DESIGN, IMPLEMENTATION AND ENGINEERING ASPECTS OF 12-PULSE TCR BASED SVC SYSTEMS FOR VOLTAGE REGULATION

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DESIGN, IMPLEMENTATION AND ENGINEERING ASPECTS OF 12-PULSE TCR BASED SVC SYSTEMS FOR VOLTAGE REGULATION

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ABSTRACT

DESIGN, IMPLEMENTATION AND ENGINEERING ASPECTS OF 12-PULSE TCR BASED SVC SYSTEMS FOR VOLTAGE REGULATION

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Thyristor controlled reactor (TCR) based static VAr compensator (SVC) systems has various types with unique characteristics. Considering power system requirements, suitable compensator type should be chosen. In this thesis work, 12-pulse TCR based voltage regulation type SVC system is analyzed, simulated and implemented. Principles of operation, strong and weak points are discussed. The developed system has been implemented in order to solve voltage regulation problem in Dhurma (Saudi Arabia). According to the requirements, power stage and control system is designed. Overall system is composed of two similar compensator systems each having a rated power of 1.5 MVAr (3 MVAr in total). Different types of control algorithms are examined in order to get the optimized solution in terms of power quality issues such as power system losses and harmonics. Power system at the corresponding area and the compensator is simulated using EMTDC/PSCAD program. Field test results are also obtained and compared with simulation results.

Key words: 12-pulse TCR, SVC, Voltage regulation, Power quality

ÖZ

12 DARBELİ TİRİSTÖR KONTROLLÜ REAKTÖR TABANLI REAKTİF GÜÇ KOMPANZASYONU SİSTEMLERİNİN GERİLİM REGÜLASYONU İÇİN TASARIM, UYGULAMA VE MÜHENDİSLİK YÖNLERİ

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Tiristör kontrollü reaktör (TKR) tabanlı statik reaktif güç kompanzasyonu (SVK) sistemleri çok çeşitli türlere ve karakteristiklere sahiptir. Şebekenin özgül ihtiyaçları göz önünde bulundurularak uygun kompanzatör tipi seçilmelidir. Bu tez çalışmasında, 12 darbeli TKR tabanlı gerilim regülasyonu modundaki reaktif güç kompanzasyonu sisteminin analizi, simülasyonu ve saha uygulaması yapılmıştır. Bununla birlikte sistemin çalışma prensibi, güçlü ve zayıf yanları tartışılmıştır. Tasarlanan sistem gerilim seviyesinde yaşanan problemlerin çözümü amacıyla Dhurma (Suudi Arabistan) bölgesine kurulmuştur. İhtiyaçlar dahilinde, güç katı ve kontrol sistemi dizayn edilmiştir. Tüm sistem her biri 1.5 MVAr gücünde iki adet benzer kompanzasyon sisteminden oluşmaktadır. Güç kalitesi bakımından (aktif güç kayıpları, akım harmonikleri vs.) optimum çözüme ulaşmak amacıyla çeşitli kontrol algoritmaları geliştirilmiş ve test edilmiştir. Sistemin bağlandığı şebeke ve kompanzasyon sistemi EMTDC/PSCAD programı kullanılarak benzetme çalışmaları yapılmıştır. Saha test sonuçları toplanarak simülasyon sonuçları ile karşılaştırılmıştır.

Anahtar kelimeler: 12 darbeli TKR, SVK, Gerilim regülasyonu, Güç kalitesi

To my family…

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ABBREVIATIONS

AN	Air natural cooling
AF	Air forced cooling
CSC	Current source converter
CT	Current transformer
DSP	Digital signal processor
FACTS	Flexible AC transmission systems
FC	Fixed capacitor
GTO	Gate turn-off thyristor
HF	Harmonic filter
IGBT	Insulated gate bipolar transistor
IGCT	Integrated gate-commutated thyristor
LV	Low voltage
MCR	Magnetically controlled reactor
MV	Medium voltage
ONAN	Oil natural air natural cooling
ONAF	Oil natural air forced cooling
PCC	Point of common coupling
PI	Proportional and integral
PLC	Programmable logic controller
PLL	Phase locked loop
PT	Potential transformer
SEC	Saudi Electricity Company
STATCOM	Static synchronous compensator
SVC	Static VAr compensator
TCR	Thyristor controlled reactor
TDD	Total demand distortion

TSC	Thyristor switched capacitor
TSR	Thyristor switched reactor
VSC	Voltage source converter

NOMENCLATURE

α	Gating delay angle
σ	Conduction angle
φ_l	Power factor angle
B_l	Load susceptance
B_L	TCR susceptance
G_l	Load conductance
I_c	Compensator current
I_{dc}	DC component of the current
I_h	RMS value of h^{th} current harmonic for odd harmonics
I_l	Load current as phasor
I_s	Source current as phasor
I_n	RMS value of n^{th} current harmonic for even harmonics
I_q	Reactive component of the current
P_c	Active power of the compensator
P_l	Active power of the load
R_s	Resistance of the source
S_c	Apparent power of the compensator
S_l	Apparent power of the load
Q_c	Reactive power of the compensator
Q_l	Reactive power of the load
X_C	Impedance of reactors in the fundamental frequency
X_L	Impedance of capacitors in the fundamental frequency
V_i	Voltage at the input of converter
V_T	Terminal voltage
V_{dc}	DC component of the voltage
X_s	Reactance of the source

$\mathbf{Y_c}$	Compensator admittance
$\mathbf{Y_l}$	Load admittance
$\mathbf{Z_s}$	Source impedance

CHAPTER 1

INTRODUCTION

1.1 Historical Background of SVC Systems

The usage of AC type of transmission instead of dc started at the end of 19th century. At first, voltage levels were low and the areas to which electricity is supplied were very limited. However, voltage levels have increased and transmission/distribution systems have become more and more complicated. Parallel to these, stability of synchronous machines in synchronism and maintaining the bus voltages near to their rated values have become more compelling objectives. Implementation of reactive power compensators was considered as the solution to these problems in addition to controlling the network and increasing the transmittable power.

Nowadays, implementation of reactive power (VAr) compensators is a well-established technique [1]. At the beginning of 20th century, basic fixed quantity VAr compensators were implemented to improve the steady-state characteristics of the power system. Switched reactors and/or capacitors were used as shunt connected devices to consume/generate reactive power. Then in 1931, the necessity for a dynamic controllable reactive power compensation system was recognized with Friedlander’s shunt connected saturated reactor [2]. Rotating machines (for example, synchronous condensers) are the first dynamic reactive power compensation devices. Then, at the middle of 1960’s, first static VAr compensation (SVC) devices were implemented. These were thyristor switched capacitors (TSC) and thyristor controlled reactors (TCR). Series and parallel combination of all these devices were used to implement more complicated systems according to specific requirements and provided a base for Flexible AC Transmission Systems (FACTS). GTO (Gate turn-off thyristor), IGCT (Integrated gate-commutated thyristor), IGBT (Insulated gate bipolar transistor) technologies made the use of better current and voltage source converters possible. Nowadays, there are thousands of SVC's in-service all over the world and their number is increasing day by day. Likewise, although the technology in this subject has come to a certain point, there are still lots of points requiring improvements and topics worth to research.

1.2 TCR Based SVC Systems

Importance of reactive power control has increased because of several reasons. First of all, the requirement for improving the efficiency of power systems is getting more and more important due to the increase in electricity generation costs. Losses can be decreased significantly if reactive power flow throughout the system is minimized. Secondly, power systems are getting larger because of the industrialization, growth in population etc. This situation basically results in stability problems and electricity disruptions. Having a highly qualified supply is the greatest solution for those problems.

A static VAr compensator (SVC) is a high voltage, flexible AC transmission systems (FACTS) device that has ability of controlling the network voltage at its coupling point dynamically. SVC systems can succeed on continuous adjustment of reactive power it exchanges with the power system. Constant voltage property is the first requirement in dynamic shunt compensation and is equally important in reducing flicker and other voltage fluctuations caused by variable loads. Speed of the response is another important property. Reactive power of the compensator should be able to react quickly to even small changes in terminal voltage [1]. Main control features for an SVC system can be categorized as;

- Voltage regulation
- Reactive power compensation
- Damping power oscillations
- Flicker reduction
- Unbalance reduction
- Harmonic and inter-harmonic current filtering

TCR based SVC operation is investigated thoroughly in Chapter 2. An example of TCR based SVC system installed in Al-Hassat / Saudi Arabia by TUBITAK power electronics group is represented in Figure 1.1.

Figure 1.1: *SVC system installed in Al-Hassat / Saudi Arabia by TUBİTAK power electronics group*

1.3 Other SVC Types

Types of SVC systems other than TCR can be classified in mainly five groups:

1.3.1 Saturated Reactor:

The saturated reactor can be considered as a transformer with a special design that goes to saturation at a predetermined operating point. It is also known as magnetically controlled reactor (MCR). Iron cores of such a reactor have the characteristics of high permeability in the unsaturated region, sharp knee, and low permeability in the saturated region and low hysteresis loop[3]. Corresponding characteristics are shown in Figure 1.2 below.

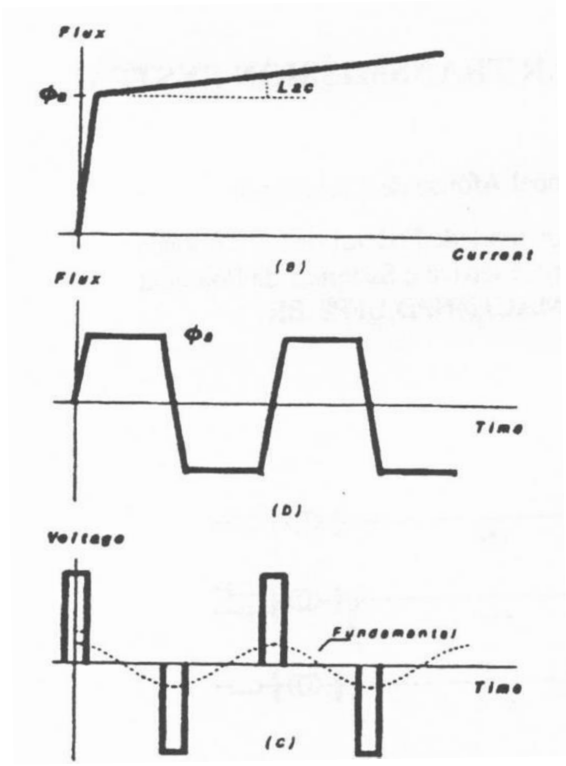


Figure 1.2: *Core characteristics of saturated reactor [3]*

1.3.2 Thyristor Switched Reactor (TSR)

Thyristor switched reactor is a very basic form of TCR in which reactors are in either full conduction, or no-conduction. In other words, system is working according to on/off principles. Thus, reactive power is controlled in a stepwise manner and it is not much flexible. However, if the load also has stepwise changing characteristics, or if it changes slowly then this simple solution can be useful.

1.3.3 Thyristor Switched Capacitor (TSC)

Thyristor switched capacitor is a variable susceptance in a stepwise manner. The structure consists of a combination of parallel connected capacitors; thyristors connected inversely parallel, and a reactance as shown in Figure 1.3. For each of three phases, the structure seen in the figure is connected parallel to form a combination of capacitor groups. This results in stepwise controllable capacitive reactive power.

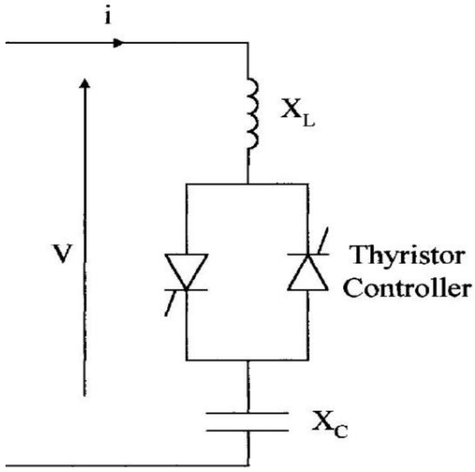


Figure 1.3: *Thyristor switched capacitor*

Reactors connected in series with the TSC capacitors are used not only to damp the inrush currents but they also limit the switching transients. Moreover, reactors and capacitors form a harmonic filter to filter out the harmonic currents arising from power system itself or any other shunt connected system.

Three phase thyristor switched capacitors can be connected in delta or Y forms. However, delta connection is usually preferred due to its better harmonic performance. In delta-connected structures 3^{rd} harmonic component of current is not injected to the power system; instead, it circulates inside delta.

1.3.4 Synchronous Condenser

Synchronous condensers have been connected at sub-transmission and transmission voltage levels in order to improve stability and maintain voltages within desired limits under varying load conditions and contingency situations [5,6]. When compared to capacitor banks, their advantage of being able to increase their output voltage even in reduced voltage situations gave them an important role in voltage and reactive power control.

Synchronous condenser is basically a synchronous machine which is kept unloaded while its excitation is under control. The structure is represented in Figure 1.4. When the machine is over-excited, it generates reactive power. On the other hand, if it is under-excited, it absorbs reactive power.

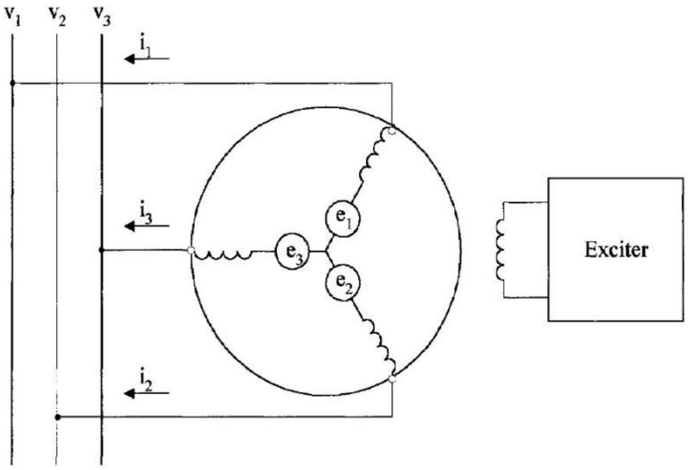


Figure 1.4: *Synchronous condenser*

1.3.5 Static Synchronous Condenser (STATCOM)

STATCOM is a shunt connected SVC system for which output voltage magnitude and phase angle can be adjusted independent from the mains voltage. Therefore, STATCOM can be used as a source or sink of the reactive power. STATCOM systems can be voltage source (VSC) or current source (CSC) type. Figure 1.5 represents both types of STATCOM systems [4]. On the other hand, in Figure 1.6, principal diagram for a voltage source converter type STATCOM is presented.

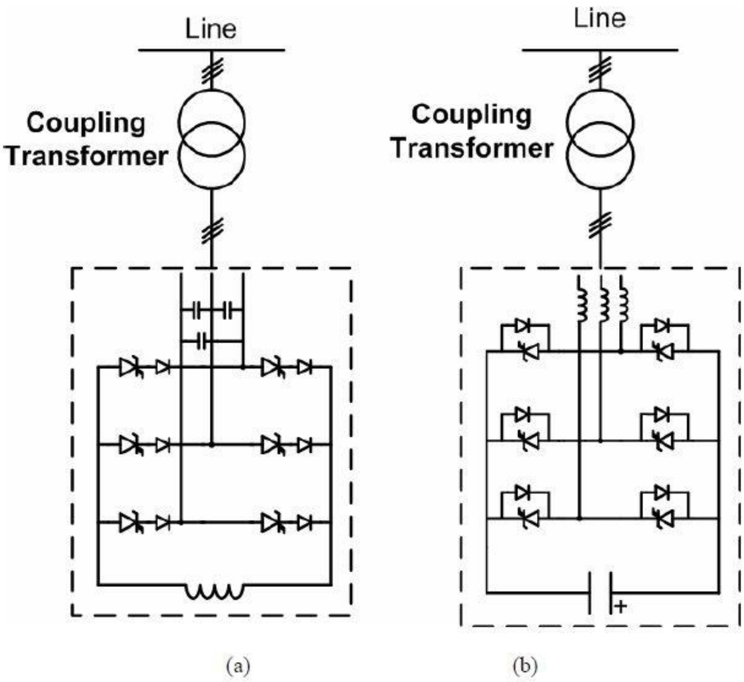


Figure 1.5: *STATCOM based on (a) Current source converter (CSC) and (b) Voltage source converter (VSC) [4]*

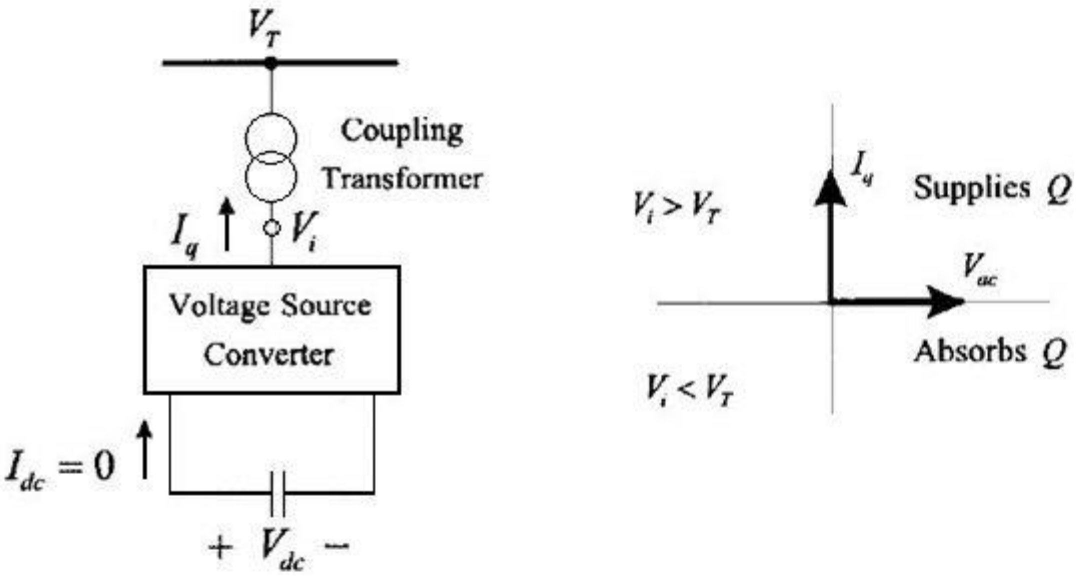


Figure 1.6: *VSC type STATCOM and its vector diagram*

To sum up, as in [1], SVC types other than TCR based SVC can be tabulated according to their strong and weak points like in Table 1.1;

