Installation&Commissioning of Static VAR Compensator at 400 kV substations.

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A DISSERTATION REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR

MBA_POWER MANAGEMENT

OF

UNIVERSITY OF PETROLEUM & ENERGY STUDIES, INDIA

CENTRE OF CONTINUNING EDUCATION
UNIVERSITY OF PETROLEUM & ENERGY STUDIES, DEHRADUN

Acknowledgment

This is to acknowledge with thanks the help, guidance and support that I have received during the dissertation.

I have no words to express a deep sense of gratitude to the management ofDubai Electricity and Water Authority for giving me an opportunity to purse my dissertation, and in particular Mr. **M J Andrews, Project manager, Energoprojekt-Entel Co. Ltd.Dubai,** UAEfor his able to guidance and support.

I must also thank my family for their valuable support.

I also place on record my appreciation of the support provided by Mr.Eijaz Hussein and other staff of my organization.

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DECLARATION BY THE GUIDE

This is certify that the **Mr. Mohamed Mohideen**, a student of MBA (Power Management), Roll No: **500024821** of UPES has successfully completed this dissertation report on **"Installation & Commissioning of Static VAR compensator in 400 kV substation"** under my supervision.

Further, I certify that the work based on the investigation made, data collected and analyzed by him and it has not been submitted in any other university or institution for award of any degree. In my opinion it is fully adequate, in scope and utility, as dissertation towards partial fulfillment for the award of degree of MBA.

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Table of Contents

List of Table and Illustration

List of Figures

ABSTRACT

The change in system voltage and frequency with changing load creates problem in systemstability. For the sake of system stability and reliability, the reactive power compensation is

Essential for flexible AC transmission system (FACTS).

The variation of reactive power causes impact on the generation units, lines, circuit breaker,transformer and relays. However, the reactive power can be compensated from the generating unit by changing the excitation of the generator. But if the total reactive power is fed by only the generating unit, it will lower the maximum real power capacity of generator. Moreover the additional current flow associated with reactive power can cause increased and excessive voltage sags.

Therefore the local VAR compensator which comprises of shunt reactors and/or shunt capacitors are used in transmission and distribution system for reactive power compensation. The conventional electro-mechanical reactive power compensator is not suitable for its slow switching speed which cannot commensurate with rapid changing system load. The electronic reactive power compensator uses fastswitching devices like thyristor which provides faster switching option than that of the conventionalswitching.

The static VAR compensator (SVC) is the combination of thyristor switched capacitor (TSC) and thyristor control reactor which is widely used in HVAC (High Voltage AC) and HVDC (High Voltage DC) system. The design of the microcontroller based SVC with harmonics suppressor is discussed in this paper. Different firing angle of thyristor valve controlling the reactor will be generating harmonics. Harmonic filters are included in the SVC system to suppress these harmonics. For precise switching of the thyristor, microcontroller is used which is asignificant feature of this designed SVC.

CHAPTER: 01 INTRODUCTION

1.1 Overview

Static VAR compensators (SVC) are being increasingly applied in electric transmission systems to economically improve voltage control and post-disturbance recovery voltages that can lead to system instability. An SVC provides such system improvement and benefits by controlling reactive power resources, both capacitive and inductive, with state-of-art electronic switching devices.

The need of SVCs will become more acute in the coming few years due to the fast development of large district cooling and chiller plants and, the anticipated penetration of more efficient Air conditioning new technologies based on inverter driven motors. Indeed, these load appliances are characterized by higher sensitivity to sudden voltage variation (voltage dips).

The SVC is an excellent tool for improving operational conditions of power systems. Its dynamic control of the reactive power flow enables very efficient voltage control during transient as well as steady state conditions, which (in conjunction with ordinary breaker switched reactors) will assist the power system as follows

- Continuous step less control of steady state voltages.
- Increasing system transient stability.
- Preventing voltage collapse during network disturbance or during temporary overloading conditions.

1.2 Back ground

The demand side of network had incurred enormous penetration of large and small motor equipments ranging from small home air conditioning appliances to large District cooling/Chiller plants.

With voltage dip (caused by network short circuit with normal fault current clearing), a significant amount of the supplied load could be disconnected due to the activation of the under voltage protection embedded in the air conditioning (AC) load appliances as well as District Cooling Plants (DCP's). Due to the activation of embedded under voltage protection at demand side, following the occurrence of faults; the steady state voltage may increase above the acceptable limits. Consequently, this may activate the under excitation Limiters (UEL) at generator, which might in worst lead to cascading tripping of generation units.

The installation of Static VAR Compensators (SVC) at 400 kV side is to enhance system voltage stability margin against under voltage and over voltage conditions.

1.3 Purpose of the study

The purpose of the study is strengthening the transmission network by introducing Static VAR compensator (SVC) in 400 kV network. A study requires power system models and study methods covering the particular problems to be solved by the SVC application. The following studies normally are required for an SVC application from the early planning stage till operation.

1. Load flow studies
2. Small and large disturbance studies
3. Harmonic studies
4. Electromagnetic transient studies
5. Fault studies

1.3.1 Modules of load flow studies

The objective of load-flow study is to determine the node voltages, active and reactive power flows in the network branches, generations and losses. The objectives of the load-flow studies related to SVC applications are:

- To determine the appropriate location and preliminary rating of the SVC
- To provide information on the effects of the SVC on the system voltages and power flows

To provide the initial conditions for system transient analysisThe standard load flow study assumes balanced steady-state condition in the network. In case the SVC is applied for load balancing, a three phase load flow model of the power system and the SVC is desirable. In the study of balances system, the load flow representation depends on whether the SVC within or outside the control range.

1.3.1.1 Operating within Control Range

Referring to below Fig: 1.1, the control range of SVC is defined as:

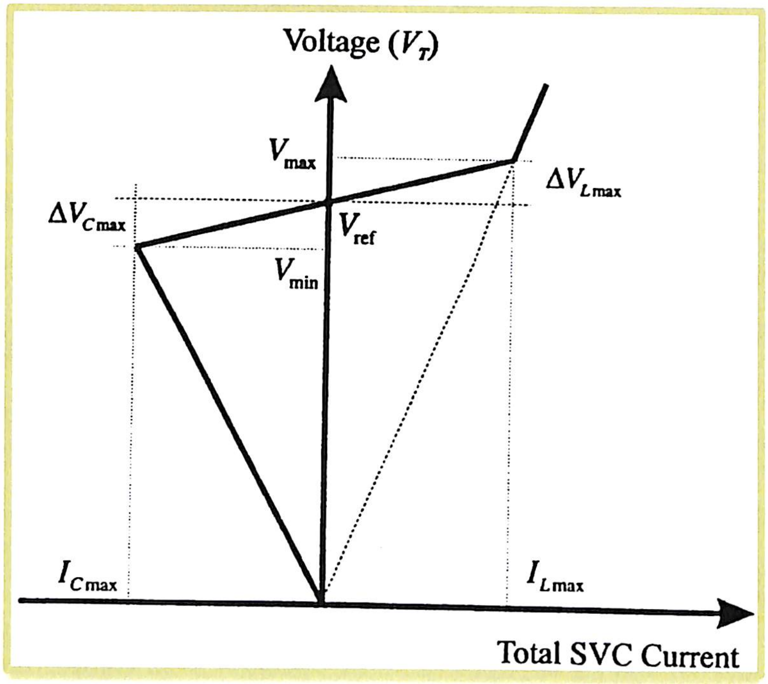


Figure 1.1 Control Range of SVC

$I_{min} < I_{svc} < I_{max}$

$V_{min} < V < V_{max}$

In this range, the SVC is represented as a PV-node (generator node) at an auxiliary bus with P=0, V=V net. A reactance of (X sl) to slope of the V-I characteristic is added between auxiliary node of coupling to the system. The node at the point of common coupling is a PQ node with P=0,Q=0, as shown in below Fig:1.2 (a,b)

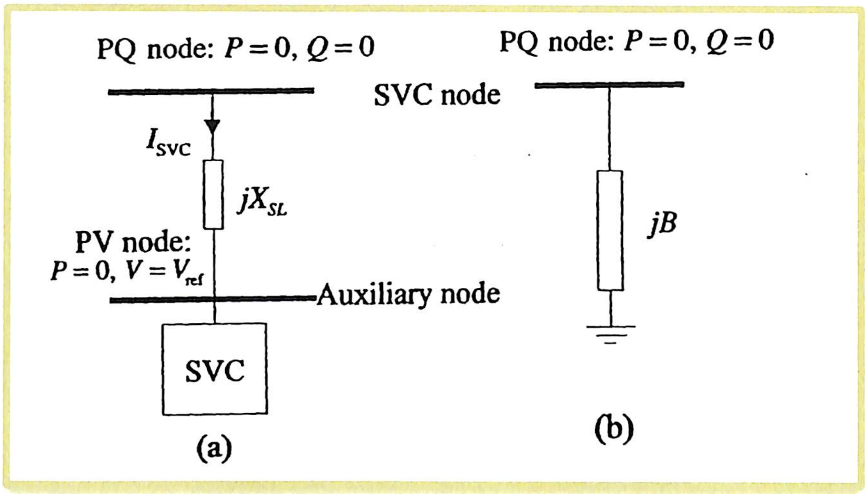


Figure 1.2 SVC operation

(a) SVC operation within control range

(b) SVC operation outage side the control range

1.3.1.2 SVC operation outside the control range

The SVC is represented as a shunt element with susceptance (*j*B). Depending on the operating point (see Fig X), B is defined as:

If $V<V_{min:}$ B = 1/Xc

If $V>V_{max:}$ B = - $1/X_L$

Where *Xc* and X_L are the reactance of the capacitance and reactor, respectively.

1.3.2 Models for large and small disturbance studies

SVC models for large and small disturbance studies should represent the positive sequence system behavior, including control action. Electromagnetic transients in the network and SVC components can be ignored in these studies as long as the disturbances being evaluated are the result of electromechanical oscillations. The objectives of large and small signal analysis studies related to SVC applications are:

- To determine the required rating of the SVC

- To determine the appropriate control parameter and signal for adequate transient and damping performance. Fig:1.3 illustrate the basis SVC model:

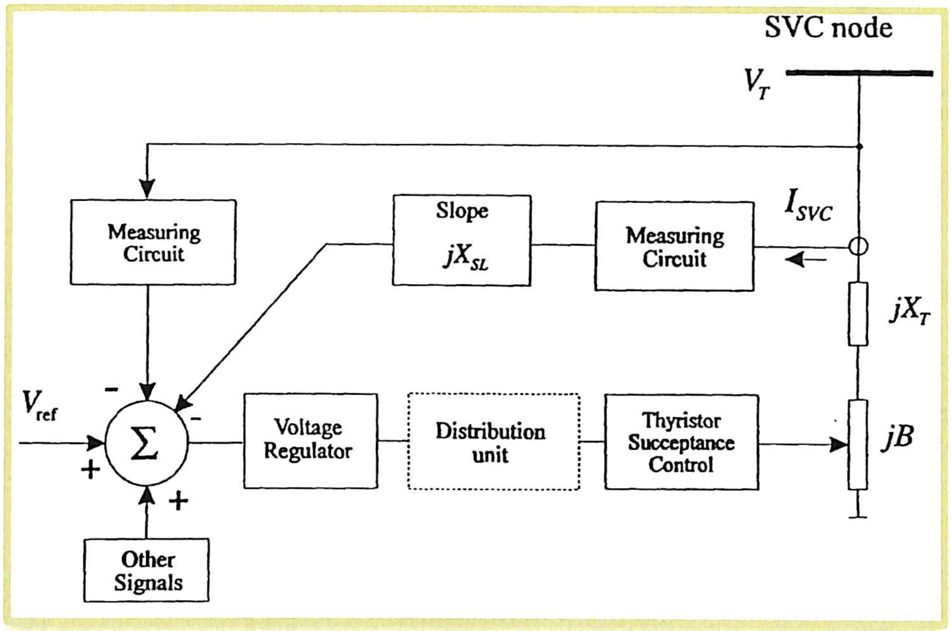


Figure 1.3: Basis SVC model for small and large disturbance studies

1.3.2.1 The basic models of the following elements:

- The voltage and current measuring (and filtering) circuits.
- A regular including possible additional signal fed to the reference point
- Additional control signal are used for system damping improvement, etc.
- A distribution unit
- A model for the thyristor susceptance control module
- A model of the interface with power system (a control susceptance).

The models above represent the physical structure of most installed SVCs.

Description of the basic model

The basic SVC models consist of the following elements:

- **Measuring module:**

The characteristic of the measuring and filter circuit can be approximated by the transfer function:

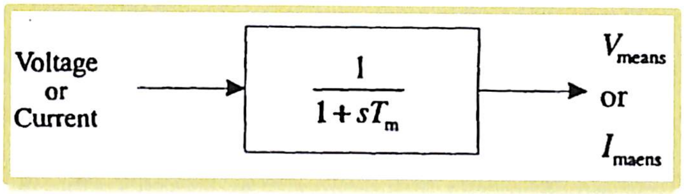


Figure 1.4: Measuring Circuit Model

- **Thyristor Susceptance Control Module:**

  Figure shows the CIGRE model for the delays associated with thyristor firing. Td is the gating transport delay and Tb represents the effect of thyristor firing sequence control.

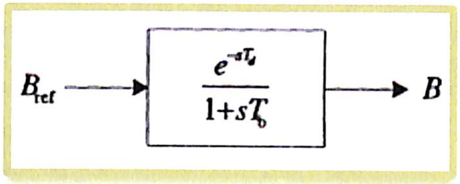


Figure 1.5: Thyristor susceptance control model

- **Voltage Regulator Module:**

  Fig.1.6 shows the model. The voltage regulator is of integral type.

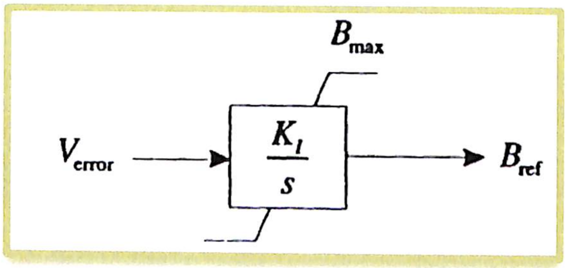


Figure 1.6: Voltage regulator model

- **Distribution Unit Module:**

  The function of a distribution is to determine the number of TSC units and level of TCR reactive power absorption (or a combination of both) based on required reactive power. For SVCs with continuous output, there is not a need to model this module. However, this module must be modeled when a discrete type SVC is used to attain a exact simulation results. Fig. X shows a distribution model for TSR-TSC SVCs, where the output is converted into individual ON/OFF orders to the different TSRs and TSCs.

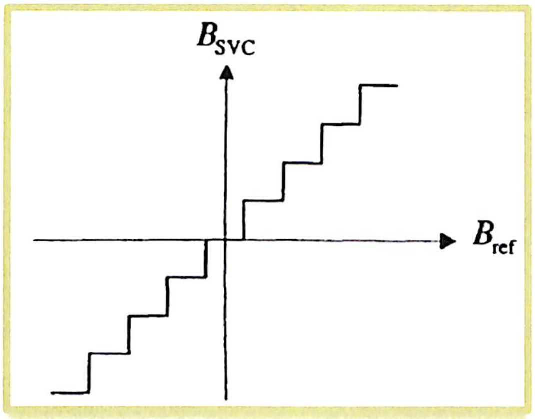


Figure 1.7: Distribution unit model for TSR-TSC type SVC

1.3.2.2 Typical parameters for SVC Models

The parameters of the SVC model have to be selected according to SVC rating and performance criteria taking into account the power system behavior under various operating conditions and SVC response under such conditions. Typical values for the various SVC models are given in Table 1.1.

Module	Parameter	Definition	Typical value
Measuring	Tm	• Measuring circuit time constant	0.01- 0.005
Thyristor control	Td	• Gating transport delay • Thyristor firing sequence control delay	0.001s 0.003 – 0.006s
Voltage regulator	Ki	• Integrator gain	-Ki is adjusted for fast and well-damped response based on selection of the slope
Slope	XSL	• Steady stage characteristic slope	0.001 – 0.005 p.u

Table 1.1 Typical Values for the various SVC models

1.3.2.3 Use of SVC for power system damping improvement

Reactive power absorption at a system node influences the voltage profile of the system. As a result, active and reactive power flows within the system are changed, modifying system stability and system damping. By using a proper SVC control scheme, system stability and damping can be improved. Application of an SVC to aid damping of power system swings requires recognition of electro mechanical oscillation modes. These models change with system configuration. Loads have an importance upon the effectiveness of an SVC to aid power swing damping. In general, a compensator maintaining constant terminal voltage is not effective in damping power oscillations. The following steps need to be taken for a proper SVC supplementary power oscillation damping control.

1.3.2.3.1Location of SVC

Location of an SVC strongly affects control ability of the swing modes. In general the best location is at a point where voltage swings are greatest. Normally, the mid-point of transmission line between the two areas is good location for placement.

1.3.2.3.2Choice of Input signal

There exist several possibilities for inputsignals upon which a damping control function can be based, namely:

- Frequency of an AC voltage
- Current or power flow on major lines
- Voltage magnitude

The selected input signal must be responsive to swing modes to damped. This means that the swings mode must be observable in the input signal. The modulation control should provide a positive contribution to damping for any power system operating condition. Local input signal are preferred to remote signals.

1.3.2.3.3 Damping Control Transfer Function Structure

The supplementary input signal is normally passed through two transfer functions which adjust gain and phase. Parameters of this function are optimized according to the input signal and operating conditions (see Fig. 1.8)

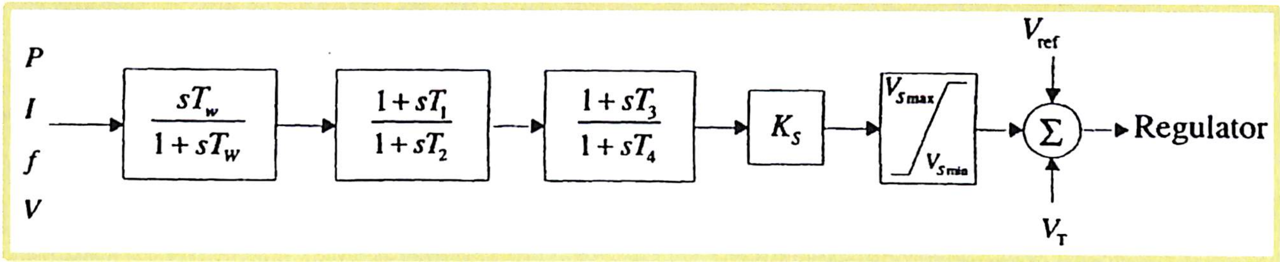


Figure 1.8: A Typical transfer function of power swing damping control

1.3.3 Harmonic Studies

Harmonic interaction between static compensator and the system is usually analyzed by means of harmonic equivalents. The results of such harmonic performance studies provide information about the effects of SVC generated harmonics on the power system as well as its elements and the overall filters requirements and the counter measures to reduce harmonic to acceptable levels. For a particular operating condition, the different firing angles of reactors that generate harmonic are represented by harmonic- current generators. Other shunt reactors, capacitor and tuned filters form a filtering complex. The transformer leakage is represented as a reactor connected in series with the system impedance as seen at the static compensator location. Fig: 1.9 shows the simplified representation of an SVC comprising TCR and filters.

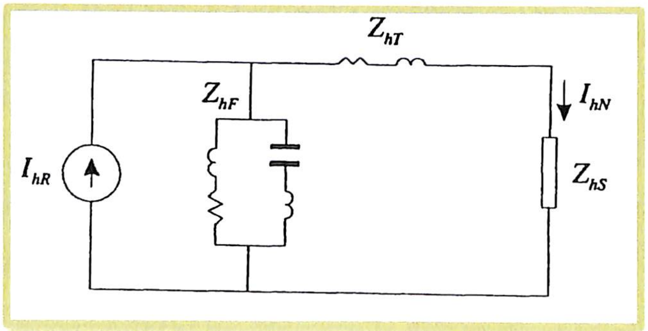


Figure 1.9 Simplified representations of the static compensator and the network

The current which flows into the network is described by the following expression:

$$I_{hN} = I_{hR}\frac{Z_{hF}}{Z_{hF} + Z_{hT} + Z_{hS}}$$

Where IhN is the harmonic current injected by a thyristor – controlled reactor, ZhF is the impedance of the filtering complex; ZhT is the impedance of the transformer and ZhS is the network impedance. The impedances are evaluated for a sufficient range of harmonic (say up to 30th harmonic). It is common to define the system impedance ZhS by an R-X locus. Fig. X gives an example of such a locus.

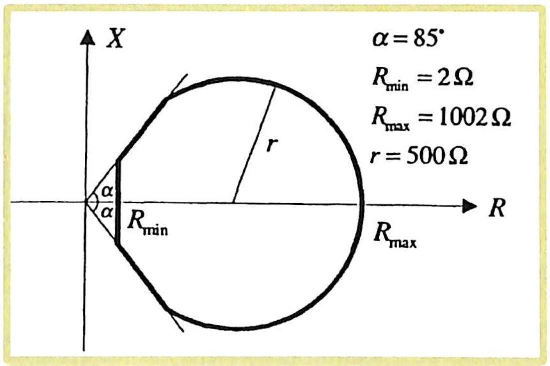


Figure 1.10: Example of an R-X locus used for harmonic generation evaluation

1.3.4 Electromagnetic Transient Studies

An abrupt change of the steady state, such as the actuation of a switch, inception of a fault, or change of a reactance value, will induce transient in an electrical power system, since the transient involve interaction of magnetic and electrical fields, these phenomena are called electromagnetic transients. SVCs are able to limit temporary and some transient overvoltage by their control or inherent characteristic. The objective of the electromagnetic transient studies related to SVC applications can be verifying the effect of the SVC during transient disturbances. The results of the studies are used to derive requirements to be included in the SVC technical specification for the particular application.

