched Capacitors

Capacitor bank connection : Ungrounded Split Wye (Figure 11)
Number of Series Groups : 2
Number of Parallel Units : 2
Installed Units in Block : 8

All capacitor units are internally fused design type [8].

Capacitor banks are usually modeled as a single lumped element [9]. To study the system behaviors during capacitor unit failure, capacitor bank was modeled as a separate block with units as shown in Figure 12.

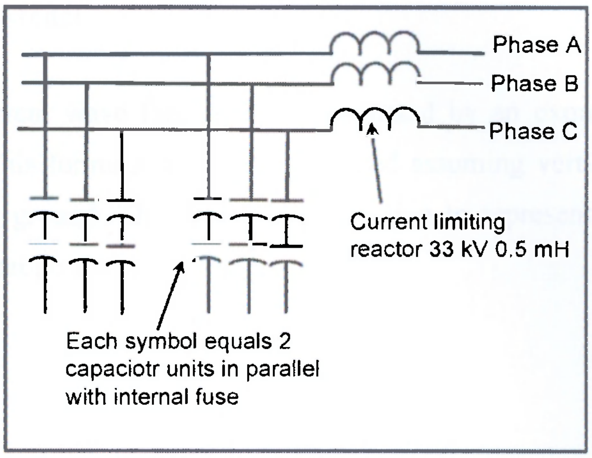


Figure 11 - Wiring Diagram of Capacitor Banks

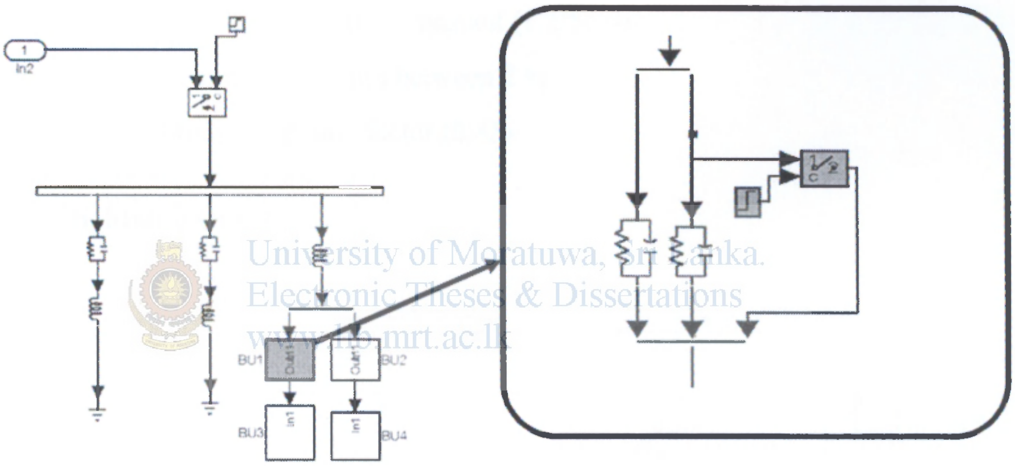


Figure 12- capacitor model used to study the unit failure effect

Time steps and Simulation length

External controller of the circuit breaker model was used to simulate the switching of capacitors, loads and fault conditions.

Time scales in seconds were selected to observe the current and voltage behavior during normal switching and to study the effect due to lightning impulse time scale in micro second range was selected.

Lightning Impulse Model

Lightning strike current wave form was approximated by an expression called Heidler Function. This formula had been developed assuming vertical lightning channel and perfect ground. The analytical expression to represent the channel base current i0(t) is proposed by Heidler [10].

$$I(0,t) = \frac{I_0 \left(t/\tau_1\right)^n}{\eta\left(t/\tau_1\right)^n + 1} \; e^{\frac{-t}{\tau_2}}$$

Where

I_0 = The magnitude of the channel base current

τ_1, τ_2 = Front and the decay time constant (1.2/50 μs)

n = Exponent having values between 2 to 10 (4.8)

η = Amplitude correction factor.(0.85)

Modeling the lightning stroke

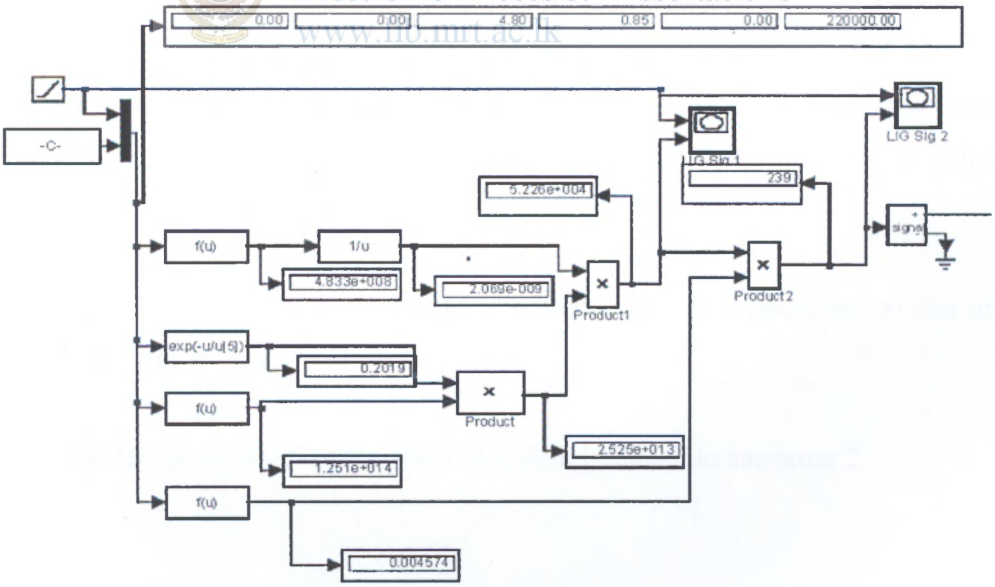


Figure 13 – Lightning Impulse Model

The induced voltage impulse at 220 kV busbar of the model due to simulated lightning impulse is shown in Figure 14.

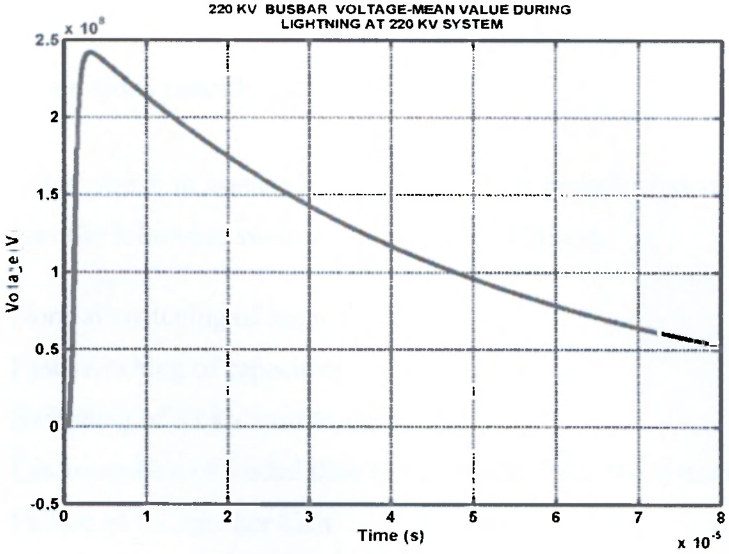


Figure 14 – Lightning Impulse at 220 kV busbar

Assumptions made for modeling

Zero sequence impedance of 132kV winding of 220/132/33 kV transformer is approximately equal to 80%-90% of positive sequence impedance of 132 kV to 33kV tertiary winding [11].

Zero sequence impedance of 220kV winding of 220/132/33 kV transformer is approximately equal to 85%-95% of positive sequence impedance of 220 kV to 33kV tertiary winding [11].

200 kVA earthing transformer winding inductance is proportional to that of 31.5 MVA transformer.

The simulink model of the selected system is shown in annexure 2.

3.4 Different fault conditions considered for analysis

Current and voltage stress in connection with the shunt power capacitors units were studied under the following switching and fault conditions.

1. Normal switching of capacitors
2. Fast switching of capacitors
3. Switching of 33 kV load to the system
4. Disconnection of loaded distribution feeder from the system
5. Failure of a Capacitor Unit
6. Unbalance faults in the system
7. Balance faults in the system
8. Lightning stroke in the 220 kV transmission line

Chapter 4

Results and Analysis

Fault conditions specified in section 0 were simulated and the voltage and current transients at capacitor banks were obtained for each fault.

Notations used in the graphs:

V33T1- Voltage variation of capacitor bank which was connected to tertiary of power transformer

V33B2- Voltage variation of capacitor bank which was connected to 33kV Busbars

I33T1- Current variation of capacitor bank which was connected to tertiary of power transformer

I33B2- Current variation of capacitor bank which was connected to 33kV Busbar

4.1 Normal Switching of Capacitor

The behavior of capacitor banks were studied while switching capacitor banks at following time intervals.

1st 5 Mvar capacitor bank	1 second
2nd 5 Mvar capacitor bank	2 second
3rd 20 Mvar capacitor bank	3 second
4th 20 Mvar capacitor bank	4 second

The selected switching times for simulation of the study were less than the practical switching times. However these times were selected considering the steady state condition of each switching event. Therefore the effects of previous switching will not influence on the next switching transient.

Switching inrush current in a capacitor bank can be explained using natural frequency (ω_0) of the circuit, which is a function of L and C of the circuit as shown in Figure 15 and surge impedance (Z_0) of the circuit of the circuit.

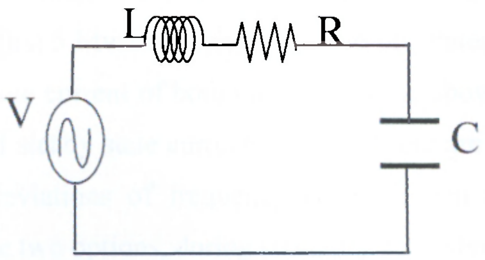


Figure 15- Equivalent model during instant of switching

Vs = Source voltage
Vc = Voltage across the capacitor
L = Equivalent circuit inductance
C = Equivalent circuit capacitance
R = Equivalent circuit resistance

$$i(t) = V_{(o)} * \frac{Sin\,(\omega_o t)}{Z_o}$$

Where $Z_o = \sqrt{\frac{L}{C}}$, $\omega_o = \frac{1}{\sqrt{LC}}$

$V_{(o)}$ is the difference between source voltage and the initial voltage of the capacitor at the instant of energization.

4.1.1 Switching of first 5 Mvar capacitor bank

The calculated surge impedance, natural frequency and steady state current for the switching of first 5 Mvar capacitor bank of the selected two options are as follows.

5 Mvar-1st Bank switching	Z0 (ohm)	f (Hz)	I (A)
Transformer Tertiary	116.52	96	87.477
Busbar	113.44	93	87.477

Table 6- Calculated values for the switching of 5 Mvar capacitor bank

Current and voltage wave forms obtained by simulating the model for the switching of first 5 Mvar capacitor bank are illustrated in Figure 15 and Figure 16. The steady state current of both the cases in the above figures were confirmed by the calculated steady state currents values. There are no major differences except few minor deviations of frequency of oscillation and magnitude of transient current for the two options, during switching of 5 Mvar capacitor bank.

First stage - Switching of first 5 Mvar capacitor bank - Switching time 1 second

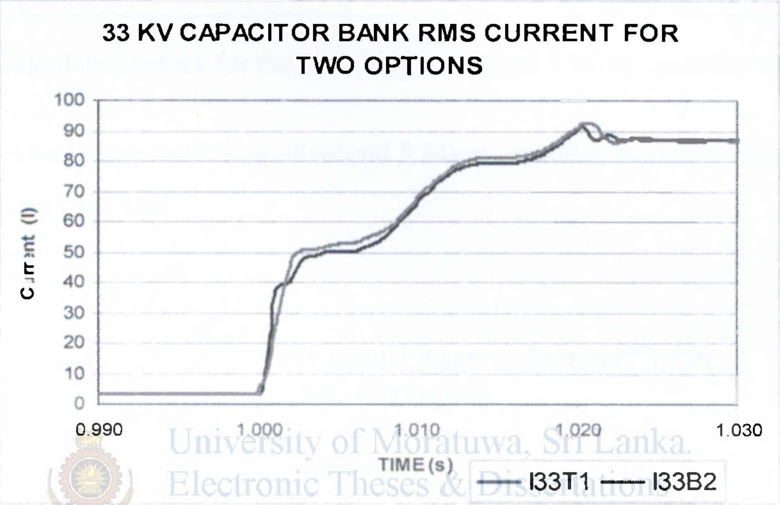


Figure 16 - Current transient during switching of 1st 5Mvar capacitor bank

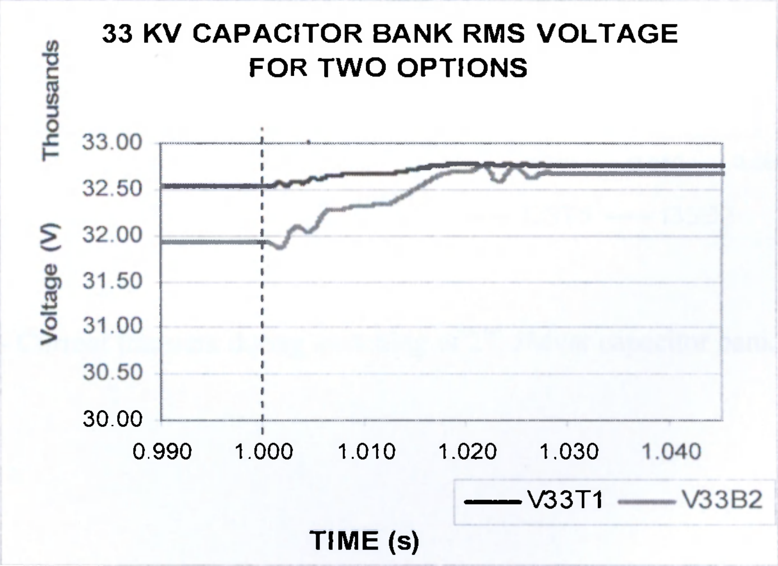


Figure 17 - Voltage transient during switching of 1st 5Mvar capacitor bank

4.1.2 Switching of second 5 Mvar capacitor bank

During the switching of the second 5 Mvar capacitor bank also, it was difficult to observe any differences of the two waveforms corresponds to the two cases of study. Below table shows the calculated values and Figure 18 and Figure 19 indicate the simulated the results obtained from the model.