Table 1.1: *Comparison of SVC systems other than TCR*

SVC Type	Advantages	Disadvantages
Saturated Reactor	• Very rugged construction • Large overload capability • No effect on fault level • Low harmonics	• Essentially fixed in value • Performance sensitive to location • Noisy
Thyristor Switched Reactor (TSR)	• Simple in control	• Un-flexible reactive power control
Thyristor Switched Capacitor (TSC)	• Can be rapidly repaired after failures • No harmonics	• No inherent absorbing capability to limit over-voltages • Complex bus-work and controls • Low frequency resonances with the system • Performance sensitive to location
Synchronous Condenser	• Has useful overload capability • Fully controllable • Low harmonics	• High maintenance requirement • Slow control response • Performance sensitive to location and requires strong foundations
STATCOM	• Performance insensitive to mains voltage • Fast response	• Typically higher losses • Cost more money

1.4 Scope of the Thesis

In this research work, a 12-pulse thyristor controlled reactor based static VAr compensator topology for medium voltage applications has been designed, implemented and commissioned. Regarding the "Collaboration and Technology Transfer Project For Static VAr Compensation (SVC) Systems Product And Service Agreement" signed on 1.6.2011 between TUBITAK UZAY and King Abdullaziz City for Science and Technology (KACST), a 3 MVAr SVC system is installed in Dhurma in Saudi Arabia. The control system is mainly designed for voltage regulation. However, other power quality concepts such as harmonic content and power losses are also taken into account and optimized. Independent and parallel (master-slave) mode of operations are defined and examined one by one. As a subsection of parallel operation, two different control methods are investigated. For all these scenarios, simulation results are obtained and analyzed. Simulation results and laboratory tests are followed by field work. In order to solve the voltage regulation problem in Dhurma / Saudi Arabia, designed system is applied and field results are collected. Field results are compared with simulation results and laboratory tests so that necessary comments are made to discuss about similarities and/or errors between all those results.

Designed 12-pulse SVC system is composed of two parallel-connected 6 - pulse structure. TCR for each system is composed of series combination of two back-to-back connected thyristors and their reactors. TCR power capacity is 1.5 MVAr per system. Both systems have coupling transformer and harmonic filters. Coupling transformers are 1.6 / 2 MVA and 33kV/1kV in their power capacity and voltage transform ratio respectively. One of the transformers is "YNyn0" and the other is "Dyn11" in terms of coupling structure. Harmonic filters are the same for each system and are tuned to eliminate 3^{rd}, 4^{th} and 5^{th} harmonics. Although 5^{th} harmonic is cancelled with the successive operation of 12-pulse algorithm, systems are designed to operate independently as well. Thus, 5^{th} harmonic filter is included. On the other hand, for current position of SVC, 4^{th} harmonic current may be generated if there is an unbalance between positive and negative firings during dynamic operation. Moreover; in future it is possible that systems may be relocated in another location with new impedance and load characteristics that may require 4^{th} harmonic filter.

This is why 4th harmonic filter is included. Power rating of harmonic filters is 500kVAr each. Systems are designed to be inside containers except their coupling transformers and heat exchanger for water cooling.

This research work has made the following contributions to the area of TCR based SVC systems:

- The SVC implementation within the scope of this thesis is the first 12 pulse SVC in the literature which is specifically designed for voltage regulation in the medium voltage level.
- Various control strategies for 12-pulse TCR based SVC were investigated. Their strengths and weaknesses are analyzed.
- A design criteria for 12-pulse TCR based SVC based on analysis, simulation work and laboratory test results is generated.
- The data collected through field tests are compared with the theoretical values and simulation results.

Design and implementation process is completed by TUBITAK power electronics team in collaboration with KACST (Saudi Arabia) engineering team. In this work, responsibilities and contributions of the author are:

- Simulation of the existing network in order to determine the nominal power of SVC systems;
- Design of all low voltage panels (control panel, protection and measurement panel, auxiliary systems panel) using "EPLAN Electric P8" panel design software;
- Development of control philosophy regarding to the voltage regulation and harmonic suppression;
- Selection of equipment (36kV and 1kV circuit breakers, current and voltage transformers, protection relays, panel equipment etc.);
- Development of protection algorithm and protection coordination between two systems;
- Field measurements and analysis of the results.

The outline of the thesis is given below:

In chapter 2, operation principles of TCR based SVC systems is defined. Circuit structure is described and then different types of configurations are investigated. Mathematical expressions are also given to clarify the way system works. Then, main objectives namely, reactive power compensation and voltage regulation are explained. After introducing preliminary information about six-pulse operation, twelve-pulse operation is presented. Circuit diagrams, expressions and figures provide information about this type of operation. Explanation of other implementation types concludes the chapter.

Chapter 3 is the structural design section about desired 12-pulse TCR based SVC systems. Information about power system components is supplied in this part. First of all, characteristics of Saudi Arabia Electricity system are provided. Then, the design criteria about main parts such as TCR, coupling transformer and harmonic filters are presented. Finally, protection logic is explained.

In Chapter 4, 12-pulse operation is analyzed in terms of control strategies namely, independent operation and parallel operation (master-slave). Having concentrated on the master-slave operation, different control algorithms are discussed. Harmonic cancellation, sequential load sharing and asymmetrical load sharing types of controls are simulated and their results are compered in terms of not only voltage regulation capabilities but also harmonic performances and power losses.

Chapter 5 is reserved for field work and actual results. In this chapter, installation and commissioning process are explained in detail. Applications of different types of control strategies which are explained before in Chapter 4 are applied, and corresponding results are shown. Moreover, simulation and field results are compared, similarities and differences are discussed.

Finally, in Chapter 6, the study is briefly summarized in terms of both theoretical and practical work. General conclusions and proposals for future work are given.

CHAPTER II

TCR BASED SVC OPERATION

2.1 TCR Based SVC Working Principles:

TCR circuit is basically composed of two thyristors and a reactor. Oppositely poled thyristors conduct current on alternate half-cycles. Current on the reactor is lagging the voltage by nearly 90 degrees. An elementary thyristor controlled reactor circuit is shown in Figure 2.1.

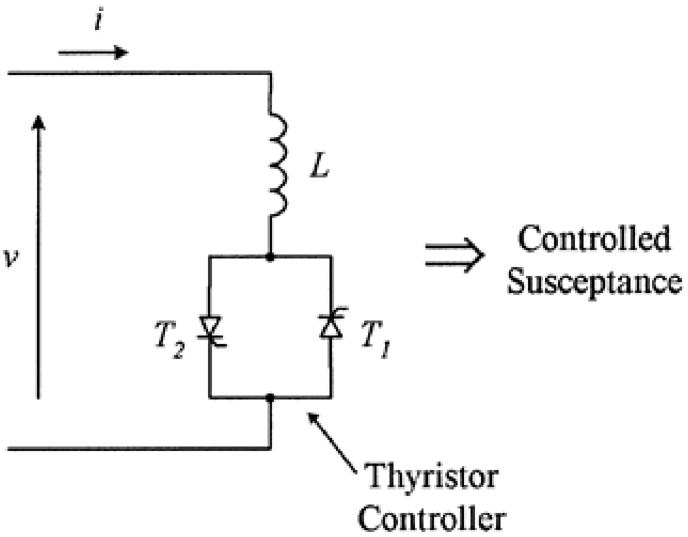


Figure 2.1: *Thyristor controlled reactor*

TCR based SVC is a controlled shunt susceptance whose reactive power is controlled according to current requirement in an electric system. Susceptance control is realized by adjusting the conduction angle of thyristors. Ideal current (I) – voltage (V) characteristics of an SVC is given in Figure 2.2.

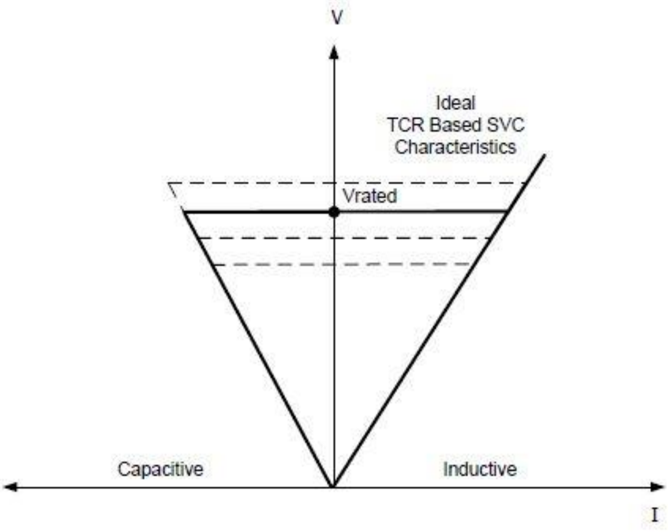


Figure 2.2: *Ideal I-V characteristics of an SVC*

Instantaneous current "i" and fundamental component of it is given by equations (2.1) and (2.2) [1],

$$i = \begin{cases} \dfrac{\sqrt{2}V}{X_L}(\cos\alpha - \cos wt), & \alpha < wt < \alpha + \sigma \\ 0 \qquad\qquad\qquad\qquad , & \alpha + \sigma < wt < \alpha + \pi \end{cases} \qquad [2.1]$$

$$I_1 = \frac{\sigma - \sin\sigma}{\pi X_L} V \qquad [2.2]$$

where "V" is the rms voltage ; "X_L = wL" is the fundamental frequency reactance of the reactor (in Ohms) , "w=2pi*f" , "α" is the gating delay angle, "σ" is the conduction angle. Gating delay angle and conduction angle has the relation,

$$\alpha + \sigma / 2 = \pi \qquad [2.3]$$

Considering equation (2.2), the circuit can be considered as having a variable susceptance with the value of

$$B_L(\sigma) = \frac{\sigma - \sin\sigma}{\pi X_L} \quad [2.4]$$

According to the needs of the application SVC can be connected to the grid terminals either directly or via coupling transformer. The point of common coupling (PCC) can be the overhead line or a transformer substation, which depends on the location. Several connection types are described in Table 2.1 and can be seen in Fig 2.3 [8].

SVC system can be a combination of FC/TCR (fixed capacitor as harmonic filter/ thyristor controlled reactor) or TSC/TCR (thyristor switched capacitor/ thyristor controlled reactor). Generally FC/TCR is preferred for easiness of control.

SVC systems can be in one of two different connection types, namely Δ connected or Y connected. The main differences between those connection types are current and voltage ratings of circuit elements, and harmonic characteristics. In Y connection, voltage on the reactors and thyristors are "$1/\sqrt{3}$"times smaller when compared to Δ connection. However, the current passing through these elements is greater with the same amount of multiplication factor. On the other hand, in balanced systems where the TCR's are connected in Δ, there will be no triple harmonics injected into the power system since triple harmonics flow within the Δ [9]. Therefore, TCR systems are generally connected in Δ.

Table 2.1: *TCR based SVC types*

Description	Figure	Typical Compensation Applications
Y connected TCR without filters connected via coupling transformer	Fig 2.3.a	Public transportation systems in which long underground cables generate nearly constant capacitive VArs while the converters demand fluctuating VArs
Delta connected TCR without filters connected via coupling transformer	Fig 2.3.b	
TCR connected to MV bus where 2nd,3rd, 4th, 5th and high frequency harmonic filters are installed	Fig 2.3.c	Feasible for arc and ladle furnace installations
TCR connected to MV bus where 2nd,3rd, 4th and 5th harmonic filters are installed	Fig 2.3.d	
TCR connected to MV bus where 3rd, 4th and 5th harmonic filters are installed	Fig 2.3.e	
TCR connected to MV bus / Overhead line where 5th and 7th harmonic filters are installed	Fig 2.3.f	Suitable for 6-pulse motor drives
TCR connected to MV bus / Overhead line where 5th, 7th and 11th harmonic filters are installed	Fig 2.3.g	Dominant 12-pulse motor drives, variable frequency motor drives, rolling mill, compressor, fan drives
TCR is coupled to the MV system via transformer, filters are at the MV side	Fig 2.3.h	Suitable for modern industrial motor drives which produce current harmonics
TCR is coupled to the MV system via transformer. Some filters are connected parallel to TCR, some filters are at the MV side	Fig 2.3.i	Conventional motor drives with rapidly varying reactive power consumption. PCC may be equipped with a detuned filter.
TCR and HF are coupled to the HV/MV system via transformer	Fig 2.3.j	Conventional motor drives connected to harmonic free bus

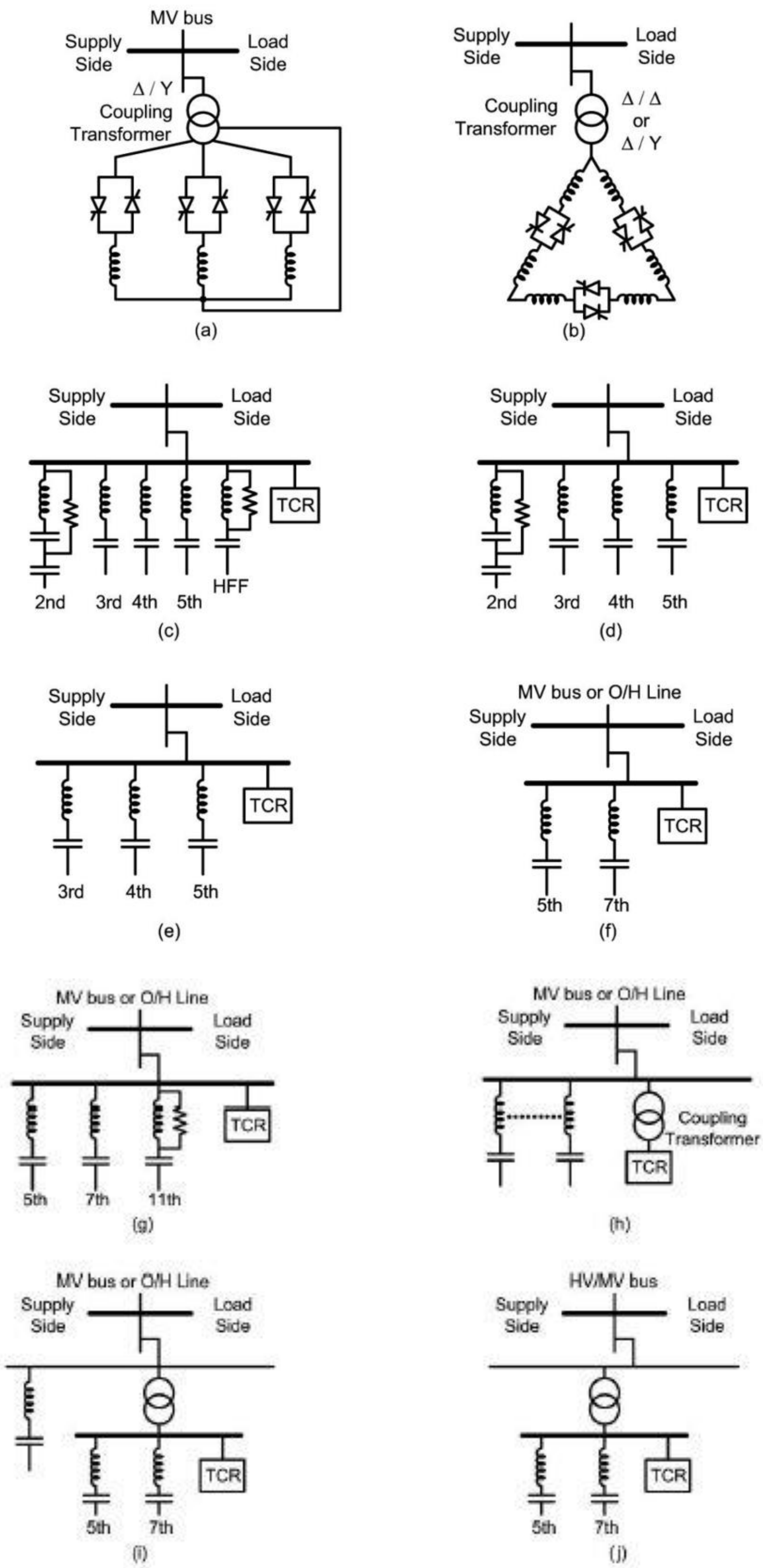


Figure 2.3: *SVC connection types [5]*

2.1.1 Current Harmonics and Filtering:

In balanced operation, TCR current harmonics are determined by the firing angle. For full conduction (meaning thyristors behave like diodes) TCR current is sinusoidal. However, as long as the firing angles are increased (conduction angle is decreased) current waveforms get further away from sinusoidal shape and harmonic content increases. When firing angles are symmetrical, only odd harmonics are generated. Magnitudes of these harmonic currents (in rms) can be calculated using equation 2.5. Magnitudes as the percentage of fundamental current are also given in Table 2.2. As it was mentioned earlier, triple harmonics do not penetrate into the line, instead they circulate in Δ.