1.3.5 Fault Studies

The objective of fault studies is to determine the short circuit current for symmetric or unsymmetric faults for various network and system demand conditions. In modeling, the generator and motors can be represented by simplified modes for transient studies. The network, transformer and SVC are modeled as reactances. Fig: 1.11 shows an example of a fault study for TSC where the fault has occurred between the two phases of the SVC.

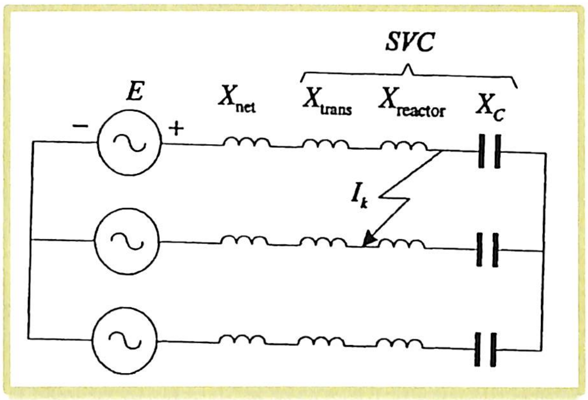


Figure 1.11: Short circuit current in a TSC

The study provides information about:

- Rating of circuit breakers
- Relays setting
- Design of SVC components

1.4 Research and Hypotheses

The computer study files to be used design the project.

The following assumption shall be mad through PSSE that are high and low load cases for 2015 and 2018 of system healthy conditions.

We have to consider the worst case fault on any bus bar, line or transformer. The worst case N-1 and N-2 (absence of equipment from original installation) on the same circuit network contingencies.

In RTDS the complete network is not required and individual can be derived for each SVC. The individual networks shall accurately represent the network in the immediate vicinity of the SVC being studied and equivalent networks. The network shall have an accurate frequency response for zero to 500 Hz. It shall be ensured the frequencies below fundamental frequencies are having good interaction with series capacitors and controller. And frequencies above fundamental frequenciesare to be considered for transient behavior of SVC.

The following network diagram shall be considered for representing the SVC in RTDS.

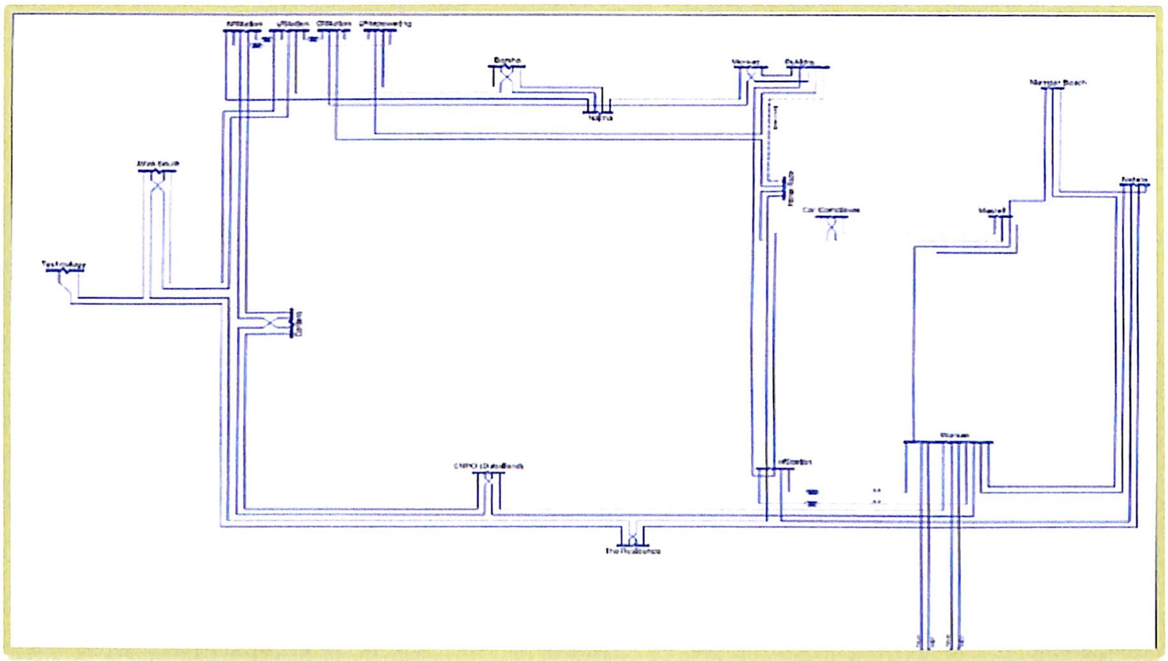


Figure 1.12: Network Diagram representing the SVC in RTDS.

1.4.1 Load Modeling

The load modeled as a combination of static and dynamic loads are specified in below table X.

The machine parameters used to model the dynamic loads are given in Table 1.2.

	Peak conditions	**Off peak conditions**
Static load as fixed impedance	35 %	65%
Dynamic load as large motors	35.1% (54% of dynamic load)	18.9% (54% of dynamic load)
Dynamic load as small motors	29.9% (46% of dynamic load)	16.1% (46% of dynamic load)

Table 1.2 Load Compositions

During a 400 kV network fault up to 50% of large and small motor can trip. The extreme cases considered are the case that no motor trip during a fault and the case that 50 % of the motor trip during a fault.

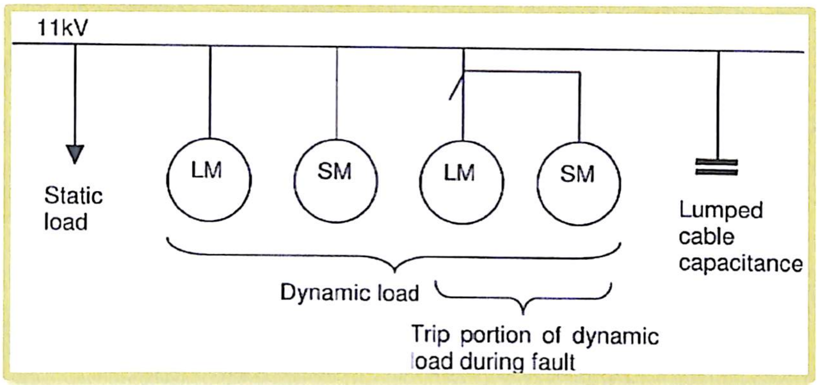


Figure 1.13 : Load Composition

Load voltage	11 kV	132 kV
Mechanical Damping [p.u.]	1	1
Inertia [s]	1	1
Ra [p.u.]	0.0314	0.0314
Xa [p.u.]	0.1536	0.1536
Xm [p.u.]	4.3878	4.3878
R_1 [p.u.]	0.0393	0.0393
X_1 [p.u.]	0.0393	0.0393
R_2 [p.u.]	0.0081	0.0081
X_2 [p.u.]	0.0561	0.0561
Mechanical damping [p.u.]	1.2	1.2
Load voltage	11 kV	132 kV
Inertia [s]	0.6	0.6
Ra [p.u.]	0.02	0.02
Xa [p.u.]	0.1719	0.1719
Xm [p.u.]	4.32	4.32
R_1 [p.u.]	0.0319	0.0319
X_1 [p.u.]	0.0001	0.0001
R_2 [p.u.]	0.022	0.022
X_2 [p.u.]	0.2971	0.2971

Table 1.3 Machine parameters

1.4.2 EMT studies

The EMT and RTDS network models represented the delayed motor stalling and prevention of overvoltages upon fault clearing in the network.

EMT study result proved the functionality of SVC technology has capability of solving motor stalling and prevention of overvoltage after fault clearing in the network. The study results are case listed in the below table. The EMT models used for this study represented the SVCs that will be installed

1.4.2.1 EMT Study Results

Basic SVC functionality	Design review	RTDS
Energisation of SVC, start up sequence	√	√
Automatic operation \, linear voltage control over compete SVC range	√	√
SVC step response in HIGH fault level network with slope = 0%,2%,5% and SVC output= 0 MVAR and almost full capacitive in order for the SVC not to saturate (-200 MVAR)	√	√
SVC step response in LOW fault level network with slope = 0%,2%,5% and SVC output= 0 MVAR and almost full capacitive in order for the SVC not to saturate (-200 MVAR)	√	√
Manual operation		√
Manual to automatic and automatic to manual change over		√
De-Energization of SVC, Stop response	√	√
Asymmetric current protection, DC, 2nd harmonic	√	√
Fixed reactive device switching	√	√
Loss of system voltage	√	√
Variation of system voltage	√	√
All control strategies	√	√
POD step strategies	√	√
Misfiring of TCS	√	√
All other control and protection functions	√	√
Degrade mode of SVC functionality		
Energies SVC in degraded mode with one TCR out	√	√
1 phase fault on filter branch, isolate filter branch	√	√
1 Phase fault on TCS branch, block and isolate TCS branch	√	√
One filter branch out, change reference voltage	√	√
One and two TSCs out, change reference voltage	√	√
One TCR out, change reference voltage	√	√
System Tests		
Energize of line/cable	√	√
1&3 phasefaulton cable/line, trip line/cable:	√	√
1&3 phase fault on 380/132 kVtransformer,trip transformer:	√	√
1&3 phase fault on load, trip 2/3 load:	√	√
Generator bus trip:	√	√

Under frequency load shedding	√	√

Table 1.4 EMT Study Results

Note: 1) fault duration = 100ms on 400 kVand 132 ms on 132 kV.

Combined network impedance at 400 kV ABC and XYZ (2 Nos of 400 kV taken as assumption)

The calculated impedance of 400 kV ABC and XYZ are combined into one set of impedance values. The filter design for both the 400 kV ABC and XYZ must be according to the combined impedance plots to ensure that the design

Contingency	**description**
System healthy	All equipment in service as per PSSE file
L24000_26000	Line from bus 24000 to 26000
L24000_24400	Line from bus 24000 to 24400
L24000_21000	Line from bus 24000 to 21000
L27000_21000	Line from bus 27000 to 21000
L24700_21000	Line from bus 247000 to 21000
L24000_24050	Transformer bus from 24000 to 24050 out of service
L24000_26000_24400	Line from bus 24000 to 26000 and bus 24400 out of service
L2400_21000_1&2	Line from bus 24000 to 21000 circuit 1&2 out of service

Table 1.5 Contingency list for 2015 off-peak case at 400kV ABC Station

Contingency	**description**
System healthy	All equipment in service as per PSSE file
L24000_26000	Line from bus 24000 to 26000 out of service
L24000_28700	Line from bus 24000 to 28700 out of service
L24000_21000	Line from bus 24000 to 21000 out of service
L27000_21000	Line from bus 27000 to 21000 out of service
L24700_21000	Line from bus 247000 to 21000 out of service
T24000_24050	Transformer bus from 24000 to 24050 out of service
L24000_26000_28700	Line from bus 24000 to 26000 and bus 28700 out of service
L2400_21000_1&2	Line from bus 24000 to 21000 circuit 1&2 out of service

Table 1.6 Contingency list for 2018 off-peak case at 400kV ABC Station

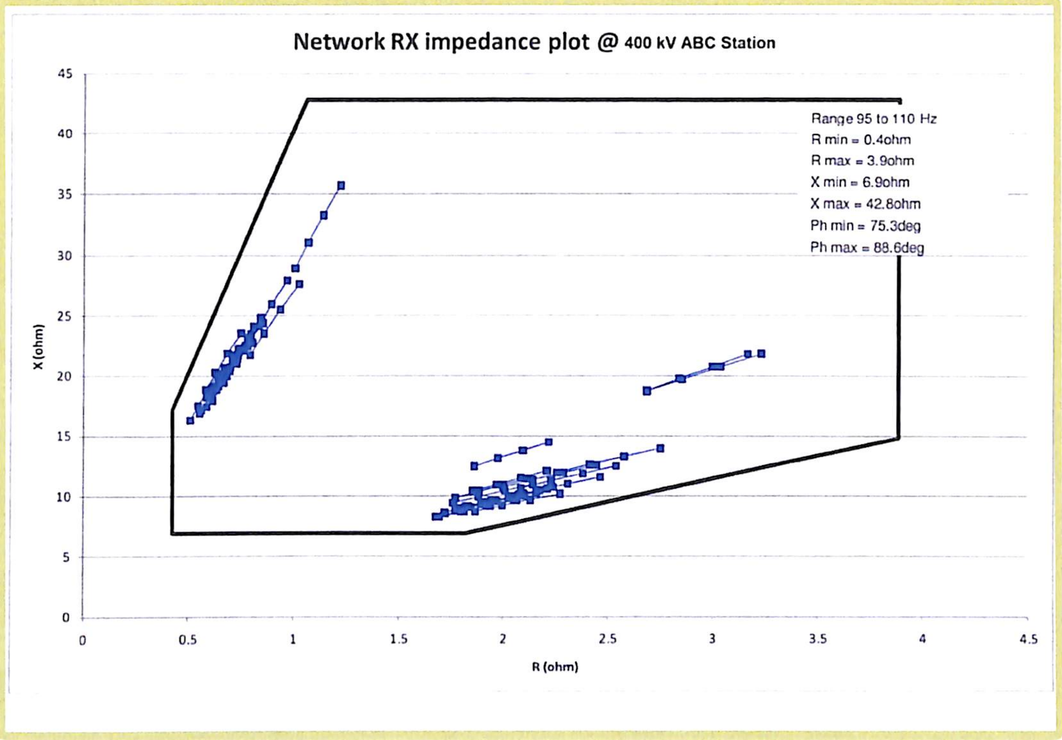


Figure1.14 : Network RX Impedance plot @ 400KV ABC Stn (95 to 110Hz)

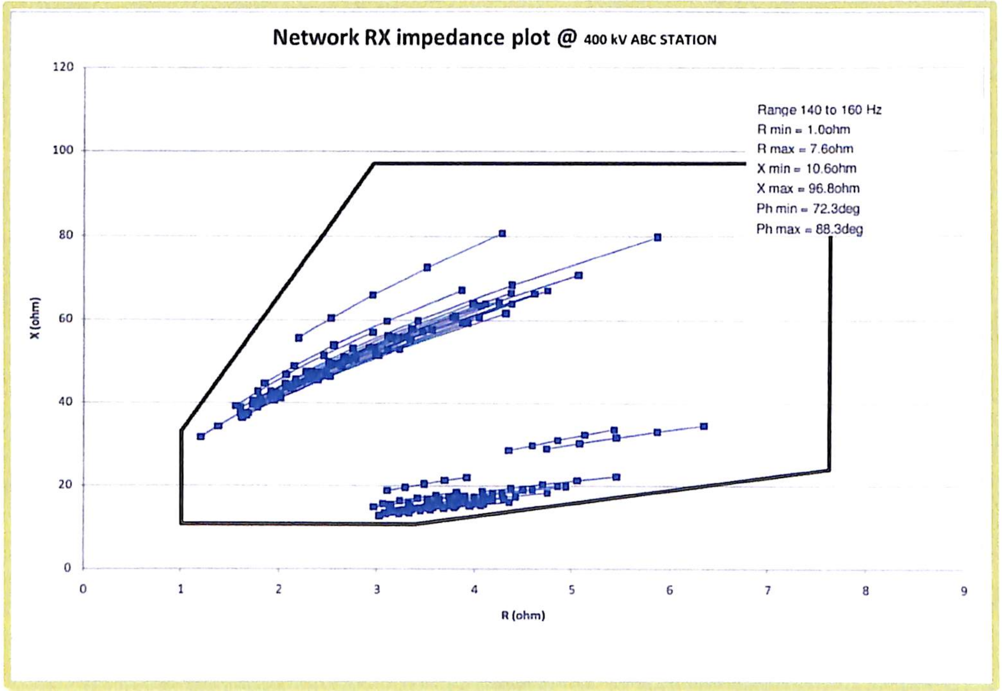


Figure 1.15: Network RX Impedance plot @ 400KV ABC Stn (140 to 160Hz)

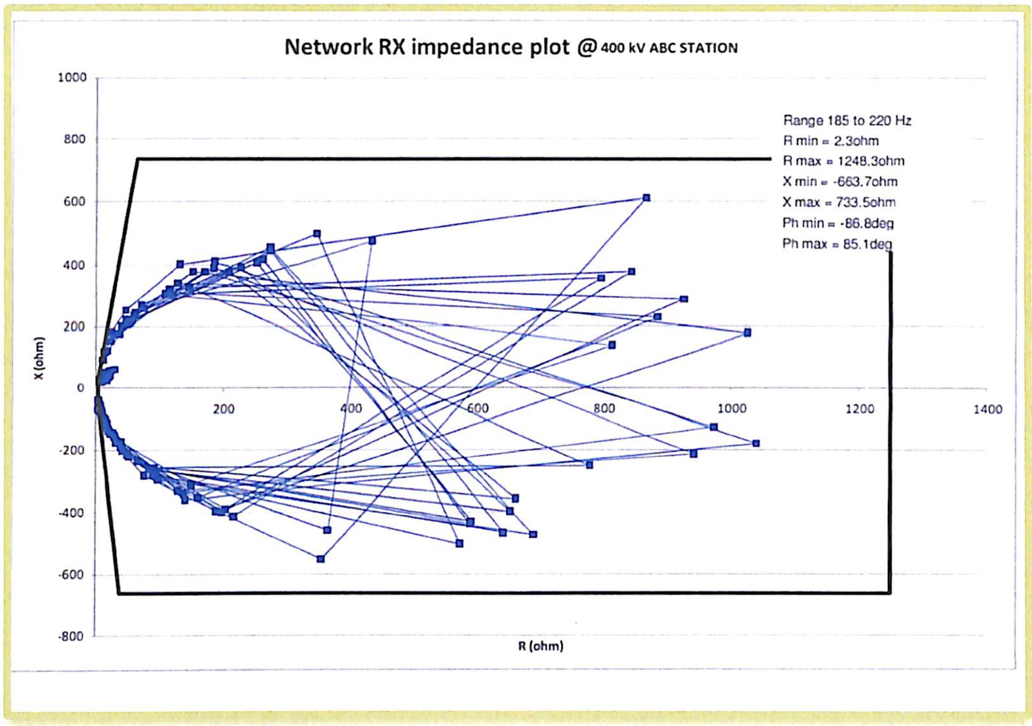


Figure 1.16: Network RX Impedance plot @ 400KV ABC Stn (185 to 220Hz)

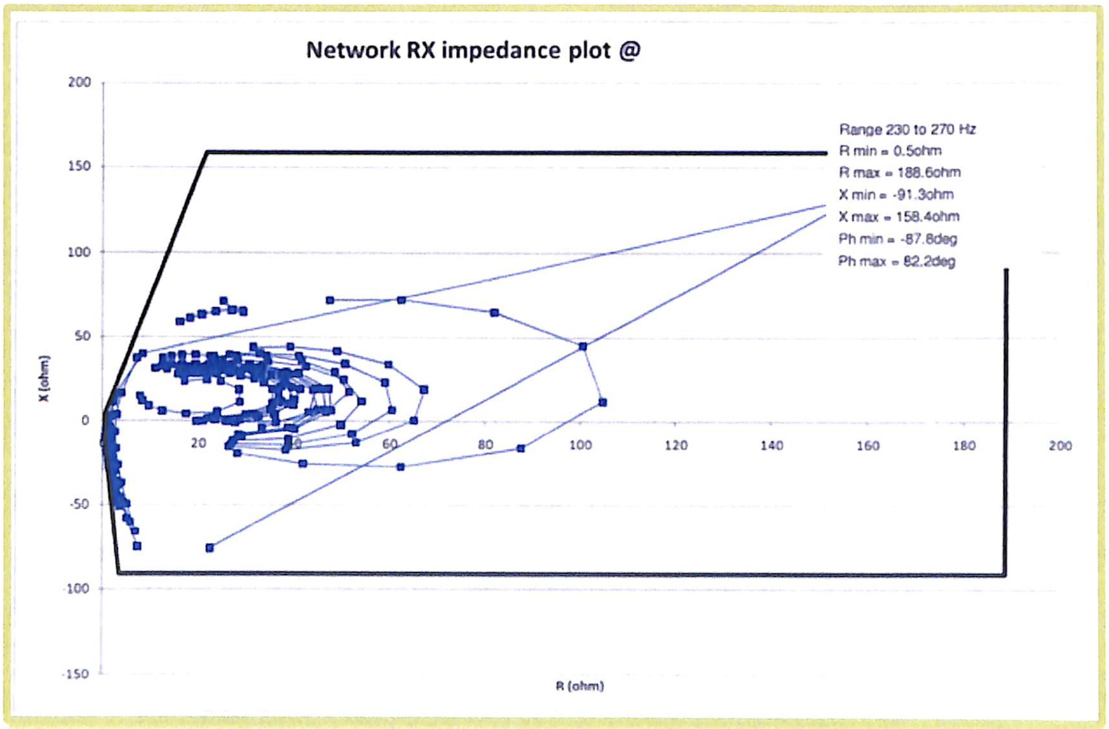


Figure 1.17: Network RX Impedance plot @ 400KV ABC Stn (230 to 270Hz)