5 Mvar- 2^{nd} Bank	Z_0 (ohm)	f (Hz)	I (A)
T/f. Tertiary	82.40	66	174.95
Busbar	80.22	68	174.95

Table 7 - Calculated values for the switching of second 5 Mvar capacitor bank

For the second stage switching of second 5 Mvar capacitor bank switching time of 2 seconds was selected.

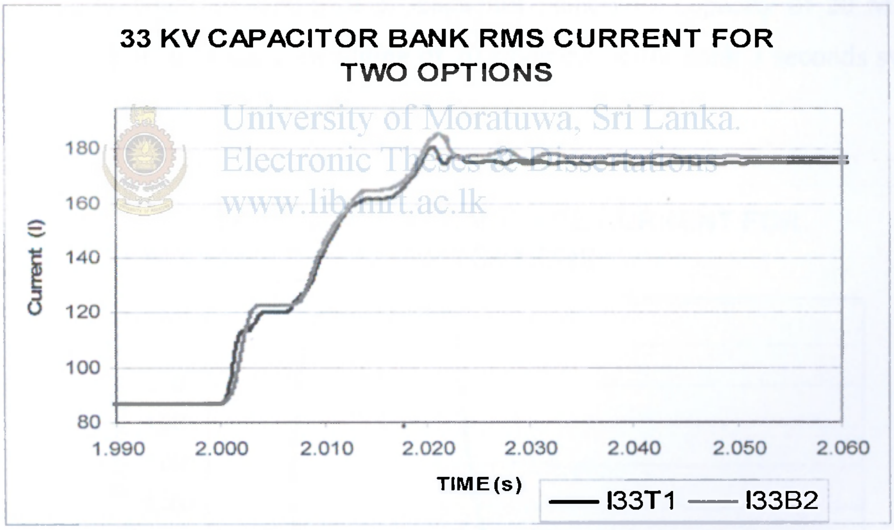


Figure 18 - Current transient during switching of 2^{nd} 5Mvar capacitor bank

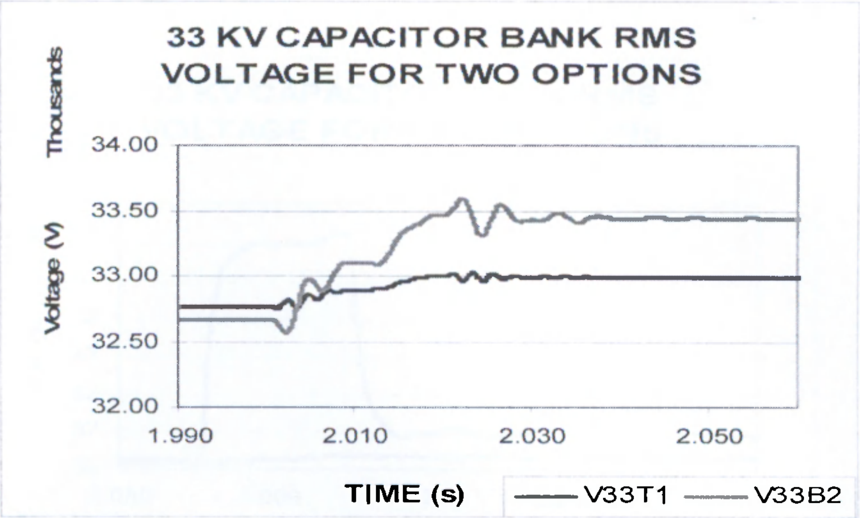


Figure 19 – Voltage transient during switching of 2^{nd} 5Mvar capacitor bank

4.1.3 Switching of 3^{rd} 20 Mvar capacitor bank

Simulated results of voltage and current transients are shown in Figure 20 and Figure 21 when switching of 3^{rd} capacitor bank with capacity of 20 Mvar at 3 seconds. For third stage switching of 20 Mvar capacitor bank 3 seconds switching was selected.

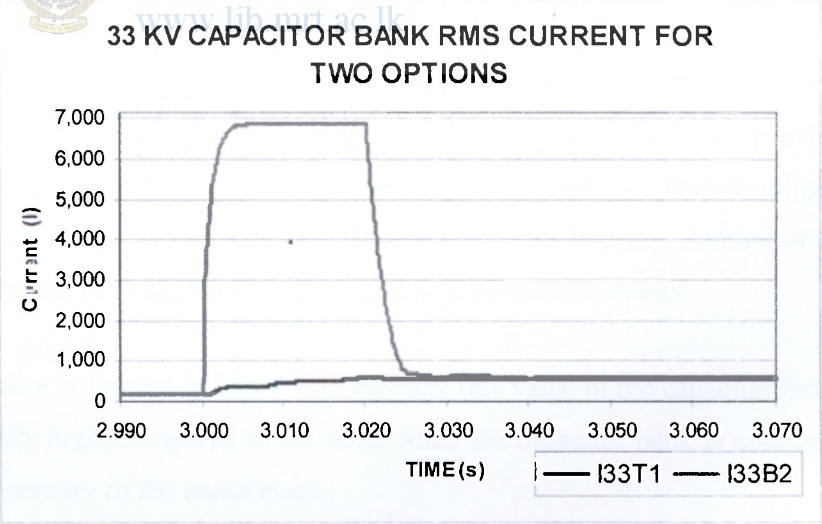


Figure 20 – Current transient during switching of 3rd 20Mvar capacitor bank

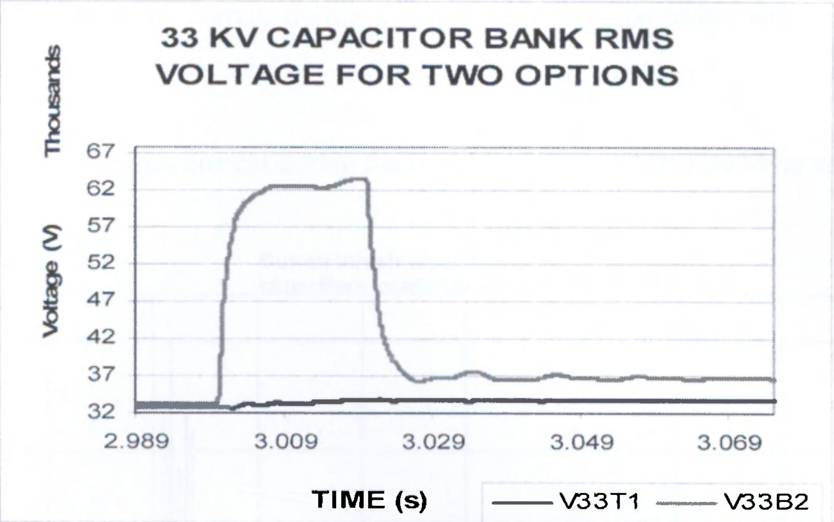


Figure 21 – Voltage transient during witching of 3rd 20Mvar capacitor bank

At the instant of switching of the 3rd 20 Mvar capacitor bank, it is in series with 10 Mvar capacitor bank, which had been switched in 1st and 2nd stage (Paralleling of two of 5 Mvar capacitor banks). Equivalent capacitances when switching on the 3rd step of the capacitor bank is 19.5 μf.

Therefore the resultant inrush current during 3rd stage 20 Mvar capacitor is higher as shown in Figure 22 due to the series combination of total capacitance of 10 Mvar, source impedance and capacitance of 20 Mvar Capacitor bank. This type of switching is called back to back switching. The energized capacitor bank provides an extremely low source-impedance for the switching capacitor bank leading to extremely high transient currents in both banks. Current limiting reactors of the capacitors should be designed to control such high transient currents.

When capacitor is located at 33 kV load busbars, rms value of the capacitor inrush current is very high, compared to the same when the capacitor bank is connected to the 33kV tertiary of the transformer.

Obtaining a solution by manual calculation is difficult of this type of circuits which involves large number of R, L and C branches. Numerical methods of solving such a system of differential equations have been developed and EMTP is an example for same.

Using the study model developed with MATLAB simulink, it can observe a higher inrush current during switching of capacitor banks when located at load busbars.

Instantaneous current during the switching of the 3rd step 20 Mvar capacitor bank.

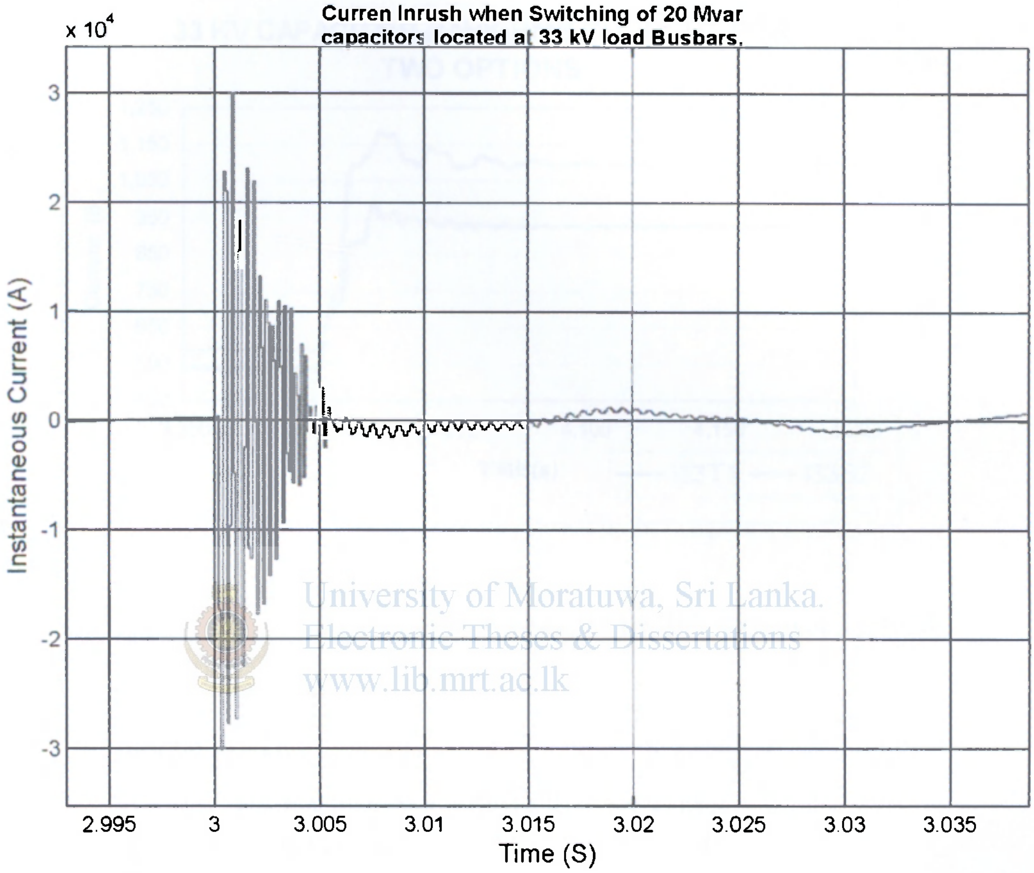


Figure 22 - Inrush current at the switching of 3rd step 20 Mvar capacitances.

4.1.4 Switching of 4th 20 Mvar capacitor bank.

Steady state currents derived by manual calculation

20 Mvar- 4th Bank	Z0/ohm	f / Hz	I/A
T/f. Tertiary	36.84	29.5	875
Busbar	35.88	30	875

Table 8- Steady state currents during switching of 4th stage

At the instant of switching on the 4th capacitor bank, the equivalent capacitance is 31.5 μf. Therefore switching inrush current to the capacitor bank is not very high compared with the switching of 3rd step of capacitor bank switching.

Simulated results of voltage and current transients are shown in Figure 20 when switching of 4th capacitor bank with capacity of 20 Mvar at 4 seconds.

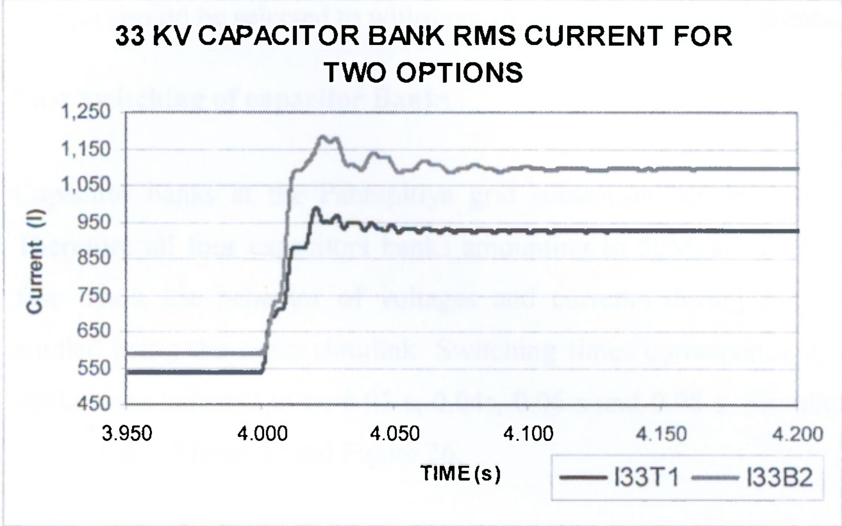


Figure 23 - Current transient during switching of 4th 20Mvar capacitor bank

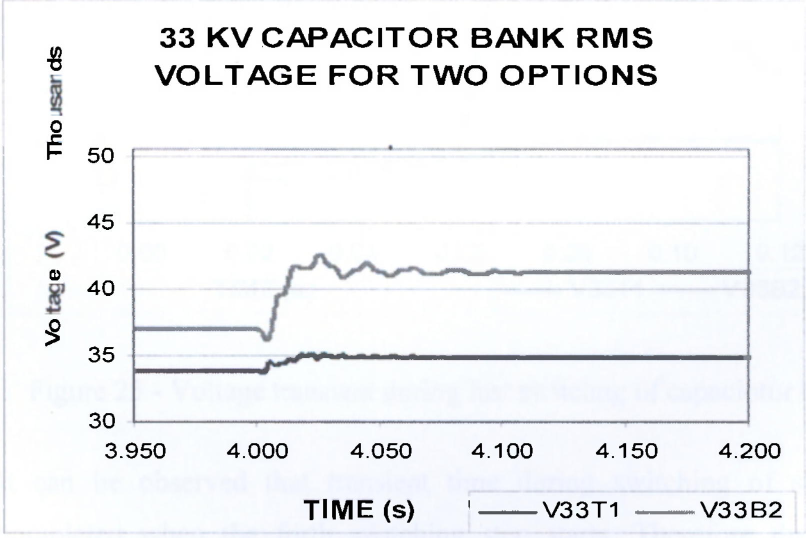


Figure 24 - Voltage transient during switching of 4th 20Mvar capacitor bank

In this case of switching, it takes few cycles to stabilize oscillation of current and voltage. This type of switching transients creates power quality problems on sensitive customer loads. Due to high switching transient current and voltage, switchgears such as circuit breakers and disconnectors connected to the capacitor feeders should be selected to withstand these high transient currents.