$$I_n = \frac{4}{\pi}\frac{V}{X_L}[\frac{\sin(n+1)\alpha}{2(n+1)} + \frac{\sin(n-1)\alpha}{2(n-1)} - \cos\alpha\frac{\sin n\alpha}{n}] \qquad n = 3,5,7... \qquad [2.5]$$

Maximum values of these harmonics for balanced operation are given in Table 2.2. On the other hand, in case of a problem in firing cycle, firing angles of thyristors may be unmatched. These unequal conduction angles would produce even harmonic components in the current, including dc. Moreover, thyristors are heated up unequally since current passing through the back-to-back connected thyristors will be different in such a case. As mentioned earlier, TCR has two thyristors for controlling the reactance for positive and negative half-cycles of the voltage. Hence, the current passing through reactor can be considered as the superposition of two components;

$$I = I_1 + I_2 \qquad [2.6]$$

$$I_1 = G_1 V \quad for \quad V > 0 \qquad [2.7]$$

$$I_2 = G_2 V \quad for \quad V < 0 \qquad [2.8]$$

where G_1 and G_2 to represent susceptances. Assuming positive half cycle susceptance is bigger than negative half cycle susceptance,

$$G_1 > G_2 \qquad [2.9]$$

Table 2.2: *Maximum Amplitudes of Harmonic Currents in TCR for balanced operation*

Harmonic Order	Percentage
1	100
3	(13,78)
5	5,05
7	2,59
9	(1,57)
11	1,05
13	0,75
15	(0,57)
17	0,44
19	0,35
21	(0,29)
23	0,24
25	0,2
27	(0,17)
29	0,15
31	0,13
33	(0,12)
35	0,1
37	0,09

In this case resultant current can be written as,

$$I = V\sqrt{2}\left\{\frac{G_1+G_2}{2}\sin wt + \frac{G_1-G_2}{\pi}\left[1-2\sum_{h=2,4,6...}\frac{\sin(hwt)}{h^2-1}\right]\right\} \quad [2.10]$$

Equation 2.10 shows that current passing through thyristors has even harmonic components when G_1 and G_2 are not equal. The situation gets worse as the difference between susceptances gets bigger. In the worst condition occurs when one of the susceptances has the biggest value (with the highest conduction angle) and the other has the smallest value (with the highest firing angle). In this case one of the susceptances is zero while the other is "G". For that case, harmonic and dc components of the current are,

$$I_h = \frac{V 2\sqrt{2} G \sin(hwt)}{\pi h^2 - 1} \qquad h = 2,4,6... \tag{2.11}$$

$$I_{dc} = \frac{V\sqrt{2}G}{\pi} \tag{2.12}$$

Harmonic components have undesired effects on power system. As mentioned in [10], main effects of voltage and current harmonics within the power system are:

- As the results of series and parallel resonances, possible amplification of harmonic current levels,
- Reduced efficiency of the generation, transmission and utilization of electric energy,
- Ageing of the insulation of electric power components with consequent shortening of their useful life,
- Malfunctioning of system or plant components.

Therefore, harmonic components should be filtered as much as possible for power quality purposes. In order to assure this point, there are strict regulations about maximum value of harmonic levels. According to "IEEE STD 519-1992", current distortion limits for voltages from 120V to 69kV is given below (see Table 2.3). Moreover, "AS/NZS 61000.3.6:2001 Standard" defines critical values for voltage harmonics as given in Table 2.4. These are the standards used in Saudi Arabia.

Table 2.3: *Current distortion limits up to 69kV in distribution systems (IEEE STD 519-1992)*

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	11≤h<17	<17≤h<23	<23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.						
*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.						

where

I_{sc} = maximum short circuit current at PCC.

I_L = maximum demand load current (fundamental frequency component) at PCC.

Table 2.4: *Compatibility levels for harmonic voltage (in percent of the nominal voltage) in LV and MV power systems (AS/NZS 61000.3.6:2001)*

Odd Harmonics non multiple of 3		Odd Harmonics non multiple of 3		Even Harmonics	
Order h	Harmonic voltage %	Order h	Harmonic voltage %	Order h	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0.5
13	3	21	0.2	8	0.5
17	2	>21	0.2	10	0.5
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
>25	0.2 + 1.3 (25/h)				
Note: Total harmonic distortion (THD) 8 %					

To sum up, harmonics are hazardous for power network and regulations force customers to keep their harmonic components below some limits. The methods to reduce or eliminate harmonics can be classified as follows:

(i) To reduce harmonics in an inverse parallel-connected circuit of two thyristor/reactor branches (UM-concept-type TCR) [11]

(ii) To reduce harmonics by changing taps of a transformer using an on-load tap changer with thyristors [12]

(iii) To eliminate triplen harmonics by a connection technique of TCRs in secondary windings of a Δ-Y transformer [13]

(iv) To reduce harmonics by a control technique of an asymmetrical firing [14]

(v) To reduce harmonics by use of multi-pulse topologies (12 pulse or more)

In this thesis work, specific harmonics that will be discussed later is eliminated using multi-phase (12-pulse) structure.

2.2 Control Strategies in SVC Systems:

Although there are different benefits of SVC systems as explained in introduction section, the main purpose of using such systems can be classified into two parts, namely power factor correction and voltage regulation.

2.2.1 Power Factor Correction:

The idea of power factor correction is to balance reactive power requirement of a specific load via compensator that is shunt connected to the load. Therefore, from source side the load is seen as a purely resistive component and there is no need to generate or absorb and reactive power for that compensated load. By doing so, power transfer capability of the source is increased. Moreover, the losses caused by that extra reactive power transfer disappears and efficiency of the mains gets better.

Consider a resistive-inductive load (as most of the loads) connected to a bus and drawing a current I_l as represented in Figure 2.4. Assume the load admittance is;

$$Y_l = G_l + jB_l \quad [2.13]$$

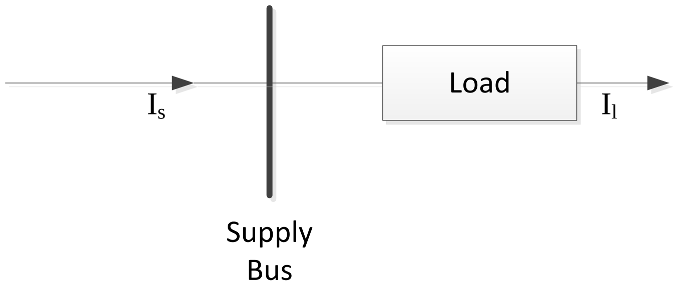


Figure 2.4: *Uncompensated load*

In this case the load current and apparent power I_l and S_l has both active and reactive components according to the equations;

$$I_l = V(G_l + jB_l) = VG_l + jVB_l = I_R + jI_X \qquad [2.14]$$

$$S_l = VI_l^* = V^2G_l - jV^2B_l = P_l + jQ_l \qquad [2.15]$$

where "V" is the voltage phasor at corresponding bus. Although only real component of current is used, current drawn from source side is greater by a factor of;

$$I_l / I_R = 1/\cos\phi_l \qquad [2.16]$$

In equation 2.16, "$\cos\phi_l$" is defined as power factor because of the relationship between apparent power and real power of the load;

$$\cos\phi_l = P_l / S_l \qquad [2.17]$$

In other words, power factor is the part of apparent power that can be used to obtain other forms of energy. Power triangle as shown in Figure2.5 represents relationship between real, reactive and apparent power.

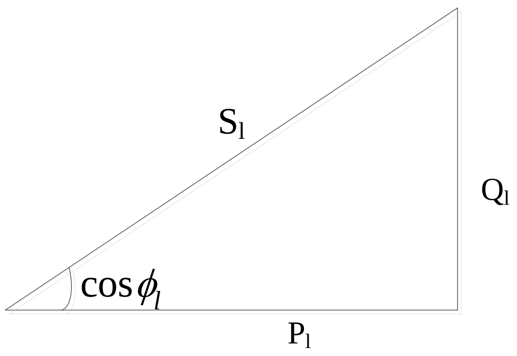


Figure 2.5: *Power triangle*

In case a compensator is connected to the same bus (Figure 2.6), then the reactive power consumption of the load is supplied by the compensator.

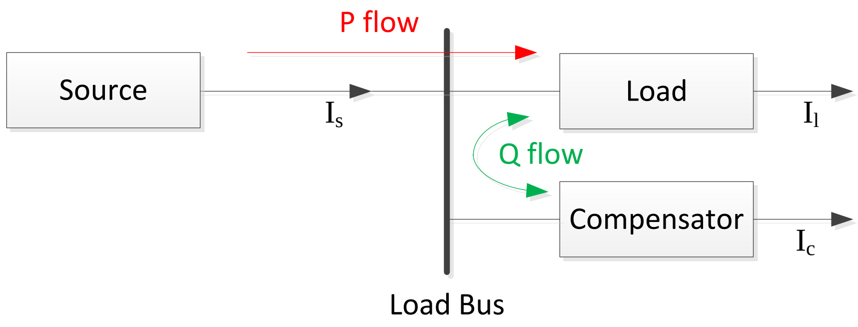


Figure 2.6: *Reactive power compensation of the load*

In this situation supply side current is sum of the load current and compensator current. In order to compensate the load, compensator admittance is purely reactive and equal to load reactive admittance with negative sign. Thus, compensator admittance and supply current is;

$$Y_c = -jB_l \qquad [2.18]$$

$$\begin{aligned} I_s &= I_l + I_c = V(G_l + jB_l) - V(jB_l) \\ &= VG_l = I_R \end{aligned} \qquad [2.19]$$

Compensator current and power can also be calculated as;

$$I_c = VY_c = -jVB_l \quad [2.20]$$

$$S_c = P_c + jQ_c = VI_c^* = jV^2 B_l \quad [2.21]$$

$$P_c = 0 \quad and \quad Q_c = V^2 B_l = -Q_l \quad [2.22]$$

Equations 2.20-2.22 prove that compensator has zero active power (ideally) and supplies the reactive current requirement of load. In Figure 2.7, current diagram is presented. Red color shows real and reactive components of load current, while yellow one is for compensator current. After compensation, supply current is equal to real component of load current.

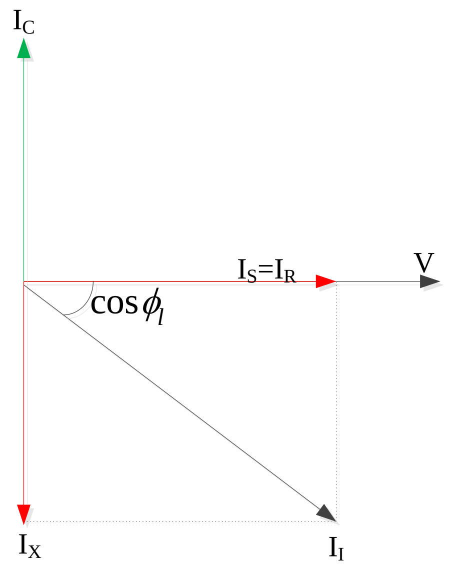


Figure 2.7: *Load, compensator and supply side current components*

2.2.2 Voltage Regulation:

Voltage regulation can be defined as the proportional (or per-unit) change in supply voltage magnitude associated with a defined change in load current (e.g., from no load to full load) [1]. This difference in voltage magnitude is basically due to the impedances between supply and load side. Supply impedance, transformer impedances, and transmission line impedances cause voltage drop.

Voltage regulation is an extremely important quantity for power quality since almost every load has a specific voltage tolerance. Under-voltage conditions result in degradation of performance whereas overvoltage causes magnetic saturation and causes harmonics as well as failures because of insulation breakdown [8]. In case of large load demand changes, even voltage collapses may occur.

Considering a simple system (Figure 2.8), Z_S is the total impedance between supply and load. Load admittance is shown as Y_I .

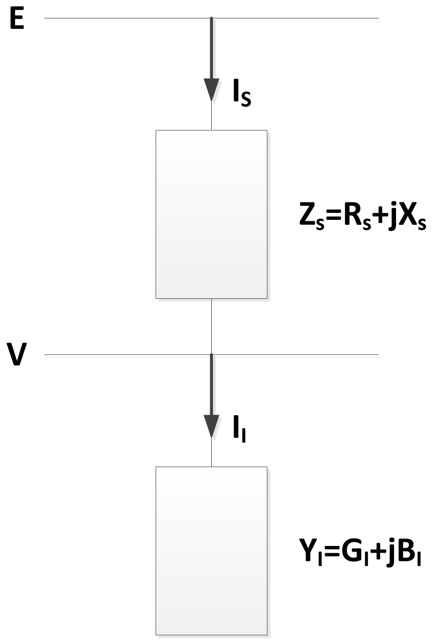


Figure 2.8: *Basic schematic for load and supply*

Voltage change from supply to load can be expressed as by showing phasors as bold;

$$\mathbf{\Delta V = E - V = Z_S I_I} \quad [2.23]$$

Where the load current I_I is,

$$\boldsymbol{I}_I = \frac{P_I - jQ_I}{V} \quad [2.24]$$

Thus;

$$\Delta V = (R_s + jX_s)\left[\frac{P_I - jQ_I}{V}\right]$$
$$= \frac{(R_s P_I + X_s Q_I)}{V} + j\frac{(X_s P_I - R_s Q_I)}{V} \qquad [2.25]$$
$$= \Delta V_R + j\Delta V_X$$

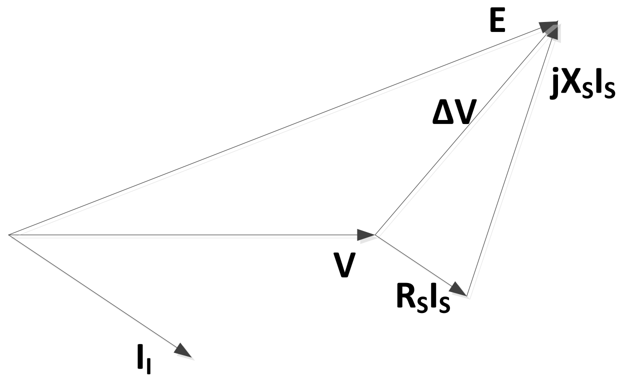


Figure 2.9: *Uncompensated load voltage regulation*

If compensator is connected to the same bus, current supplied by source changes. In [1], current voltage characteristics of TCR compensator is explained in detail (see Figures 2.10 and 2.11). According to these figures, junction point for system load line and TCR characteristics is the operating point. Positive slope of TCR characteristics provide stability for operation.

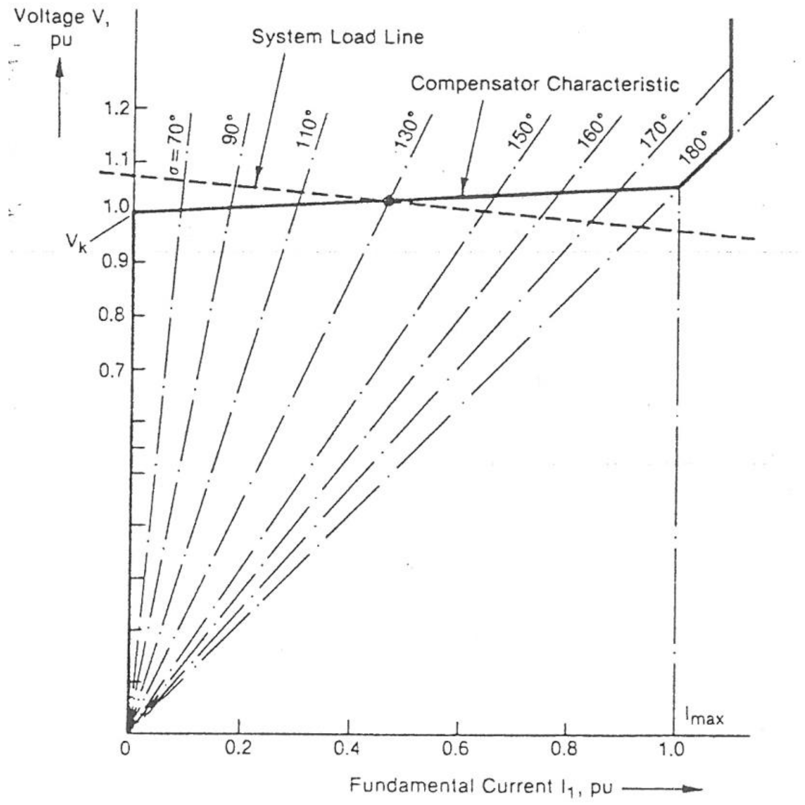


Figure 2.10: *Formation of fundamental voltage / current characteristics in the TCR compensator [1]*

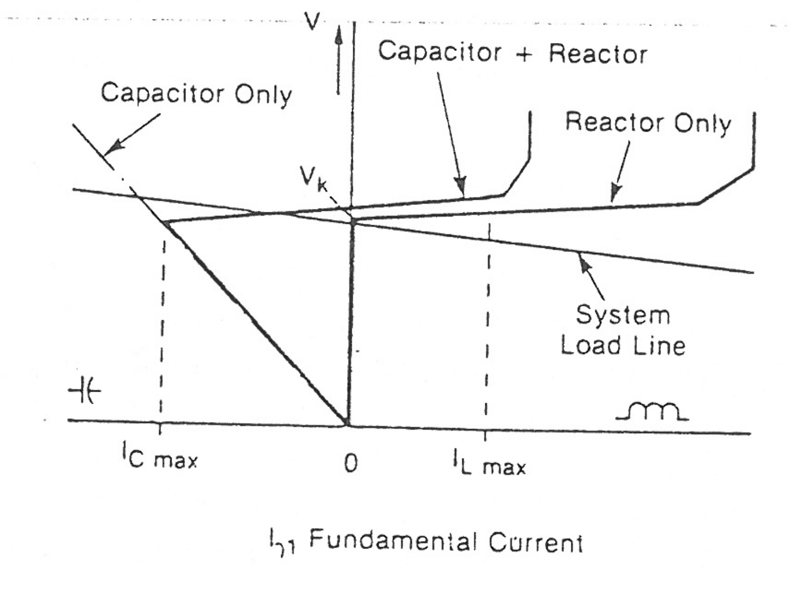


Figure 2.11: Voltage / current characteristics of TCR with different combinations [1]

In that situation, supply voltage and load voltage can be equated in magnitude. In equation 2.25, the term Q_I is replaced with $Q_I + Q_C = Q_S$. Supply voltage magnitude in squared form can be written using equations 2.23 and 2.25 as;

$$|E|^2 = \left[V + \frac{R_S P_I + X_S Q_S}{V}\right]^2 + \left[\frac{X_S P_I - R_S Q_S}{V}\right]^2 \quad [2.26]$$

It is clear that for perfect voltage regulation; i.e. zero magnitude deviation, $|E| = |V|$. Using this equality and equation 2.26, solution for Q_S yields,

$$Q_S = \frac{-2V^2 X_S \pm \sqrt{4V^4 X_S{}^2 - 4\left(R_S{}^2 + X_S{}^2\right)\left[\left(V^2 + R_s P_I\right)^2 + X_S{}^2 P_I^2 - E^2 V^2\right]}}{2\left(R_S{}^2 + X_S{}^2\right)} \quad [2.27]$$

Looking at equation 2.27, it is seen that there exists a solution for Q_S independent of the value of P_I . Then the necessary compensator power can be found by subtracting the reactive power of the load from Q_S. For compensated load, vector diagram is given in Figure 2.12. It should be noted that load voltage phase is not controlled; only magnitude is under control.