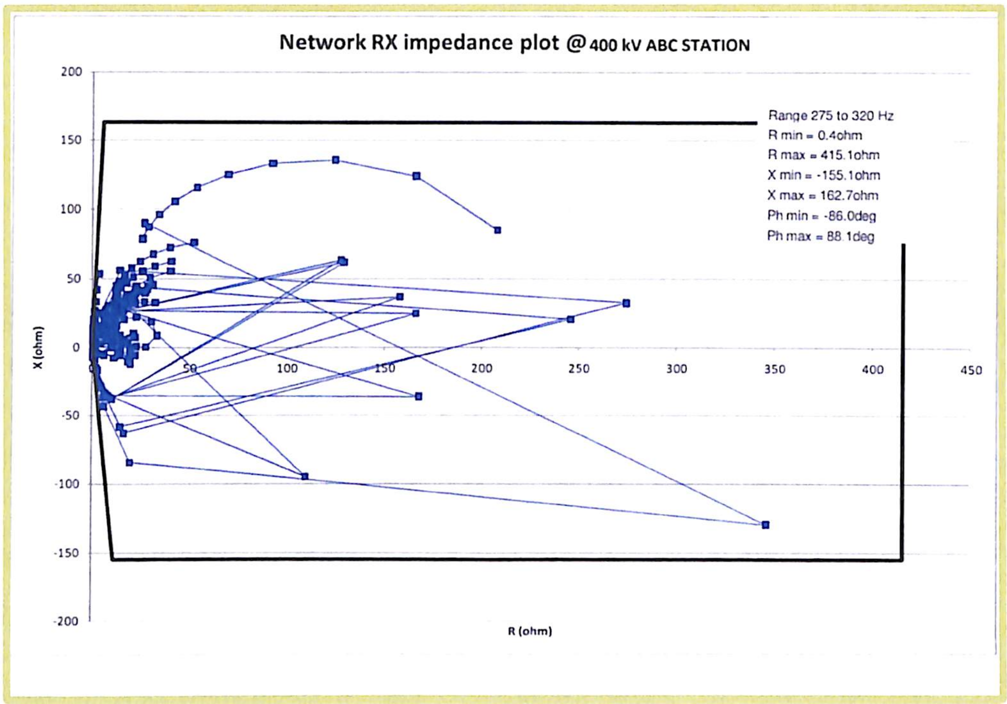


Figure 1.18: Network RX Impedance plot @ 400KV ABC Stn (275 to 320Hz)

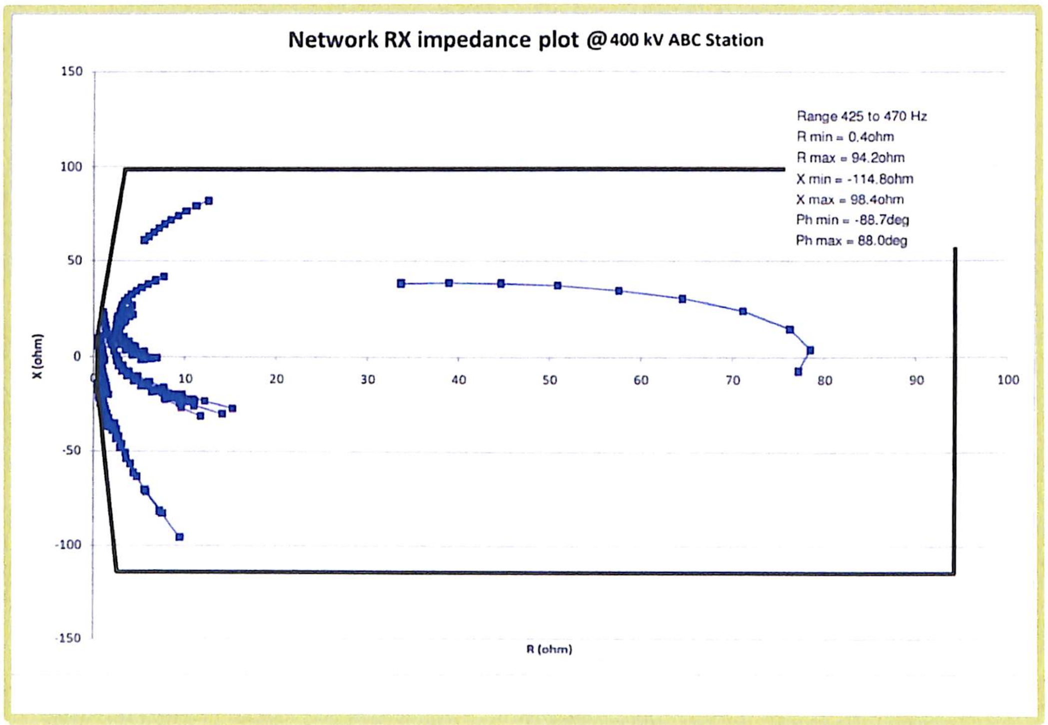


Figure 1.19: Network RX Impedance plot @ 400KV ABC Stn (425 to 470Hz)

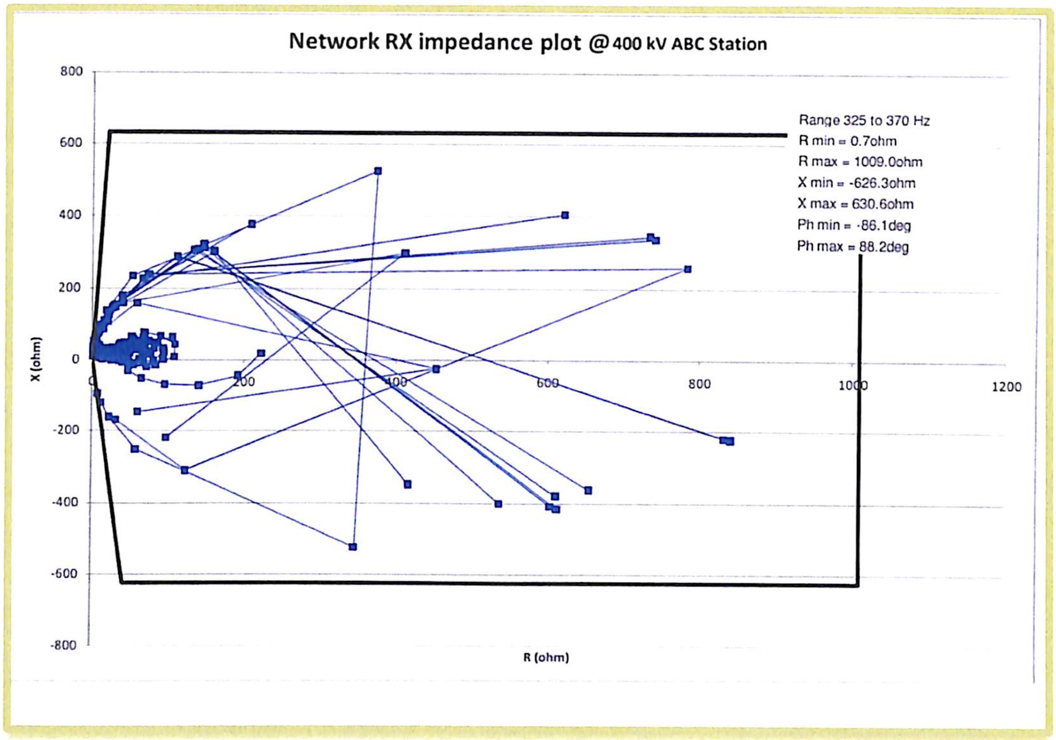


Figure 1.20 : Network RX Impedance plot @ 400KV ABC Stn (230 to 270Hz)

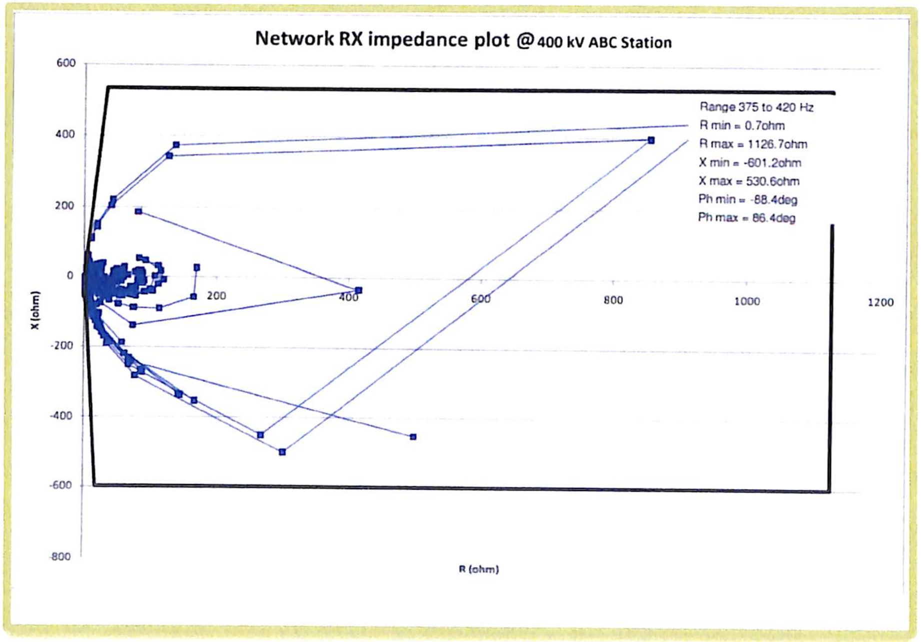


Figure 1.21: Network RX Impedance plot @ 400KV ABC Stn (375 to 420Hz)

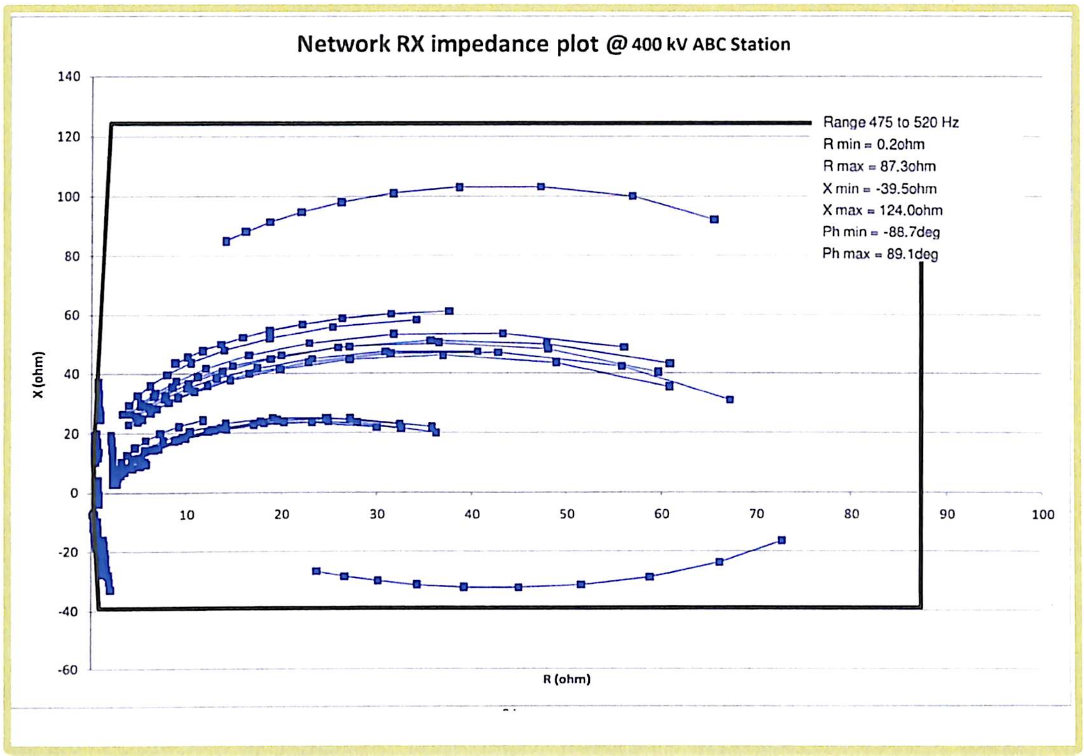


Figure 1.22: Network RX Impedance plot @ 400KV ABC Stn (475 to 520Hz)

CHAPTER: 02 LITERATURE REVIEW

2.1 Review Area Broad

It is recommended to install SVC at 400 kV buses. The rating of [± 200] MVAR found to be adequate to enhance the system voltage control of the system.

A single line diagram of a Static VAR Compensator (SVC) is given below Fig 2.1.

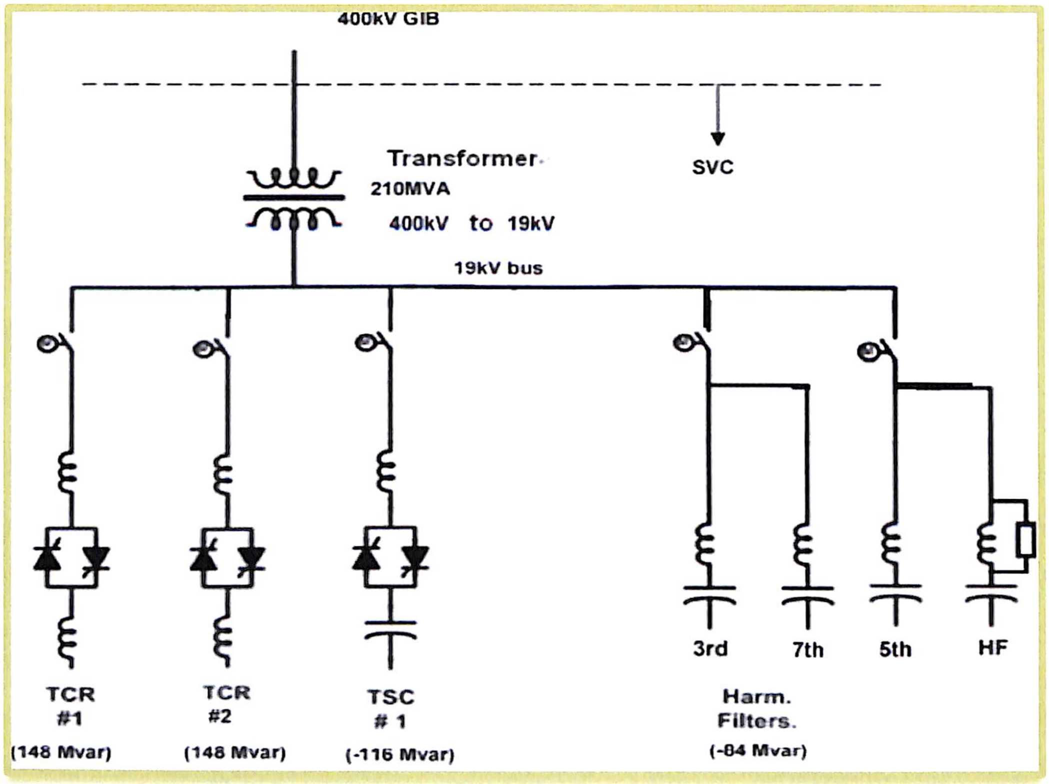


Figure 2.1: Single Line Diagram of a Static VAR Compensator

The dynamic nature of the SVC lies in the use of thyristor devices. The thyristor, usually located indoors in a "valve house", can switch capacitor or inductor in and out of the circuit on a per-cycle basis, allowing for very rapid superior control of system voltage. The thyristor are turned on by suitable control that regulates the magnitude of the current.

Static VAR Compensator (SVC) includes several high voltage equipment such as a

1. Power transformer.
2. Thyristor Controlled Reactor (TCR),
3. Thyristor Switched Capacitors (TCS) and
4. Harmonic Filters.

2.2 Review Area Narrow

The following area to be reviewed as follows,

2.2.1 SVC Equipment Rating

The equipment rating has to be finalized by studies. The ratings of the following SVC equipment are to be finalized:

a. Power Transformer
b. Thyristor Switched Reactors
c. Thyristor Switched Capacitors with associated damping reactors
d. Harmonic filters

2.2.2 Overall Control System of SVC

The main purpose of the SVC system is to control the system voltage. The is accomplished by supplying inductive and/or capacitive power to the transmission system via a combination of a step-up transformer , Thyristor controlled Reactor (TSC), Thyristor Switched capacitor (TSC),Fixed Capacitor (FC) for harmonic filters.

The main purpose of the SVC control system is to control, supervise, monitor and protect these reactive power producing devices and their associated support components.

2.2.3 Thyristor Valve and associated cooling system

The reactors of TCR and capacitors of TSC are switched in or out by conduction of Thyristor valves. The TSC is switched in or out by firing and non firing of the TSC Thyristor valves. The TCR is controlled by varying the firing angle of Thyristor valves. The TCR will be fully conducting when the firing angle is 90 degrees and will be fully non-conducting when the firing angle is 180 degrees. Accordingly the number of Thyristor valves have to be selected for each branch

Thyristor valve operating condition

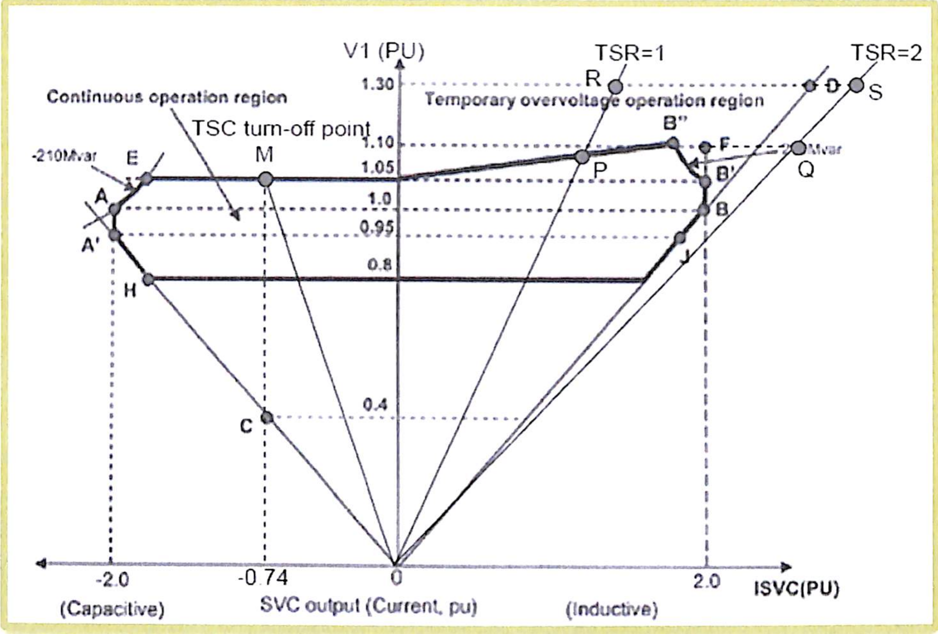


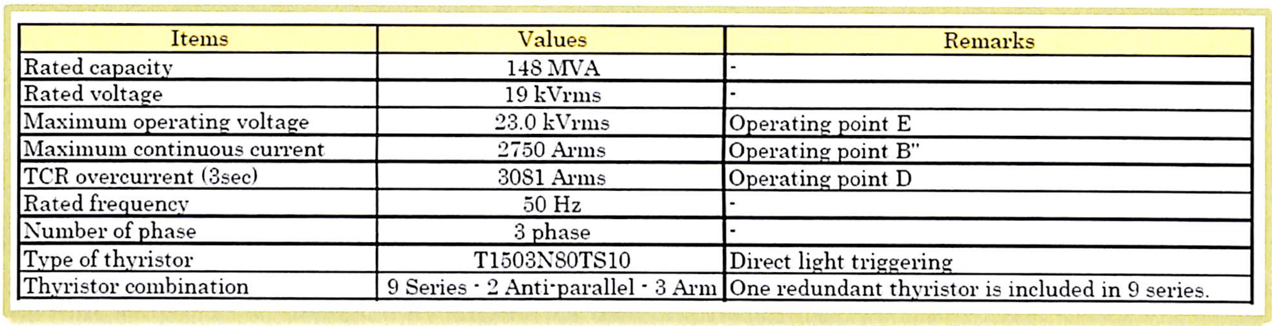
Figure 2.2: V-I characteristic of SVC operation

O/P	Operating Mode	Qsvc(MVA)	V1(pu)	V2(kV)	I1(A)	I2(A)	Thyristor valve current ITCR1(A)	 ITCR2(A)	 ITSC(A)
A'	Nominal capacitive output at V1=0.95	200.0	0.95	20.90	303	6.380	22	0	2.192
A	Nominal capacitive output at V1=1.00	210.0	1.00	21.90	303	6.381	199	0	2.291
E	Maximum capacitive output at V1=1.05	210.0	1.05	23.00	289	6.078	841	0	2.603
M	Maximum TCR current at TSC turn off	81.6	1.05	21.10	112	2.361	2.632	0	2.360
H	Nominal capacitive output at V1=0.80	141.8	0.80	17.92	256	5.387	271	0	1.995
C	Short term capacitive output at V1=0.40	35.5	0.40	8.96	128	2.697	134	0	998
J	Nominal inductive output at V1=0.95	180.5	0.95	15.41	274	5.774	2.375	2.156	0
B	Nominal inductive output at V1=1.00	200.0	1.00	16.22	289	6.078	2.500	2.270	0
B'	Maximum inductive output at V1=1.05	210.0	1.05	17.17	289	6.078	2.646	2.197	0
B"	Maximum inductive output at V1=1.1	210.0	1.10	18.20	276	5.812	2.750	2.013	0
F	Maximum inductive output at V1=1.1 (for 15min)	220.0	1.10	18.12	289	6.078	2.737	2.313	0
D	Maximum inductive output at V1=1.3 (for 3sec)	338.0	1.30	21.20	275	5.780	3.081	3.081	0
P	TSR operation with 1 TSR	179.0	1.087	18.40	238	5.001	2.887	0	0
Q	TSR operation with 2 TSRs (for 3sec)	331.0	1.10	16.80	434	9.131	2.636	2.636	0
R	TSR operation with 1 TSR (for 3sec)	256.0	1.30	22.00	284	5.980	3.450	0	0
S	TSR operation with 2 TSRs (for 3sec)	462.0	1.30	19.90	513	10.791	3.115	3.115	0

Table 2.1: Thyristor valve operating condition

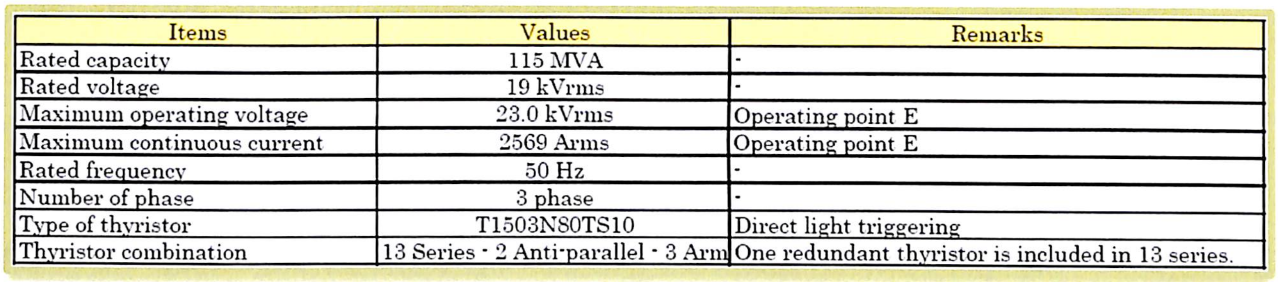
WhereQsvc (MVA): Reactive power (Q) of SVC
V1 (Pu): primary voltage of transformer
V2 (kV): Secondary voltage of transformer
I1 (A): Primary current of transformer
I2 (A): Secondary current of transformer
ITCR1 (A): Current of TCR-1
ITCR2 (A): Current of TCR-1&ITSC (A): Current of TSC

Rated voltage and current



Items	Values	Remarks
Rated capacity	148 MVA	-
Rated voltage	19 kVrms	-
Maximum operating voltage	23.0 kVrms	Operating point E
Maximum continuous current	2750 Arms	Operating point B"
TCR overcurrent (3sec)	3081 Arms	Operating point D
Rated frequency	50 Hz	-
Number of phase	3 phase	-
Type of thyristor	T1503NS0TS10	Direct light triggering
Thyristor combination	9 Series - 2 Anti-parallel - 3 Arm	One redundant thyristor is included in 9 series.