4.2 Fast Switching of capacitor Banks

Capacitor banks at the Pannipitiya grid substation can be switched manually. Therefore all four capacitors banks amounting to 50Mvar can be switched very fast. Thus, the behavior of voltages and currents during fast switching were studied using the same simulink. Switching times corresponds to four capacitor banks were selected to be 0.03 s, 0.04s, 0.06 s and 0.08 s. Simulation results are illustrated in Figure 25and Figure 26.

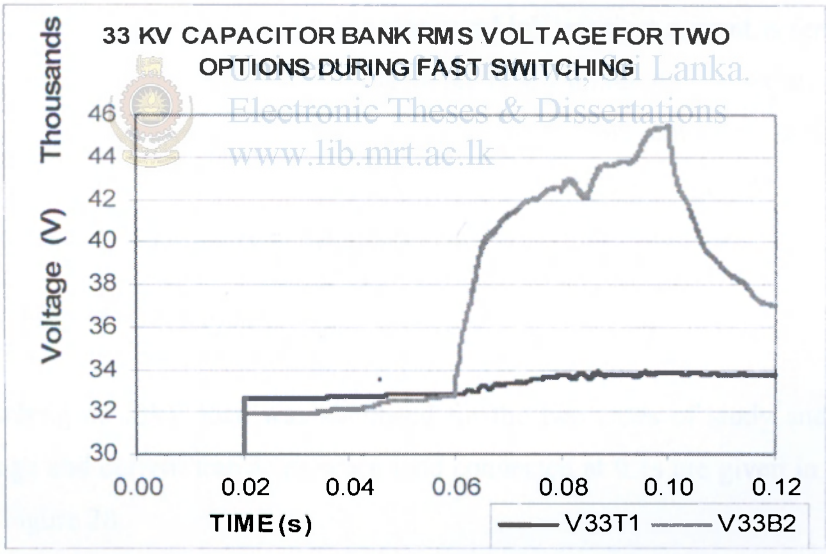


Figure 25 - Voltage transient during fast switchng of capaciotor banks

It can be observed that transient time during switching of step 3 was not completed when the forth switching step starts. Therefore the magnitude of transient voltage and transient time increased to higher values where capacitor performance could be adversely affected. Undue increase of voltages across the capacitor units will reduce the life time of the capacitors by dielectric failures. Due to fast switching, quality of the supply power at distribution level also adversely affects.

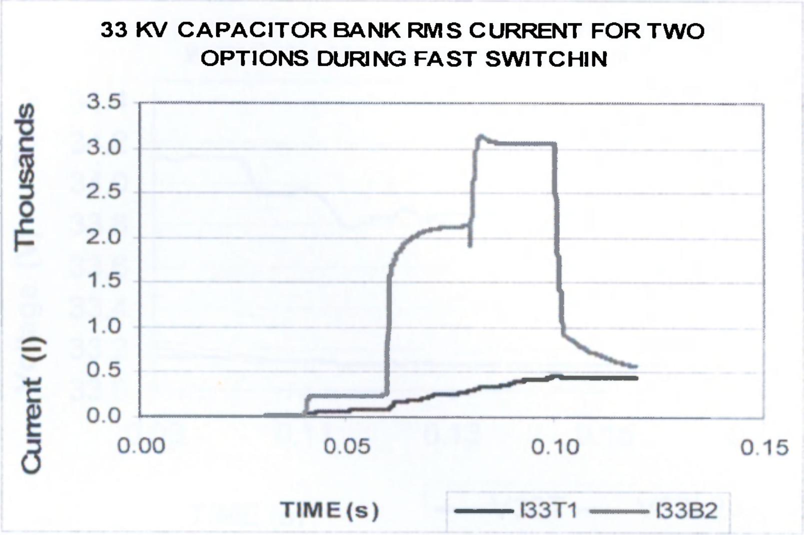


Figure 26 - Current transient during fast switchng of capaciotor banks

Due to fast switching of 20 Mvar capacitors high transient current is remained for a considerable duration. Current magnitude is few hundreds of rated rms currents. Due to this type of transient over voltages and current not only capacitors but also other equipments in the capacitor bays subjected to voltage stresses that could result insulation failures and reduced the life time of the equipment.

4.3 Switching of 33 kV load to the system

Switching of 33kV load was simulated for the two cases of study and resulting voltage and current transients when load connected at 0.1s are given in Figure 27 and Figure 28.

When the load is switched on, voltage of the capacitors will reduced depending on the capacity of the load and the current flow from the capacitor will increase, if the capacitor banks were located at 33 kV busbar, compared to the case where the capacitor banks were connected to the tertiary of the 220/132/33kV transformer.

When the capacitors were at busbars, the capacitors had been more sensitive to the changes in voltage and currents due to sudden connection of load. If capacitor banks were located at tertiary of the auto transformers, capacitor banks would not stress due to switching of load feeders.

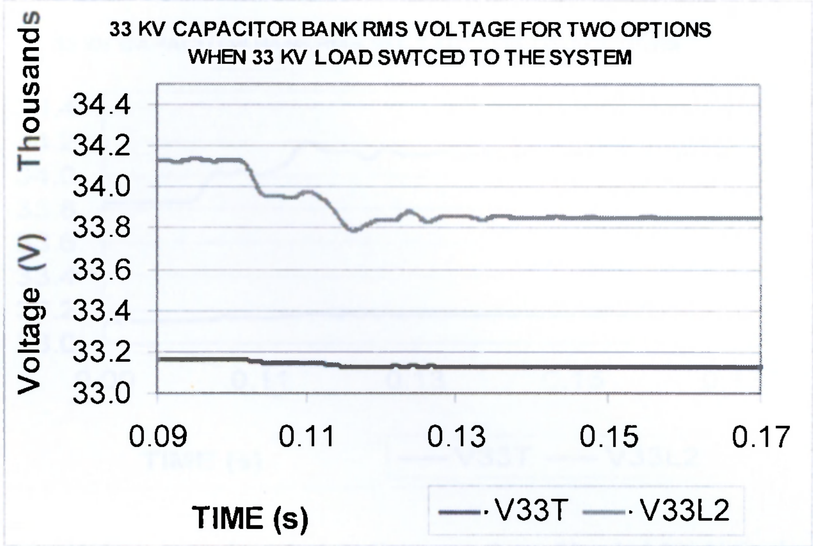


Figure 27 - Voltage transient during switched the loaded 33 kV feeder

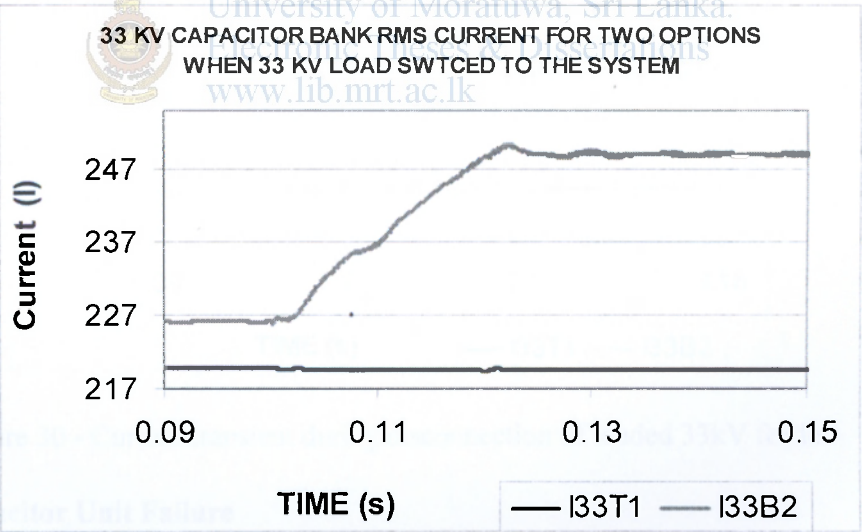


Figure 28 – Current transient during switched the loaded 33kV feeder

4.4 Disconnection of loaded distribution feeder from the system

Similarly, for sudden disconnection of 33 kV loads, stresses to the capacitor banks were low if the capacitors were located at the tertiary of the power transformer.

With the sudden disconnection of load, voltage of the load busbar will increase. It will directly affect to the capacitors located at the busbars. Simulated results of voltage and current transients are shown in Figure 29 and Figure 30 when ·load disconnected at 0.1s.

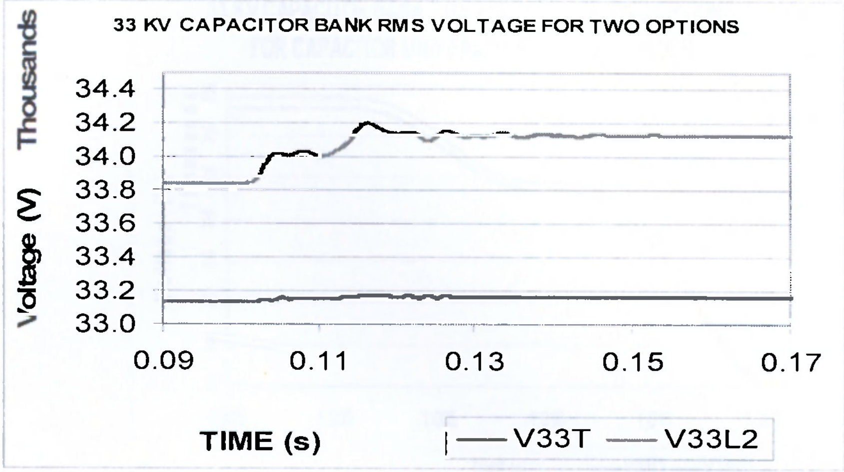


Figure 29 - Voltage transient during disconnection of loaded 33kV feeder

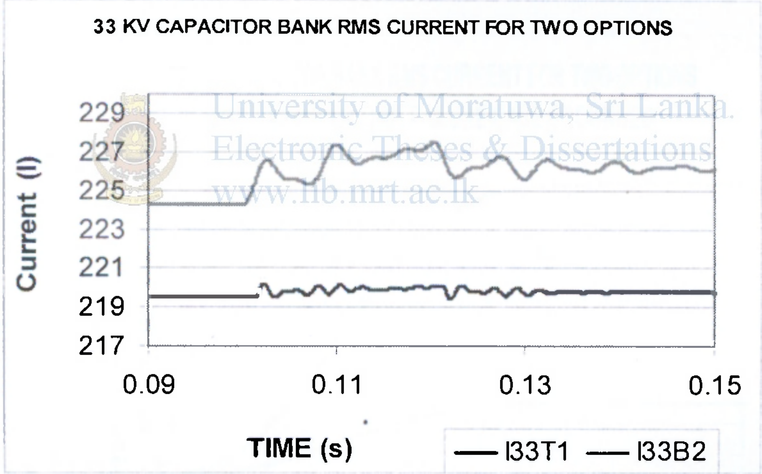


Figure 30 - Current transient during disconnection of loaded 33kV feeder

4.5 Capacitor Unit Failure

During capacitor unit failure transient voltage and current impact to the capacitor banks were studied for two options.

1. Capacitor case is grounded
2. Capacitor case is isolated from ground

4.5.1 Grounded case

Simulated results of voltage and current transients are shown in Figure 31 and Figure 32, when a grounded case capacitor unit failed at 1 second.

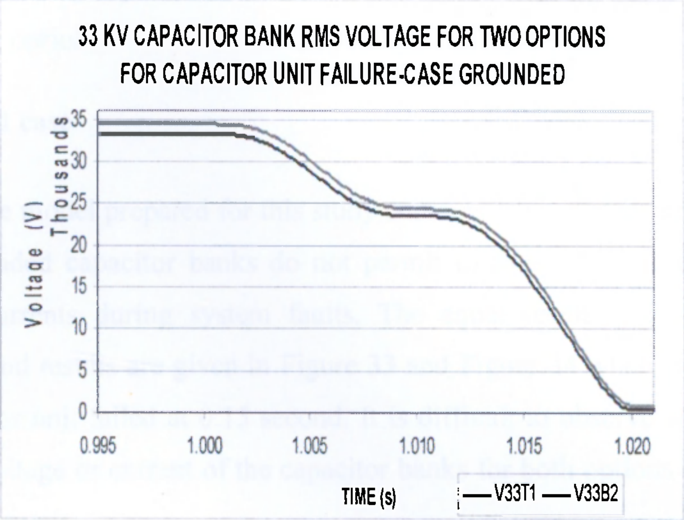


Figure 31 - Voltage transient during capacitor unit failure with grounded case

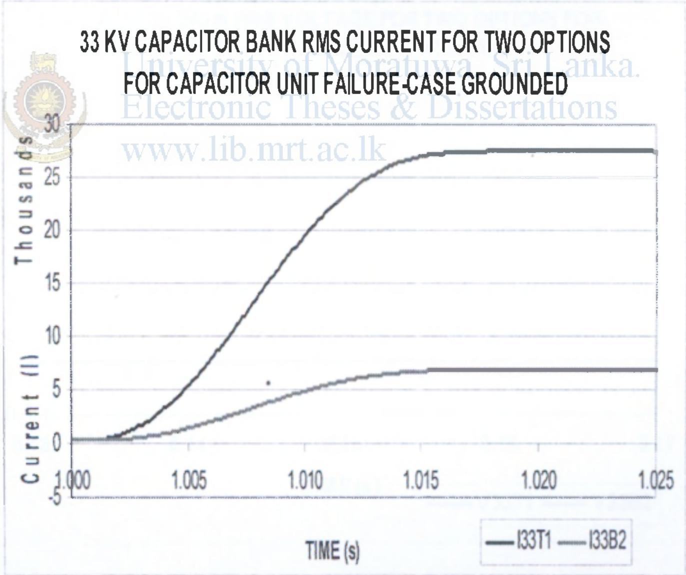


Figure 32 - Current transient during capacitor unit failure in grounded case

During a unit failure of the capacitor bank, the grounded cover provides low impedance path to discharge the charges remain in the faulty capacitor. These charges will drain off as a transient current.