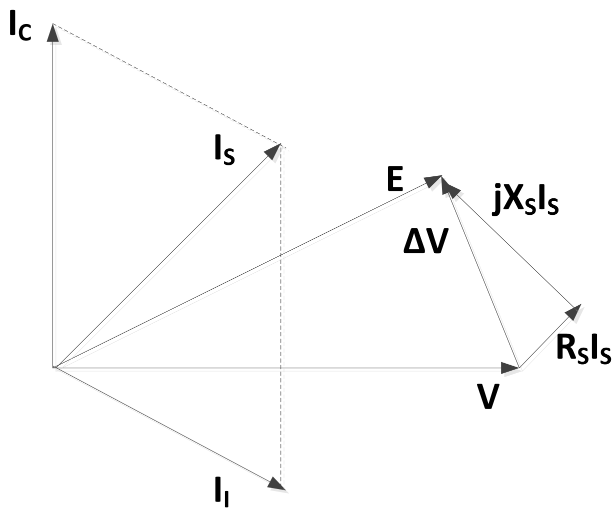


Figure 2.12: *Compensated load voltage regulation*

According to power factor correction control algorithm, Q_S should be zero. In that case, equation 2.25 becomes;

$$\Delta V = \left(R_s + jX_s\right)\left[\frac{P_I}{V}\right] \qquad [2.28]$$

Therefore, voltage regulation goes out of the compensator control as there is no related term in the equation. This proves, compensator cannot be used in both control types. In other words, a compensator cannot maintain power factor correction and voltage regulation at the same time. It can also compensate flicker which occurs in weak distribution systems when heavy loads are turned on and off; however one compensation type should be chosen.

2.3 Six-Pulse Operation:

Typical six-pulse thyristor controlled reactor is composed of back-to-back connected thyristor group and a series reactor. Considering the reverse blocking voltage value, a few numbers of thyristors are connected in series. Generally, a safety factor is also considered or “n-1” principle is used in determining the number of thyristors in the stack (string of series connected thyristors).

In order to protect thyristors against high voltages, protection devices (like small surge arresters) are used. Moreover, interruption of current flow through inductor results in a sharp rise in voltage. This voltage may cause unexpected turn-on of the thyristor. Snubber circuitry consisting of series connected resistor and capacitor is connected in parallel to each thyristor. Hence, the rate of rise of the voltage (dV/dt) on the thyristor cannot reach the values that automatically trigger the device.

Six-pulse term comes from the fact that there are six firing pulses in a period. Back-to-back connected thyristors are fired with 180 degrees apart. Working principle and current relations are explained in Chapter 2.1 with equations 2.1-2.4. The relationship between firing angle and conduction angle, and current waveforms for different firing angles are represented in Figure 2.13. In figure, voltage on the thyristor is labeled with red color and the current is shown as green. Firing angle "α" and conduction angle "σ" are also shown. Firing angle is measured from zero crossing of voltage. As explained before, conduction angles of positive and negative half-cyle thyristors are separated from each other by 180 degrees.

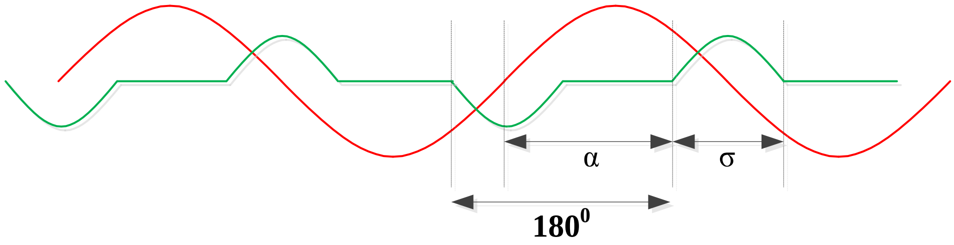


Figure 2.13: *Thyristor current and voltage waveforms*

2.4 Twelve-Pulse Operation:

Twelve-pulse configuration is obtained using two six-pulse configurations. These configurations are connected in parallel with different transformer or TCR couplings. Main idea is to create phase difference between two TCR systems. However, due to control problems regarding the neutral point and 3rd harmonic current, Y-connected TCR is not preferred. Instead, phase difference is obtained by adjusting transformer couplings. For example, if one of TCR system is connected using Y - Y connected transformer, the other coupling transformer is chosen as Y - delta. Schematic diagram is given in Figure 2.14.

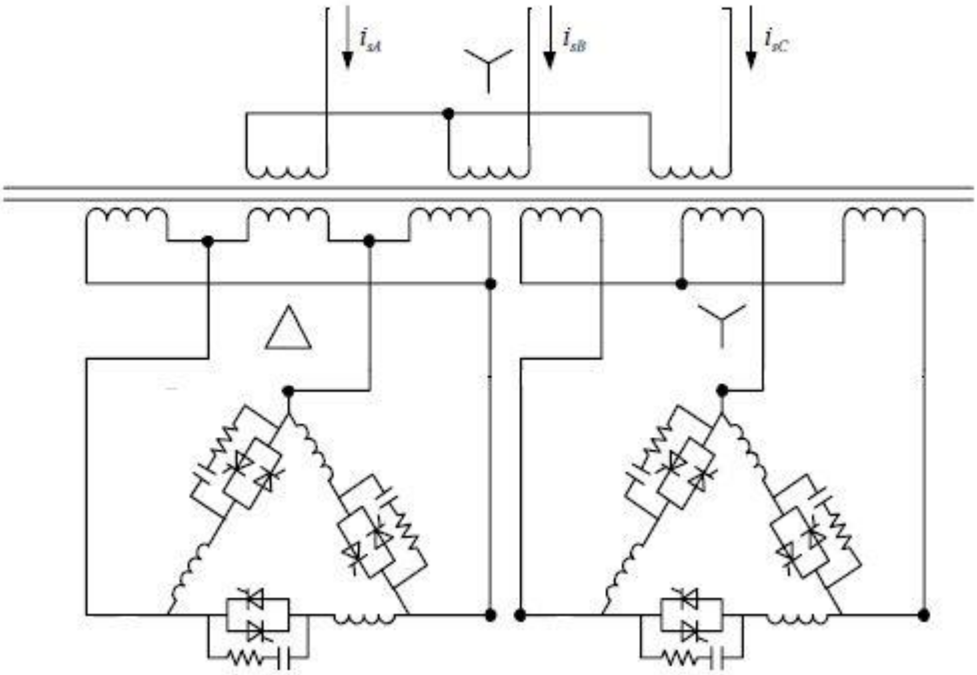


Figure 2.14: *Twelve-pulse TCR configuration*

As a result of this phase shift, 5th and 7th current harmonics do not appear on supply side. For a six pulse configuration of current source converters, the frequency domain representation of the a.c. current in phase a is given as;

$$i_a = \frac{2\sqrt{3}}{\pi} I_d (\cos(wt) - \frac{1}{5}\cos(5wt) + \frac{1}{7}\cos(7wt) - \frac{1}{11}\cos(11wt) + \frac{1}{13}\cos(13wt)... \quad [2.29]$$

According to the equation, harmonic components of 6 pulse structure are of orders 6k$\pm$1 for integer values of k. Harmonics of orders 6k+1 are of positive sequence and those harmonics of orders 6k-1 are of negative sequence. If the transformer connection type is changed, frequency domain representation of the current changes also. Having Y - delta connected transformers instead of Y - Y connected ones, results in 30^0 phase shift for current and voltage signals in the primary side. The frequency domain representation of the primary a.c current in “phase a” for Y - delta transformer is;

$$i_a = \frac{2\sqrt{3}}{\pi} I_d (\cos(wt) + \frac{1}{5}\cos(5wt) - \frac{1}{7}\cos(7wt) - \frac{1}{11}\cos(11wt) + \frac{1}{13}\cos(13wt) + \frac{1}{17}\cos(17wt) - ... \quad [2.30]$$

Comparing this result with the one belongs to the star-star connected; the only difference is the sign of harmonic orders 6k$\pm$1 for odd values of k, i.e, the 5th, 7th, 17th, 19th …

In twelve-pulse configuration, the resultant AC current is given by the sum of two Fourier series of the star-star (equation 2.29) and delta-star (equation 2.30) transformers;

$$i_a = 2(\frac{2\sqrt{3}}{\pi}) I_d (\cos(wt) - \frac{1}{11}\cos(11wt) + \frac{1}{13}\cos(13wt) - \frac{1}{23}\cos(23wt) + \frac{1}{25}\cos(25wt)... \quad [2.31]$$

This means that the primary current only contains harmonics of order 12k$\pm$1. On the other hand, the harmonic currents of order 6k$\pm$1 with k=1,3,5,7,… circulate between the two converter transformers but do not penetrate into the AC network.

Vector diagram of currents proves the same result (Figures 2.15 and 2.16). As the reference vector is chosen to be the primary A-phase fundamental line current, same phase fundamental current is the same in the primary of transformer generated by the two six-pulse TCR, and considering that two groups of transformer valve current is the same as primary line current, which is made in transformer design. Therefore, fundamental current magnitudes in primary are the same. And for 5 and 7 times or higher (6(2n+1)$\pm$, n=0,1,2,…) harmonic current, harmonic current magnitude are equal in the primary of transformer generated by two groups of 6-pulse TCR and the phase is the opposite so these two counteract [11].

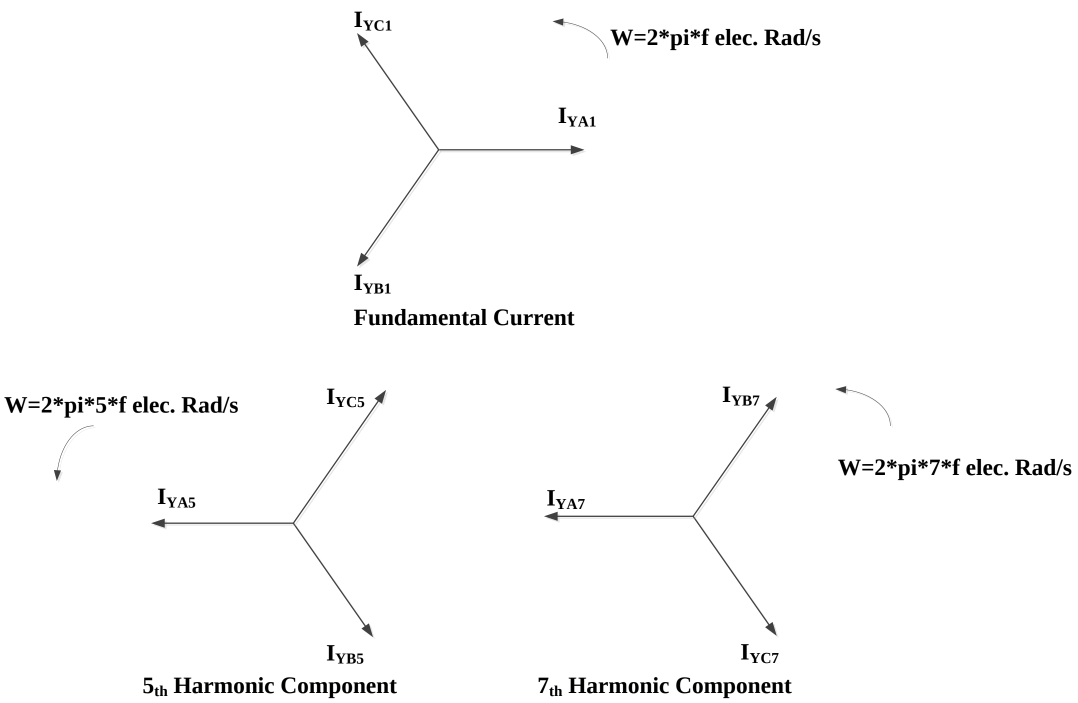


Figure 2.15: *Transformer primary current components in Y-Y connection*

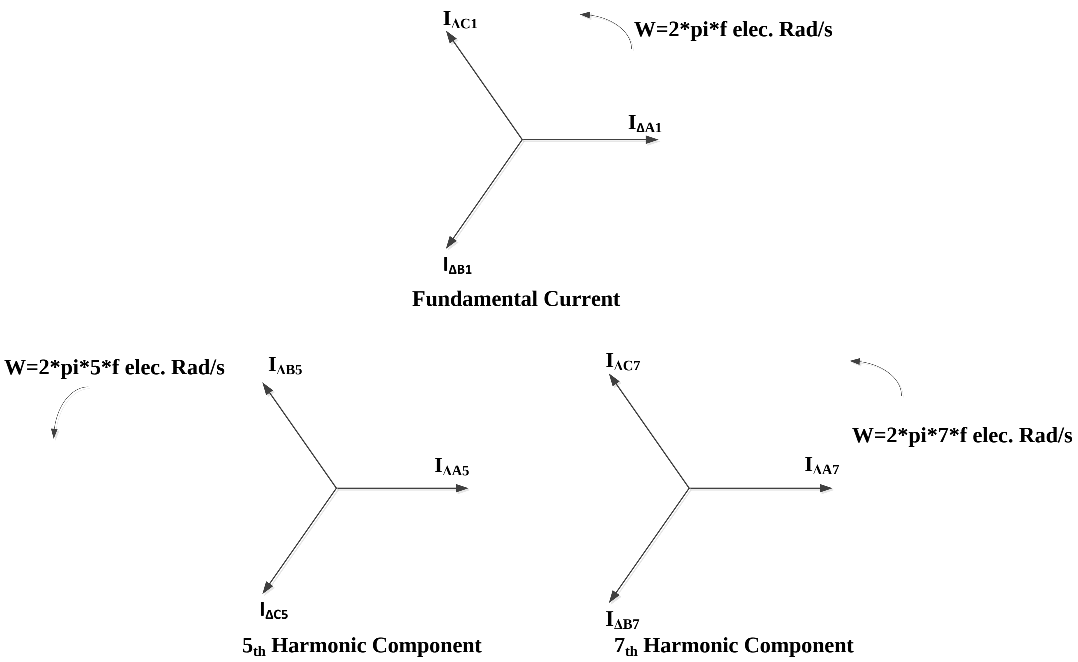


Figure 2.16: *Transformer primary current components in Y – Δ connection*

In twelve-pulse operation, systems can be operated independently or they can be operated in parallel. In parallel operation they share load equally, or asymmetrically. If two systems are operated in parallel and share the load equally, firing angle is under the control for only one system (master system). The other system (slave) just takes the reference from master and operates accordingly.

There are other advantages of such a system than having low harmonics. In [38] and [39] these advantages are discussed. First of all, whole system becomes more flexible in terms of load sharing. Assuming that the coupling transformer has enough capacity, overall system power is doubled and this power can be divided into two resulting in less current passing through thyristors so that the cooling requires less energy. Secondly, overall system reliability is increased since even if one of the systems has some problems and goes out of the work, the other can still work in six-pulse algorithm. This opportunity creates a solution for emergency situations and makes the overall system more stable.

2.5 Other Implementations:

As explained in [1], applying the same principle explained in previous section, pulse number can be increased further. This basically means more structures connected in parallel with different transformer couplings.

Four transformers is used to obtain 24-pulse configuration. In order to filter out the harmonics in de order of $12k \pm 1$, those transformers should be connected in parallel with 15^0 of phase shift. In this case, the lowest harmonic becomes 23th harmonic component, and the next one is 25^{th} harmonic component. Similarly, when 8 transformers with $7{,}5^0$ of phase shift is used, 48-pulse configuration is obtained with lowest harmonic components of order 47 and 49. Although distortion in supply voltage waveforms makes the control of higher pulse configurations very hard, theoretically pulse number can be increased further. The critical point is to design coupling transformers so that common fundamental frequency voltages on their primary and secondary sides are in-phase.