Table 2.2 Rated voltage current of TCR Thyristor valve



Items	Values	Remarks
Rated capacity	115 MVA	-
Rated voltage	19 kVrms	-
Maximum operating voltage	23.0 kVrms	Operating point E
Maximum continuous current	2569 Arms	Operating point E
Rated frequency	50 Hz	-
Number of phase	3 phase	-
Type of thyristor	T1503NS0TS10	Direct light triggering
Thyristor combination	13 Series - 2 Anti-parallel - 3 Arm	One redundant thyristor is included in 13 series.

Table 2.3: Rated voltage current of TSC Thyristor valve

2.2.4 Protections relay.

The SVC system including the SVC transformer has to be protected from all kinds of faults. Accordingly, a reliable, sensitive protective relaying system is to be designed for the SVC System.

2.2.5 Earthing Transformer &Neutral grounding resistor

The 19kV side of the SVC transformer is delta connected. So the 19kV system has to be earthed for earth fault currents. Hence it is required to perform analysis of earth-fault conditions in the 19kV SVC plant with earthing transformer used for 19kV neutral point earthing at 400/132kV Substation.

2.3 Factors critical to success of study

The following factors are critical to success for studies

a) Load flow studies

b) Disturbance studies

c) Harmonic studies
d) Electromagnetic transient studies
e) Fault studies

2.4 Summary

The following is to be designed by studies for the SVC System:

a. Equipment rating design
b. Overall control system of SVC
c. Thyristor valve design and associated cooling system design
d. Protective relaying design
e. Earthing Transformer and Neutral grounding resistor design

Fig: 2.2showsthe single line diagram of the SVC. The SVC consists of a 210MVA transformer and SVC equipments on the secondary side of the transformer. The secondary consist of two 148MVAR TCRs (Thyristor Controlled Reactors), one 116MVAR TSC, and 84MVAR harmonic filters consisting of a 3rd harmonic filter, a 5th harmonic filter, a 7th harmonic filter and a HF (high frequency) filter.

The secondary voltage of the transformer is selected as 19kV. Since this is the optimal value considering the impedance of the SVC transformer.

Each TCR branch consists of a string of two reactors and a thyristor valve in each phase, and three strings are connected in delta for three-phase construction.

The TSC is made up of one TSC branch, consisting of a string of a reactor and a capacitor and a thyristor valve in each phase, and three strings are connected in delta for three-phase construction.

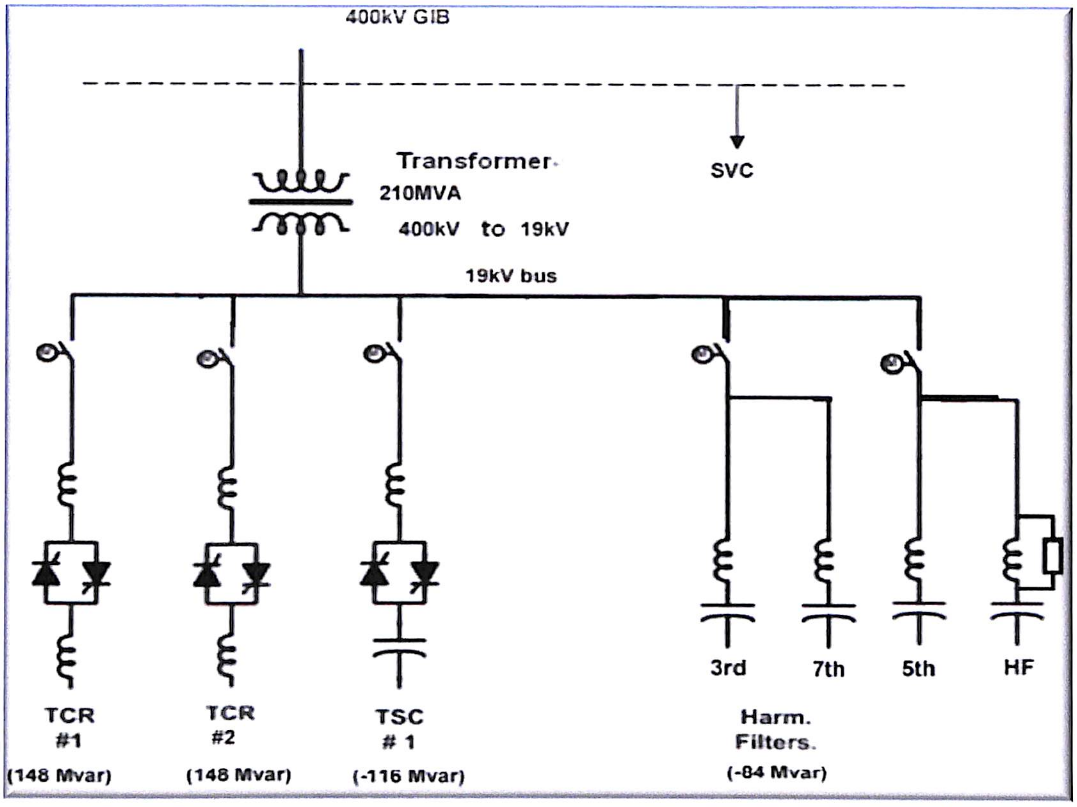


Figure 2.3 :Single line diagram of the SVC

Note: The MVAR ratings show the ratings at V=0.95pu of AC bus voltage

CHAPTER: 03

RESEARCH DESIGN, METHODOLOGY & PLAN

3.1 Data Sources

a) System network data
b) System impedance detail
c) System planning details
d) System harmonic measurement details

3.2 Research Design

3.2.1 Design considerations on ratings of SVC

3.2.1.1 Design consideration of SVC ratings

The steady state Voltage-Current characteristics of the SVC are shown in Fig: 3.1.

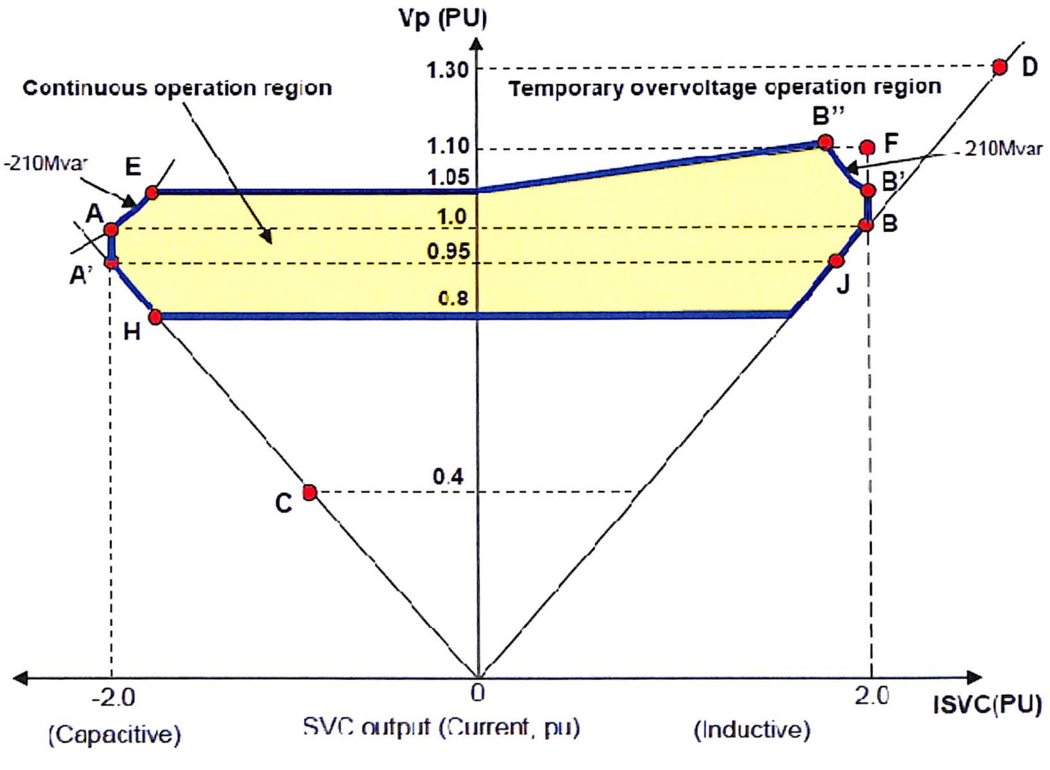


Figure 3.1: V-I characteristics of SVC operation

Operating point	Operating mode	Operating condition				Remarks
		SVC output (pu)	Voltage (pu)	Freq: (Hz)	Ambient Temp C	
A	Nominal capacitive reactive power output of SVC	-2.1	1.0	49.5	55	
A’	Nominal capacitive reactive power output of SVC	-2.0	0.95	49.5	55	
B	Nominal inductive reactive power output of SVC	2.0	1.0	50.5	55	
B’	Nominal inductive reactive power output of SVC	2.1	1.05	50.5	55	
B*	Nominal inductive reactive power output of SVC	2.1	1.1	50.5	55	Slope=5%,vref=1.05 Pu
C	Short term capacitive power output for 1.5 seconds	-0.35	0.4	50	55	Min: value of operating voltage
D	Short term inductive power output for 3 seconds	3.38	1.3	50.5	55	
E	Maximum continuous capacitive power output	-2.1	1.05	50.5	55	
F	Short term inductive power output for 15 seconds	2.2	1.1	50.5	55	

Table. 3.1: Operating Point of SVC operation

3.2.1.2 Continuous Output Region

(a) Nominal Capacitive Output:

The nominal capacitive output will be defined at the operating point of A’ in Fig: 3.1 .Theoperating point A’ gives the nominal capacitive susceptance for -200 MVAR at V=0.95pu.The nominal capacitive susceptance will be defined on the following conditions:

i. System voltage = 0.95 p
ii. Power frequency = 49.5 Hz (minimum)
iii. Ambient temperature = 55 °C (maximum)

(b) Nominal Inductive Output:

The nominal inductive output will be defined at the operating point of B in Fig: 3.1.Theoperating point B gives the nominal inductive susceptance for 200 MVAR at V=1.0pu.Thenominal inductive susceptance will be defined on the following conditions:

i. System voltage = 1.0 pu
ii. Power frequency = 50.5 Hz (maximum)
iii. Ambient temperature = 2.8 °C (minimum)

(c) Maximum Continuous Capacitive Output

The maximum continuous capacitive output will be determined at the operating point of E in

Fig: 3.1. The operating point E gives the maximum continuous capacitive operating ratings

for -210 MVAR at V=1.05 pu.

(d) Maximum Continuous Inductive Output

The maximum continuous inductive output will be defined at the operating points of B' and B" in Fig: 3.1. The operating points B' and B" give the maximum continuous inductive operation points

3.3 Survey Question

3.3.1 Define system configuration

System configuration of SVC is shown Fig: 3.2

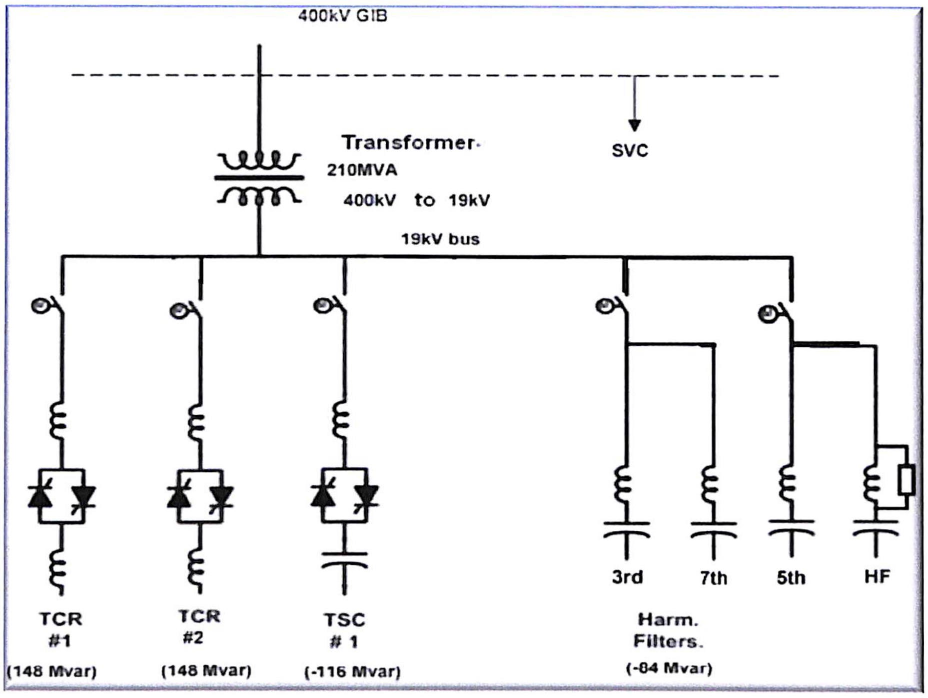


Figure 3.2: System configuration of SVC

3.3.2 Describe the tool to analyze system resonance and system stability phenomena

No	Name of the program	Analysis objective
1	EMTP or equivalent	F-Z characteristic analysis of power impedances
2	PSSE or equivalent (M-HO)	Power system stability analysis

Table 3.2 Tool to analyze system resonance and system stability phenomena

3.3.3 Describe system studies

Task- Electrical system study (Main Equipment Rating Design)

(1) General

The proposed SVC system will be designed to meet the requirement of functionality described in this proposal. We have to ensure design parameters are engineering studies to determine the required design parameters and to verify that the specified performance criteria are met for the applicable range of system conditions.

(2) Study tool

This analysis will be carried out using a fast transient digital system representation. The model should be relevant portion of the utility system and SVC equipment and control using a cycle-by-cycle transient program such as EMPT or PSCAD

(3) Content of studies

This task will include following:

(a) Studies to determine the design rating and requirements of main equipments of SVC

(b) Simulation studies to verify the performance and rating of SVC in steady state conditions.

(c) The study will include all modes of operation specified in the specification and the worst case condition up to including first contingency outage in the networks.

(4) Deliverables

The results of this task will be the final main equipment rating and design. The definition of main-circuit components sufficient to perform overall grid stability studied will be provided (i.e., rating of individual TCS, TCR, Filters and main transformer, as applicable). The studies will include design and simulation and simulation verification.

3.3.4 EMT study

A. General

The purpose of the study task is to design and verify that the SVC control perform is required and that the equipment is adequately protected against overvoltage and over current (including valve recovery voltage)

B. Study tool
This analysis will be carried out using a fast transient digital system representation. The relevant portion of the utility system and SVC equi8pment and SVC equipment and control using a cycle-by-cycle transient program such as EMTP or PSCAD.

C. Content of study
This task will include followings:

(a) Dynamic over voltages

(b) Fault transient (1line to ground, phase-to-phase , 3 phase, across TCR and TSC)

(c) Misfiring of TCR and TSC

An insulation coordination criterion of temporary over voltage (TOV) is that the voltage should not exceed the fundamental frequency voltage for any equipment.

D. Deliverables

The result of this study task will be used to design the SVC controls and overvoltage protection and the results of the verification analysis will be presented in a detailed written report. This report will contain details of the study procedure and summary of the result verifying that the SVC perform adequately and as expected during system disturbance such as major fault and during dynamic overvoltage situation if they occur as well as identifying any switching or temporary overvoltage that may need addressed by control or protection modification.

3.4 Interview Procedures

Interview procedure is not applicable for this project…

3.5 Data Analysis Procedures

3.5.1 Calculation of nominal capacitance and inductance of reactive devices

(a) Calculation conditions

Following manufacturing tolerances was considered in the calculation of nominal capacitance and inductance.

i. Inductance of filter = +/- 1 %
ii. Inductance of TCR reactor = +/- 1 %
iii. Inductance of TSC reactor = +/- 2 %
iv. Capacitance of filter and TSC capacitors = 0/+ 1.5 %
v. Frequency tolerance
    a. Nominal frequency = 50 Hz
    b. Maximum frequency = 50.5 Hz
    c. Minimum frequency = 49.5 Hz
vi. Ambient temperature
    a. Maximum ambient temperature = 55 °C

b. Minimum ambient temperature = 2.8°C

(b) Nominal capacitive output

The SVC was designed to be capable to output continuously the specified nominal capacitive power of -200 MVAR at 0.95 pu ac bus voltage at Point A' in Figure 3-1. Since the harmonic filters and TSC determine the capacitive output at the operating point A', following manufacturing tolerances are the worst condition for the calculation of nominal capacitive power.

(a) Inductance of filter = - 1 % (minimum)
(b) Inductance of TSC reactor = - 2 % (minimum)
(c) Capacitance of filter and TSC capacitors = 0 % (minimum)

The calculation results gave following capacitance and inductance of harmonic filters and TSC to allow the output of nominal capacitive power of -200 MVAR on the worst conditions of manufacturing tolerance.

(c) Harmonic filter

Harmonic impedance analysis at 400kV substation to provide system harmonic impedance characteristics to be included in design work associated with the SVC installations The size and configuration of harmonic filters were determined from the harmonic performance study.

(d) Nominal inductive output

The TCR parameters were determined to be capable to output continuously the specified nominal inductive power of 200 MVAR at V=1.0pu ac bus voltage, considering following manufacturing tolerances.

i. Inductance of filter reactor = +1 / -1 %
ii. Capacitance of capacitors = +1.5 / 0 %
iii. Inductance of TCR reactor = +1 / -1 %

At the operating point B, TCR has to output the nominal inductive power of 200 MVAR with offsetting the capacitive output of the harmonic filters. The operating point B determines the nominal inductance of TCR reactor.

Since the inductance of TCR shall offset the capacitive power of harmonic filters, the following manufacturing tolerance of harmonic filters should be considered as the worst condition.

(a) Inductance of filter reactor = +1 % (maximum)
(b) Capacitance of capacitors = +1.5 % (maximum)
(c) Inductance of TCR reactor = +1 % (maximum)
(d) Transformer impedance = -5 % (minimum)
(e) AC power frequency = 50.5 Hz (maximum)
(f) Ambient temperature = 2.8 °C (minimum)

3.5.2 Equivalent circuit for calculation

Figure 3.3 shows an equivalent circuit for rating calculation. Calculation formula is shown in Table 3-4.