Total impedance of the fault path was less, when capacitors were located at transformer tertiary compared to the other option, where capacitor banks located at load busbars. Therefore a higher current in transformer tertiary can be observed in Figure 32 during capacitor unit failure of grounded capacitor system compared to the busbar option.

4.5.2 Ungrounded case

However, the model prepared for this study contains ungrounded capacitor banks. The ungrounded capacitor banks do not permit to flow fault currents, or large discharge currents during system faults. The equal results were obtained by simulation and results are given in Figure 33 and Figure 34 when an ungrounded case capacitor unit failed at 0.15 second. It is difficult to observe any significant change of voltage or current of the capacitor banks for both options due to failure of a capacitor unit.

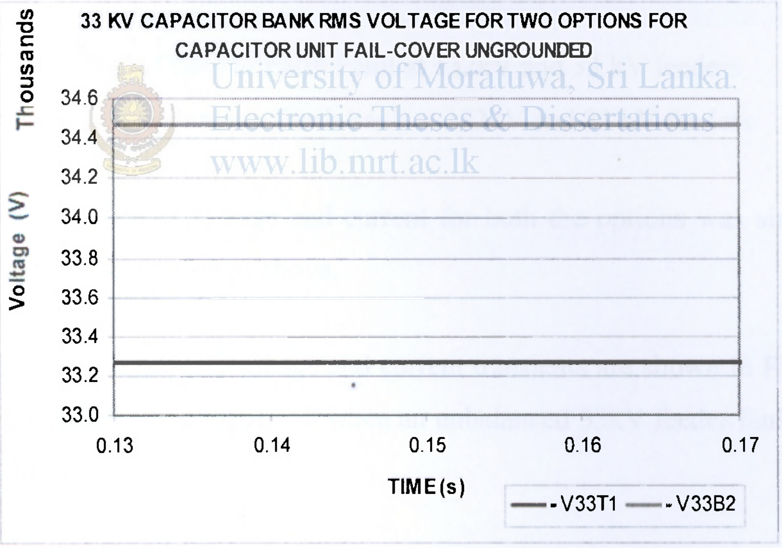


Figure 33 - Voltage transient during capacitor unit failure with ungrounded case

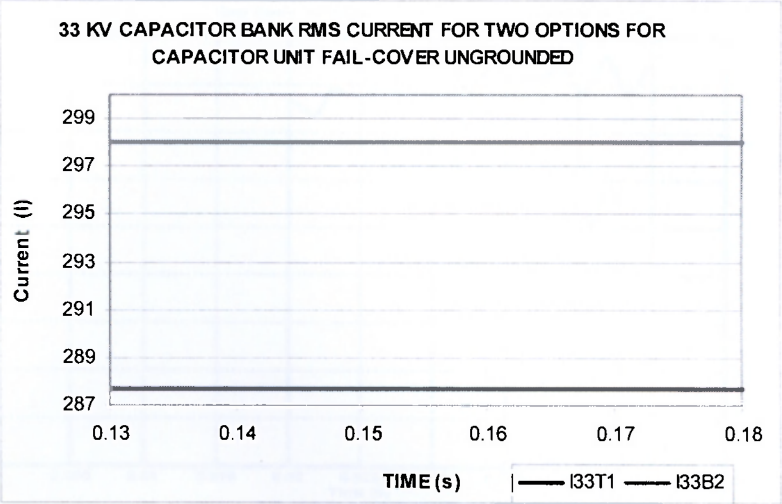


Figure 34 - Current transient during capacitor unit failure with ungrounded case

4.6 Unbalance feeder faults in the system

Voltage and current behaviors at capacitors for proposed two options were analyzed for the following faults conditions.

- Single Phase to Earth Fault at 132kV and 33 kV feeders
- Double Phase to Earth Fault at 132kV and 33 kV feeders

The behavior of voltage and current for both the options was similar for all the feeder faults described above.

Simulated results of voltage and current transients are shown in Figure 39, Figure 40, Figure 37 and Figure 38 when an unbalanced 33kV feeder fault occurred at 23 millisecond time.

According to Figure 39 and Figure 40, when capacitor banks were located at the tertiary of the transformers, voltage fluctuations due to unbalanced 33 kV feeder faults were high compared to the busbar option.

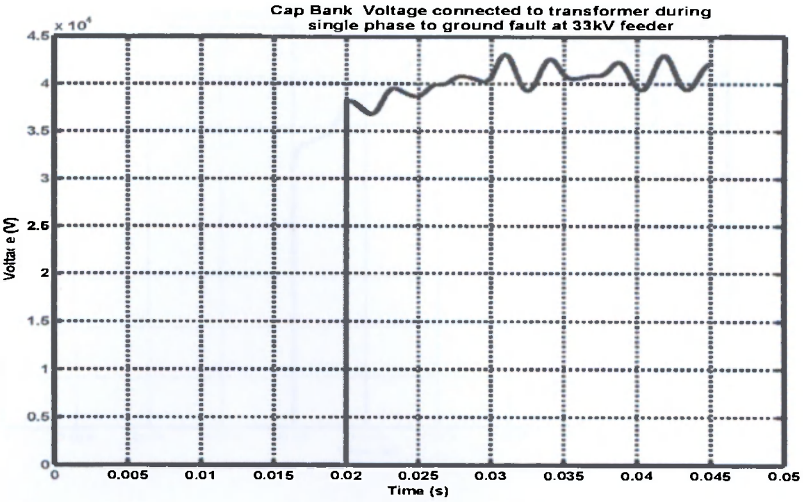


Figure 35 - Voltage transient during 33 kV line fault at transformer option

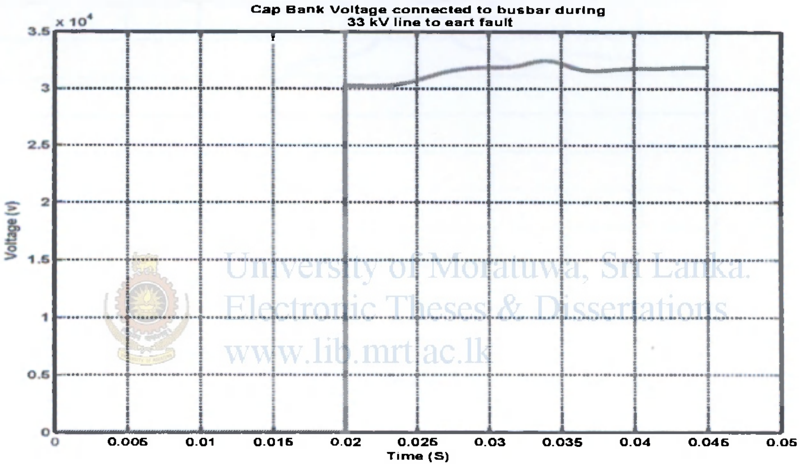


Figure 36 - Voltage transient during 33 kV line fault at busbar option

According to Figure 37 and Figure 38, when capacitor banks were located at the tertiary of the transformers, current fluctuations due to unbalanced 33 kV feeder faults were high compared to the busbar option.

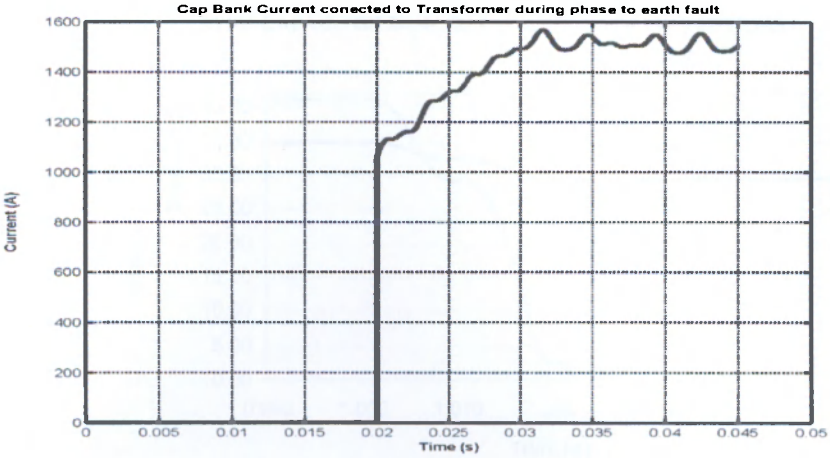


Figure 37 - Current transient during 33 kV line fault at transformer option

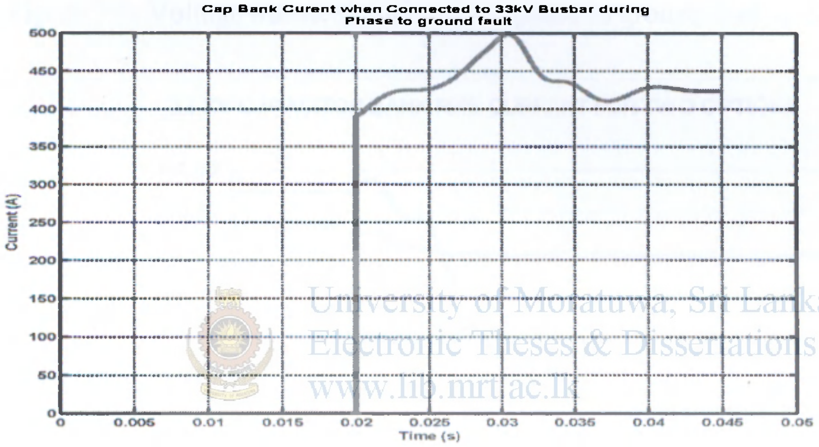


Figure 38 - Current transient during 33 kV line fault at busbarr option

4.7 Three phase balance fault in the system

Simulated results of voltage and current transients are shown in Figure 39 and Figure 40 when three phase to ground fault at 33 kV feeder occur at 1 second

With 100Mvar capacitor bank operating in steady state during a three phase ground fault at the end of 33 kV feeder, capacitor discharges fully into the fault, if capacitors were located at bus bar as in Figure 40. If the capacitor banks were located at tertiary of the transformer, voltage of the capacitor bank would not be reduced to zero as in previous case due to impedance of 220/132/33 kV and 132/33 kV the transformers.

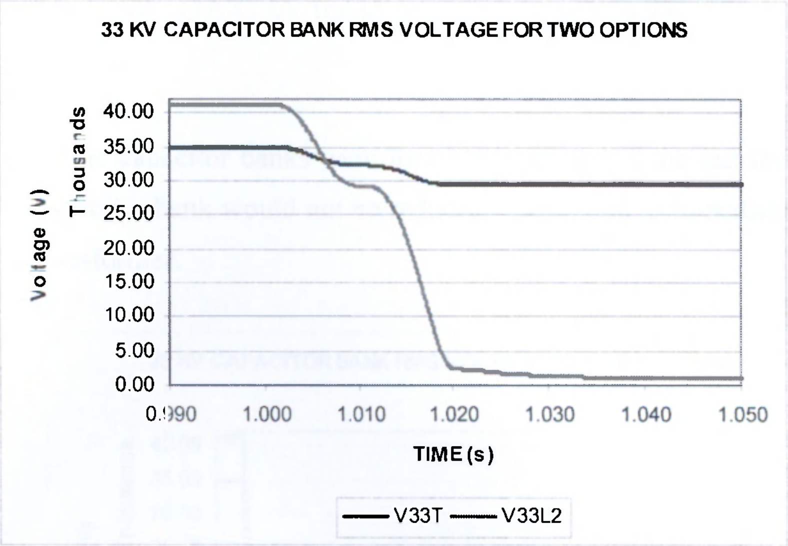


Figure 39 - Voltage transient during three phase to ground fault at 33 kV feeder

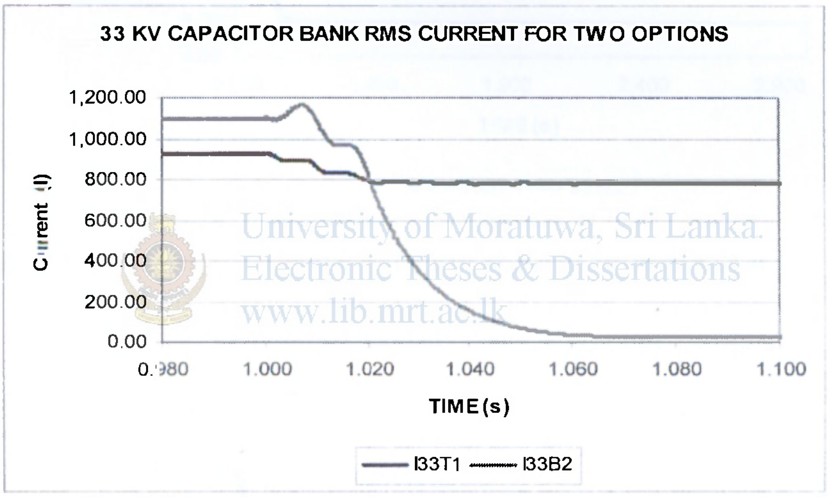


Figure 40 - Current transient during three phase to ground fault at 33 kV feeder

4.8 Three phase to ground fault at 132 kV feeder.

Simulated results of voltage and current transients are shown in Figure 41 and Figure 42, when three phase to ground fault at 132 kV feeder occurred at 1 second.

With 100Mvar capacitor bank operating in steady state during a three phase ground fault at the end of 132 kV feeder, capacitor discharges into the fault, however does not fully discharge as in the case of 33 kV feeder fault due to the impedance of 132/33 kV transformer when the capacitor bank was at the 33 kV load busbar.

When the capacitor banks were located at tertiary of the transformer, voltage of the capacitor bank would not be reduced to zero due to impedance of 220/132/33 kV transformer.