As the number of pulses increase the lowest harmonic component has higher order values. General principle is that for a “p” pulse configuration, harmonics are in the order of $kp \pm 1$. Significant harmonics for different pulse configurations is represented in Table 2.5 below.

Table 2.5: *Current harmonics for different pulse configurations in three phase steady state balanced operation*

	1	*5*	*6*	*7*	*11*	*12*	*13*	*17*	*18*	*19*	*23*	*24*	*25*
Fundamental	X												
6 - pulse	X	X		X	X		X	X		X	X		X
12 – pulse	X				X		X				X		X
18 – pulse	X							X		X			
24 - pulse	X										X		X

CHAPTER III

12 - PULSE SVC DESIGN

3.1 Investigation of the Power System Before Installation of SVC:

Regarding the "Collaboration and Technology Transfer Project for Static VAr Compensation (SVC) Systems Product And Service Agreement" signed on 1.6.2011 between TUBITAK and KACST, a 3 MVAr SVC system is installed in Dhurma in Saudi Arabia. Design procedure of 12 pulse SVC system is provided in Figure 3.2. The sizing is based on the contract (*). SVC system in Dhurma is located at 75 km. south-west of Riyadh (Figure 3.3). The length of distribution line is nearly 40km which causes the line characteristics to be highly capacitive during light load. Moreover, for high load situations, drops on the line result in voltage problem at load point. Characteristics of electricity system according to the measurements taken from Al-Hassat substation that has similar results with Dhurma substation are given in Figure 3.1, Figure 3.3 and Table 3.1. Figures 3.4 and 3.5 provide information about the locations of Dhurma transformer substation and SVC systems.

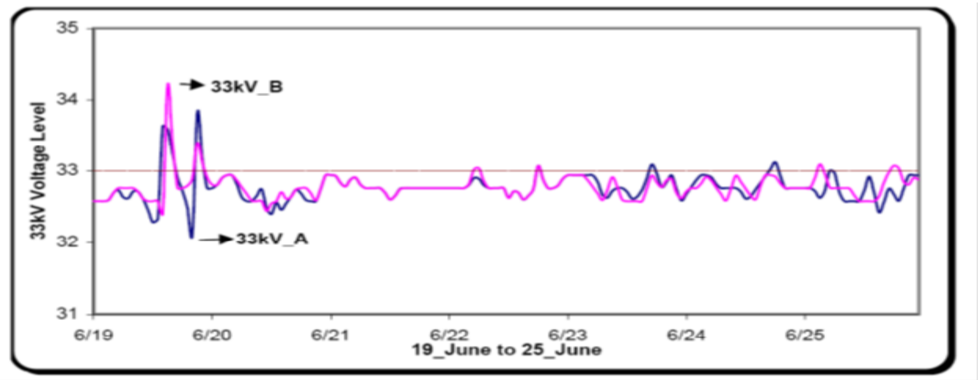


Figure 3.1: *Weekly voltage profile*

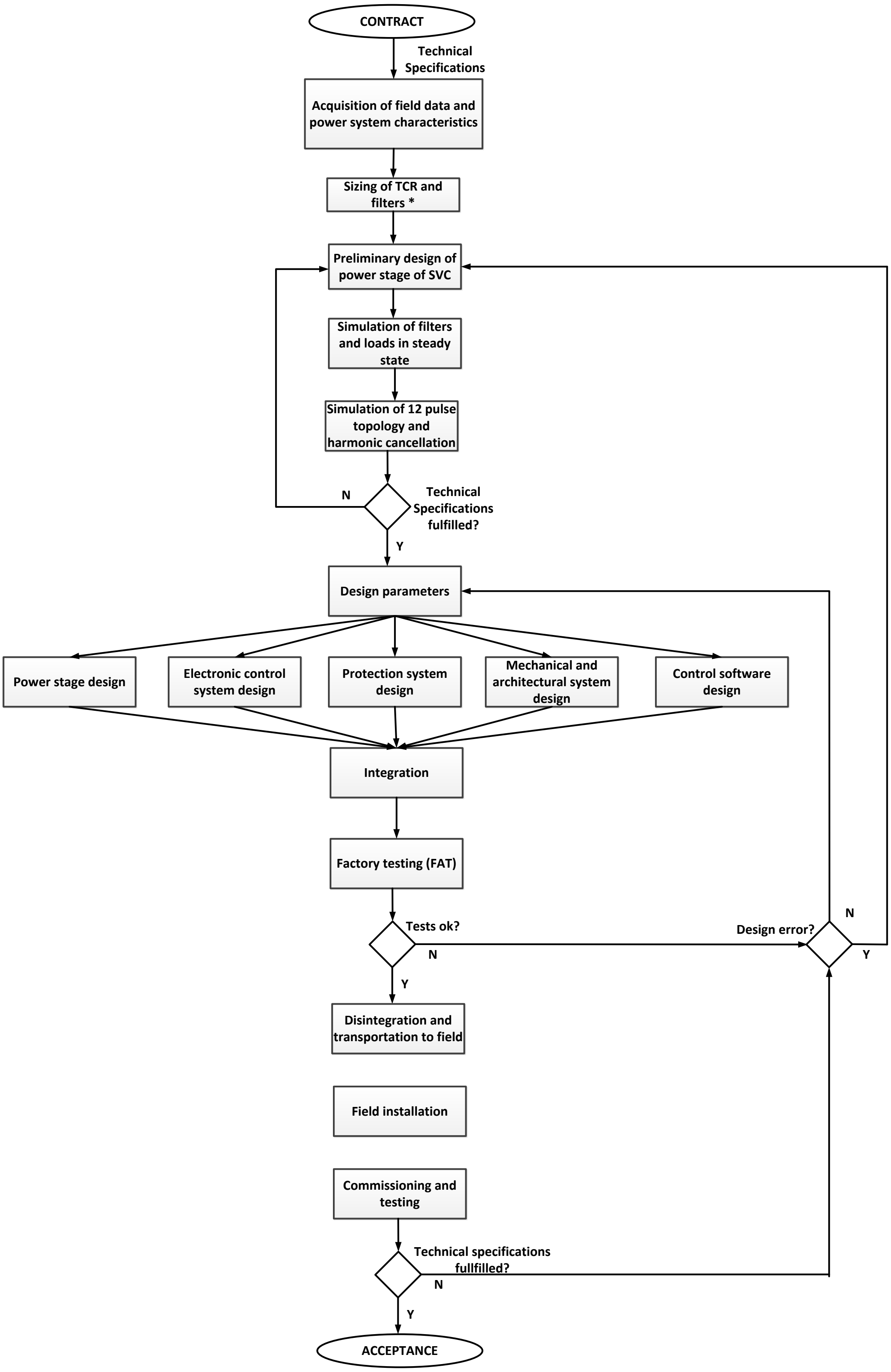


Figure 3.2: *Design procedure of 12 pulse TCR based SVC for voltage regulation*

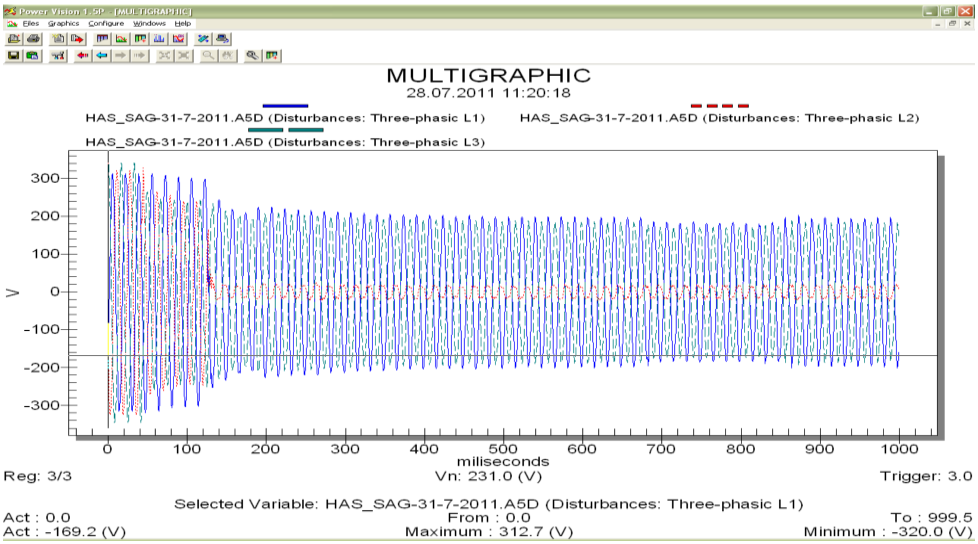


Figure 3.3: *Voltage sag example*

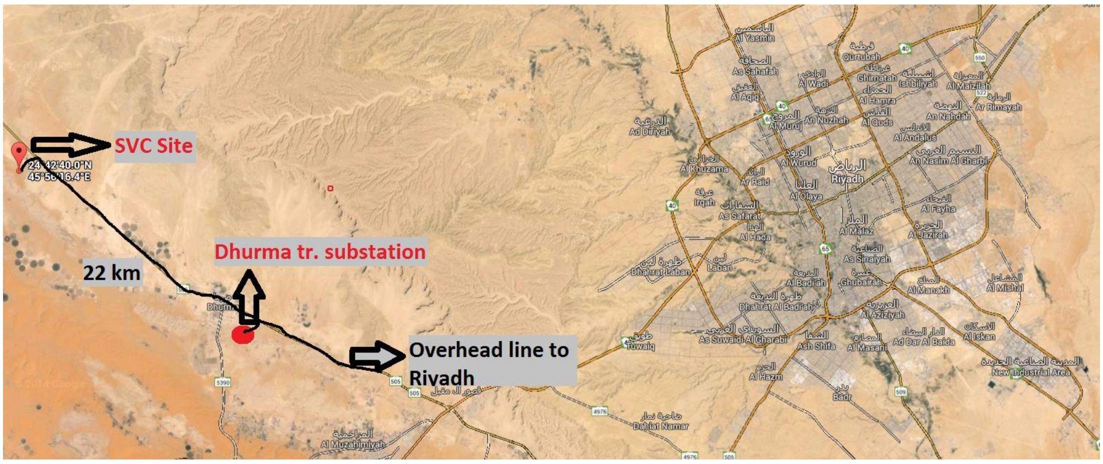


Figure 3.4: *SVC and transformer substation at Dhurma*

Figure 3.5: *Location of SVC systems*

Table 3.1: *Power system characteristics*

Nominal ac system voltage, line-to-line	33 kV
Maximum continuous ac system voltage,line-to-line	34.7 kV
Minimum continuous ac system voltage,line-to-line	31.4 kV
Maximum short-term ac system voltage, line-to-line	42.9kV (130%)
Maximum duration of maximum system voltage	3 s
Minimum short-term ac system voltage, line-to-line	9.9 kV (30%)
Maximum duration of minimum system voltage	10 s
Continuous negative-sequence voltage component	1-2%
Continuous zero-sequence voltage component	1-2%
Nominal ac system frequency	60 Hz
Maximum continuous ac system frequency	60.2 Hz
Minimum continuous ac system frequency	59.8 Hz
Maximum shor-term ac system frequency	61.5 Hz
Duration of maximum short-term ac system frequency	30 s
Maximum rate of change of frequency (df/dt)	1.2 Hz/sec
Minimum shor-term ac system frequency	58.2 Hz
Duration of minimum short-term ac system frequency	A few minutes
Lightning impulse protective level (BIL)	170 kV
Switching impulse protective level	170 kV
Maximum three phase fault current	1 kA

The location where SVC system is connected to the grid is shown in Figure 3.4. Moreover, Dhurma substation connections provided by Saudi Electricity Company (SEC) are shown in Figure 3.5 below. In the figure, “F5” represents the feeder to which the SVC is connected.

Figure 3.4: *SVC site before installation*

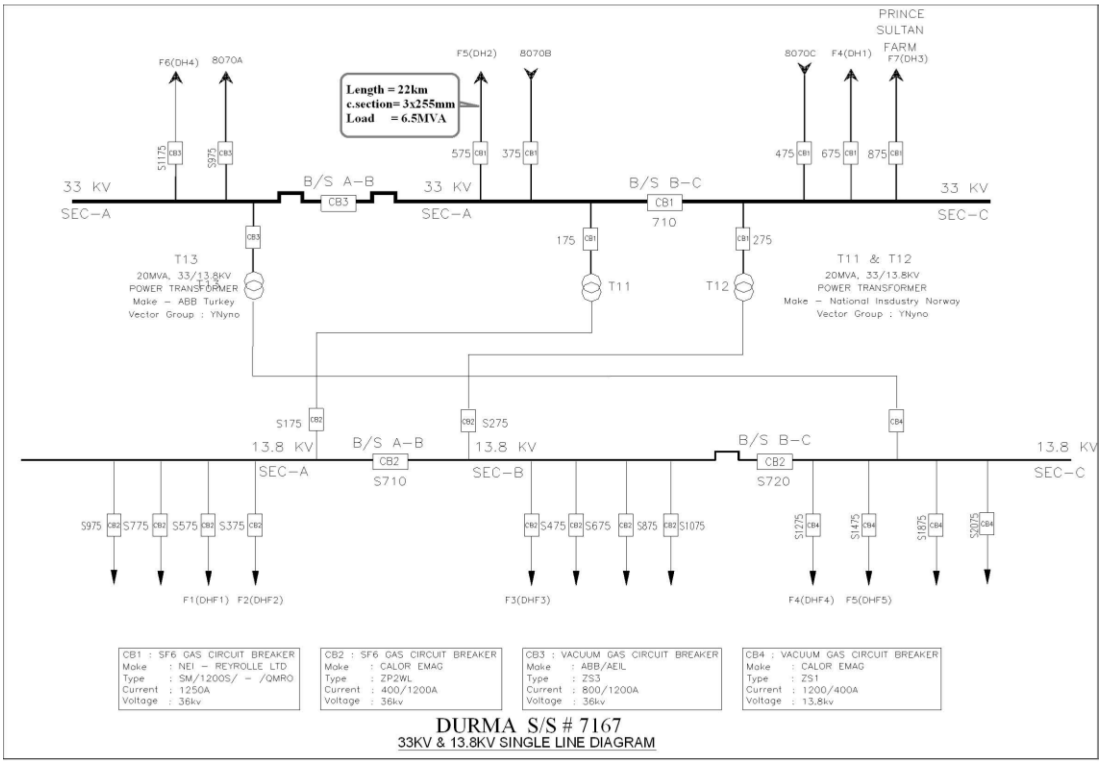


Figure 3.5: *Single line diagram of Dhurma power distribution system*

3.2 Design overview:

Considering the mains requirements, SVC system having rated power of 3 MVAr consists of HF and a TCR whose ratings are given in Table 3.2 below. Although there are some other alternatives like STATCOM, during design process 12-pulse SVC system is chosen due to three main reasons. First of all, with two parallel systems redundancy is an important advantage in case having problems with one system. Secondly, 12-pulse design allows elimination of specific harmonics explained in previous chapter. Finally, as an objective of technology transfer project, 12-pulse TCR with voltage regulation is a suitable choice since there is no identical system in literature. System is simulated in PSCAD / EMTDC according to the information taken from Saudi Electricity Company (SEC) as seen in Figure 3.6.

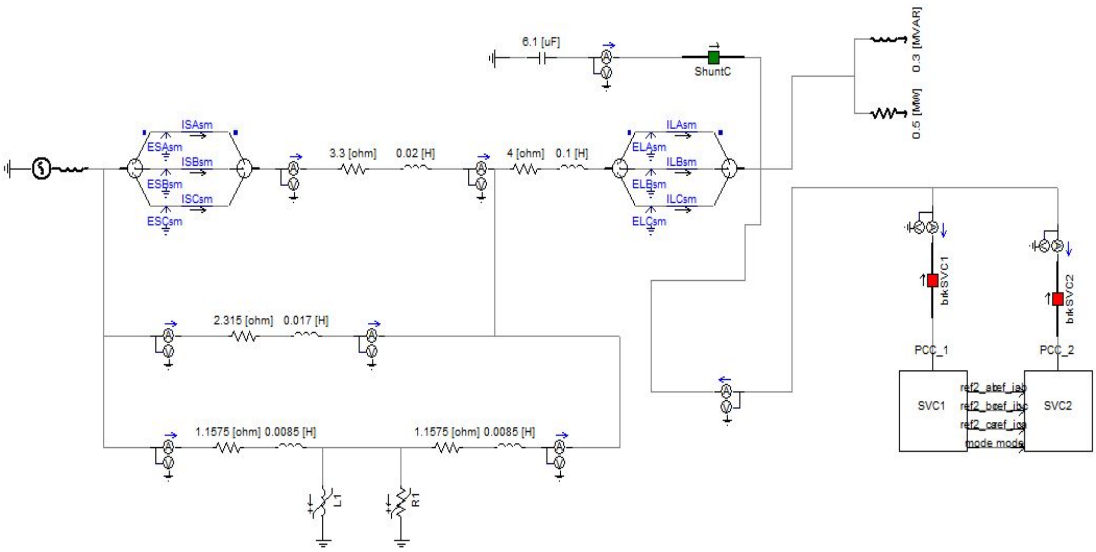


Figure 3.6: *Single line diagram of simulated electricity system with two SVC systems*

Table 3.2: *SVC technical characteristics*

ITEM	**RATINGS**
Voltage Rating:	1 kV
Coupling Transformer 1:	1.6 / 2 MVA, 33 kV : 1 kV, Y-Y (YNyn0), 6% Uk
Coupling Transformer 2:	1.6 / 2 MVA, 33 kV : 1 kV, **Δ**-Y (Dyn11), 6% Uk
Filter 1:	3^{rd} Harmonic Filter 1 kV, 0.5 MVAr (170-180 Hz)
Filter 2:	4^{th} Harmonic Filter 1 kV, 0.5 MVAr (230-240Hz)
Filter 3:	5^{th} Harmonic Filter 1 kV, 0.5 MVAr (280-300Hz)
TCR:	1 kV, 16 MVAr, Series thyristor operation

Single line diagram of designed system is given in Figure 3.7.