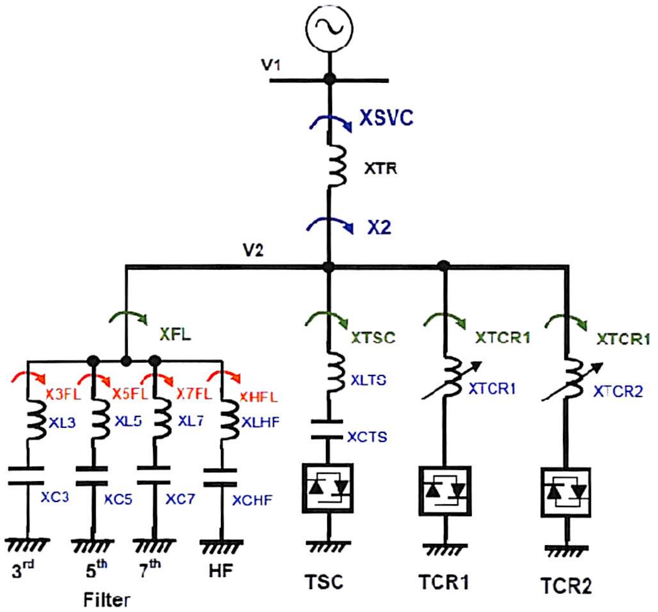


Figure 3.3 Equivalent circuit for TCR current calculation

Categories	Name of branch		Calculation formula
Reactance calculation	Harmonic filter	(a) 3rd harmonic filter reactance	X3FL=XL3+XC3
		(b) 5th harmonic filter reactance	X5FL=XL5+XC5
		(c) 7th harmonic filter reactance	X7FL=XL7+XC7
		(d) HF harmonic filter reactance	XHFL=XLHF+XCHF
		(e) Total harmonic filter reactance	XFL=1/(1/X3FL+1/X5FL+ 1/X7FL+1/XHFL)
	TSC	(a) TSC reactance	XTSC=(XLTS+XCTS)/3
	TCR	(a) TCR1 reactance	XTCR1
		(b) TCR2 reactance	XTCR2
	Total reactance on LV side	Total LV reactance	X2=1/(1/XFL+1/XTSC+1/ XTCR1+1/XTCR2)
	Transformer	Transformer reactance	XTR
	Total reactance of SVC	Total SVC reactance	XSVC=X2+XTR

Output Calculation	SVC output	SVC output reactive power	QSVC=V1^2/XSVC
	Secondary voltage	Secondary voltage of transformer	V2=(X2/XSVC)*V1
	Branch current	(a) Transformer	ITR=V1/XSVC
		(b) 3rd filter current	IF3 = V2/(X3FL×√3)
		(c) 5th filter current	IF5 = V2/(X5FL×√3)
		(d) 7th filter current	IF7 = V2/(X7FL×√3)
		(e) HF filter current	IHF = V2/(XHFL×√3)
		(f) TSC current	ITSC = V2/(XTSC× 3)
		(g) TCR1 current	ITCR1 = V2/(XTCR1×3)
		(h) TCR2 current	ITCR2 = V2/(XTCR2×3)

Table 3.3 : Formula for rating calculation

3.5.3 System Dynamic Performance Analysis

(a) General

The purpose of this study is to demonstrate and verify that the SVC control the system dynamic performance during system disturbance such a major faults (3 phase fault with normal clearing, 1 line to ground fault with delayed clearing). The design shall investigate the adequacy of the SVC to ensure stability and prevent under/over-voltage during system transient, dynamic and fault condition.

(b) Study tool

For the purpose of this study, PTI Power System Simulation for Engineers Simulation Program (PSSE/E) and shall utilize an accurate models of the SVC compatible with the PSSE/E program. The model shall accurately simulate the expected performance of the SVC for the operating scenarios to be developed and those identified.

Note: PSSE/E version 30/31 will be required for the study.

(c) Content of study

This task will include followings:

(a) Dynamic over voltages

(b) Fault transients (1LG with delayed clearing,3LG with normal clearing)

(c) Power system stability

When performing the designs, all modes of operation and the worst case system conditions upto and including first contingency outage shall be considered.

(d) Deliverables

The results of this study will be used to design the SVC controls for system dynamic performance and the results of the verification

CHAPTER: 04 FINDING AND ANALYSIS

4.1 Descriptive Statistics

From the system studies nominal capacitive output calculation are as follows.

SVC Output Calculation Sheet (Nominal Capacitive Output)

4.1.1 Power system nominal conditions and Circuit parameter conditions

V1= 0.95pu TR MVA= 210 MVA
V2nom= 19 kV %X= 16 %
F0= 50 Hz

C3= 96.3 μF
L3= 11.39 mH
C5= 172.3 μF
L5= 2.4 mH
C7= 225 μF
L7= 0.94 mH

QSVC= -200 MVAR

4.1.2 Circuit Reactance Calculation

a) 3rd filter reactance calculation **[Calculation Formula]**

XC3= -34.069 Ohm XC1=-1/(ω1*C3*KC*KTEMP) XSVC= -1.6290125 Ohm
XSVC=(V1*V2nomi)^2/QSVC
XL3= 3.507 Ohm XL1=ω1*L3*KL XTR= 0.2587 Ohm
X3FL= -30.562 Ohm X3FL=XC1+XL1 X2= -1.8877 Ohm
X2=XSVC-XTR

b) 5th filter reactance calculation

XC5= -19.042 Ohm XC5=-1/(ω1*C5*KC*KTEMP)
XL5= 0.739 Ohm XL5=ω1*L5*KL
X5FL= -18.303 Ohm X5FL=XC5+XL5

c) 7th filter reactance calculation

XC7= -14.582 Ohm XC7=-1/(ω1*C7*KC*KTEMP)
XL7= 0.289 Ohm XL7=ω1*L7*KL
X7FL= -14.292 Ohm X7FL=XC7+XL7

d) HF-filter reactance calculation

XCHF= -16.462 Ohm XCHF=-1/(ω1*CHF*KC*KTEMP)
XLHF= 0.129 Ohm XLHF=ω1*LHF*KL
XHFL= -16.333 Ohm XHFL=XCHF+XLHF

4.1.3 TSC Reactance calculation

XCTS= -3.366 Ohm XCTS=-1/(ω1*CTSC*KC*KTEMP)/3
XLTS= 0.185 Ohm XLTS=ω1*LTSC*KL/3
XTSC= -3.181 Ohm XTSC=XCTS+XLTS Xcpara=-1.876499205 Ohm

Xcpara=1/(1/X3FL+1/X5FL+1/X7FL+1/XHF+1/XTSC)

4.1.4 TCR Reactance calculation

XTCR1= 316.398 Ohm XTCR1=ω1*LTCR*KTCR*2/3 XTCR= 316.3978613 Ohm
XTCR=1/(1/X2-1/Xcpar)

SVC Output Calculation Sheet (Nominal Capacitive Output)

4
4.1.1
4.1.2
4.1.3
4.1.4

4.1.5 Power system nominal conditions and Circuit parameter conditions

V1= 1 pu TR MVA= 210 MVA
V2nom= 19 kV %X= 16 %
F0= 50 Hz
C3= 96.3 μF
L3= 11.39 mH
C5= 172.3 μF
L5= 2.4 mH
C7= 225 μF
L7= 0.94 mH

QSVC= -200 Mvar

4.1.6 Circuit Reactance Calculation

a) 3rd filter reactance calculation [Calculation Formula]

XC3= -34.069 Ohm XC1=-1/(ω1*C3*KC*KTEMP) XSVC= -1.719047619 Ohm
XSVC=(V1*V2nomi)^2/QSVC
XL3= 3.507 Ohm XL1=ω1*L3*KL XTR= 0.2587 Ohm
X3FL= -30.562 Ohm X3FL=XC1+XL1 X2= -1.9777 Ohm
X2=XSVC-XTR

b) 5th filter reactance calculation

XC5= -19.042 Ohm XC5=-1/(ω1*C5*KC*KTEMP)
XL5= 0.739 Ohm XL5=ω1*L5*KL
X5FL= -18.303 Ohm X5FL=XC5+XL5

c) 7th filter reactance calculation

XC7= -14.582 Ohm XC7=-1/(ω1*C7*KC*KTEMP)
XL7= 0.289 Ohm XL7=ω1*L7*KL
X7FL= -14.292 Ohm X7FL=XC7+XL7

d) HF-filter reactance calculation

XCHF= -16.462 Ohm XCHF=-1/(ω1*CHF*KC*KTEMP)
XLHF= 0.129 Ohm XLHF=ω1*LHF*KL
XHFL= -16.333 Ohm XHFL=XCHF+XLHF

e) TSC Reactance calculation

XCTS= -3.366 Ohm XCTS=-1/(ω1*CTSC*KC*KTEMP)/3
XLTS= 0.185 Ohm XLTS=ω1*LTSC*KL/3
XTSC= -3.181 Ohm XTSC=XCTS+XLTS
Xcpara=-1.876499205 Ohm Xcpara=1/(1/X3FL+1/X5FL+1/X7FL+1/XHF+1/XTSC)

f) TCR Reactance calculation

XTCR1= 36.661 OhmXTCR1=ω1*LTCR*KTCR*2/3
XTCR=1/(1/X2-1/Xcpar)
XTCR1=ω1*LTCR*KTCR*2/3

4.1.7 Nominal SVC Output calculations

(QSVC) min= -210.0 Mvar (QSVC)min=(0.95*V2nom)^2/(XSVC)max
ITR= -6,381 A ITR=(QSVC)min/(√3*0.95*V2nom)
V2= 21.9 kV V2=(X2)max/(XSVC)max*V2nom*V2

4.1.8 Total Reactance calculation

(X2) max= -1.888 Ohm
(X2)max=1/(1/X3FL+1/X5FL+1/X7FL+1/XHFL+0/XTSC+1/TCR1+1/TCR2)
(XTR) min= 0.2587 Ohm (XTR)min=XTR0*KTR*(Fmin/F0)
(XSVC) max= -1.629 Ohm (XSVC)max=(X2)max+(XTR)min

SVC Output Calculation Sheet (Nominal Inductive Output)

4.1.9 Power system nominal conditions and Circuit parameter conditions

V1= 1 pu
V2nom= 19 kV
F0= 50 Hz
C3= 96.3 µF
L3= 11.39 mH
C5= 172.3 µF
L5= 2.4 mH
C7= 225 µF
L7= 0.94 mH

TR MVA= 210 MVA
%X= 16 %

QSVC= 200 MVAR

4.1.10 Circuit Reactance Calculation

a) 3rd filter reactance calculation **[Calculation Formula]**

XC3= -32.215Ohm XC1=-1/(ω1*C3*KC*KTEMP) XSVC= 1.805 Ohm
XSVC=(V1*V2nomi)^2/QSVC
XL3= 3.650 Ohm XL1=ω1*L3*KL XTR= 0.2639 Ohm
X3FL= -28.565 Ohm X3FL=XC1+XL1 X2= 1.5411Ohm
X2=XSVC-XTR

b) 5th filter reactance calculation

XC5= -18.005 Ohm XC5=-1/(ω1*C5*KC*KTEMP)
XL5= 0.769 Ohm XL5=ω1*L5*KL
X5FL= -17.236 Ohm X5FL=XC5+XL5

c) 7th filter reactance calculation

XC7= -13.788 Ohm XC7=-1/(ω1*C7*KC*KTEMP)
XL7= 0.301 Ohm XL7=ω1*L7*KL
X7FL= -13.487 Ohm X7FL=XC7+XL7

d) HF-filter reactance calculation

XCHF= -15.566 Ohm XCHF=-1/(ω1*CHF*KC*KTEMP)
XLHF= 0.135 Ohm XLHF=ω1*LHF*KL
XHFL= -15.431 Ohm XHFL=XCHF+XLHF

e) TSC Reactance calculation

XCTS= -3.183 Ohm XCTS=-1/(ω1*CTSC*KC*KTEMP)/3
XLTS= 0.196 Ohm XLTS=ω1*LTSC*KL/3
XTSC= -2.986 Ohm XTSC=XCTS+XLTS
Xcpara=-4.310762181 Ohm Xcpara=1/(1/X3FL+1/X5FL+1/X7FL+1/XHF+1/XTSC)

f) TCR Reactance calculation

XTCR1= 2.207 Ohm XTCR1=ω1*LTCR*KTCR*2/3 XTCR= 316.3978613
Ohm XTCR=1/(1/X2-1/Xcpar)
XTCR2= 2.338 Ohm XTCR1=ω1*LTCR*KTCR*2/3

4.1.11 Total Reactance calculation

(X2) max= 1.541 Ohm
(X2)max=1/(1/X3FL+1/X5FL+1/X7FL+1/XHFL+0/XTSC+1/TCR1+1/TCR2)
(XTR) min= 0.2639 Ohm (XTR)min=XTR0*KTR*(Fmin/F0)
(XSVC) max= 1.805 Ohm (XSVC)max=(X2)max+(XTR)min

4.1.12 Nominal SVC Output calculations

(QSVC) min= 200.0Mvar (QSVC)min=(0.95*V2nom)^2/(XSVC)max
ITR= 6,078 A ITR=(QSVC)min/(√3*0.95*V2nom)
V2= 16.2 kV V2=(X2)max/(XSVC)max*V2nom*V2

4.1.13 TCR rating

The calculation results give following inductance for SVC to allow the output of nominal inductive power of 200 MVAR on the worst conditions of above tolerances.

Name of branch	Inductance of reactor
TCR1	2 × 10.33 mH / phase
TCR2	2 × 10.33 mH / phase

Table 4.1: Nominal inductance of TCR reactors

4.1.14 Filter Rating

The study results showed that the configuration of harmonic filters of Table 4.2 is required in order to satisfy the harmonic performance requirements, which sized the harmonic filters at capacitive power of 84 MVAR at V=0.95 pu and F=49.5 Hz.

No	Filter branch	Rating (MVAR) at V = 0.95pu	C (µF)	L (mH)	Damping resister (Ω)	Tuned freq.(Hz)
1	3rd harmonic filter	12.6	90.1	17.17		152
2	5th harmonic filter	21.0	175.4	2.40		247
3	7th harmonic filter	26.8	225.0	0.94		346

4	HF harmonic filter	23.6	199.3	0.42	5.0	550
Total		84.0				

Table 4.2 : Parameters of Harmonic filters

4.1.15 TSC Rating

Since the total capacitive output of harmonic filters becomes 84 MVAR as shown in Table 4.3, the capacitive output of TSC should be 116 MVAR at V=0.95 pu, in order to ensure the total capacitive output to be 200 MVAR at V=0.95 pu.

From above capacitive output requirements for the TSC, the parameters of TSC were determined, considering the worst tolerance conditions below

(i) Power system frequency = 49.5 Hz
(ii) Ambient temperature = 55 °C
(iii) Capacitance tolerance = 0 % (minimum)
(iv) Inductance tolerance = -2% (minimum)
(v) Transformer impedance tolerance = -5 %

The calculation results of TSC parameters are summarized in Table 4.3.

No	TSC branch	TSC branch Rating (MVAR) at V = 0.95pu	C (µF)	L (mH)	Tuned freq.(Hz)
1	TSC-1	11.6	330.1	1.44	208

Table 4.3: Parameters of TSC

Note: The tuned frequency of TSC was determined from the harmonic performance study

4.1.16 Nominal capacitive output

The nominal capacitive output of SVC at the operating point A' was calculated on the following worst tolerance conditions:

(i) Power system frequency = 49.5 Hz
(ii) Ambient temperature = 55 °C
(iii) Capacitance tolerance = 0 % (minimum)
(iv) Inductance tolerance = -1% (minimum)
(v) Transformer impedance tolerance = -5 %

The calculation results are summarized in Table 4.4.

Table 4.4 shows that the SVC can provide nominal capacitive power of 200 MVAR at V=0.95pu on the worst tolerance conditions.

Operating point	Q MVAR	V1 pu	V1 kV	V2 kV	Branch current (A)						
					3rd filter	5th filter	7th filter	HF filter	TSC	TCR 1	TCR 2
A'	-200	0.95	380	20.9	-395	-660	-845	-739	-2191	22	0

Table 4.4 Nominal capacitive output at operating point A'

4.1.17 Nominal inductive output

The calculation results of nominal output of SVC at Point B are shown in Table 4.5.

Table 4.5 shows that the SVC can provide nominal inductive power of 200 MVAR at V=1.0pu on the worst tolerance conditions with margin of control angle (Alp1 and Alp2)

Operating point	Q MVAR	V1 pu	V1 kV	V2 (kV)	Branch current (A)								
					3rd filter	5th filter	7th filter	HF filter	TSC	TCR 1	Alp 1 def	TCR 2	Alp 2 def
B	200	1	400	16.2	-330	-546	-698	-610	0	2450	90	2450	90

Table 4.5 Nominal inductive output at operating point B

Alp1: Control angle of TCR1 thyristor valve
Alp2: Control angle of TCR2 thyristor valve

4.1.18 SVC Transformer Impedances

Impedance parameters of SVC Transformer is given in Table 4.6.

Name of components	% Reactance	Remarks
Transformer	16%	210MVA base

Table 4.6 : Impedance parameters of transformer

4.1.19 Summary of selected Equipment

The ratings of the selected equipment are summarized below in Table 4.7

Name of equipment		Parameter	Remarks
TR % X		**18 %**	**200 MVA Base**
TSC	**C**	**330.1 µF**	
	L	**1.44 mH**	
3rd Filter	**C**	**90.1 µF**	
	L	**17.17 m H**	
5th Filter	**C**	**175.4 µF**	
	L	**2.4 mH**	
7th Filter	**C**	**225 µF**	
	L	**0.94 mH**	
HF Filter	**C**	**199.3 µF**	
	L	**0.42 mH**	
	R	**3.5 Ohm**	
TCR # 1		**10.33 mH**	**2*10.33 mH/Phase**
TCR # 2		**10.33 mH**	**2*10.33 mH/Phase**

Table 4.7: Summary of selected Equipment

4.2 Overall Control System

4.2.1 Outline of Overall Control System

The overall SVC control system consists of four major sub systems to provide these functions:

a. Operator workstation –OWS
b. SVC control panel- SCP
c. Thyristor valve control panel – TVC
d. Valve Base Electronic Panel –VBE

There are two sub components, which provide conventional relay protection and cooling system control.

Fig:2.2 on the following page shows a simplified one-line diagram configuration diagram of the overall control system, from the SVC main circuit to the OWS and SCADA interface through Gateways (GW).

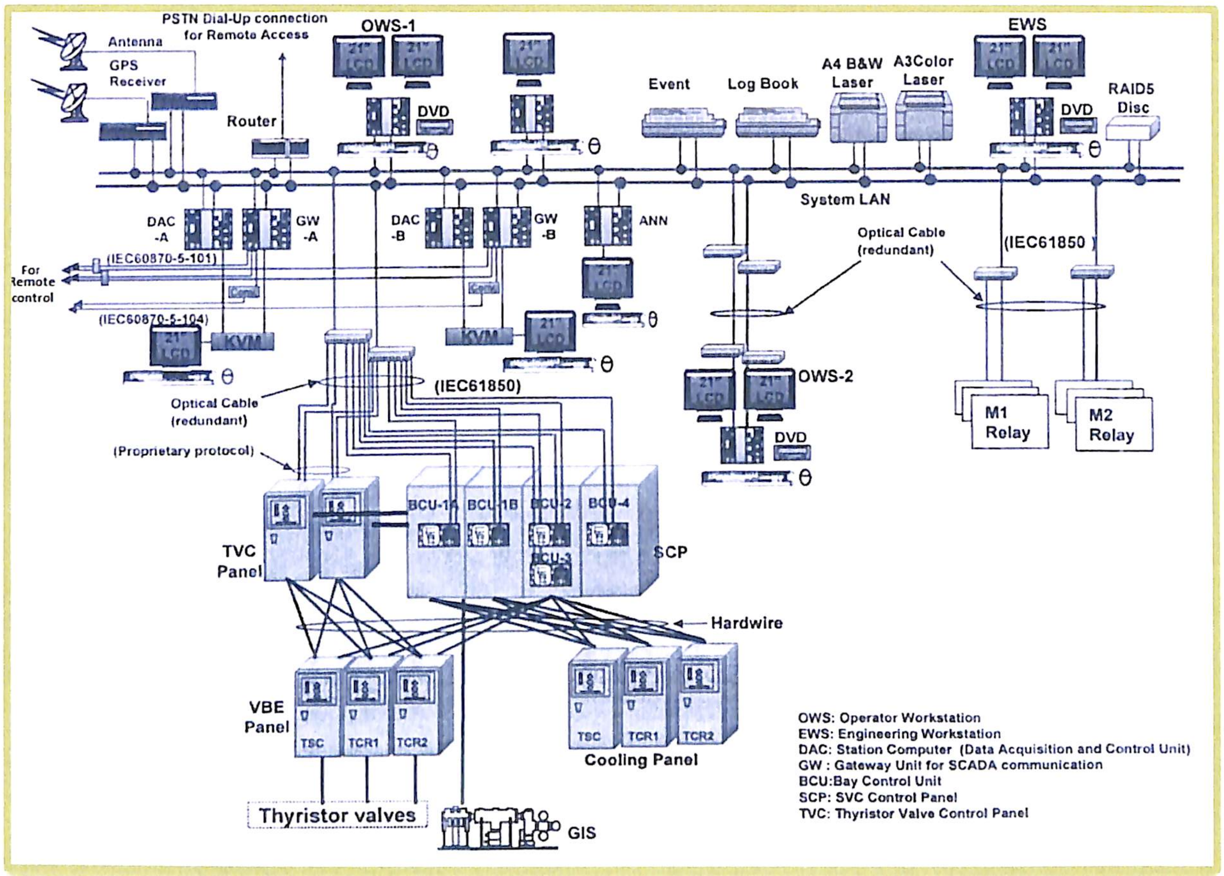


Figure 4.1: System Configuration of overall SVC control

The local OWS perform the following functions:

a. SVC system operation including SVC control parameter change
b. SVC parameter indication
c. Metering value indication
d. Monitoring SVC equipment and fault event record

SVC control level

The SVC control level consists of a SVC control panel (SCP), a Thyristor Valve panel (TVC panel) and a valve Base Electronic panel (VBE panel).

A. SVC control panel (SCP)

The SCP provides the following functions;

a. Interface between TVC panel and OWS in the SVC building. Sequence signal (voltage free auxiliary relay contact) are applied between the SCP and the TVC panel.
b. Control and operation of circuit breaker (CB) in main circuit
c. Interlock for safety of equipment and personnel
d. Sequencing and orderly startup and shutdown of the SVC equipment.

B. Thyristor Valve panel (TVC panel)

The TVC panel control and monitor the valve base electronic panels (VBE panels) to generate suitable reactive power for mitigation of power system disturbance by measuring AC quantities in the SVC system and synchronizing the system.

The TVC panel has the following control function:

a. Automatic voltage regulation (Fast voltage controller)
b. Coordinated control

Control function

Overall control function

Figure 4.2 below shows a general one-line of the SVC control system.