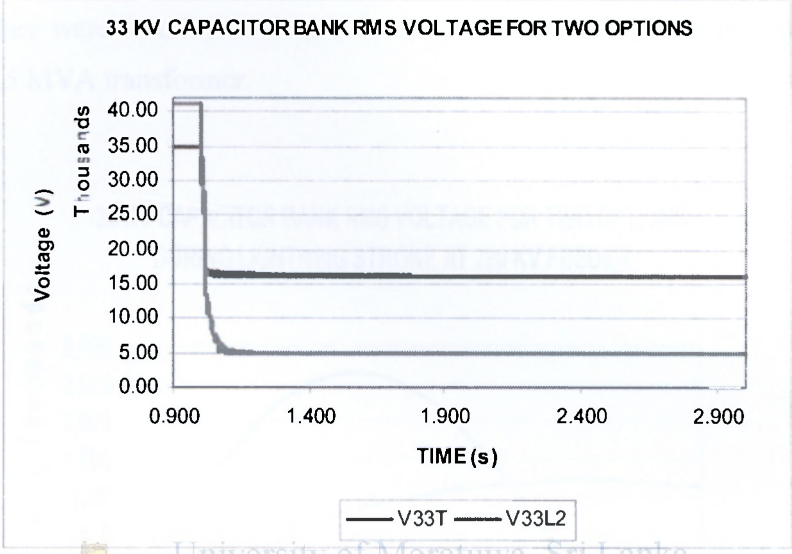


Figure 41 - Voltage transient during three phase to ground fault at 132 kV feeder

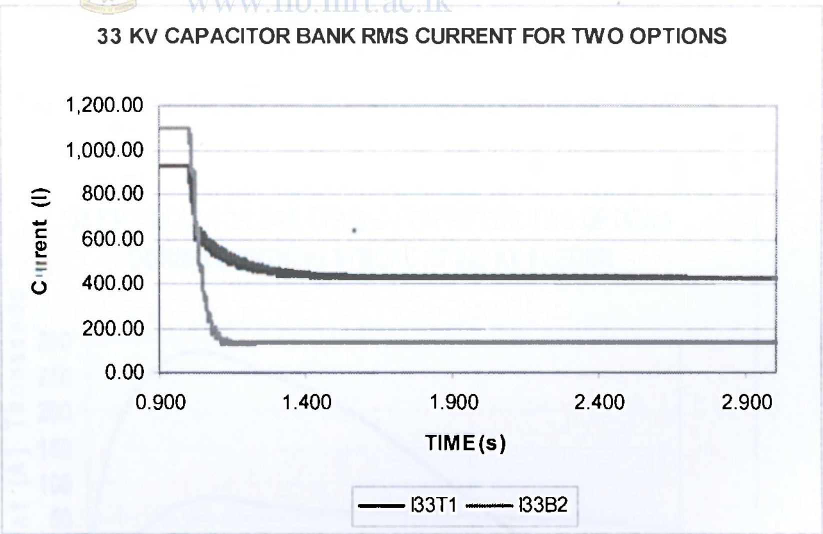


Figure 42 - Current transient during three phase to ground fault at 132 kV feeder

During balance faults at 132 kV system, settling time was greater and frequency of oscillation also high when capacitors were located at transformer tertiary.

4.9 Lightning to 220 kV Feeder

Lightning stroke at 220 kV transmission network affected to two options differently as shown in Figure 43 and Figure 44. When capacitors were installed at transformers, total impedances were less compared to the 33 kV load busbar. Therefore high voltage and high current will appeared in capacitors when they were at Transformer tertiary. The affect of lightning stroke to capacitor was much less if they were installed at 33 kV load busbar due to addition of impedances from 31.5 MVA transformer.

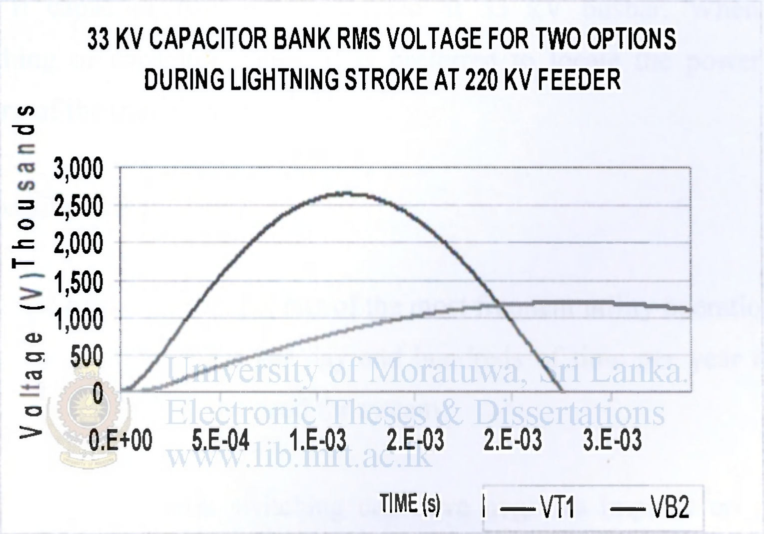


Figure 43 - Voltage transient at capacitor during lightning stroke at 220 kV feeder

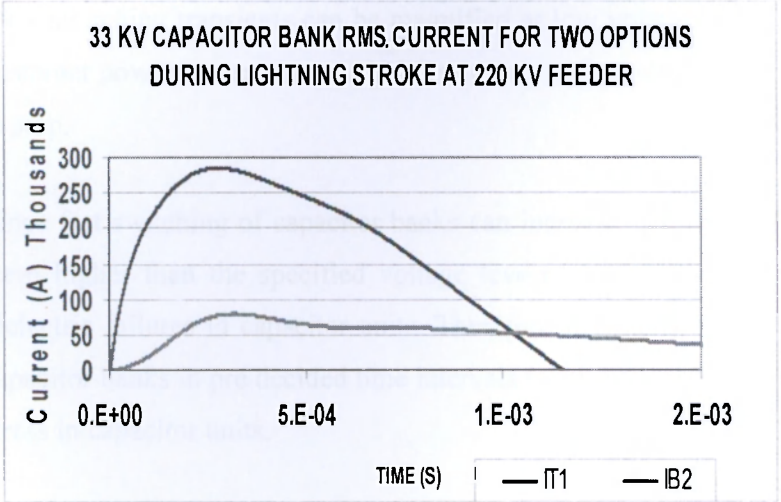


Figure 44 - Transient current at capacitor during lightning stroke at 220 kV feeder

Chapter 5

Conclusion

From the simulation results, optimal location for fixing the power capacitors in a grid can be summarized as below.

5.1 Switching of Capacitor Banks

During energization of capacitors, transient over current and over voltages were high if capacitor banks were located at 33 kV busbar. When consider the switching of capacitor banks, it is preferred to locate the power capacitors at tertiary of the transformers.

The reasons were:

Capacitor bank switching is one of the most frequent utility operations, potentially occurring multiple times per day and hundreds of time per year throughout the system, depending on the need for system.

Utility capacitor bank switching can have negative impacts on power quality, especially for customer power systems. AC and DC drives, along with other electronic equipment, can be very sensitive to transient voltages. Utility capacitor bank switching transients can be magnified at low voltage capacitor locations on customer power systems, causing drives to trip and production and other processes to stop.

Since fast switching of capacitor banks can increase the voltage variations which were higher than the specified voltage levels of capacitor banks, could causes dielectric failures in capacitor units. Therefore it is more preferred to switch the capacitor banks in pre decided time intervals to avoid development of unnecessary stress in capacitor units.

5.2 Switching of distribution loads

During connecting and disconnecting of 33 kV loads changes in voltage and currents were high at capacitors, when they were connected to the 33 kV load busbars. The reason was that capacitors and loads were in the same busbars and changes in voltage will directly transfer to the capacitors.

5.3 Capacitor unit failure

For both options it is difficult to observe significant effect to the capacitor banks due to failure of a capacitor unit. However capacitor units in parallel in the same group may have slightly higher voltage across them.

Since the capacitor cover is not grounded a unit failure of capacitor not have much influence for both options.

5.4 Unbalance system faults

During 33 kV and 132 kV feeder faults, changes in capacitor bank voltage and current were similar for both options. At transformer locations less damping can be observed.

5.5 Balance system Faults

For 33 kV balance faults two options have similar behavior but during 132 kV balance fault less damping and high oscillations were present when capacitors at transformer tertiary.

5.6 Lightning to 220 kV Feeder

Resultant effects due to lightning stroke were high when capacitors located at transformer tertiary. The high voltages and current in capacitor could ultimately lead to the failure to capacitor banks. In practically suitable energy dissipation lightning arrestors were installed to divert these lightning impulses at line end of the grid and at high voltage and low voltage sides of the power transformers.

5.7 Summary

If capacitor banks were installed at tertiary of the power transformers capacitors were open to less stresses during

- Switching of capacitor banks frequently

If capacitor banks were located at 33 kV busbars the Capacitors have less stresses for

- Phase to earth faults in feeders
- Lightning strikes at high voltage side. Generally lightning arrestors are installed in the grid substation to suppress the lightning strokes. Lightning arrestor function was not included for this model.

5.8 Recommendation

Capacitor banks at tertiary of 220/132/33 kV transformers are recommended for grid substations at industrial areas where the capacitor banks were switched frequently and distribution line faults are less. Example locations are,

- Kotugoda
- Pannipitiya
- Thulhiriya

Capacitor banks at 33 kV busbars are recommended to the grid substations where voltage improvement is required due to long transmission power lines. Since most of these are end grid substations and availability of tertiary transformers also limited. Example locations are,

- Anuradhapura
- Habarana
- Panadura
- Puttalama
- Kurunegala

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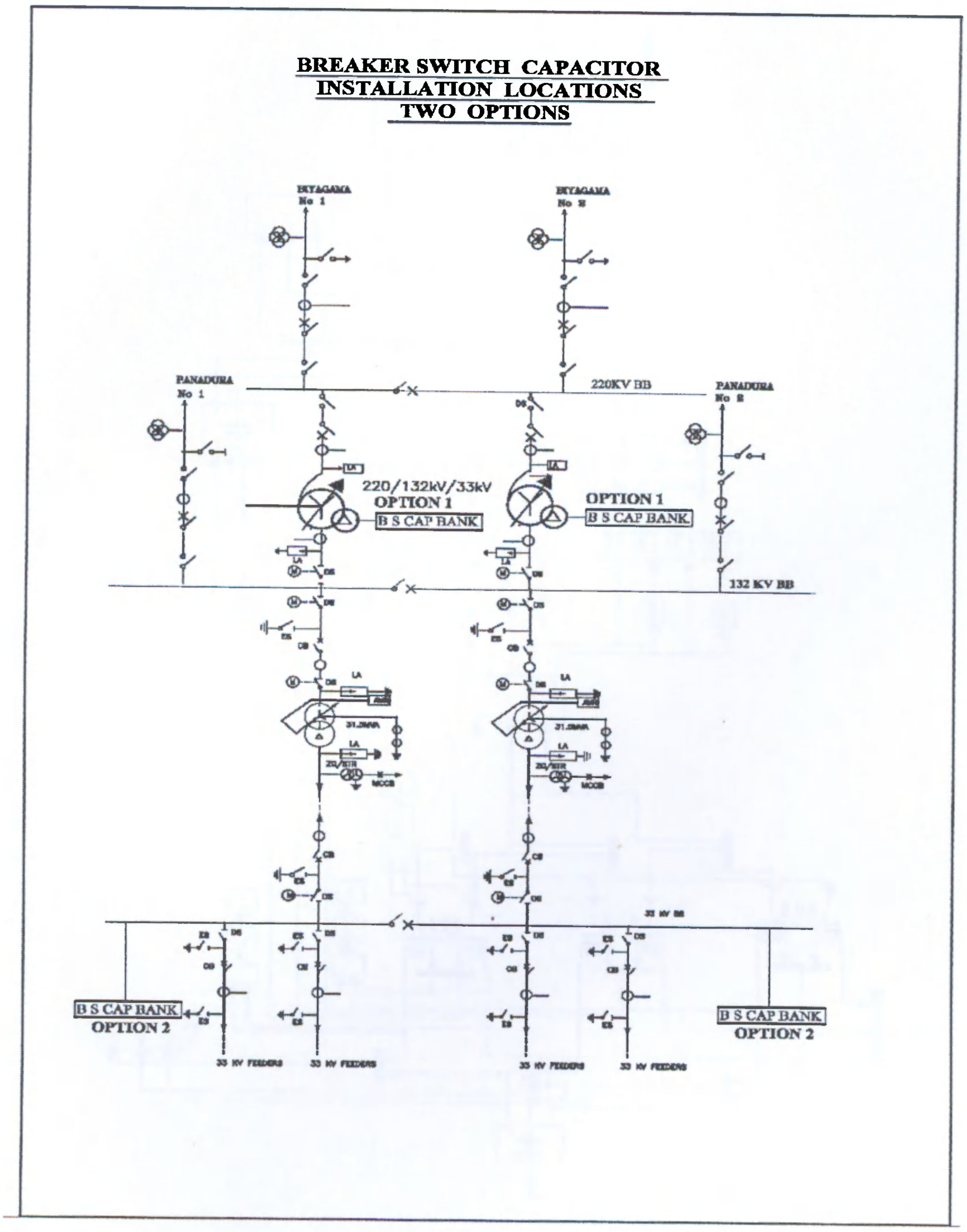
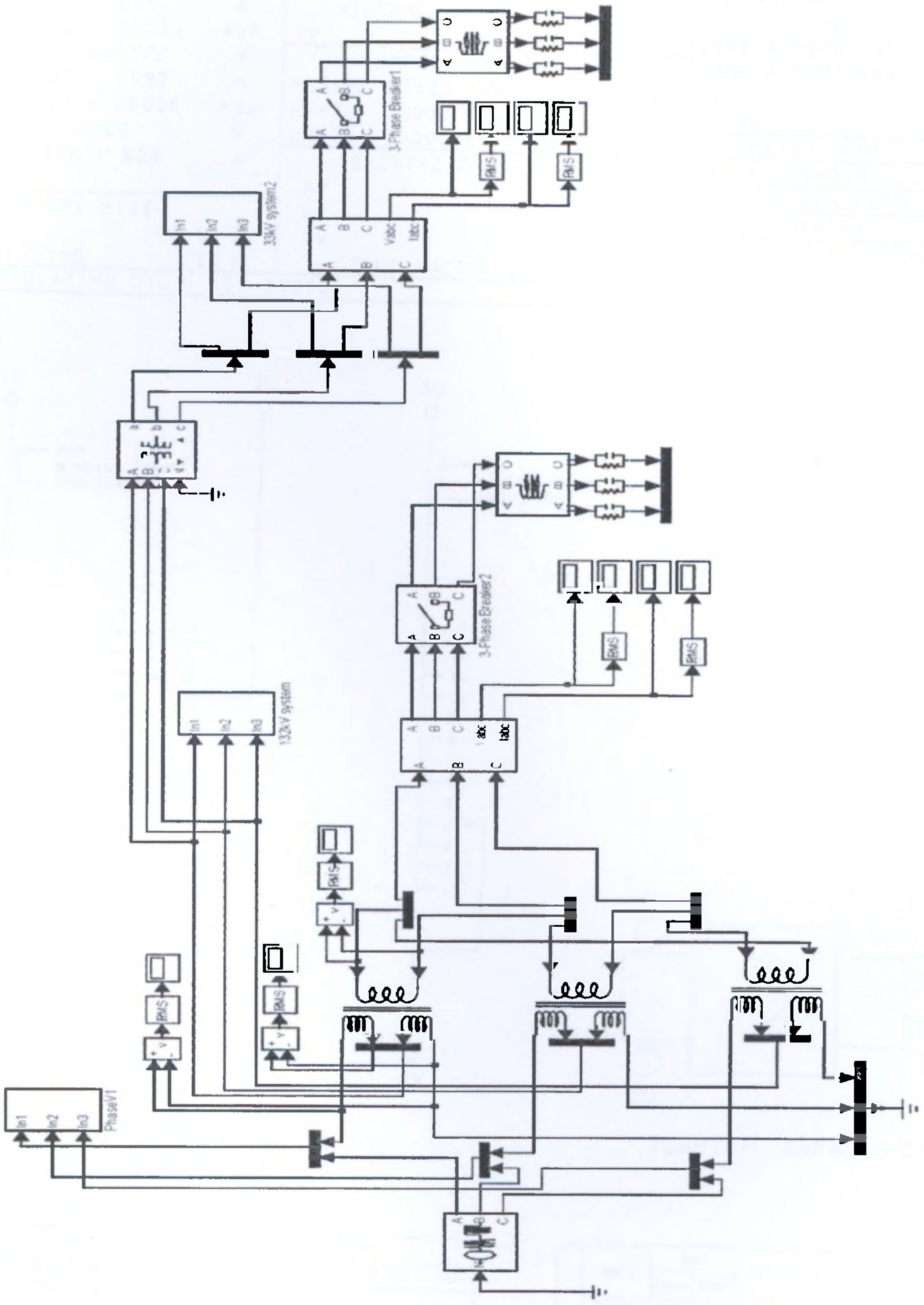
[12] Electrical Transients in Power Sysems, Allan Greenwood, John Wiely & Sons Inc, 1971.