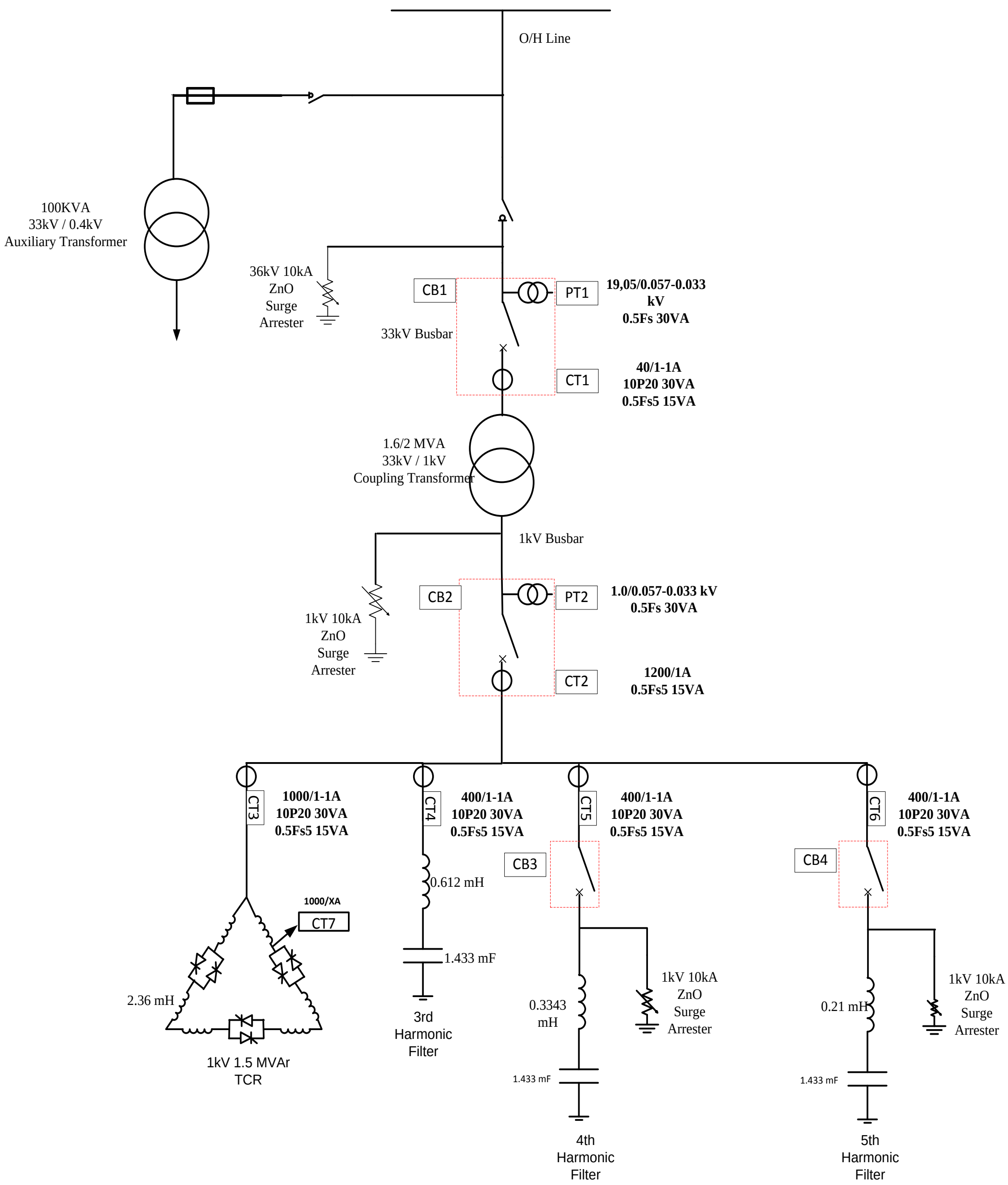


Figure 3.7: *Single line diagram of the developed system, only the 6-pulse master SVC shown, slave SVC power system topology is also exactly the same*

As explained before, there are two SVC systems connected in parallel. Their alignment in the field is shown in Figure 3.8. There are two power connections for each SVC system one of which is for compensation and the other is for internal power requirement.

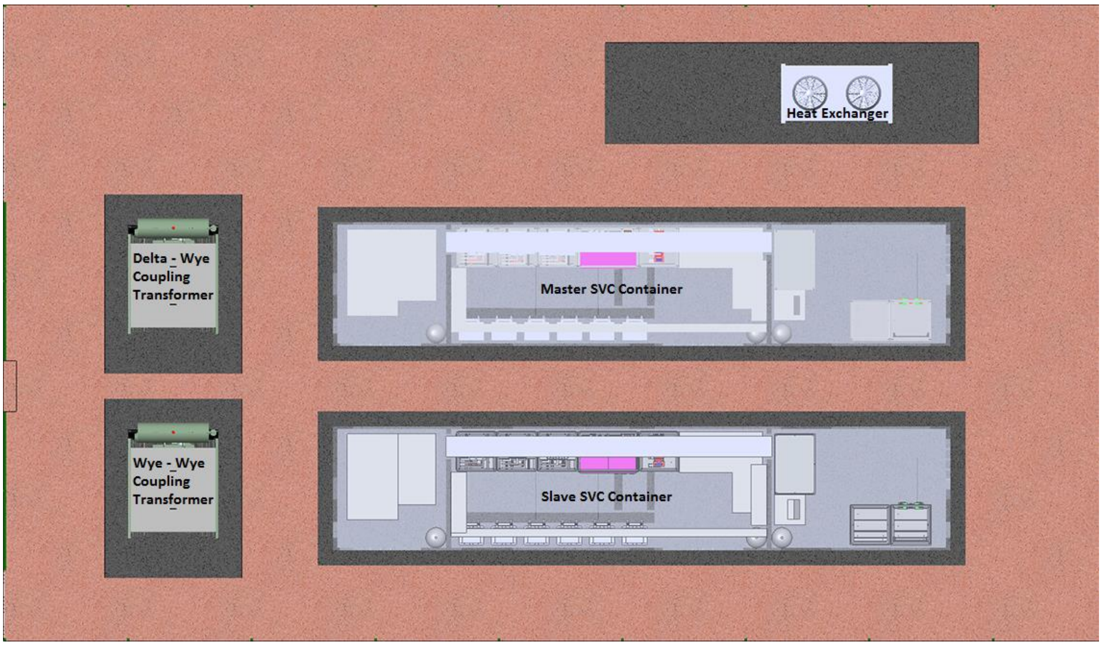


Figure 3.8: *Platform design of SVC systems*

In Figure 3.8, top view of the overall system is provided. Coupling transformers with characteristics, master and slave systems, and heat exchanger is labelled.

Both systems are designed to be fit in containers. There are mainly three parts of containers. They can be differentiated as 33 kV side, 1 kV side and low voltage side. In Figure 3.9, overall design of the container is seen with 33 kV side at the leftmost and low voltage side at the rightmost. In 33 kV side, circuit breaker cubicles are placed (1). This is the connection part of the system to the mains. The other part, 1 kV side, is composed of distribution panel (3), thyristor panel (4) and harmonic filter groups (2). Water cooling system panel (6) is also placed in this part of container. Finally, there is the low voltage room in which control panel, auxiliary systems panel and protection/measurement panel is placed (7, 8, 9). Rectifier (used to convert ac to dc) is also in this part (10).

Finalized overall design with side view is also represented in Figure 3.10. Overall platform dimensions are 22m x 12.5m. Dimensions for container, coupling transformer and heat exchanger are 12.8m x 3.1m; 2.2m x 3.03m; and 2.2m x 1.1m respectively. Thus, platform area is nearly 275 m^2.

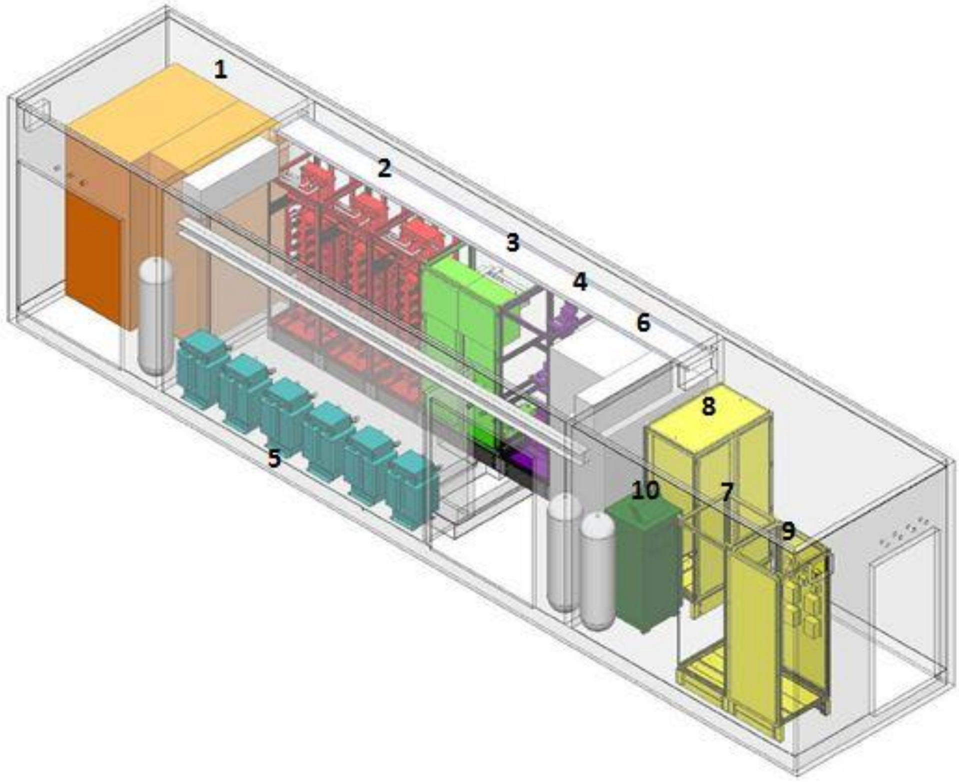


Figure 3.9: *SVC container design*

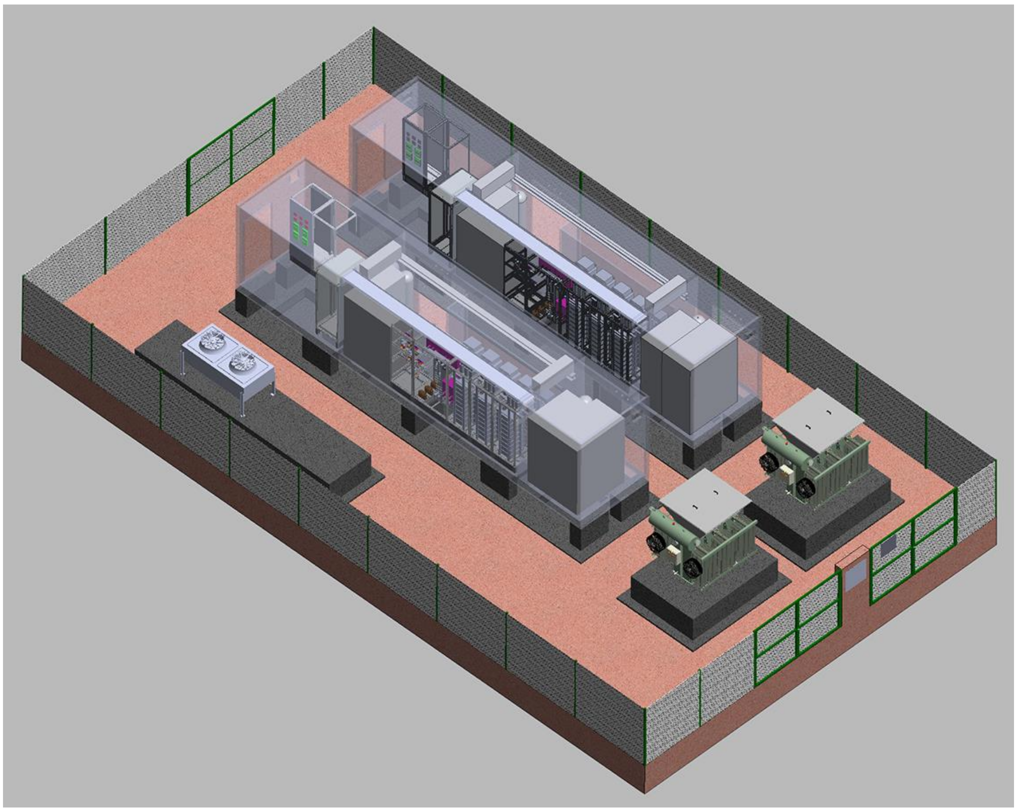


Figure 3.10: *System design*

3.3 Thyristor Controlled Reactor Design:

TCR can be considered as the most important component of SVC system since it is the part that reactive power is controlled. Therefore, both component selection and control issues should be considered carefully.

3.3.1 Technical Specifications of Thyristor Group:

It is a very important criterion for thyristors to meet the voltage and current requirements of design. Thyristors are characterized by their technical properties:

Rms Forward Current, I_{TRMS}:

I_{TRMS} of a thyristor defines the limiting value for the absolute maximum value of on-state rms current for a specified current waveform and cooling situation. In case of excessing the limit for I_{TRMS}, thyristor may be burned due to excessive heat generation depending on the ambient temperature. I_{TRMS} can be calculated as [13],

$$I_{TRMS} = I_{TCR} \times \sqrt{\frac{(\pi-\alpha)\times[1+2\cos^2(\pi-\alpha)]-1.5\sin[2(\pi-\alpha)]}{\pi}} \quad [3.1]$$

Mean On-state Current, I_{TAV}:

Similar to I_{TRMS}, mean on-state current is the maximum value of on-state load current for a thyristor for a defined temperature and cooling situation with a defined current waveform. I_{TAV} can be calculated as [13],

$$I_{TAV} = I_{TCR} \times \frac{\sqrt{2}}{\pi} \times [\sin(\pi-\alpha)-(\pi-\alpha)\cos(\pi-\alpha)] \quad [3.2]$$

It is important to note that in this limit value (I_{TAV}) there is no safety margin for thyristor cooling. Hence, in practice usually $0.8I_{TAV}$ is used as continuous on-state current.

Another important point to care about is the operating frequency. If standard diodes and thyristors (designed for line operation) are used at frequencies between 200Hz and 500Hz, then their maximum current carrying capabilities should be reduced by considering the switching losses that are no longer negligible.

Surge On-state Current, I_{TSM}:

Surge on-state current, I_{TSM} is the maximum value of surge current that the thyristor can withstand. Surge current is in the form of single sinusoidal wave with duration of 10ms. After carrying a surge current with defined duration, thyristors can withstand the reverse blocking voltages given in datasheets.

Repetitive Peak Reverse and Off-state Voltages:

Repetitive peak reverse voltage (V_{RRM}) and repetitive off-state voltage (V_{DRM}) defines maximum permissible voltage value for repetitive transient reverse and off-state voltages. They may have different values.

dV/dt:

Critical rate of rise of off-state voltage (dV/dt) defines the maximum rate of increase of the voltage across anode and cathode of the thyristor that the device will hold-off, with gate open, without turning on. If this value is exceeded, then misfiring may occur. Although, this type of turning-on is not destructive if the resultant current is in the limits of thyristor ratings, control on the thyristor is completely lost.

dI/dt:

"di/dt" rating of a thyristor defines the upper limit of the rate of rise of current that the thyristor carries during turn-on process. Such a limit exists because when thyristor is triggered, at first, only part of the chip conducts current. Pushing the limits may cause localized overheating and damages the device.

According to [14], di/dt of a surge current can be calculated using equation,

$$\frac{di}{dt} = \frac{\pi(I_{TM})}{t} \quad [3.3]$$

as it is also seen in Figure 3.11.

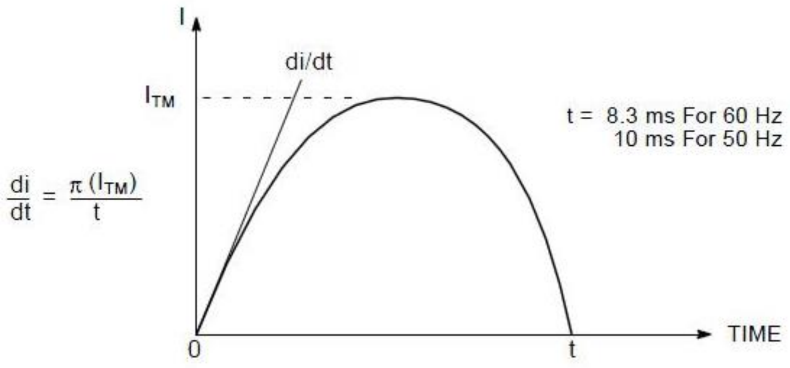


Figure 3.11: *Rate of rise of current for surge condition [14]*

Cooling Strategy:

Excessive heat generated by thyristors must be taken out. For that, there are different kind of methods; namely, air natural cooling (AN), air forced cooling (AF), and liquid based cooling.

Heat generation capacity of thyristors and other design objectives are considered when determining the cooling type.

In liquid based cooling, some type of a material such as de-ionized water is used. Ionization level of the water should be checked carefully since above a limit, it may cause electrical arcs.