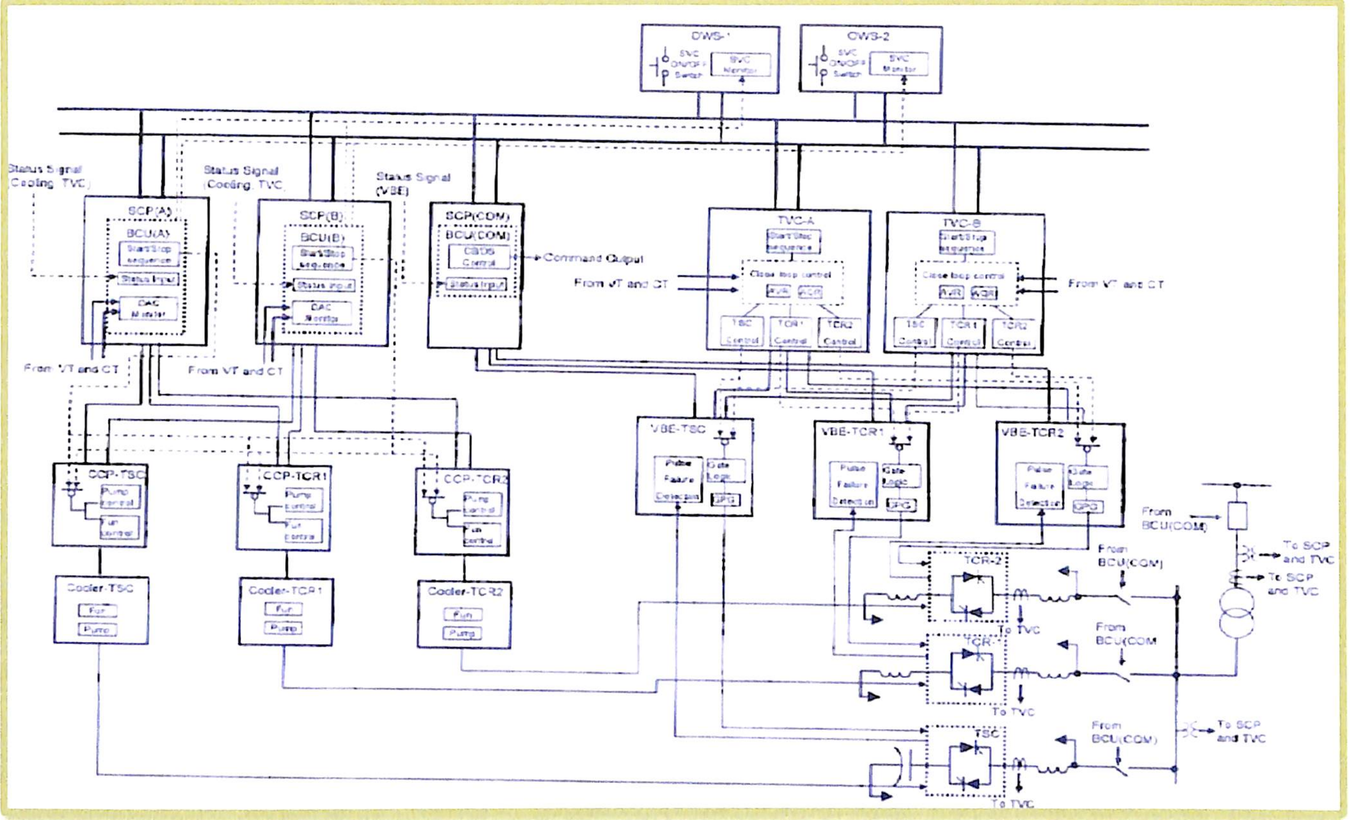


Figure 4.2: General one-line of the SVC control system

SVC control panel and OWS functions

SCP function

- Normal start sequence control
- Normal stop sequence control
- HV CB control and interlock
- DS,GS status monitoring
- SVC output current monitoring
- HV bus voltage monitoring
- MV bus voltage monitoring
- TCR-1 and TCR-2 feeder current monitoring
- TSC feeder current monitoring
- Harmonic filter current monitoring
- Protection alarm and trip monitoring
- Cooling status monitoring

OWS function

- SVC ON/OFF function
- SVC control parameter setting (Vref,slope,Qref,etc)
- SVC operation status indication
- CB,DS,GS status indication
- Voltage and current indication
- Communication to SCADA
- Time indication
- Event recorder

Thyristor valve control (TVC)

Basic control function

Figure 4.3 shows a basic SVC control block diagram.

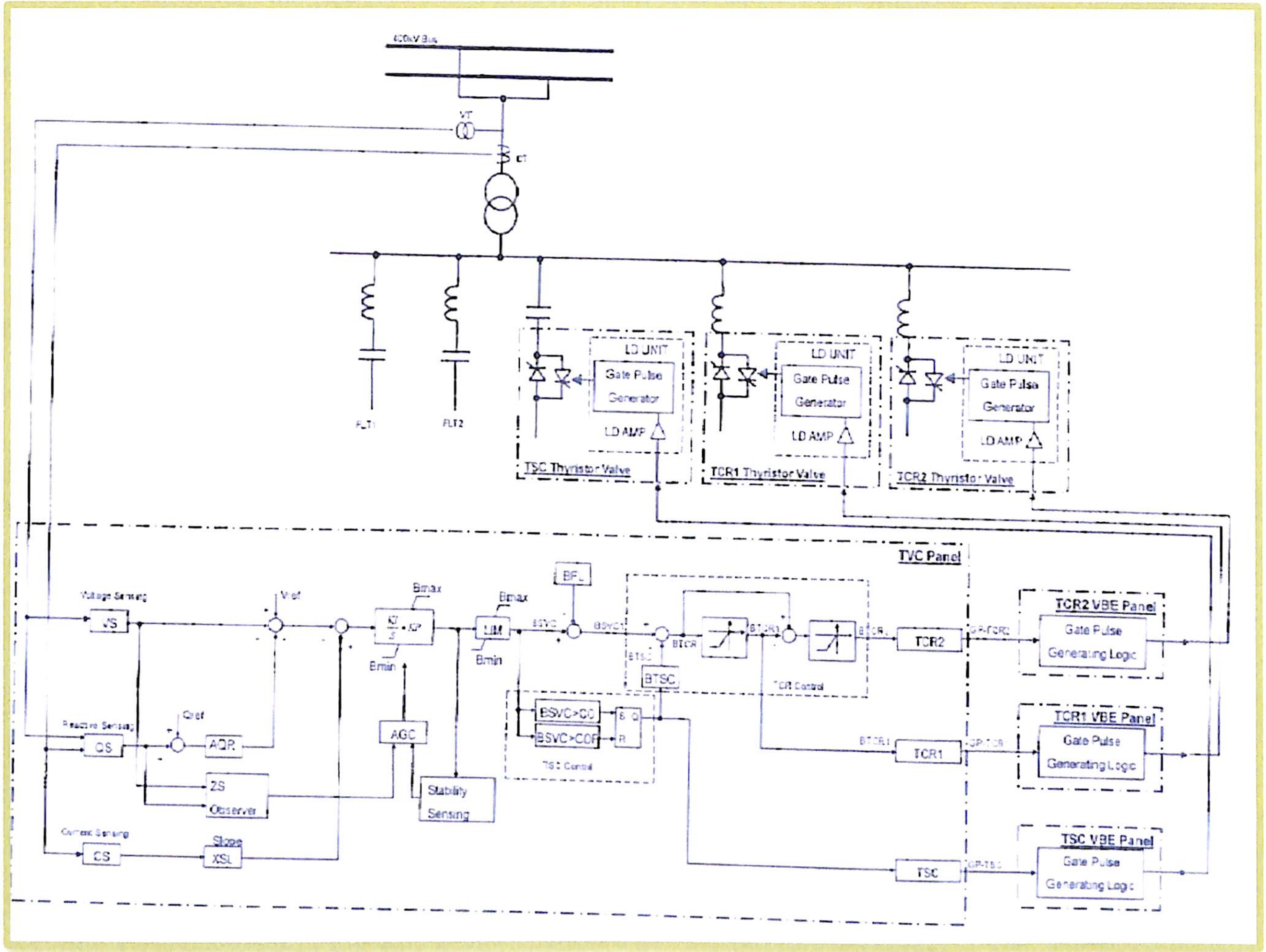


Figure 4.3: Control block diagram of SVC

In the TVC panel, following control functions are incorporated:

a. Voltage detector
   The magnitude of system voltage is measured in this function unit
b. Voltage reference control
   Voltage reference is applied to the automatic voltage regulation loop in this function unit.
c. PI controller
   PI control consists of proportional gain function (P) and integral function (I) and provides the function of feed-back control for voltage regulation.
d. Slope (SL) control
   The slope control provides the drop in the V-I characteristic of SVC control.

Valve Base Electronic (VBE)

The TVC output a gate pulse signal to the VBE panel to the VBE and the VBE rectifies it using a gate pulse generating logic and provide the gate pulse signal to a gate firing circuit incorporated in the thyristor valve.

As shown in Fig: 4.3, VBE outputs gate pulse signal to thyristor valves according to the phase control signal from TVC.

Gate firing system

Light triggered thyristor (LTT) are used for the SVC thyristor valve. Laser diodes are used for light-emitting to trigger a LTT.

The directly triggering system has the following advantages compared with indirectly triggering system for electrical triggering thyristor (ETT)

a. High reliability
b. Easy maintenance
c. Better noise immunity
d. Better operation characteristic in the under voltage condition of the power system
e. Compactness

The light emitting circuits are duplicated in order to achieve high reliability of the light triggering system shown in Fig 4.3

The light guides consist of two optical fibers and the fibers branch out into two fibers at the LD side. Each fiber is connected individual LD. Each LD has enough power to operate the thyristor valve on the either LD is available for the triggering.

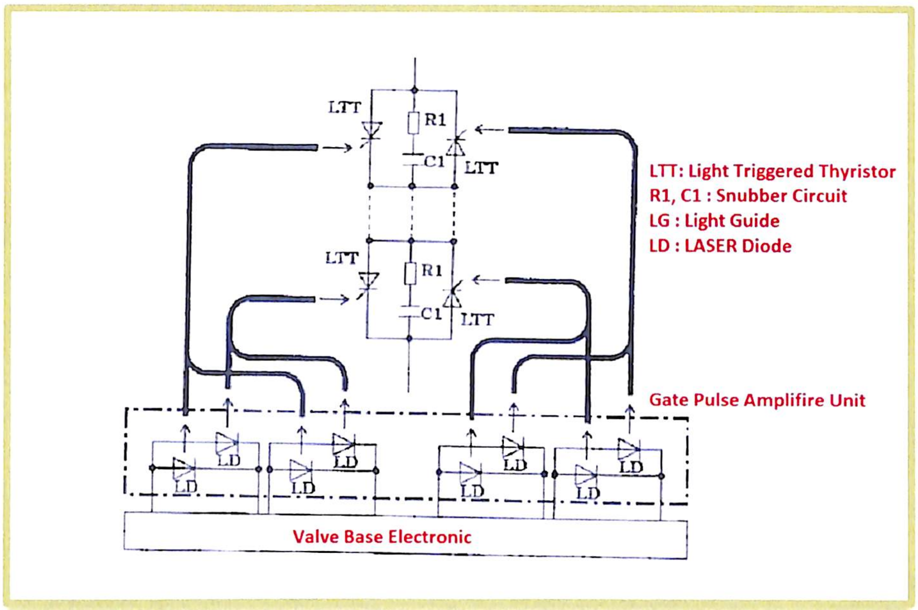


Figure 4.4: Gate firing circuit

SVC control system redundancy

The proposed SVC control system will consist of the following redundancy levels:

a) Operator workstation (OWS)
b) SVC Control Panel (SCP)
c) Thyristor Valve Control (TVC)
d) Valve Base Electronics (VBE)

OWS system description

The DAC/GW consists of redundant system, DAC (A)/GW (A) and DAC (B)/GW (B) as shown in Figure 4.5. One DAC/GW is assigned as main and other assigned as a stand by DAC/GW.

The SVC operation is implemented from the main DAC. If the main DAC fail, the failed DAC will be changed-over to the stand-by DAC automatically without any interruption of SVC operation.

SVC control panel

The SCP consists of redundant SCP panels (SCP-A and SCP-B) and a common SCP panel (SCP-COM), as shown in Fig 4.5.

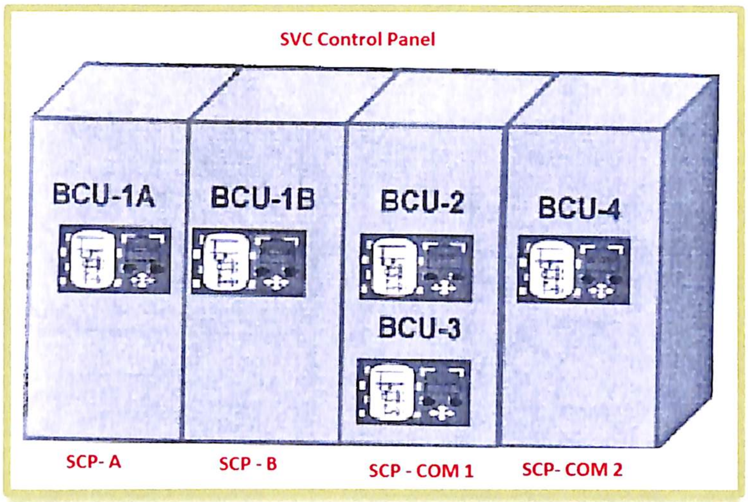


Figure 4.5: Outline of SCP

TVC (Thyristor valve control)

The TVC consists of two identical TVC panels (TVC-1 and TVC-2) that form a redundant control system. Two TVC panels (TVC-1 and TVC-2) are operated individually in normal operation. If any one of the TVC panel fails, the other TVC panel can control the SVC without any interruption. When the failed TVC becomes ready for operation, the TVC can be connected to the control system when the SVC is off.

VBE (Valve Base Electronic)

Each VBE receives two individual control signal from two TVC panels. Each VBE operated by "OR" logic of two signals from the TVC panels. If one of the TVC panel fails, the VBE is still maintained in operation by the control signal from the other TVC panel.

Though the VBE panel consists of a single system, the firing circuit and optical light guides to thyristor are duplicated as shown in Fig: 4.6.

Figure 4.6 shows a circuit diagram of VBE and gate pulse generating circuit.

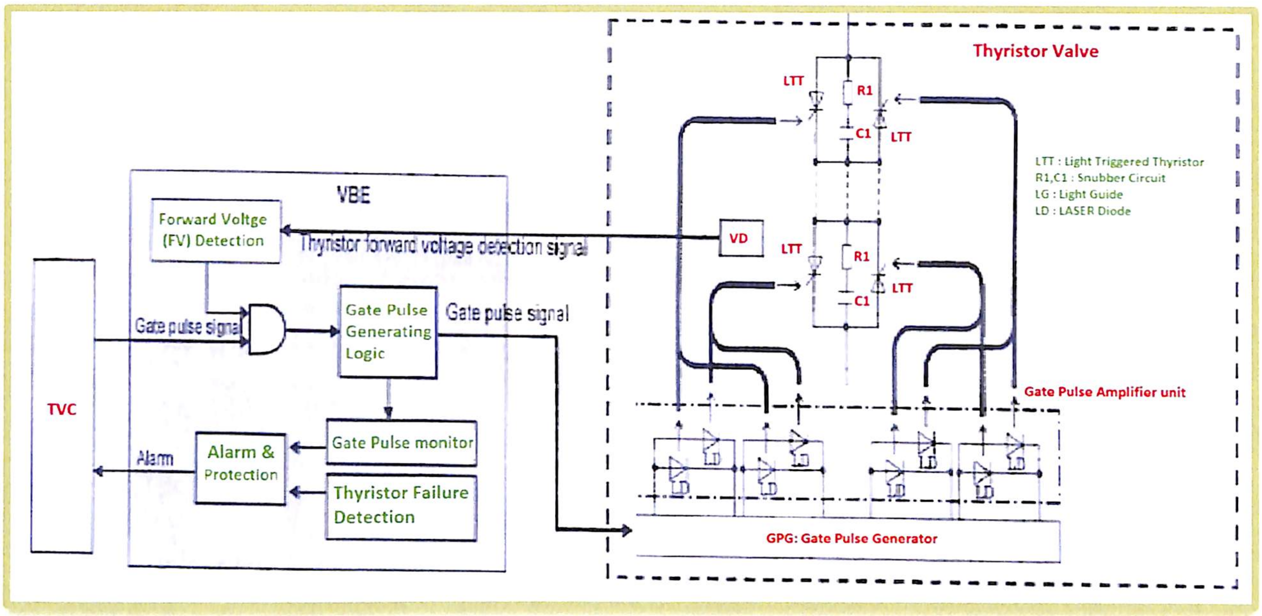


Figure 4.6: VBE and gate firing circuit diagram

4.2.2 Cooling control

TCR and TSC have individual cooling system, and each cooling system is controlled by each cooling control panel, as shown in figure 2.8

When one cooling system is in failure, SVC control system stop operation and open HV circuit breaker. Then cooling control system open the disconnecting switch of the failed branch and close the HV circuit breaker. SVC can be restarted in degraded mode operation.

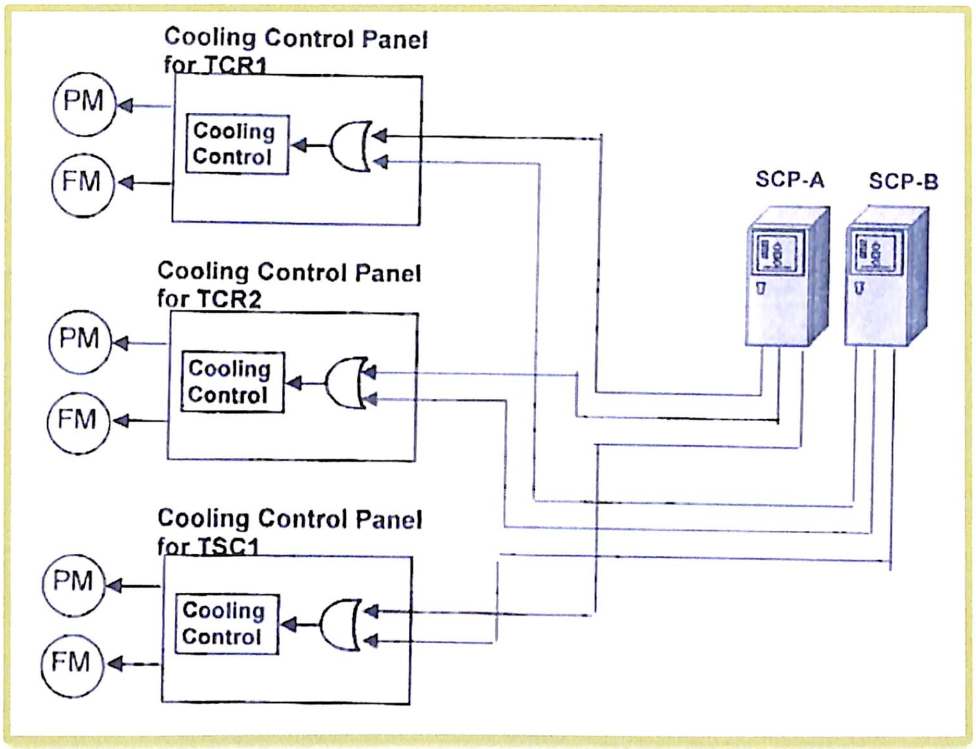


Figure 4.7: Signal flow of cooling control panel

Control

The primary SVC control block diagram incorporated in TVC is shown in Figure 2.9

Automatic voltage control

In the automatic voltage control, SVC reactive output is controlled to control the 400 kV- bus voltage in accordance with voltage reference set point (**V_{ref}**) and slope reactance set point (**X_{slope}**) both in steady state and transient state.

When the system voltage is changed by Delta- V form system-1 to system-2 as shown in Figure 4.8, a voltage sensor (VS) detects the voltage change and increase the SVC output to maintain the system voltage, resulting in the movement of the operating point from A to B as shown in Figure 4.9.

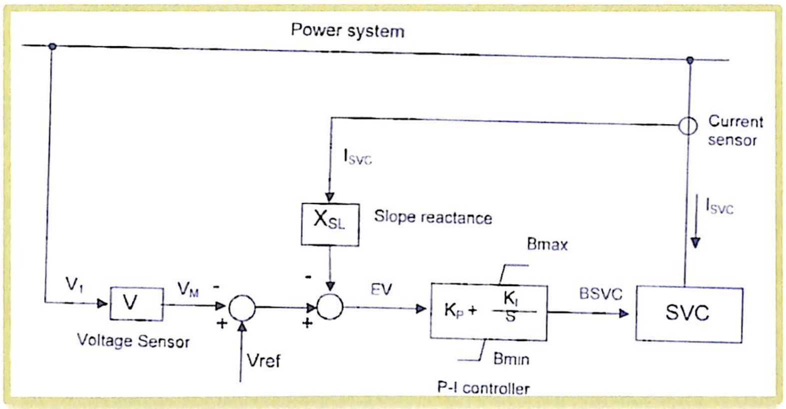


Figure 4.8: Basic AVR control block diagram

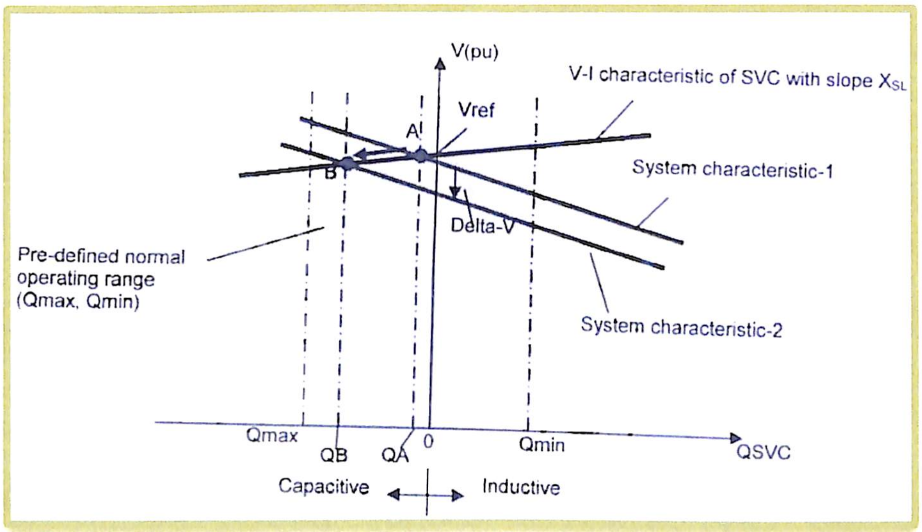


Figure 4.9: V-I characteristic of AVR control

4.3 Thyristor

4.3.1 Insulation Coordination of TCR Thyristor Valve

The number of series connection of Thyristors in TCR was determined by the following process.