Annexure 1 - Proposed options for Pannipitiya GSS



Annexure 2 - The model Developed for simulation



Annexure 3 - 83.3 MVA Transformer data sheets

AUTOTRANSFORMER

WITH ON-LOAD TAP-CHANGER

50 Hz
SINGLE PHASE
TYPE OF COOLING ONAN/ONAF
HV 58333 / 83333 kVA
220000/√3 V
459 / 656 A
LV 58333 / 83333 kVA
132000/√3 V
765 / 1093 A
TV 20000 / 20000 kVA
33000 V
606 / 606 A

TEMPERATURE RISE
OIL 50 K
WINDING 55 K

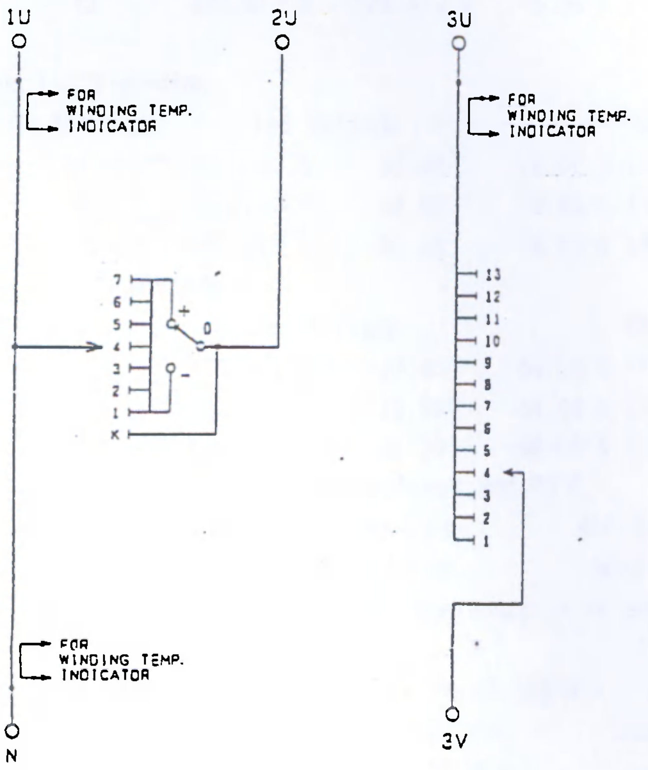
IEC-60076(1993)
CONTINUOUS RATING
INSULATION LEVEL
HV LINE 950 kV
LV LINE 650 kV
NEUTRAL 650 kV
TV 170 kV

IMPEDANCE VOLT
HV-LV 83333 kVA 14.18 %
HV-TV 20000 kVA 16.67 %
LV-TV 20000 kVA 12.02 %

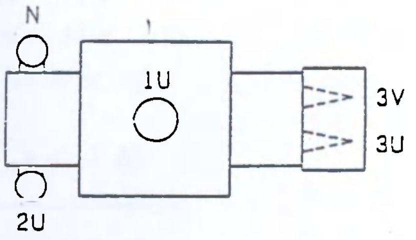
SHORT-CIRCUIT CURRENT
HV 6580 A
LV 9798 A
TV 9113 A
TIME-FACTOR 3 SECONDS

TYPE SRS-MRM
SHELL FORM
OIL
TRANSFORMER L
TAP CHANGER L
MASS
CORE & WINDINGS kg
TANK & FITTINGS kg
OIL kg
TOTAL kg
UNTANKING MASS kg
SERIAL NUMBER 01FT240101
YEAR OF MANUFACTURE 2001
DESIGN NUMBER HE11177
PURCHASER'S SERIAL NUMBER

TYPE OF INSULATING OIL : IEC-60296



SUBTRACTIVE POLARITY



TERMINAL ARRANGEMENT

	VOLT	AMP		POSITION	CONNECTION	
		ONAN	ONAF		TAP SELECTOR	REVERSING SWITCH
LV	151800	666	951	1	1	+
	149600	675	965	2	2	
	147400	685	979	3	3	
	145200	696	994	4	4	
	143000	707	1009	5	5	
	140800	718	1025	6	6	
	138600	729	1041	7	K	
	136400	741	1058	8	2	-
	134200	753	1076	9	3	
	132000	765	1093	10	4	
	129800	776	1112	11	5	
	127600	792	1131	12	6	
	125400	806	1151	13	7	

	VOLT	AMP		POSITION	CONNECTION
		ONAN	ONAF		TAP SELECTOR
TV	37950	527	527	1	1
	37400	535	535	2	2
	36850	543	543	3	3
	36300	551	551	4	4
	35750	559	559	5	5
	35200	568	568	6	6
	34650	577	577	7	7
	34100	587	587	8	8
	33550	596	596	9	9
	33000	606	606	10	10
	32450	616	616	11	11
	31900	627	627	12	12
	31350	638	638	13	13

MITSUBISHI ELECTRIC CORPORATION
JAPAN

Characteristic list

Serial No. 01FR240101

	Guaranteed value	Measured value
1. No-load loss at 100% of rated voltage	48/3 kW (Tole. + 0%)	15.57 kW
2. No-load current At 100% of rated voltage	0.15 %	0.09 %
(Primary)	approx.1.0 A	0.59 A

3. Impedance voltage at 83.333MVA ,rated frequency, rated voltage and 75°C.

HV winding to LV winding

LV Tap pos.	Tap Voltage		Impedance	
1	$220.0/\sqrt{3}$	$151.8/\sqrt{3}$	10.00 % (Tol. + 15%/-15%)	10.00 %
10	$220.0/\sqrt{3}$	$132.0/\sqrt{3}$	14.00 % (Tol. + 10%/-10%)	14.18 %
13	$220.0/\sqrt{3}$	$125.4/\sqrt{3}$	16.50 % (Tol. + 15%/-15%)	16.38 %

H winding to TV winding

TV Tap pos.	Tap Voltage		Impedance	
1	$220.0/\sqrt{3}$	37.95	76.00 % (Tol. + 15%/-15%)	69.17 %
10	$220.0/\sqrt{3}$	33.00	75.00 % (Tol. + 15%/-15%)	69.46 %
13	$220.0/\sqrt{3}$	31.35	75.00 % (Tol. + 15%/-15%)	69.75 %

LV winding to TV winding

LV Tap pos.	TV Tap pos.	Tap Voltage		Impedance	
1	1	$151.8/\sqrt{3}$	37.95	60.00 % (Tol. + 15%/-15%)	52.62 %
10	10	$132.0/\sqrt{3}$	33.00	56.00 % (Tol. + 15%/-15%)	50.08 %
13	13	$125.4/\sqrt{3}$	31.35	56.00 % (Tol. + 15%/-15%)	49.58 %

4. Load loss at rated frequency, rated voltage and 75°C.

At 83.333 MVA on HV winding to LV winding.	420/3 kW (Tole. + 0%)	137.62 kW
At 10.000 MVA on LV winding to TV winding.	50/3 kW (Tole. + 0%)	16.19 kW

5. Efficiency at 75°C, rated voltage and frequency on HV and LV windings.

Base on 83.333 MVA	P.F.:1.00	
At 100 % of 83.333 MVA	----------------	99.82 %
At 75 % of 83.333 MVA	----------------	99.85 %
At 50 % of 83.333 MVA	----------------	99.88 %
At 25 % of 83.333 MVA	----------------	99.88 %

6. Regulation at 75°C, rated voltage and frequency on HV and LV windings.

At 83.333 MVA P.F. 1.0 ---------------- 1.18 %

7. Temperature rise test

			ONAN	ONAF
Top Oil temp.rise		50 K	40.5	32.0
Winding	Series	55 K	42.0	42.9
	Common	55 K	42.7	45.9
	TV	55 K	49.8	44.6

CUSTOMER	SEYLON ELECCTRICITY BOARD, SRI LANKA	ORDER No.	07-FT24.01	TRANSFORMER CAPACITY	83.333 MVA

MITSUBISHI ELECTRIC CORPORATION, JAPAN

Characteristic list

Serial No. 01FR240101

7. Acoustic sound level	75 dB(A)	67.9 dB(A)
8. Power consumption for cooling equipment		
All fans operated	21.00/3 kW (Tole. + 0%)	3.22 kW

CUSTOMER	SEYLON ELECCTRICITY BOARD, SRI LANKA	ORDER No.	07-FT24.01	TRANSFORMER CAPACITY	83.333 MVA

TRANSFORMER TEST REPORT

Tested by	Arita

te of test: 6th Aug. 2001

Serial No. 01FT240101

esurement of winding resistance

inding	Tap position	Terminal		(Ω)	Oil temp. °C			Calculate at 75 °C (Ω)
Series	-	1U - 2U		0.1047	30.0			0.1225
Common	1	2U - N		0.2361	30.0			0.2762
	2	2U - N		0.2346	30.0			0.2744
	3	2U - N		0.2331	30.0			0.2727
	4	2U - N		0.2317	30.0			0.2710
	5	2U - N		0.2303	30.0			0.2694
	6	2U - N		0.2289	30.0			0.2678
	7	2U - N		0.2269	30.0			0.2654
	8	2U - N		0.2287	30.0			0.2675
	9	2U - N		0.2300	30.0			0.2691
	10	2U - N		0.2316	30.0			0.2709
	11	2U - N		0.2330	30.0			0.2726
	12	2U - N		0.2344	30.0			0.2742
	13	2U - N		0.2359	30.0			0.2760
Tertiary	1	3U - 3V		0.08691	30.0			0.1017
	2	3U - 3V		0.08577	30.0			0.1003
	3	3U - 3V		0.08456	30.0			0.09892
	4	3U - 3V		0.08347	30.0			0.09764
	5	3U - 3V		0.08225	30.0			0.09622
	6	3U - 3V		0.08107	30.0			0.09484
	7	3U - 3V		0.07994	30.0			0.09351
	8	3U - 3V		0.07872	30.0			0.09209
	9	3U - 3V		0.07763	30.0			0.09081
	10	3U - 3V		0.07641	30.0			0.08939
	11	3U - 3V		0.07529	30.0			0.08808
	12	3U - 3V		0.07403	30.0			0.08660
	13	3U - 3V		0.07292	30.0			0.08530

P4

0·000211

0·000457

0·000161

Customer	CEYLON ELECTRICITY BOARD, SRI LANKA	Order	07-FT24.01	Capacity	83.333 MVA

MITSUBISHI ELECTRIC CORPORATION, JAPAN

IEMENS

Annexure 4 - 31.5 MVA Transformer data sheets

Serial number		n°	:	0605201/01		
Rated Power		[kVA]	:	24000	ONAN / 31500	ONAF
Rated Voltage	HV	[V]	:	132000	+ 7 - 10 x 1,5 %	
Rated Voltage	MV	[V]	:	33000	-	

Summary of guaranteed and measured values

Measurement of no-load loss and current.

ONAF: 31,5 MVA;

			GUARANTEED	TOLERANCES	MEASURED
Loss	W	Vn	18000	+ 0 %	17188
Current	%	Vn	0,20%	+ 30 %	0,086%
Current	%	0,9 Vn	0,15%	+ 30 %	0,067%
Current	%	1,1 Vn	0,40%	+ 30 %	0,243%
Current	%	1,2 Vn	5,00%	+ 30 %	1,291%

Measurement of short-circuit impedance and load loss.