Power Losses:

Although thyristor controlled reactor systems are assumed to be lossless structures ideally, they dissipate power in reality. According to [8] which is compatible with IEEE 1031-2011, this dissipation can be classified as,

- Thyristor losses (conduction, switching and on-state losses)
- Snubber losses
- Equalizing resistor losses
- Valve reactor losses (if present)
- Protection circuit losses
- Gate triggering circuit losses
- Bus bar or cable losses

The last three type is usually negligible when compared to the other losses. For thyristors, the conduction losses are the most significant part and it can be calculated as,

$$P_T = V_{TO} \times I_{TAV} + r_T \times I^2_{Trms} \qquad [3.4]$$

where V_{To} is on-state voltage drop on thyristor and r_T is the conduction slope resistance.

3.3.2 Firing Circuitry:

Thyristors must be triggered at the angle that is calculated by control system. Firing circuitry supplies the required current to gate terminal of the thyristors. Moreover, usage of fiber optical cables guarantees the voltage isolation and noise immunity.

The firing system is composed of a main gate driver card and individual gate cards for each thyristor in the stack.

The only power requirement of the system is a mains supply to the gate driver card.

Isolation to the individual gate drives is provided by the transformer action of the loop from the main gate driver card. The amount of isolation is governed by the insulation rating of the loop cable. Figure 3.12 shows the gate driver card manufactured by Dynex Company.

Figure 3.12: *Dynex gate driver circuitry*

3.3.3 Technical Specifications of Reactors

Shunt reactor design is a very important part of the system and should be compatible with the standards.

Reactance value for reactors is determined according to the calculations given before. Once system size is known with required current and voltage values, reactance can be calculated easily.

“IEC standard for reactors” [16], and IEEE guides [17-18-19-20] should be checked for analysis of design, protection, test procedures and loss concepts.

In general, technical specifications and critical points are determined using simulation tools. Corresponding information is supplied to the manufacturer and the rest is done accordingly.

3.3.4 Thyristor and Reactor Alignment

Thyristors are used as controlled switches to adjust the conduction of reactors. Detailed working principle has been given in previous chapters. Thyristors are connected in series to reactors. Reactors can be divided into two parts or they can be used as single part. Both alignments are shown in Figure 3.13.

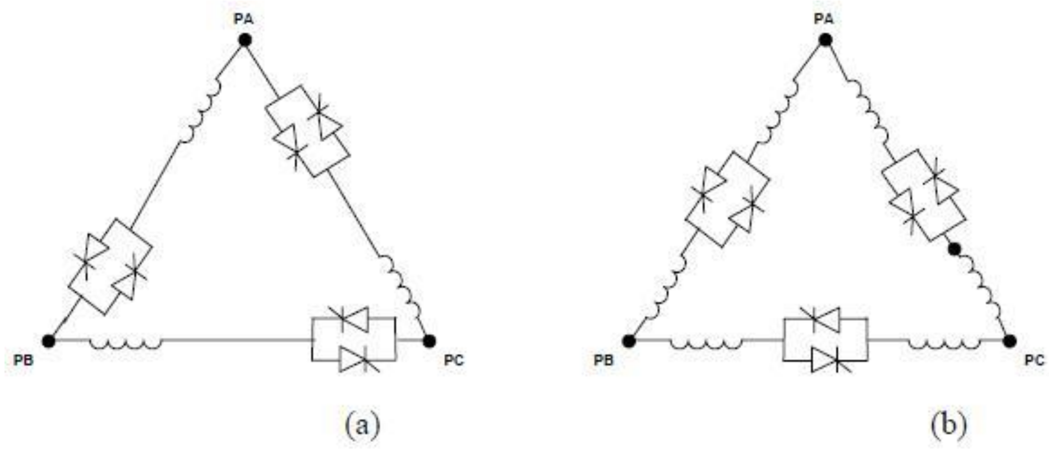


Figure 3.13: *Reactor alignments, a) single piece, b) two pieces*

According to [8], dividing the reactors into two pieces with the same reactance helps protecting thyristors against a short circuit. Connecting the thyristor valves in between these series reactors will limit the maximum fault currents. If one reactor is short circuited, the fault current will be limited by the other reactor. If phase is short circuited, no fault current will flow through thyristors.

3.3.5 Design Aspects

Thyristors are chosen to be suitable for indoor installation as they should be mounted in panels in the container. For each phase, single back-to-back thyristor stack is used. Thyristors are designed for vertical mounting. Their snubbers are mounted on the heatsink and triggering circuitry is mounted on the stack. Triggering operation is based on fiber-optic interconnection.

According to the design specifications, thyristor stacks are obtained as seen in Figure 3.14 and Figure 3.15 below.

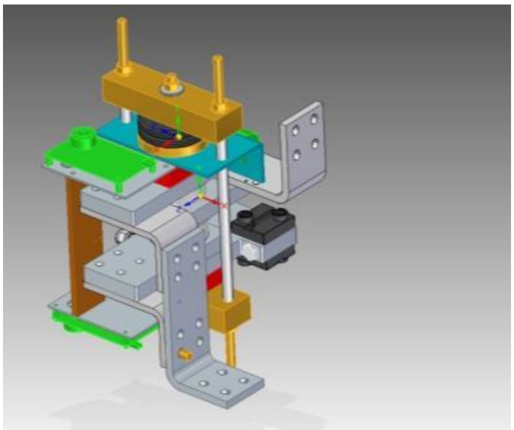


Figure 3.14: *Single phase thyristors*

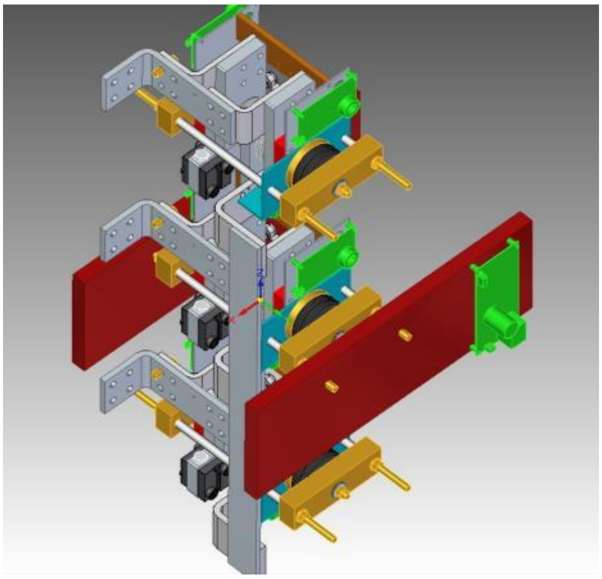


Figure 3.15: *Three phase thyristor alignment*

Technical specifications of thyristor based on [12] and corresponding stack is represented in Table 3.3 and Table 3.4 respectively. Reactors are also designed for system requirements and their technical properties are also given in Table 3.5.

Table 3.3: *Thyristor characteristics*

Rms forward current at 85 ^{0}C, I_{TRMS}	550 A
Mean on-state current at 85 ^{0}C, I_{TAV}	225 A
Surge (non-repetitive) on-state current, I_{TSM}	10.5 kA
Repetitive peak reverse voltage, V_{DRM}	4200 V
Maximum linear rate of rise of off-state voltage, dV/dt	1500V /µs
Rate of rise of on-state current, dI/dt	400A/µs

Table 3.4: *Thyristor stack characteristics*

Rated system voltage (V_{nom})	1 kV
System Highest voltage	1.5 kV
Voltage safety factor (V_{stack}/V_{nom})	3
Basic insulation level (BIL), Stack to ground	20 (kV, peak)
Rated frequency	60 Hz
Maximum ambient temperature	+50 (°C)

Table 3.5: *Shunt reactor characteristics*

Rated system voltage	1 kV
Reactor voltage	0.5 kV
System highest voltage	1.5 kV
BIL (across reactor and reactor to ground)	20 kV (peak)
Rated frequency	60 Hz
Rated inductance per reactor unit	2.36 mH
Tolerance on rated inductance	3%
Rms total current	550 A
Rated short time thermal / mechanical currents	• 1 (kA, rms/2s) • 2.5 (kA, peak)
Cooling method	AN/water cooled
Maximum ambient temperature	+50 ^{0}C
Winding material	Aluminum
Standards	EN60076

3.4 Harmonic Filter Design:

Capacitor banks themselves are sources of capacitive reactive power and it is common to strategically place capacitor banks to help raise the voltage profile back to nominal values [21].

Passive harmonic filters are the combinations of capacitors and reactors. In addition to supplying reactive power to the system, these structures filter harmonic currents that they are tuned to. As explained in [22]; passive filters, which consist of reactor and capacitor, typically provide an alternative impedance path for harmonic currents generated by the harmonic sources. Single tuned passive filters are cheap and easy to operate in practice. However, unlike active filters, they cannot adopt the changes in the system to filter out other harmonics. Therefore, single tuned passive filters need to be custom designed considering specific system impedances, load current harmonics, background voltage distortions; otherwise it results in poor performance due to interactions, and overall system performance may get worse [7, 23, 24].

Another important point is not to cause a parallel resonance during filter design. Parallel resonance is very dangerous since if the parallel resonance peak is aligned with the frequency of a characteristic harmonic injected by the load, high voltage and currents can flow causing damage to equipment in the network [25].

Harmonic filter device selection process begins with defining rated voltage, required reactive power and tuning frequency. Then, to meet reactive power requirement,

$$\frac{V^2}{X_C - X_L} = Q \qquad [3.5]$$

where "V" and "Q" are rated voltage and reactive power respectively. "X_C" and "X_L" are reactances of the capacitor and the reactor, respectively.

$$X_C = \frac{1}{(2\pi f) \times C} \qquad [3.6]$$

$$X_L = (2\pi f) \times L \qquad [3.7]$$

Secondly, tuning frequency is determined according to equation,

$$\frac{1}{2\pi\sqrt{L \times C}} = f_{tuning} \qquad [3.8]$$

Hence, equations 3.8 and 3.5 should be solved simultaneously yielding capacitance and inductance values.

Voltage rise on capacitor should also be taken into account in order not to damage the equipment. Capacitor voltage rating should be selected according to the equation,

$$V_C = V \frac{X_C}{X_C - X_L} \qquad [3.9]$$

Moreover, switching transients and voltage transients on mains side should also be taken into account. Usually, voltage is multiplied with a safety factor as well.In the light of these information, the parameters are conducted to the manufacturer (see Table 3.6). Capacitors are designed with built in fuses and are compatible for indoor installation.

Table 3.6: *Technical specifications of capacitors*

Material	Stainless steel
Dielectric	Polypropylene film
Impregnate	Non-PCB
Discharge resistors	Built in
Standards	IEC 60871-1
Voltage	1.2 kV
Maximum continuous voltage	1.3 kV
BIL	20 kV
Reactive power rating for each capacitor	540kVAr (@ 1kV)
Capacitance per phase Y	477.5 uF

3.5 Coupling Transformer Design:

Coupling transformers for SVC systems require more attention than regular distribution or power transformers. According to [5], these differences can be tabulated as given in Table 3.7.

As explained in Chapter 2, TCR itself is a source of harmonic currents. Some of the harmonics can be (and in general they are) filtered using harmonic filters; however all the harmonics cannot be filtered out due to economical and practical reasons. This brings the obligation for coupling transformer to tolerate harmonic components in current. Harmonic components cause extra heat generation as they increase transformer losses. Moreover, if they coincide with parallel resonance frequency of the system, they are amplified and become more dangerous for system safety.

Dc bias current may saturate the transformer resulting in an increase of the harmonics. Main reasons of dc bias current in the valve windings of converter transformer can be summarized as [11];

- **Firing angle asymmetry:** This is the result of firing error. If a thyristor valve firing is delayed dc bias current is generated [12]. The firing angle asymmetry in triggering system is mainly the result of low digital resolution (especially in terms of PLL generation) and delays due to hardware. Typically it is about 1.0^0.
- **Unbalance of the converter transformer commutation reactance:** It causes an overlapping time during which one valve is commutated to another one. The unbalance in commutation reactance is usually less than 2.5%.
- **Asymmetrical AC voltages (negative sequence 3rd harmonics):** Voltage unbalance can produce harmonics by its influence on the firing angle and overlap in the different phases resulting in harmonics of the order $n = k \times p \pm 3$ where k takes the integer values 0, 1, 2…., and p is the pulse number of the converter. Within these harmonics, the 3rd harmonic is the lowest one and the most probable cause of dc bias on the valve-side of the converter transformer due to its sideband influence. The percentage of the negative sequence voltage is normally less than or equal to 0.5% in normal operating condition and 2% in extreme condition.

In order to prevent coupling transformer from undesirable effects of direct current component and harmonics generated by TCR, the magnetic operating point can be placed to the linear portion of the B-H characteristics [13]. B_{op} can be selected below 1.6Wb/m^2 instead of 1.8 Wb/m^2 which is used normally for distribution transformers [8].

Table 3.7: *Comparison between conventional power / distribution transformers and SVC coupling transformer*

Property	**Conventional Power or Distribution Transformers**	**SVC Coupling Transformer**
Total demand distortion (TDD)	Limits defined by [28,29,30]	High if filters are mostly at the primary side
Even harmonics in the load (and SVC)	Limits defined by [28,29,30]	Higher than limits
Dc current	None	Depends on the controller, may be excessive in misfiring conditions
Voltage fluctuation	Limits defined in [31,32]	Depends on load bus, mostly higher than regular
Transformer design	IEC 600076-1, ANSI C.57 [33,34]	IEC 76, ANSI c.57; with minor additions
Core size and physical dimensions	Regular	Core and case dimensions are bigger for the same MVA
Overloads	Rare, depending on load busbar	Usual, depending on load busbar
Load fluctuation	Low	High, especially in arc furnace applications
Saturation	IEC 600076-1	Needs extra precautions
Hot spot probability	IEEE/ANSI C.57.91-1995 [34]	IEEE/ANSI C.57.91-1995 [34]

Two transformers with Δ-Y and Y-Y type of coupling (requirement for 12-pulse operation) is another important concept to pay attention. For Δ connection, triplen harmonics do not penetrate into the power system, instead they circulate in Δ (see chapter 2). Hence, transformer windings must be capable of carrying those currents also.

Coupling transformer in the developed system is designed to be used outdoor. It is oil impregnated. In terms of protection, it has bucholtz relay as well as thermal detector/relay for winding and oil temperatures. Offline tap changer is added so that for different operating conditions (for summer and winter for example) voltage ratio can be changed. Considering solar radiation level and heavy pollution, appropriate painting is selected. Technical properties are presented in Table 3.8 and 3.9.

Finally, according to the document sent by the manufacturer; magnetic field strength, specific power losses and apparent power of transformer is provided in Figure 3.16.

Table 3.8: *Coupling transformer technical characteristics*

Connection Type	YNyn0 / Dyn11 (2 different connection types as required for 12-pulse operation
Rated power	1.6 / 2 (MVA)
Rated primary voltage	33 (kV)
Rated secondary voltage	1 (kV)
Primary highest voltage	38 (kV)
Secondary highest voltage	1.2 (kV)
Insulation (1 min, AC)	70 / 3 (kV, peak)
BIL	170 / 20 (kV, peak)
Rated frequency	60 Hz
Short-circuit impedance voltage	% 6
Rms primary total current	35 A
Rms secondary total current	1155 A
TDD (secondary)	% 4 (see Table 3.8 for details of maximum values)
Rated short time currents (secondary)	• Thermal : 23 (kA, rms / 3s) • Mechanical : 58 (kA, peak)
Magnetic flux density (B)	≤1.55 (Tesla)
Cooling method	ONAN / ONAF
Number of taps	+15%/-15%, 7 taps (5% steps)
Maximum ambient temperature	+50 (°C)
Solar radiation level	1127.4 (W/cm^2)
Maximum altitude a.m.s.l.	≤1000 (m)
Standards	IEC 60076-1

Table 3.9: *Harmonic currents for 3 seconds average (without considering the voltage harmonic levels from measurement at the PCC), I_L=924 A*

Harmonic Order	Transformer Secondary Nominal Current (%)
2	0.92
3	2.71
4	0.43
5	1.95
6	0.25
7	1.52
8	0.2
9	0.5
10	0.13
11	0.5
12	0.12
13	0.4
14	0.11
15	0.4