.

Voltage waveforms across TCR thyristor valve

Voltage waveforms across the TCR thyristor valve are shown in Fig. 4.10 The voltage ofthyristor valve consists of following factors;

(a) AC voltage at 50Hz

The peak of AC voltage applied to the thyristor valve is same as the peak voltage on the 19kV bus. The magnitude of AC voltage is determined by the operating point of SVC.

(b) Extinction overshoot voltage

At turn-off of thyristor valve, an extinction overshoot voltage is superimposed to the AC voltage.
To limit the overshoot voltage at turn-off of thyristor, C-R snubber circuits are used in each thyristor level.

4.3.1.1 Insulation coordination of TCR thyristor valve

Fig. 3.1.2 shows insulation coordination between protection level and valve insulation level.
In Fig. 3.1.2, following parameters are introduced.
VPMAX = VACP x kc

Where, VACP: Peak of AC voltage at specified operating point
kc: Extinction overshoot factor

From Table 3.1.1, the maximum voltage at each thyristor level is calculated by the following formula. Vfmax = VPMAX x ks x kd

Where,
ks: Test safety factor from IEC 61954; 2011
kd: Voltage distribution factor

4.3.1.2 Overvoltage protection of LTT (VBO)

Each thyristor has an overvoltage protective function (Voltage Break Over function - VBO) integrated in the LTT thyristor element.
If the voltage applied to the thyristor exceeds the threshold level of VBO, the VBO provides protective firing of LTT to turn on.

4.3.1.3 Ratings of thyristor element

Ratings of thyristor element used for the TCR valve is shown in Table 3.2.
With a minimum number of 8 thyristor levels in series the TCR valves have sufficient blocking capability as shown in Table 3.1.

One redundant thyristor level is implemented; hence the total number of thyristor level is **8 + 1 = 9.**

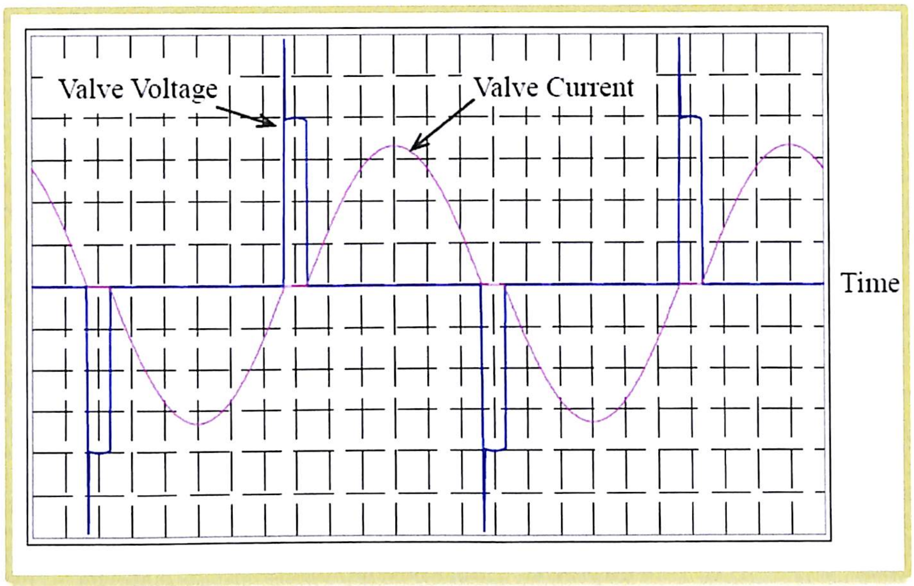


Figure 4.10: Voltage wave form across TCR thyristor valve

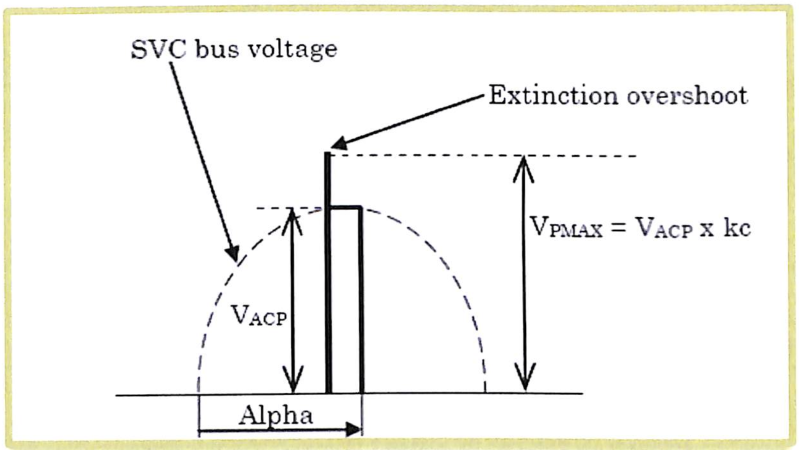
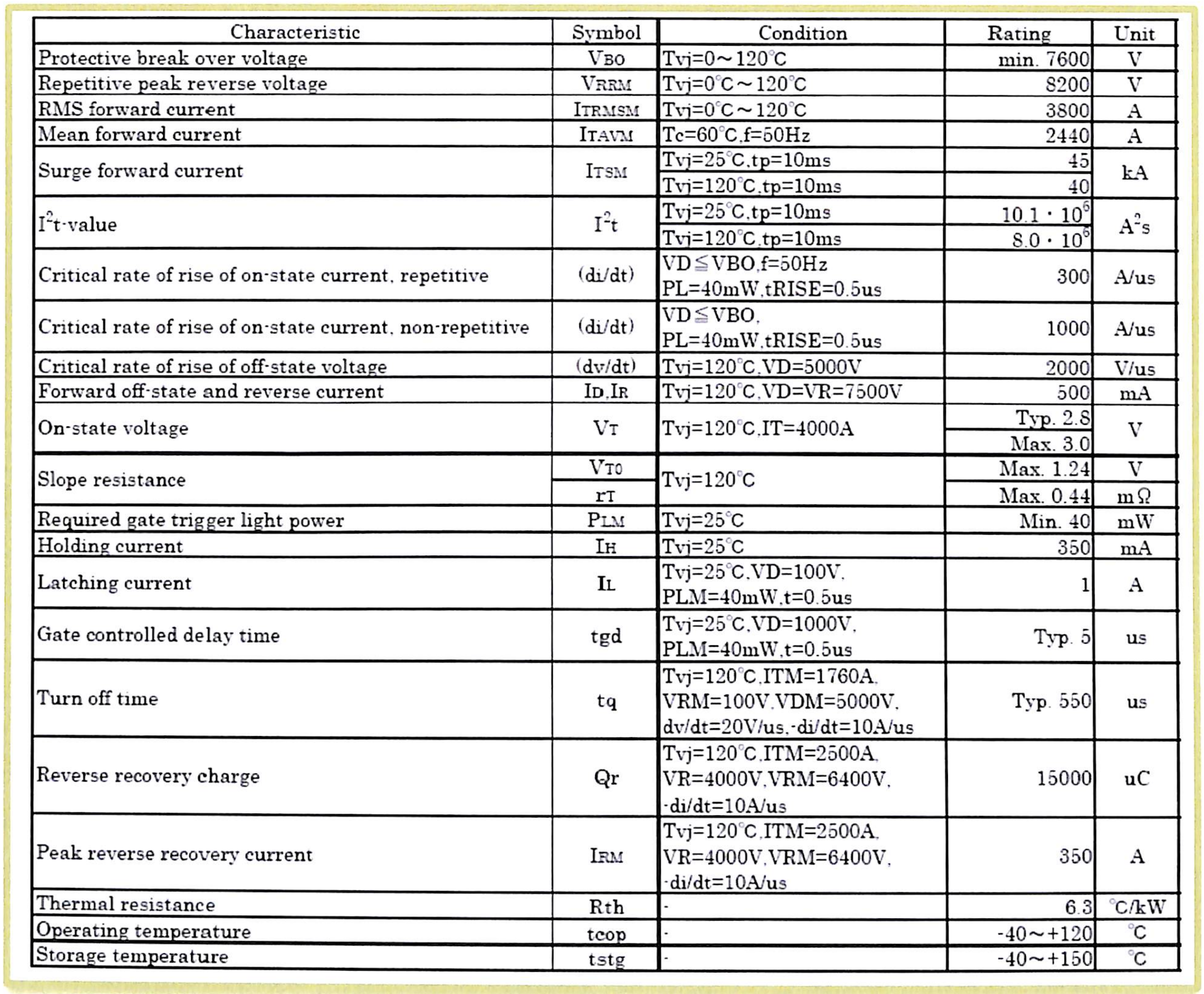


Figure 4.11: Insulation coordination of TCR thyristor valve



Characteristic	Symbol	Condition	Rating	Unit
Protective break over voltage	V_{BO}	Tvj=0～120℃	min. 7600	V
Repetitive peak reverse voltage	V_{RRM}	Tvj=0℃～120℃	8200	V
RMS forward current	I_{TRMSM}	Tvj=0℃～120℃	3800	A
Mean forward current	I_{TAVM}	Tc=60℃,f=50Hz	2440	A
Surge forward current	I_{TSM}	Tvj=25℃,tp=10ms	45	kA
		Tvj=120℃,tp=10ms	40	
I^2t-value	I^2t	Tvj=25℃,tp=10ms	$10.1 \cdot 10^6$	A^2s
		Tvj=120℃,tp=10ms	$8.0 \cdot 10^6$	
Critical rate of rise of on-state current, repetitive	(di/dt)	VD≦VBO,f=50Hz PL=40mW,tRISE=0.5us	300	A/us
Critical rate of rise of on-state current, non-repetitive	(di/dt)	VD≦VBO, PL=40mW,tRISE=0.5us	1000	A/us
Critical rate of rise of off-state voltage	(dv/dt)	Tvj=120℃,VD=5000V	2000	V/us
Forward off-state and reverse current	I_D,I_R	Tvj=120℃,VD=VR=7500V	500	mA
On-state voltage	V_T	Tvj=120℃,IT=4000A	Typ. 2.8	V
			Max. 3.0	
Slope resistance	V_{T0}	Tvj=120℃	Max. 1.24	V
	r_T		Max. 0.44	mΩ
Required gate trigger light power	P_{LM}	Tvj=25℃	Min. 40	mW
Holding current	I_H	Tvj=25℃	350	mA
Latching current	I_L	Tvj=25℃,VD=100V, PLM=40mW,t=0.5us	1	A
Gate controlled delay time	tgd	Tvj=25℃,VD=1000V, PLM=40mW,t=0.5us	Typ. 5	us
Turn off time	tq	Tvj=120℃,ITM=1760A, VRM=100V,VDM=5000V, dv/dt=20V/us,-di/dt=10A/us	Typ. 550	us
Reverse recovery charge	Qr	Tvj=120℃,ITM=2500A, VR=4000V,VRM=6400V, -di/dt=10A/us	15000	uC
Peak reverse recovery current	I_{RM}	Tvj=120℃,ITM=2500A, VR=4000V,VRM=6400V, -di/dt=10A/us	350	A
Thermal resistance	Rth	-	6.3	℃/kW
Operating temperature	tcop	-	-40～+120	℃
Storage temperature	tstg	-	-40～+150	℃

Table 4.7: Thyristor rating and characteristic

4.3.2 Insulation Coordination of TSC Thyristor Valve

The number of series connection of Thyristors in TSC was determined by the following process.

Voltage waveforms across TSC thyristor valve.

The voltage of thyristor valve consists of following factors;

(a) AC voltage at 50Hz

The peak of AC voltage applied to the thyristor valve is same as the peak voltage on the 19kV bus. The magnitude of AC voltage is determined by the operating point of SVC.

(b) DC voltage

Since the capacitor is charged at the peak of voltage at turn-off of thyristor valve, the AC voltage superimposed to the DC voltage is applied to the TSC thyristor valve.

4.3.2.1 Insulation coordination of TSC thyristor valve

Fig. 4.12 shows insulation coordination between protection level and valve insulation level.
The TSC valve is protected by metal-oxide arresters.
Therefore, thyristor series number is set to the level that thyristors never turn on at TSC off.
(In other words, VBO operation of thyristor is never worked at TSC off.)

In Fig. 4.12, following parameters are introduced.
Vac = VACP
Vdc = VACP x KDC
Where,
VACP: Peak of AC voltage at specified operating point
KDC: TSC reactor voltage factor

The maximum voltage applied to the TSC thyristor valve is determined at the event of misfiring of TSC valve at V1=1.5pu.
According to IEC standard, the misfiring shall take place at the protective level (HFV detection level).

The number of thyristors can be determined by the maximum valve voltage after the misfiring of TSC valve at V1=1.5pu.

Analysis of misfire from HFV detection level at V1=1.5pu is shown in Fig. 4.13.
HFV detection level: Vhfv = 28.0kV
Arrester protective level: Vcms = 78.0kV
Maximum valve voltage: Voff2 = 78.0kV

Thyristor valve should not turn on by VBO protection at the maximum valve voltage.
Therefore, the maximum valve voltage should be below the minimum VBO protection level.
The number of series connection of thyristors in TSC is shown in Fig. 4.12.
With a minimum number of 12 thyristor levels in series the TSC valves have sufficient blocking capability as shown in Fig. 4.13.
One redundant thyristor level is implemented; hence the total number of thyristor level is 12 + 1 = 13.

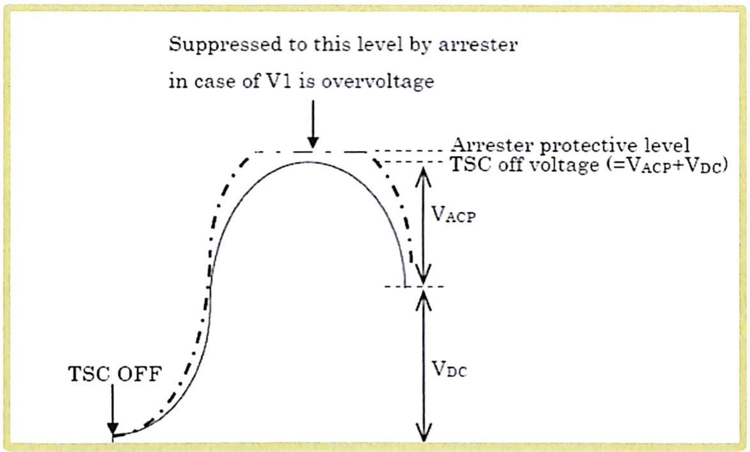


Figure 4.12: Insulation coordination of TSC Thyristor valve

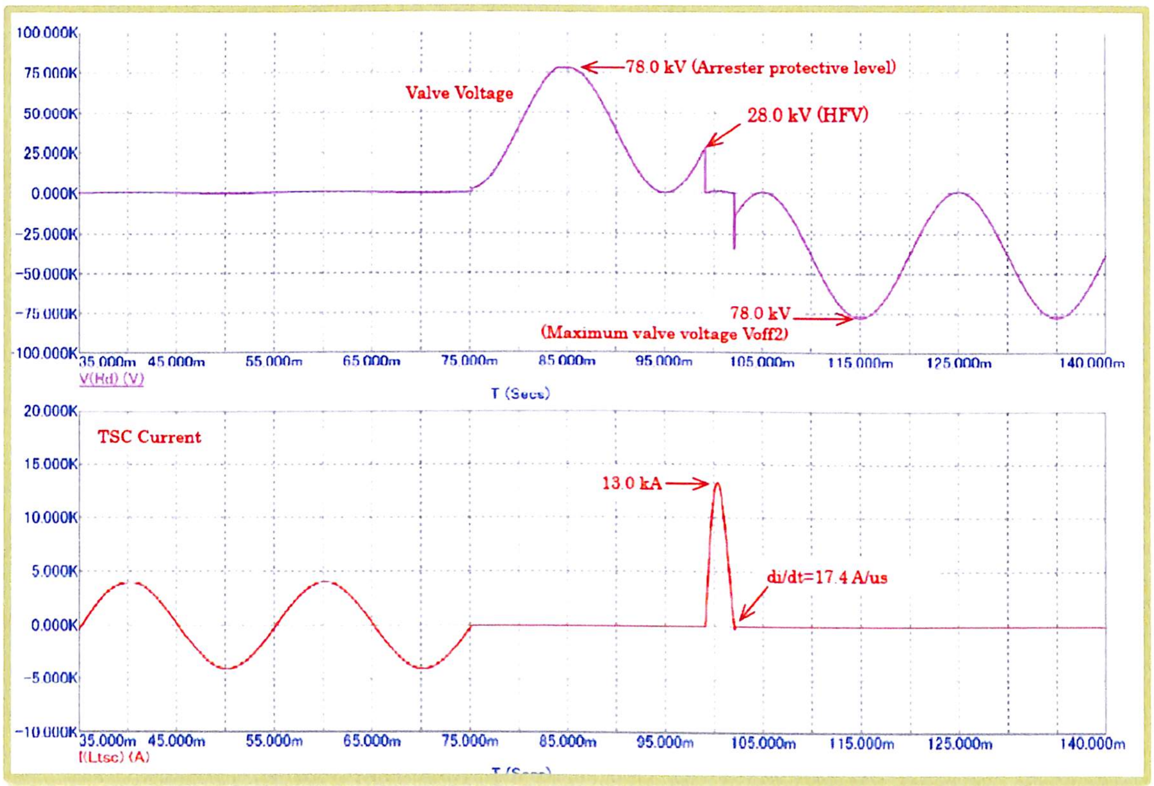


Figure 4.13:Analysis of Misfire from HFV detection level at V1 = 1.5 pu

4.3.3 Thyristor valve cooling

Cooling system in the TCR1, 2 and TSC1 thyristor valves is shown in Fig. 4.1. Cooling systems in the modules of TCR and TSC thyristor valves are shown in Figs. 4.2 and 4.3, respectively.

In the thyristor module, the main cooling path is divided into two groups from the central cooling pipe.

TCR thyristor valve: 10 cooling paths exist in parallel in one group.
TSC thyristor valve: 14 cooling paths exist in parallel in one group.

In one cooling path, one thyristor and one water cooled resistor are cooled in series.
Rating cooling water flow rate of each cooling path is 7.1 L/min in thyristor module.
The margin for flow rate has 1.1 between each cooling path and 1.05 between two cooling groups.

Furthermore, thyristor valve has three thyristor modules. The margin for flow rate has 1.05 between each thyristor modules. Therefore, rating cooling water flow rate of thyristor valves are as follows.

TCR thyristor valve

Q (group) = 7.1 L/min x 10 paths x 1.1 = 79 L/min.
Q (module) = 79 L/min x 2 groups x 1.05 = 166 L/min.
Q (valve) = 166 L/min x 3 phase x 1.05 = 530 L/min.

TSC thyristor valve

Q (group) = 7.1 L/min x 14 paths x 1.1 = 110 L/min.
Q (module) = 110 L/min x 2 groups x 1.05 = 231 L/min.
Q (valve) = 231 L/min x 3 phase x 1.05 = 730 L/min.

Total water flow rate of cooling system (TCR1 + TCR2 + TSC1)

Q (system) = 530 L/min + 530 L/min + 730 L/min = 1790 L/min.