OLTC Position	Off-LTC Position			GUARANTEED	TOLERANCES	MEASURED
ONAN: 24 MVA;						
		Loss	W	87070	+ 0 %	84026
8	-	Impedance 75°C	%	7,62	± 7,5 %	7,71
		No-Load + Load Losses	W	105070	+ 0 %	101213
		Loss	W	-	+ 0 %	83771
1	-	Impedance 75°C	%	8,08	± 7,5 %	8,21
		No-Load + Load Losses	W	-	+ 0 %	100959
		Loss	W	-	+ 0 %	87297
18	-	Impedance 75°C	%	7,16	± 7,5 %	7,17
		No-Load + Load Losses	W	-	+ 0 %	104484
ONAF: 31,5 MVA;						
		Loss	W	150000	+ 0 %	144747
8	-	Impedance 75°C	%	10,00	± 7,5 %	10,12
		No-Load + Load Losses	W	168000	+ 0 %	161935
		Loss	W	-	+ 0 %	144309
1	-	Impedance 75°C	%	10,60	± 7,5 %	10,77
		No-Load + Load Losses	W	-	+ 0 %	161496
		Loss	W	-	+ 0 %	150382
18	-	Impedance 75°C	%	9,40	± 7,5 %	9,41
		No-Load + Load Losses	W	-	+ 0 %	167570

Date 21 ÷ 24/09/07

Siemens Transformers S.p.A.
Testing Service

Customer

SIEMENS

Annexure 4 - 31.5 MVA Transformer data sheets

Serial number	n°	:	0605201/01		
Rated Power	[kVA]	:	24000	ONAN / 31500	ONAF
Rated Voltage HV	[V]	:	132000	+ 7 - 10 x 1,5 %	
Rated Voltage MV	[V]	:	33000	-	

Summary of guaranteed and measured values

Measurement of no-load loss and current.

ONAF: 31,5 MVA;

			GUARANTEED	TOLERANCES	MEASURED
Loss	W	Vn	18000	+ 0 %	17188
Current	%	Vn	0,20%	+ 30 %	0,086%
Current	%	0,9 Vn	0,15%	+ 30 %	0,067%
Current	%	1,1 Vn	0,40%	+ 30 %	0,243%
Current	%	1,2 Vn	5,00%	+ 30 %	1,291%

Measurement of short-circuit impedance and load loss.

OLTC Position	Off-LTC Position			GUARANTEED	TOLERANCES	MEASURED
ONAN: 24 MVA;						
		Loss	W	87070	+ 0 %	84026
8	-	Impedance 75°C	%	7,62	± 7,5 %	7,71
		No-Load + Load Losses	W	105070	+ 0 %	101213
		Loss	W	-	+ 0 %	83771
1	-	Impedance 75°C	%	8,08	± 7,5 %	8,21
		No-Load + Load Losses	W	-	+ 0 %	100959
		Loss	W	-	+ 0 %	87297
18	-	Impedance 75°C	%	7,16	± 7,5 %	7,17
		No-Load + Load Losses	W	-	+ 0 %	104484
ONAF: 31,5 MVA;						
		Loss	W	150000	+ 0 %	144747
8	-	Impedance 75°C	%	10,00	± 7,5 %	10,12
		No-Load + Load Losses	W	168000	+ 0 %	161935
		Loss	W	-	+ 0 %	144309
1	-	Impedance 75°C	%	10,60	± 7,5 %	10,77
		No-Load + Load Losses	W	-	+ 0 %	161496
		Loss	W	-	+ 0 %	150382
18	-	Impedance 75°C	%	9,40	± 7,5 %	9,41
		No-Load + Load Losses	W	-	+ 0 %	167570

Date 21 + 24/09/07

Siemens Transformers S.p.A.
Testing Service

Customer

SIEMENS

Siemens Transformers S.p.A., Zona Ind.le Nord – Settore C
38014 Spini di Gardolo, Trento - Italy

Customer			:	SIEMENS AG OESTERREICH for Ceylon Electicity Board			
Order		n°	:	9501411529		dated	01/02/2007
Serial number		n°	:	**0605201/01**			
Rated Power		[kVA]	:	24000	ONAN / 31500	ONAF	
Rated Voltage	HV	[V]	:	132000	+ 7 - 10 x 1,5 %		
Rated Voltage	MV	[V]	:	33000	-		
Vector group			:	Y N d 1			
Frequency		[Hz]	:	50			
Type of cooling			:	ONAN / ONAF			
Plant location			:	PSDTP - LOTA - SRI LANKA			

LIST OF TESTS PERFORMED ACCORDING TO STANDARD: **IEC 60076.**

ROUTINE TESTS

Date 21 ÷ 24/09/07

Customer

Siemens Transformers S.p.A.
Testing Service

Serial number n° : **0605201/02**
Rated Power [kVA] : 24000 ONAN / 31500 ONAF
Rated Voltage HV [V] : 132000 + 7 - 10 x 1,5 %
Rated Voltage MV yn [V] : 33000

ONAF

Winding cold resistance measurement.

HV Winding PHASES : **1V-1W**

Δ V	kv	[V]	Δ A	ka	[A]	[Ω]
7,652	1,00	7,652	47,24	0,10	4,724	1,620
7,653	1,00	7,653	47,23	0,10	4,723	1,620
7,653	1,00	7,653	47,24	0,10	4,724	1,620

MV Winding PHASES : 2v-2w

Δ V	kv	[V]	Δ A	ka	[A]	[Ω]
0,8362	1,00	0,8362	72,07	0,10	7,207	**0,11603**
0,8356	1,00	0,8356	72,01	0,10	7,201	**0,11604**
0,8363	1,00	0,8363	72,06	0,10	7,206	**0,11606**

OIL TEMPERATURE :

Top of Radiators : **26,4** °C
Bottom of Radiators : **24,8** °C
Top of Transformers tank : **26,8** °C

AVERAGE : 26,0 **°C**

Average value of HV winding ($R_{1\ 1V\text{-}1W}$) : **26,0** °C 1,62007 Ω

Average value of MV winding ($R_{1\ 2v\text{-}2w}$) : **26,0** °C 0,11604 Ω

ate 18/09/07

Customer

Siemens Transformers S.p.A.
Testing Service

Annexure 5 - 200kVA Transformer data sheet

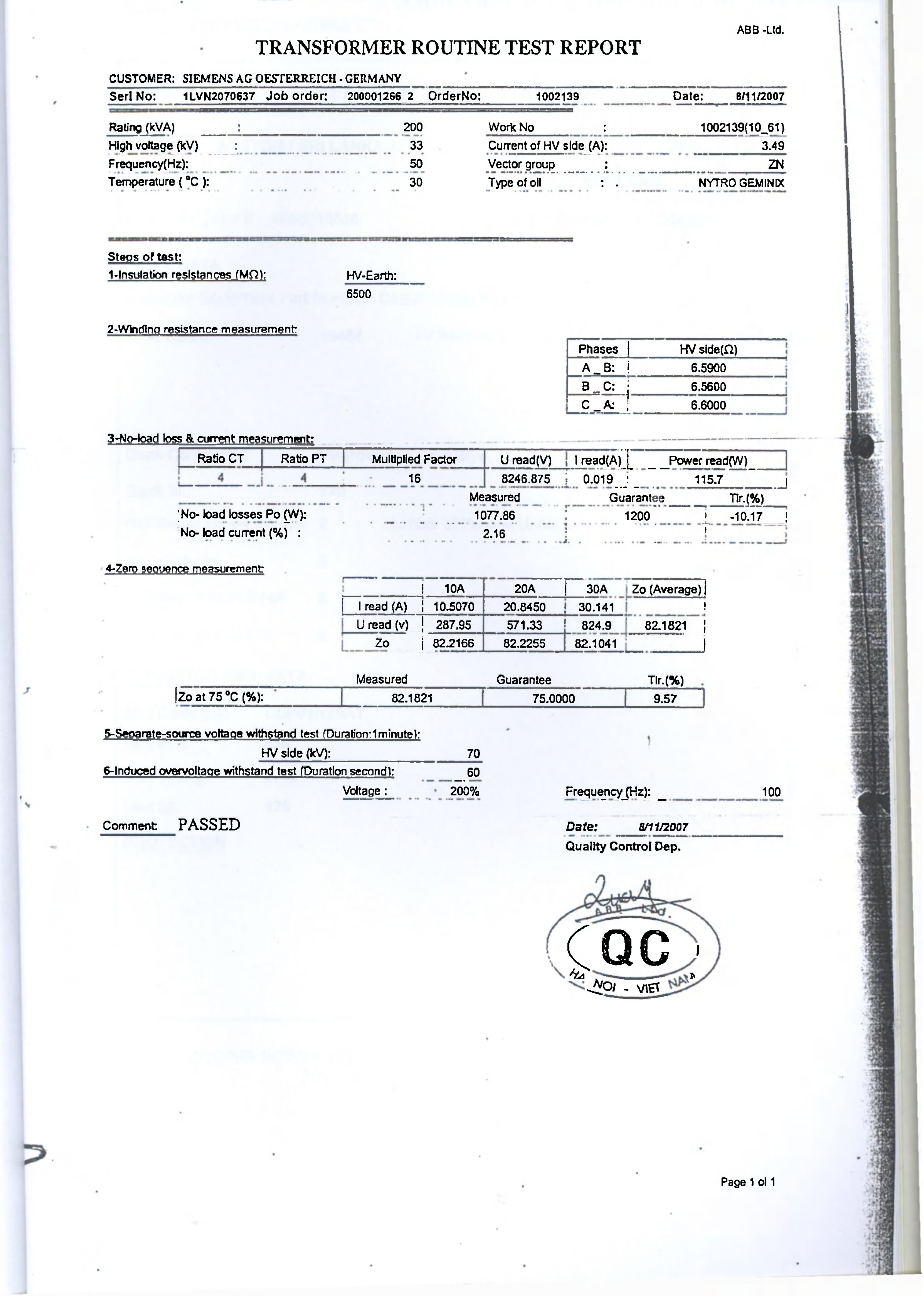


ABB -Ltd.

TRANSFORMER ROUTINE TEST REPORT

CUSTOMER: SIEMENS AG OESTERREICH - GERMANY

Serl No: 1LVN2070637 Job order: 200001266 2 OrderNo: 1002139 Date: 8/11/2007

Rating (kVA) :	200	Work No :	1002139(10_61)
High voltage (kV) :	33	Current of HV side (A):	3.49
Frequency(Hz):	50	Vector group :	ZN
Temperature (°C):	30	Type of oil :	NYTRO GEMINIX

Steps of test:

1-Insulation resistances (MΩ):

HV-Earth: 6500

2-Winding resistance measurement:

Phases	HV side(Ω)
A _ B:	6.5900
B _ C:	6.5600
C _ A:	6.6000

3-No-load loss & current measurement:

Ratio CT	Ratio PT	Multiplied Factor	U read(V)	I read(A)	Power read(W)
4	4	16	8246.875	0.019	115.7

	Measured	Guarantee	Tlr.(%)
No- load losses Po (W):	1077.86	1200	-10.17
No- load current (%) :	2.16		

4-Zero sequence measurement:

	10A	20A	30A	Zo (Average)
I read (A)	10.5070	20.8450	30.141	
U read (v)	287.95	571.33	824.9	82.1821
Zo	82.2166	82.2255	82.1041	

	Measured	Guarantee	Tlr.(%)
Zo at 75 °C (%):	82.1821	75.0000	9.57

5-Separate-source voltage withstand test (Duration:1minute):

HV side (kV): 70

6-Induced overvoltage withstand test (Duration second): 60

Voltage : 200% Frequency (Hz): 100

Comment: PASSED

Date: 8/11/2007

Quality Control Dep.

ABB Ltd.
QC
HA NOI - VIET NAM

COOPER
COOPER POWER SYSTEMS

Annexure 6 - Capacitor bank data shee

CAPACITOR BANK DATA SHEET

Customer: **ALSTOM / SRI LANKA**

Date: **5/13/02**

State/ Country: **ENGLAND**

Customer Order #: **4500010836**

CPS Order Number: **360107**

BANK DATA

Capacitor Equipment Part Number: **CEB01024N0308F1**

kVAr Rated: **10464**

kV Rated L-L: **33.77**

Bank Connection: **Ungrounded Split Wye**

Bank BIL: **170**

Number of Series Groups: **2**

Number of Parallel Units: **2**

No. of Blocks: **3**

Installed Units in Block: **8**

Future Units in Block: **8**

CAPACITOR UNIT DATA

Unit Catalog #: **CEP01N35A1**

Unit kVAr: **436**

Unit Voltage: **9750**

Unit BIL: **125**

PROTECTION

PART NUMBER VRX0041

Supplier: Trench
Description: Current Limiting Reactor
Environment: Outdoor
System Voltage: 33 kV
Frequency: 50 Hz
Current: 209 AMP
Inductance: 0.5 mH
Coil BIL: 75 Kv
Mounting: 1S
TERMINAL: (2) POSITIONED 180° APART
Insulators: Std. Strength, Supplied by CPS (3" BOLT CIRCLE)
Pedestals: Trench to recommend and supply, assuming aluminum closed loops beneath coils.

Supplier to provide outline drawings, nameplate drawings, maintenance & installation manuals, and certified test reports.