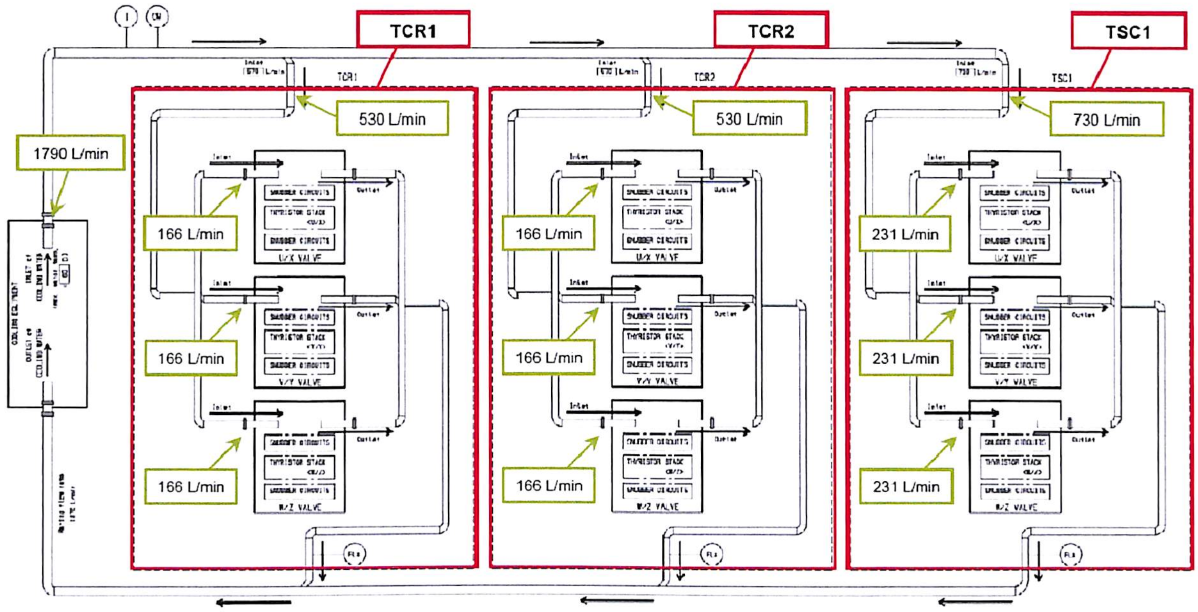


Figure 4.14: Thyristor valve cooling system

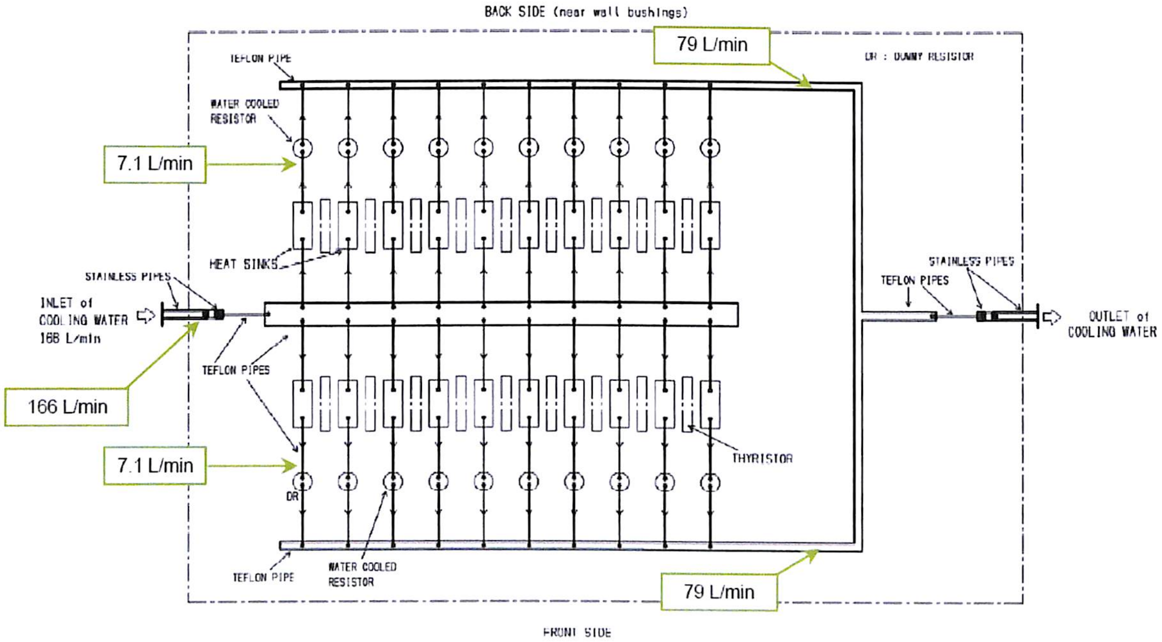


Figure 4.15: Thyristor module cooling system for TCR Thyristor valve

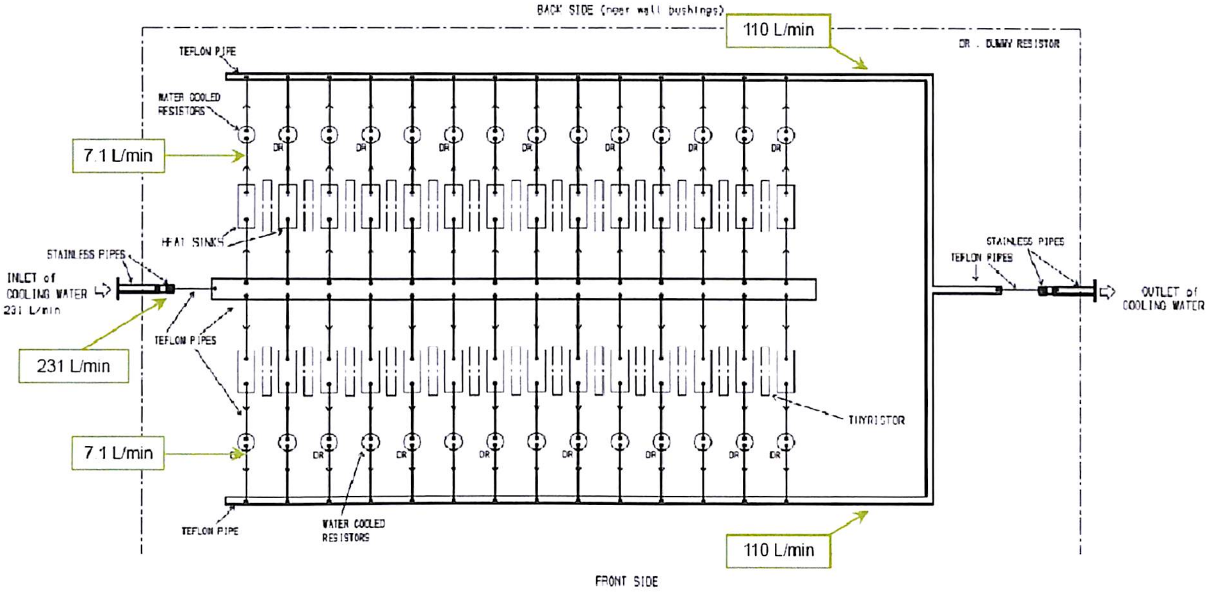


Figure 4.16: Thyristor module cooling system for TSC thyristor valve

4.4 Protective relay selection

To obtain a reliable, sensitive protection system for SVC, the relays are selected for each branch as per Table 4.1 below:

Sl.No	Equipments	CT selection detail	Protection relay
01	Transformer	Primary 1500-750/1A,Class 5P20 Secondary 6500/1A,Class PX Neutral 1500-750/1A,Class 5P20	87T1-Transformer differential 64 REF-Restricted earth fault 51N1- Stand by protection 50/51- Over current protection 50G/51G- Earth fault protection + Mechanical protection
02	TCR	5000/1A, Class PX	87-Differential protection 49-Thermal overload protection 50/51- Over current protection 50G/51G- Earth fault protection 46-negative sequence protection
03	TSC	5000/1A, Class PX	87-Differential protection 49-Thermal overload protection 50/51- Over current protection 50G/51G- Earth fault protection 46-negative sequence protection
04	Harmonic filters	2000/1A, Class PX	87-Differential protection 49-Thermal overload protection 50/51- Over current protection

			50G/51G- Earth fault protection 46-negative sequence protection
05	Auxiliary/Earthing transformer	Primary 400/1A,Class PX Secondary 2500/1A,Class PX Neutral 1500-750/1A,Class 5P20	87T1-Transformer differential 64 REF-Restricted earth fault 51N1- Stand by protection 50/51- Over current protection 50G/51G- Earth fault protection + Mechanical protection

Table 4.8 : Protection Relays selection

4.5 Earthing Transformer & Neutral Grounding Resistor

The calculation of earthing transformer and neutral grounding resistor has been performed to include the following:

i. Earth-fault short-circuits current at various locations
ii. Currents through relevant elements during earth-fault
iii. Phase voltages during earth-fault
iv. Voltage rise across relevant elements during earth-fault.

With reference to calculation results and conclusion for arrangement of 19kV neutral point earthing with earthing transformer only, additional calculation have been carried out for neutral point earthing arrangement made with earthing transformer and neutral earthing resistor.

SVC 19kV system is impedance earthed via earthing transformer. SVC transformer secondary winding is delta connected. Therefore, for all considered earth-faults zero sequence impedance at the fault location is equal only to zero-sequence impedance of the earthing transformer.
Furthermore, triple zero-sequence fault currents exist only through earthing transformer and SVC Earthing system.

With reference to conclusion made after review of calculation results for arrangement of neutral point earthing made with earthing transformer only, 19kV neutral point earthing is proposed with earthing transformer and neutral earthing resistor.

Earthing transformer and neutral earthing resistor for earthing of MV system is usually selected on such way to provide neutral point current in range 300-800A. Limitation of earth fault current is required to reduce damage of equipment which could occur when fault current have higher value.

However, in order to come closer to level of fault currents which could be detected by protection relays for fault on 19kV bus we propose specification for earthing transformer and resistor which will result with higher fault currents. Earthing transformer impedance and resistance of neutral earthing resistor is selected to satisfy as much as possible Fault level criteria.

Proposed Earthing Transformer (Z0=j10 Ohms) and NER (40/3 Ohms) will limit earth fault current at 19kV bus to level of ~1000A, level of earth fault current which could be detected by 19kV BBP relay.

Descriptive Statistics summary

Harmonic impedance analysis at 400kV substation to provide system harmonic impedance characteristics to be included in design work associated with the SVC installations.

Harmonic data was organized in the form of tables and harmonic impedance plots. Note that the effects on system harmonics of current limiting reactors, harmonic filters associated with existing or future equipment, harmonic generating loads were not considered in this analysis.

PSCAD MODEL

The PSCAD system model represents the 400kV and 132kV system. The ABC 400kV kV substation was considered the main study area for the model.

The PSCAD model was created using the PSS/E database on assumption for the year of 2013, 2014 and 2018, in conjunction with E-TRAN translation software. The following components were included in the model:

(1) Transmission Lines and Cables
(2) Transformers
(3) Reactive Devices
(4) Generators
(5) Loads
(6) Equivalent Network

RESULTS

A harmonic impedance analysis was performed at the ABC 400kV bus to provide realistic, detailed information on the system harmonic impedance characteristics to be included in the harmonic filter design work associated with the SVC installation. Harmonic data was organized in the form of tables and harmonic impedance plots.

Correlation/Regression Analyses

A harmonic impedance analysis was performed at 400kV substation to provide system harmonic impedance characteristics to be included in design work associated with the SVC installations. Harmonic data was organized in the form of tables and harmonic impedance plots.

APPROACH

The harmonic impedance of the system from 400kV bus was determined by generating the system impedance matrix for the electrical network in the phase domain. Then, the matrix was collapsed into an equivalent matrix for each frequency from 1 Hz to 2000 Hz.
The equations were solved in the phase domain itself without using sequence networks,thus giving accurate representations for unbalanced system components. The harmonic impedance data was calculated for a number of cases that were chosen to represent different system configurations during normal operating and contingency conditions, including variations in the 132kV cable systems and dispatch of shunt reactors.

Sensitivity analysis in contingency cases

Sensitivity to 400kV impedance by 132kV cable system

In order to check the sensitivity to harmonic impedance on 400kV system influenced by variation of 132kV cable system, following sensitivity analysis was performed by applying variation in 132kV cable branch numbers between 100%, 75% and 50%, as shown in Table 4.9. The F-Z characteristics of 400 kV systems are shown in Figure 4.17. As shown in Figure 4.18, influence factor by 132kV cable system to the F-Z characteristics of 400kV system is negligible small.

Table 4.10 Case list of sensitivity analysis influenced by 132 kV cable systems

S/stn	Case no of plots	CASE name (400 kV system condition)	400 kV System	132 kV cable system
400 kV Substation	**2018 D_C01_100 %**	**2018D_C01_System healthy**	**All equipment in service**	**100 % in service**
	2018 D_C01_75 %	**2018D_C01_System healthy**	**All equipment in service**	**75 % in service**
	2018 D_C01_50 %	**2018D_C01_System healthy**	**All equipment in service**	**50 % in service**
	2018 D_C09_100 %	**Line from bus 2400 to 2100 circuit 1&2 out of service**	**N-2**	**100 % in service**
	2018 D_C09_100 %	**Line from bus 2400 to 2100 circuit 1&2 out of service**	**N-2**	**75 % in service**
	2018 D_C09_100 %	**Line from bus 2400 to 2100 circuit 1&2 out of service**	**N-2**	**50 % in service**

Table 4.10 Case list of sensitivity analysis influenced by 132 kV cable systems

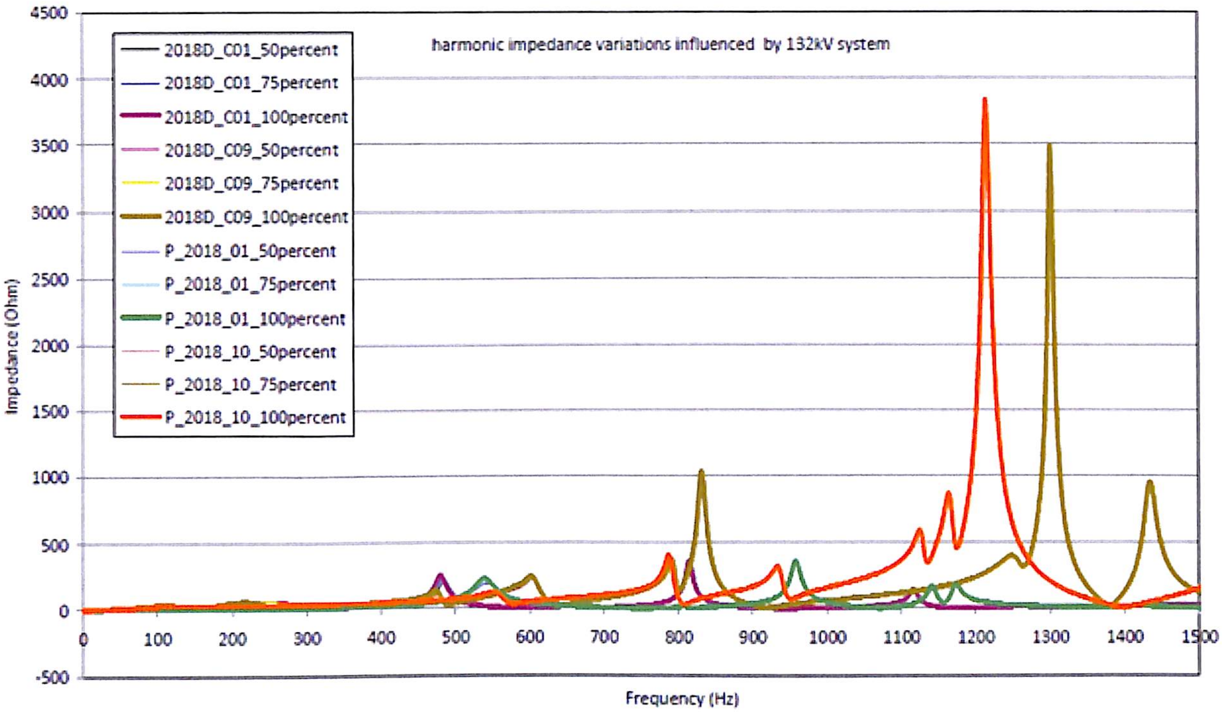


Figure 4.17: F-Z characteristics of 400kV impedance

4.3.2 Sensitivity to 400kV impedance by shunt reactors

In order to check the sensitivity to harmonic impedance on 400kV system influenced byvariation of shunt reactors, following sensitivity analysis was performed by applying variationin 400kV and 132kV shunt reactors as shown in Table 4.10.

The F-Z characteristics of 400 kV systems are shown in Figure 4-2.As shown in Figure 4.17, influence factor by shunt reactors to the F-Z characteristics of400kV system is negligible small.

S/stn	Case no of plots	CASE name (400 kV system condition)	Shunt reactors
400 kV Substation	**2014_C01_SH0**	**2014_CD01_ system healthy**	
	2014_C01_SH0	**2014_CD01_ system healthy**	**400 kV 120 MVARSh-reactor out of service**
	2014_C01_SH0	**2014_CD01_ system healthy**	**132 kV 80 MVARSh-reactor out of service**

Table 4.11 Case list of sensitivity analysis influenced by shunt reactors

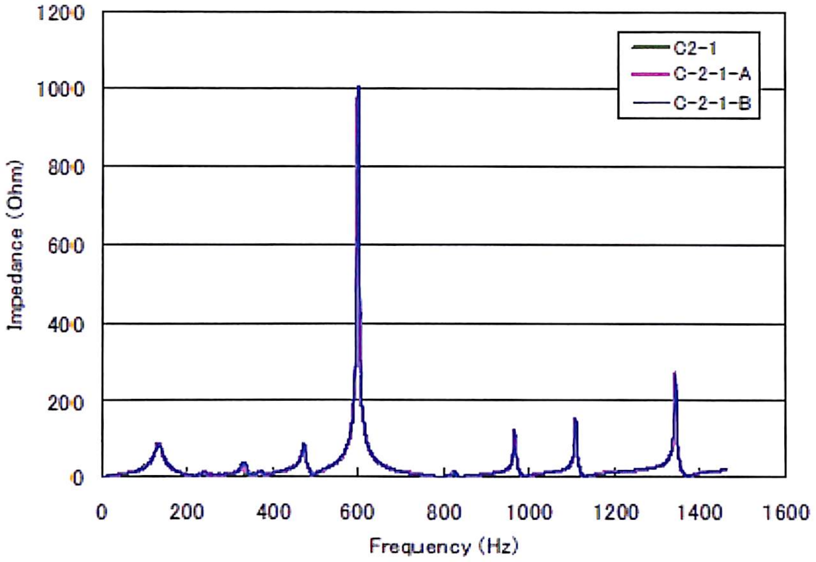


Figure 4.18: F-Z characteristics of 400kV impedance with shunt reactors

CHAPTER: 05 INTERPRETATION OF RESULTS

5.1 and 5.2 Interpretation of Results& comparison of Results with assumption.

S.NO	Test category	Check point	Criteria	Results
01	Normal start sequence	Check 400 kV circuit breaker closed and normal operation sequence is stared and completed	SVC to be energized according to the normal start sequence. After closing of CB, the LDS1 &LDS2 will be closed in series, after closing of LDS1; the TCR-1 will be compensating the filters.	√
02	Normal stop sequence	Check 400 kV circuit breaker tripped for stopping for SVC. the normal stop operation sequence is completed	SVC to be de-energized according to the normal stop sequence. Reactive power limit are reduced to 0 MVAR. After SVC output of 0 MVAR, the CB is opened.	√
03	V/Q characteristic with normal slope	V/Q curve	Within linear control range curve to be liner with slope	√
04	Step response with minimum slope at medium short circuit	SVC output performance	SVC operation will not be unstable	√
05	Step response with maximum slope at medium short circuit	SVC output performance	SVC operation will not be unstable	√
06	TCR current limitation	The TCR current will be limited to the set valve of current limiter	TCR current limit function to limit the TCR current the limiter reference	√
07	TCR over current protection	When protection stop-1 is provided,CB is tripper and then the sequence for protection stop-1 is proceed as follows 1. To make the thyristor valve gate blocked immediately.	When over current by misfiring is detected. SVC is stopped by protection stop-1 sequence.	√
08	Sinusoidal frequency variation in VCM (50.4 Hz & 49.6)	SVC output performance	SVC continues working normally and stably.	√
09	Frequency protection control	The performance of frequency protection	SVC will be tripped	√
10	TCS on/off control discharged capacitor	TSC switching operation	TSC to be operate normally without hunting operation.	√
11	Under voltage control strategy	TCR switching performance	The TCR is blocked and de-blocked at the designed primary voltage levels and no instability occurs.	√

12	Over voltage control stategy	SVC control performance during over voltage condition	TSC to be blocked when the overvoltage is detected. TCR to maintain in control	√
13	Load switching off	SVC performance at the load switching	SVC working stable at switching and the SVC output is changed when the all the load of SVC station is switched off.	√
14	Load switching off	SVC performance at the load switching	SVC working stable at switching and the SVC output is changed when the all the load of SVC station is switched on.	√
15	Local fault (3 phase to earth fault)	To verity the transient performance of SVC	SVC to be operated at the system fault. TSC will be lock as UV strategy when the primary voltage is low.	√
16	Local fault (3 phase to earth fault)- future load condition	To verity the transient performance of SVC	SVC to be operated at the system fault. TSC will be lock as UV strategy when the primary voltage is low.	√

Table 5.1: Interpretation of Results & comparison of Results with assumption

CHAPTER: 06Conclusion and scope of Future Work

6.1 Conclusions

It is concluded that SVC (Static VAR Compensator) will successfully control the dynamic performance of power system and voltage regulation of the power system. Using the SVC in the network is more efficient in stabilizing the power system during severe contingencies.

The following benefits are there in the Transmission System:

a. SVC system will provide fast acting continuously controlled reactive power to the 400kV system

b. SVC system will enhance voltage stability margin of Transmission system against under voltage and over voltage conditions following major disturbances in the system since this is required due to the fast developing of large district cooling and chiller plants and anticipated penetration of more efficient Air Conditioning technologies based on inverter driven motors.

   SVC system will ensure dynamic voltage stability under post fault conditions

c. Under steady state conditions the SVCs will provide continuous voltage support by providing + 200 to -200MVAR, as required, when the AVR mode of operation is selected.

d. Under steady state conditions the SVCs will provide the required VAR support (either capacitive or inductive as required upto 200MVAR) when operated under AQR mode. When operating under AQR mode, if the system voltage is going beyond set limits, the SVC will automatically change to AVR mode and will provide MVAR support as required to bring back the voltage to normal.

e. SVCs will provide voltage support to the transmission network when it is being restored under a black start condition.

6.2 Future scope of works

The SVC installed is providing benefits to the system. Hence system studies are to be further conducted and additional SVC s shall be installed. From the studies it was noticed that the installations of SVCs in 132kV system will be more beneficial. Accordingly, the new SVCs shall be installed in 132kV substations. State-of- the-art technology of STATCOMs are recommended to be installed

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Appendix: interviewer Script