COOPER

CONFIDENTIAL
MUST NOT BE USED IN
ANY WAY DETRIMENTAL TO
COOPER POWER SYSTEMS

CURRENT LIMITING REACTOR

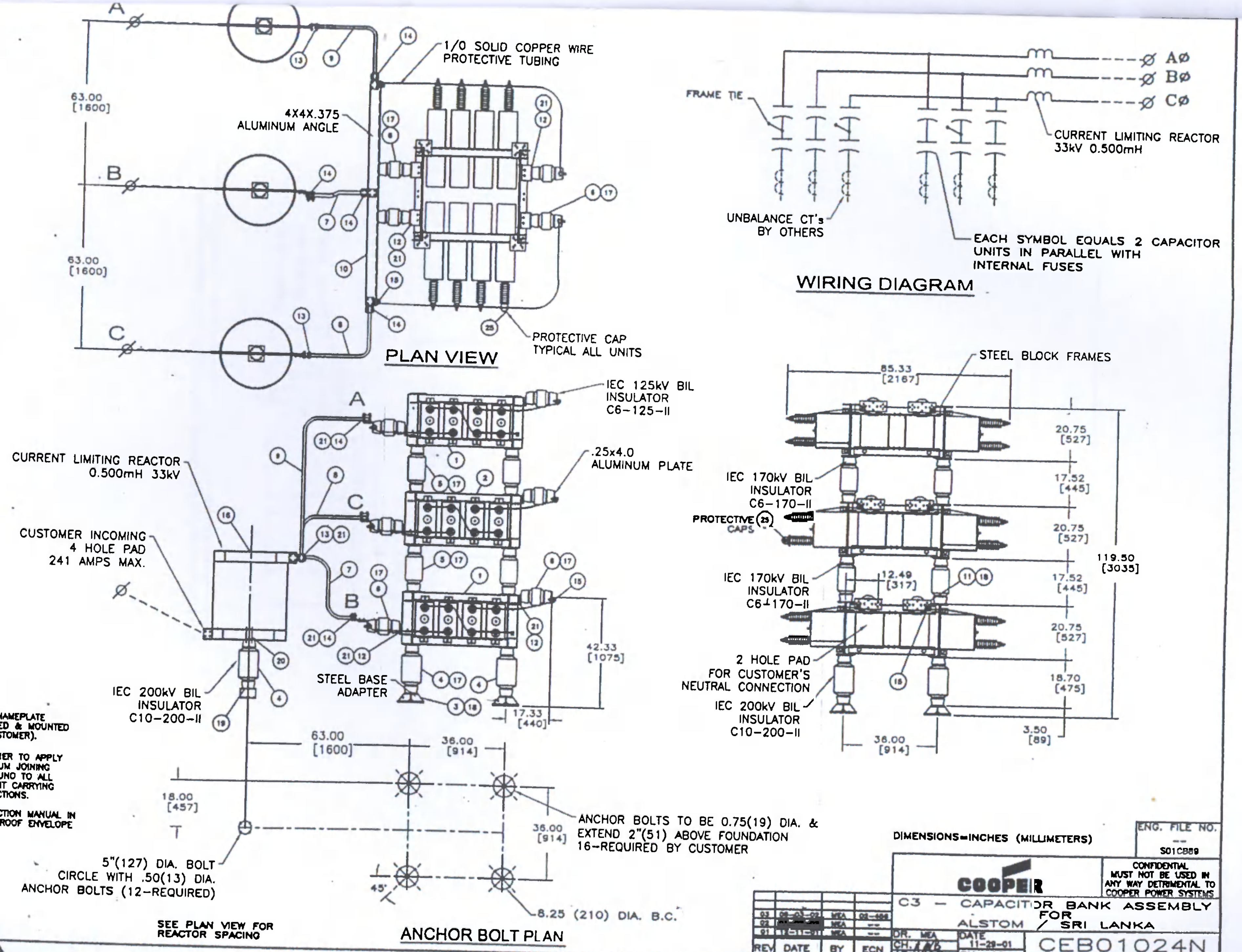
ENG. FILE NO.
--
S01CB089

01	12-20-01	LAS	01-1402
REV	DATE	BY	ECN

DR. MEA
CH. RWB
AP. RWB

DATE
12/17/01
SH 1 OF 1

VRX0041



㉓ — BANK NAMEPLATE (LOCATED & MOUNTED BY CUSTOMER).

㉒ — CUSTOMER TO APPLY ALUMINUM JOINING COMPOUND TO ALL CURRENT CARRYING CONNECTIONS.

㉔ — INSTRUCTION MANUAL IN WATERPROOF ENVELOPE

DIMENSIONS=INCHES (MILLIMETERS)

ENG. FILE NO.
--
S01C889

COOPER

CONFIDENTIAL
MUST NOT BE USED IN ANY WAY DETRIMENTAL TO COOPER POWER SYSTEMS

C3 — CAPACITOR BANK ASSEMBLY FOR ALSTOM / SRI LANKA

REV	DATE	BY	ECN
03	[illegible]	MEA	[illegible]
02	[redacted]	MEA	--
01	[illegible]	MEA	--

DR. MEA
CH. [illegible]
AP. [illegible]
DATE 11-29-01
SH__OF__

CEB01024N

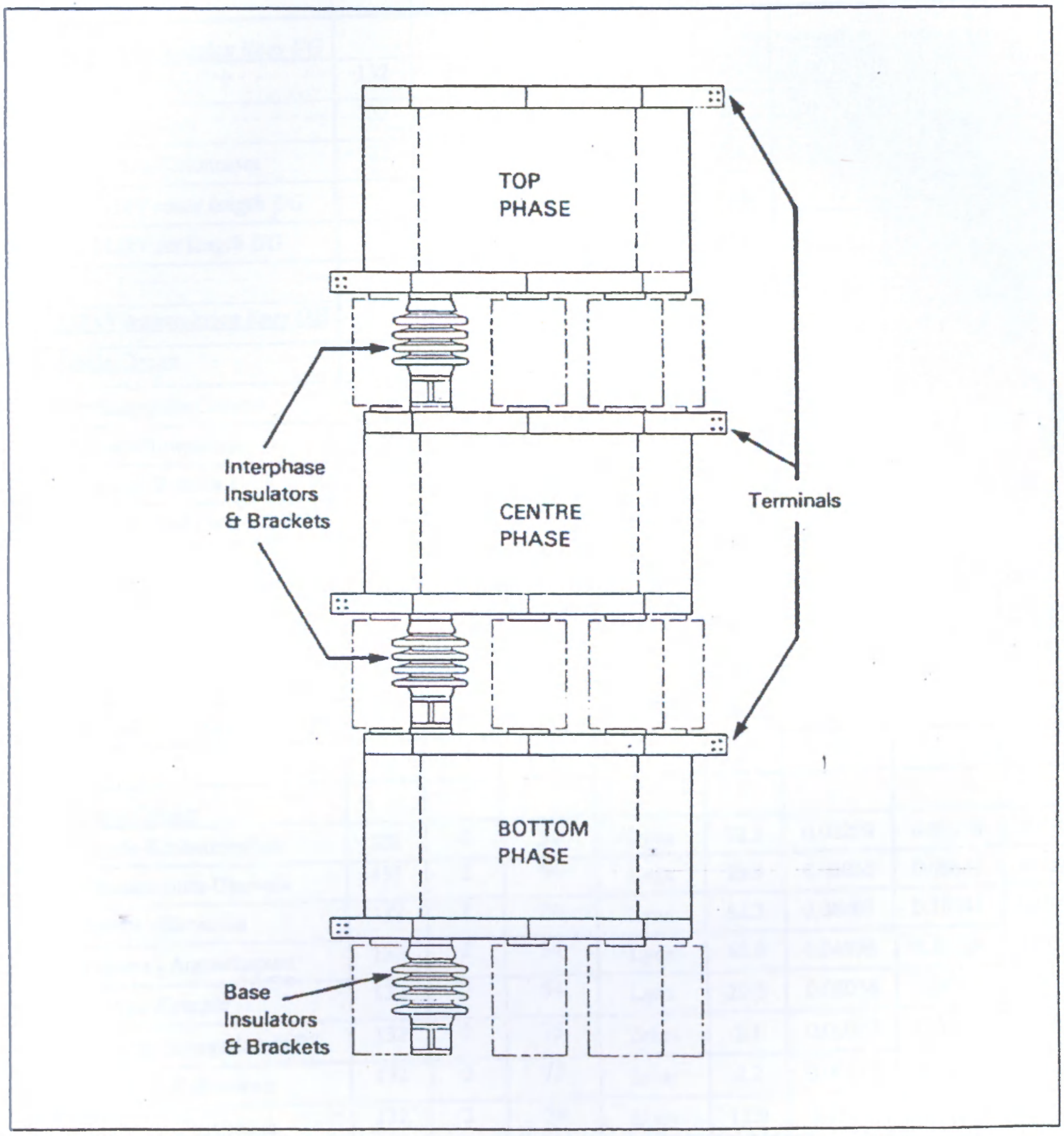


Fig. 5D Side View of Typical Three Phase Stacked Reactor after Assembly, Showing Arrangement of Coils, Insulators and Brackets

Annexure 7 - Transmission line data sheet

Annex 3. Electrical data used for power system analysis

Table 3.1 Existing transmission lines/UG cables

Line Section	Volt. / (kV)	Ccts.	Max. Oper. temp °C	Conductor	Length / (km)	R /cct in p.u.	X/cct in p.u.	Y / cct in p.u.
132 kV transmission lines UG								
Kelamtissa-Fort	132	1		Cu 500	4.9	0.00143	0.00267	0.10997
Fort-Kollupitiya	132	1		Cu 350	2.7	0.00093	0.00153	0.05321
Kollupitiya-Kolonnawa	132	1		Cu 500	5.4	0.00158	0.00294	0.12119
Total 132kV route length UG					***13.0***			
Total 132kV cct length UG					***13.0***			
132 kV transmission lines OH								
Single Circuit								
New Laxapana-Canyon	132	1	54	Lynx	10	0.01022	0.02301	0.00487
Ukuwela-Bowatenna	132	1	54	Lynx	30	0.03065	0.06904	0.01462
Rantembe-Badulla 1	132	1	75	Lynx	37	0.03780	0.08515	0.01803
Rantembe-Badulla 2	132	1	75	Lynx	33	0.03371	0.07595	0.01608
Badulla-Inginiyagala	132	1	54	Oriole	79.9	0.08759	0.19993	0.03866
Inginiyagala - Ampara	132	1		Lynx	25	0.02554	0.05754	0.01218
Habarana-Valachchena	132	1	75	Lynx	99.7	0.10185	0.22945	0.04857
Total 132kV 1 cct route length					***314.6***			
Total 132kV 1 cct circuit length					***314.6***			
Double Circuit								
Kotmale-Kiribatkumbura	132	2	54	Lynx	22.5	0.02299	0.05178	0.01096
Kiribatkumbura-Ukuwela	132	2	54	Lynx	29.9	0.03055	0.06881	0.01457
Ukuwela - Habarana	132	2	54	Lynx	82.3	0.08408	0.18941	0.04009
Habarana - Anuradhapura	132	2	54	Lynx	48.9	0.04996	0.11254	0.02382
Polpitiya-Kotmale	132	2	54	Lynx	29.5	0.03014	0.06789	0.01437
Biyagama-Sapugaskanda PS	132	2	75	Zebra	2.1	0.00092	0.00466	0.00109
Kelanitissa-Kolonnawa	132	2	75	Invar	2.2	0.00119	0.00513	0.00108
Kolonnawa-Pannipitiya	132	2	54	Lynx	12.9	0.01318	0.02969	0.00628
Kotugoda-Bolawatta(T)	132	2	75	Zebra	22.0	0.00960	0.04886	0.01144
Bolawatta(T)-Madampe(T)	132	2	54	Lynx	22.6	0.02309	0.05201	0.01101
Balangoda-Ratnapura	132	2	75	Zebra	40.0	0.01745	0.08884	0.02080
Madampe(T)-Puttalam	132	2	54	Lynx	61.4	0.06272	0.14131	0.02991

Note : The line parameters are given in p.u. values w.r.t. $Z_{base} = V_{base}^2 / MVA_{base}$ (MVA_{base}=100, V_{base} in kV).

Table 3.1 Existing transmission lines/UG cables *cont.*

Line Section	Volt. / (kV)	Ccts.	Max. Oper. temp ^{0}C	Conductor	Length / (km)	R /cct in p.u.	X/cct in p.u.	Y / cct in p.u.
<u>Double Circuit cont..</u>								
Madampe(T)-SS	132	2	75	Lynx	6.8	0.00695	0.01565	0.00331
Kolonnawa-Athurugiriya	132	2	54	Lynx	14	0.01430	0.03222	0.00682
Athurugiriya-Oruwala	132	2	54	Lynx	3.4	0.00347	0.00782	0.00166
Athurugiriya-Thulhiriya(T)	132	2	54	Lynx	36	0.03678	0.08285	0.01754
Thulhiriya(T)-SS	132	2	54	Lynx	23.9	0.02442	0.05500	0.01164
Thulhiriya(T)-Polpitiya	132	2	54	Lynx	28	0.02860	0.06444	0.01364
Kolonnawa-Kosgama(T)	132	2	54	Lynx	31.9	0.03259	0.07342	0.01554
Kosgama(T)-SS	132	2	75	Lynx	0.5	0.00051	0.00115	0.00024
Kosgama(T)-Polpitiya	132	2	54	Lynx	34.4	0.03514	0.07917	0.01676
Pannipitiya-Ratmalana	132	2	54	Lynx	6.9	0.00705	0.01588	0.00336
Pannipitiya-Panadura(T)	132	2	75	Goat	12.3	0.00629	0.02734	0.00631
Panadura (T)-Matugama	132	2	75	Goat	29.1	0.01488	0.06467	0.01493
Panadura (T)-SS	132	2	75	Lynx	4.7	0.00480	0.01082	0.00229
Polpitiya-Laxapana	132	2	54	Lynx	8.3	0.00848	0.01910	0.00404
Laxapana-Wimalasurendra	132	2	54	Lynx	5.1	0.00521	0.01174	0.00248
Laxapana-New Laxapana	132	2	54	Lynx	0.6	0.00061	0.00138	0.00029
New Laxapana-Polpitiya	132	2	54	Lynx	8	0.00817	0.01841	0.00390
Kiribatkumbura-Kurunegala	132	2	54	Lynx	34.6	0.03535	0.07963	0.01686
NewAnuradhapura-Trinco.	132	2	54	Lynx	103.3	0.10553	0.23774	0.05033
New Laxapana-Balangoda	132	2	54	Lynx	43.9	0.04485	0.10103	0.02139
Balangoda-Samanalawewa	132	2	75	Zebra	19	0.00829	0.04220	0.00988
Samanalawewa-Embilipitiya	132	2	75	Lynx	38	0.03882	0.08745	0.01851
Balangoda-Deniyaya (T)	132	2	54	Tiger	44.2	0.06266	0.10527	0.02093
Deniyaya (T)-Galle	132	2	54	Tiger	57.3	0.08123	0.13648	0.02713
Laxapana-Nuwara Eliya	132	2	75	Lynx	38.8	0.03964	0.08930	0.01890
Nuwara Eliya-Badulla	132	2	75	Lynx	35.4	0.03616	0.08147	0.01725
Embilipitiya-Matara	132	2	75	Lynx	52	0.05312	0.11967	0.02533
Embilipitiya - Hambantota	132	2	75	Zebra	35	0.01527	0.07774	0.018201
Puttalam-Anuradhapura	132	2	75	Lynx	75	0.07662	0.17261	0.03654
Anuradhapura-New Anuradhapura	132	2	75	Lynx	1.5	0.00153	0.00345	0.00073
Anuradhapura - Vavunia	132	2	54	Lynx	54	0.05588	0.12589	0.02665
Kotugoda - Veyangoda	132	2	75	2xZebra	17	0.00371	0.02986	0.01195

Note : The line parameters are given in p.u. values w.r.t. $Z_{base} = V_{base}^2 / MVA_{base}$ (MVA_{base}=100, V_{base} in kV).