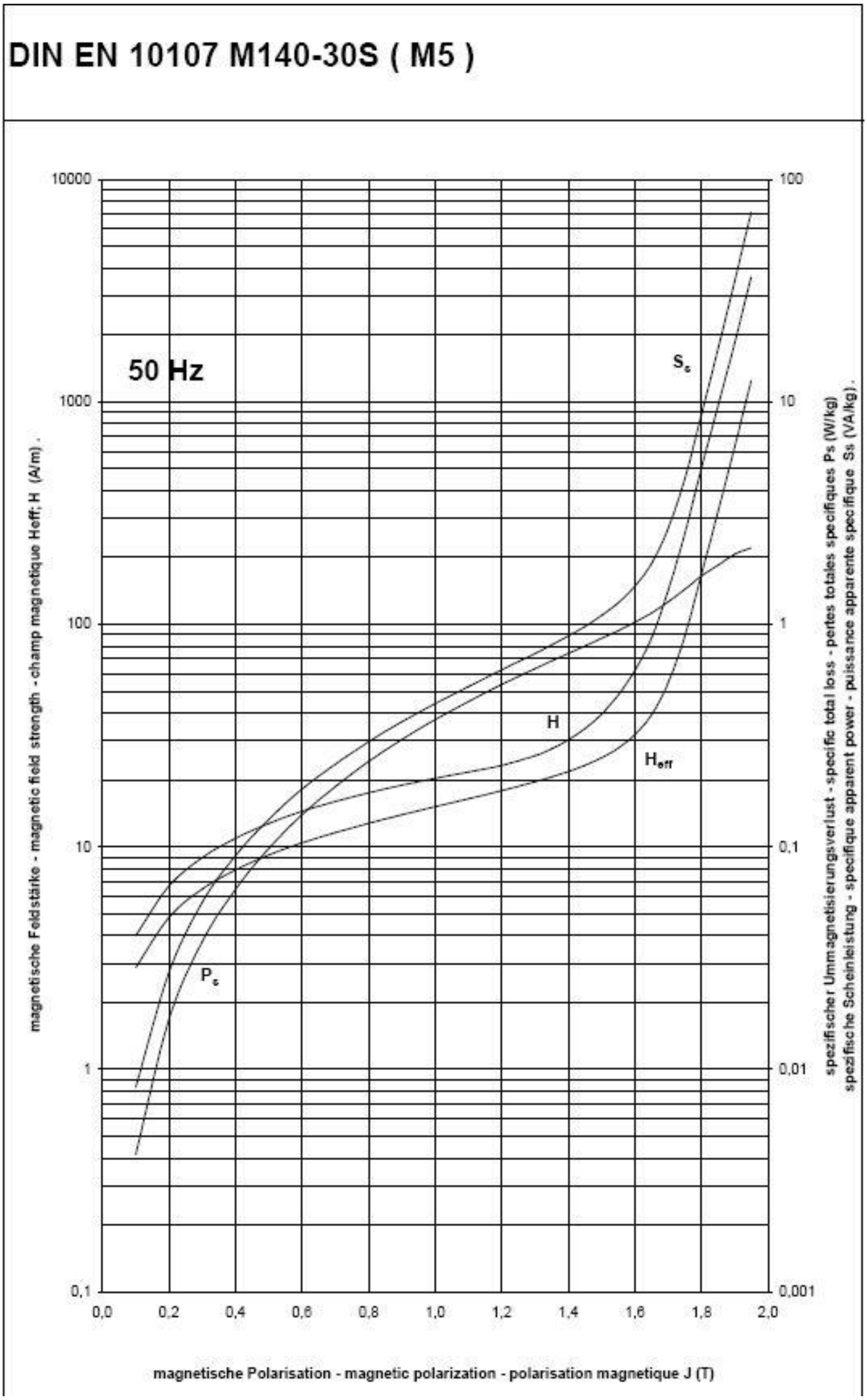


Figure 3.16: *B-H characteristics of coupling transformer*

3.6 Power System Protection Design:

During the operation of SVC systems there is always risk of facing with electrical faults. Short-circuits, overloads, thyristor misfiring problems etc. are typical faults. In case of an electrical fault both the SVC system and electrical network must be protected.

Protection action should be as quick as possible to minimize the damage. Moreover, part of the system that requires isolation should be detected carefully in order not to de-energize unnecessary parts.

Protection system consists of protection relays, measurement transformers (current and voltage), a digital signal processor (protection DSP) and circuit breakers.

Designed system has 5 protection relays and one DSP as the main controller of protection coordination. According to the single line diagram (see Figure 3.3), their sources of signals, protection types and corresponding circuit breaker operations are given in Table 3.9.

According to IEEE standard [26], there are two levels of alarms; first level alarms lead to a warning and second level alarms lead to a shutdown.

When selecting the switchgear equipment power factor impact should be taken into account. This is because most of the switchgear equipment are suitable to operate at high power factors. Therefore, their rated values are smaller for low power factors. In SVC system it is very possible to have highly inductive and/or capacitive currents. Especially purely capacitive and purely inductive currents may cause re-striking which imposes high voltage surges because of arcing. In such cases, a damping or snubber circuit may be necessary [27]. In order to solve any possible re-striking, special attention is paid. Firstly, switchgear equipment is selected in a way that its capacitive current operation limit is more than rated filter current. Moreover, in faulty conditions thyristor triggering is stopped to prevent excessive current on thyristors. Finally, 3rd harmonic filter being parallel with TCR behaves like a snubber circuitry for reactor currents.

Table 3.10 summarizes protection coordination. In the table, "X" represents circuit breaker openings (see Figure 3.5 for corresponding positions). In addition to overload and overvoltage protections, DSP protects system against dc current fault. Threshold value for dc current fault is calculated assuming that the firing angles for positive and negative cycles are at limiting values, meaning full conduction for positive half-cycle and zero conduction for negative half-cycle. Then by adding a safety factor to that dc value, threshold is set. DSP creates measuring windows to calculate dc value.

Table 3.10: *Protection coordination*

Protection Device	**Source**	**Fault Type**	**Circuit Breaker Action**			
			CB1	CB2	CB3	CB4
Busbar Protection Relay1	**PT1/CT1**	Transformer Overload/Overcurrent	X	X	X	X
		Overvoltage		X	X	X
		IRF	X	X	X	X
Busbar Potection Relay2	**PT2/CT3**	TCR Overload/Overcurrent		X	X	X
		Undervoltage		X	X	X
		IRF		X	X	X
Feeder Protection Relay1	**CT4**	3rd HF Overload/Overcurrent		X	X	X
		IRF		X	X	X
Feeder Protection Relay2	**CT5**	4th HF Overload/Overcurrent			X	X
		IRF			X	X
Feeder Protection Relay3	**CT6**	5th HF Overload/Overcurrent				X
		IRF				X
Protection DSP	**PT2/CT7**	Overvoltage		X	X	X
		Dc current fault		X	X	X
		Overload / Overcurrent		X	X	X

In developed system, 36kV switchgear is manufactured as cubicles by the manufacturer. 1 kV circuit breakers; on the other hand, are designed to be fit in the panels. They are seen in Figures 3.17 and 3.18 respectively.

Figure 3.17: *36kV circuit breaker cubicle*

Figure 3.18: *1kV circuit breakers mounted on the distribution panel*

CHAPTER IV

VOLTAGE REGULATION STRATEGIES FOR 12 - PULSE OPERATION

In this thesis work, two parallel 6-pulse systems are designed to be suitable for both independent and parallel (master-slave) operation. Simulation results and field achievements are obtained for both conditions. Main objective during studies is to regulate voltage while suppressing $6n \pm 1$ (n is odd) harmonics.

4.1 Independent Mode of Operation

In independent mode of operation, systems do not interact with each other; instead, they behave like 6-pulse individual systems. They do not have to communicate with each other since they generate their own reference current and so their own firing angles.

Independent mode is the basis for master-slave operation. It can be explored in two main structures, firing angle calculation and phase locked loop (PLL) generation.

For calculating firing angles; transformer primary side voltages (line-to-line), primary side currents and secondary side voltages (line-to-line) are measured as inputs. Using equations explained in Chapter 2, SVC voltage is calculated. Then this voltage is compared with the reference voltage, which is adjustable and initially 33kV for this system. As a result, voltage error is generated. Voltage error shows how much SVC current should be adjusted. Using Proportional-Integral (PI) type controller, magnitude of current that SVC should generate is calculated. Finally, this current is converted into firing angle using pre-generated lookup table. Figure 4.1 summarizes working diagram of the control system in independent mode.

On PLL generation, secondary voltages (line-to-line) are used. Each phase is considered alone and PLL is generated independently for all three phases. According to line-to-line voltage measured, other two phases are generated by creating 120 degrees of phase difference. Firstly, these three voltage components are transformed into two components using alpha-beta transformation matrix. Then, d-q transformation is applied. Reference frame is chosen in such a way that direct (d) component and corresponding line-to-line voltage are on alignment. At the end, d-component is compared with zero and error is fed to PI controller in order to stick to correct angle. In Figure 4.2, PLL generation algorithm is shown.

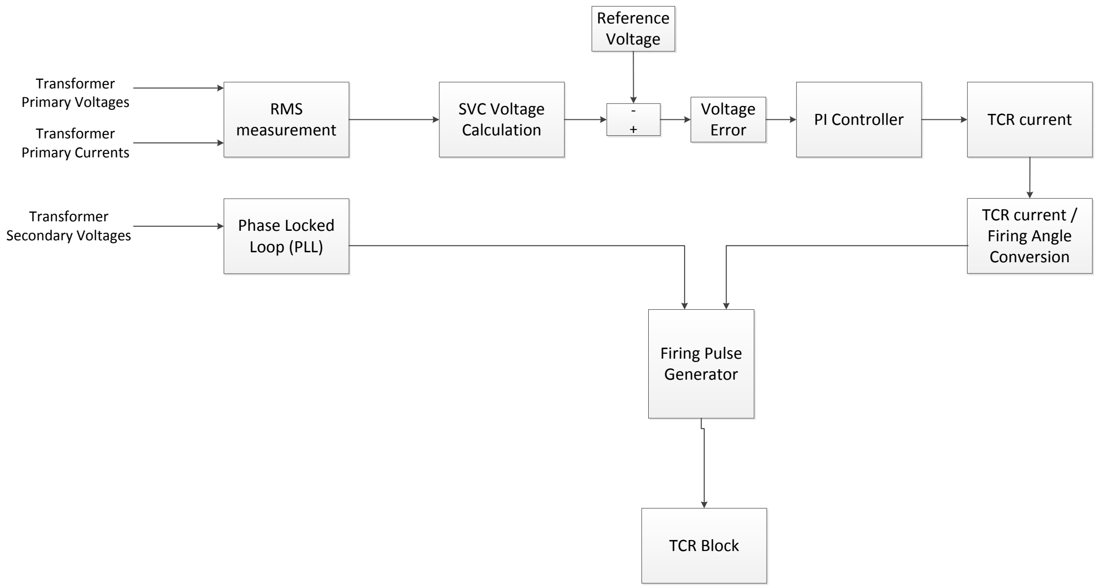


Figure 4.1: *Operational diagram for independent mode of operation*

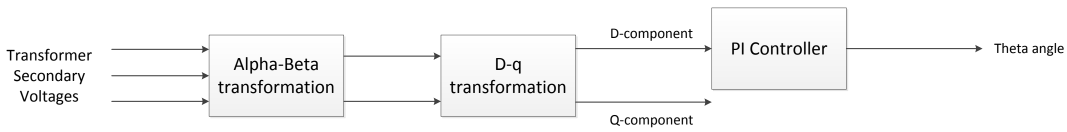


Figure 4.2: *PLL algorithm*

SVC slope is one of the critical points on control algorithm. Slope (or voltage droop) can be considered as the tolerance of SVC to the difference between reference voltage and actual voltage. Slope creates a reduction in SVC response. With no slope, SVC system shows very large changes in its output as a response to small changes in the mains voltage. Moreover, slope prevents early reaction of SVC systems so that it is useful for parallel operation. Slope can be either positive or negative (see Figure 4.3). However, it should be selected as positive for stability reasons since negative slope causes avalanche effect for changes in the busbar voltage. For designed SVC system, resultant SVC I-V characteristics for different topologies are presented in Figure 4.4 below.

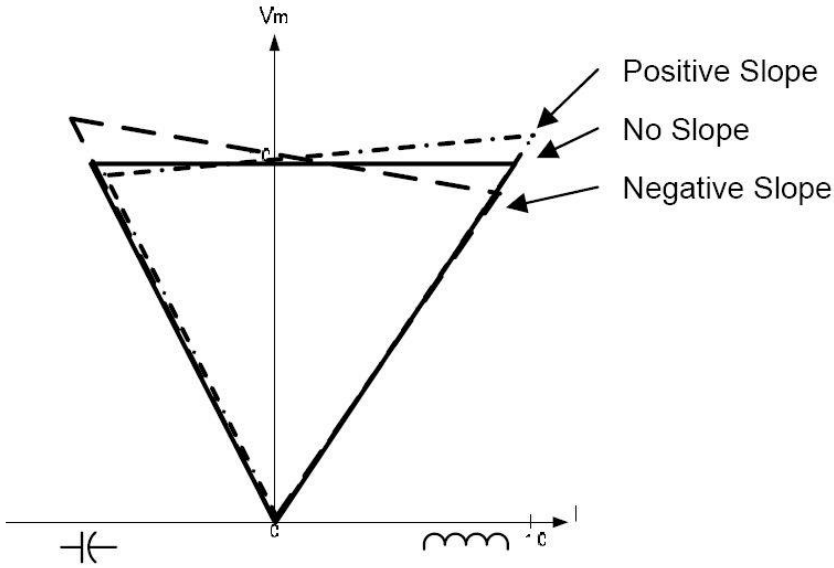


Figure 4.3: *Slope effect on SVC characteristics*

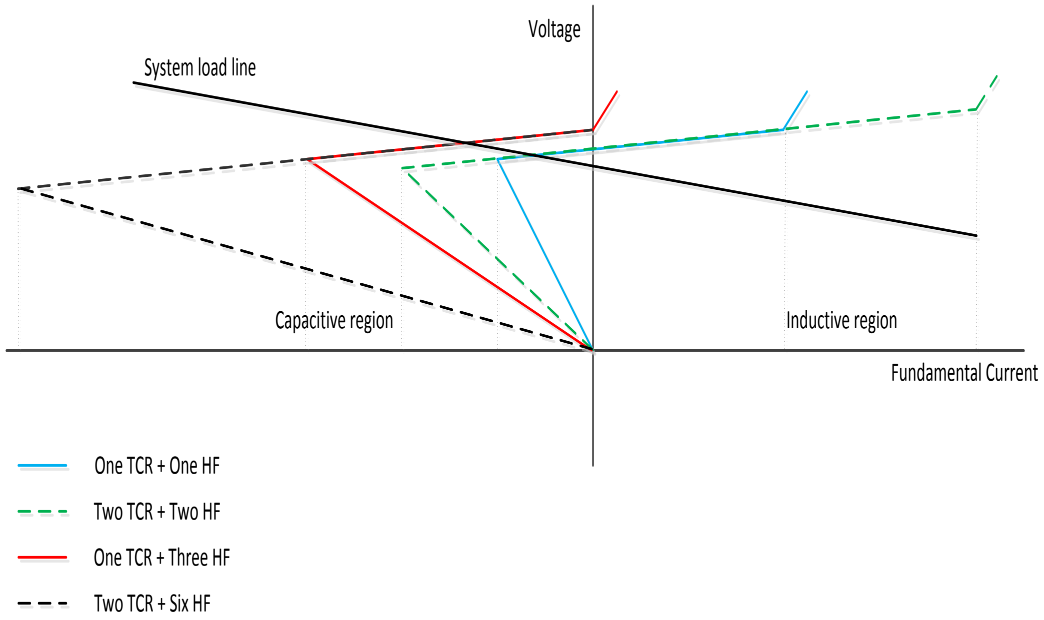


Figure 4.3: *I-V Characteristics of SVC system with different topologies*

On simulation environment it is proven that as long as SVC power is enough, algorithm is successful on voltage regulation. PLL generation, firing angle calculation and triggering operations are controlled for different reference voltages and the results are satisfying. In Figure 4.5, PLL and triggering pulse waveforms with corresponding voltage component is given. At that figure firing angle is measured as nearly 115 degrees.

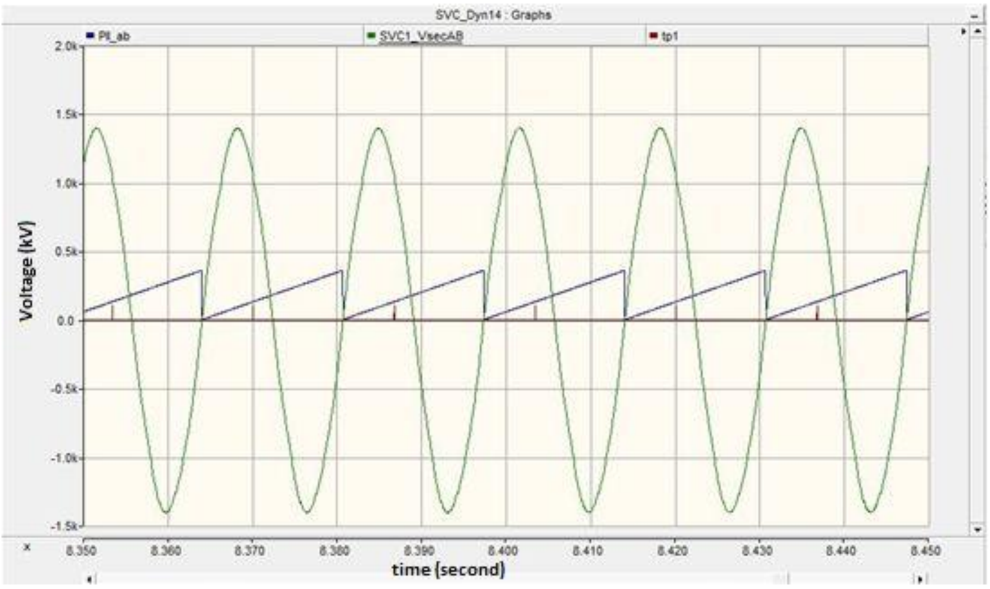


Figure 4.5: *Waveforms for firing angle of nearly 115 degrees (simulation)*

Load sharing is the main disadvantage of independent operation. In detail, since systems do not communicate with each other, they don't share load equally. Although they have the same control parameters, one system reacts faster and injects reactive power after a change in voltage. The other system tries to follow the first one by taking some of the load. Then the first system reacts to this change. As a result, there may be an oscillation and unbalance of reactive power distribution between SVC's. To show the affects clearly, reactive power of both systems are drawn according to the changes in reference voltage. In Figure 4.6, reference voltage is changed from 33kV to 31kV with the steps of 0.5kV. Figure represents the distinction between reactions of two systems. Oscillations in reactive power generations and so in mains voltage is also seen in the figure.

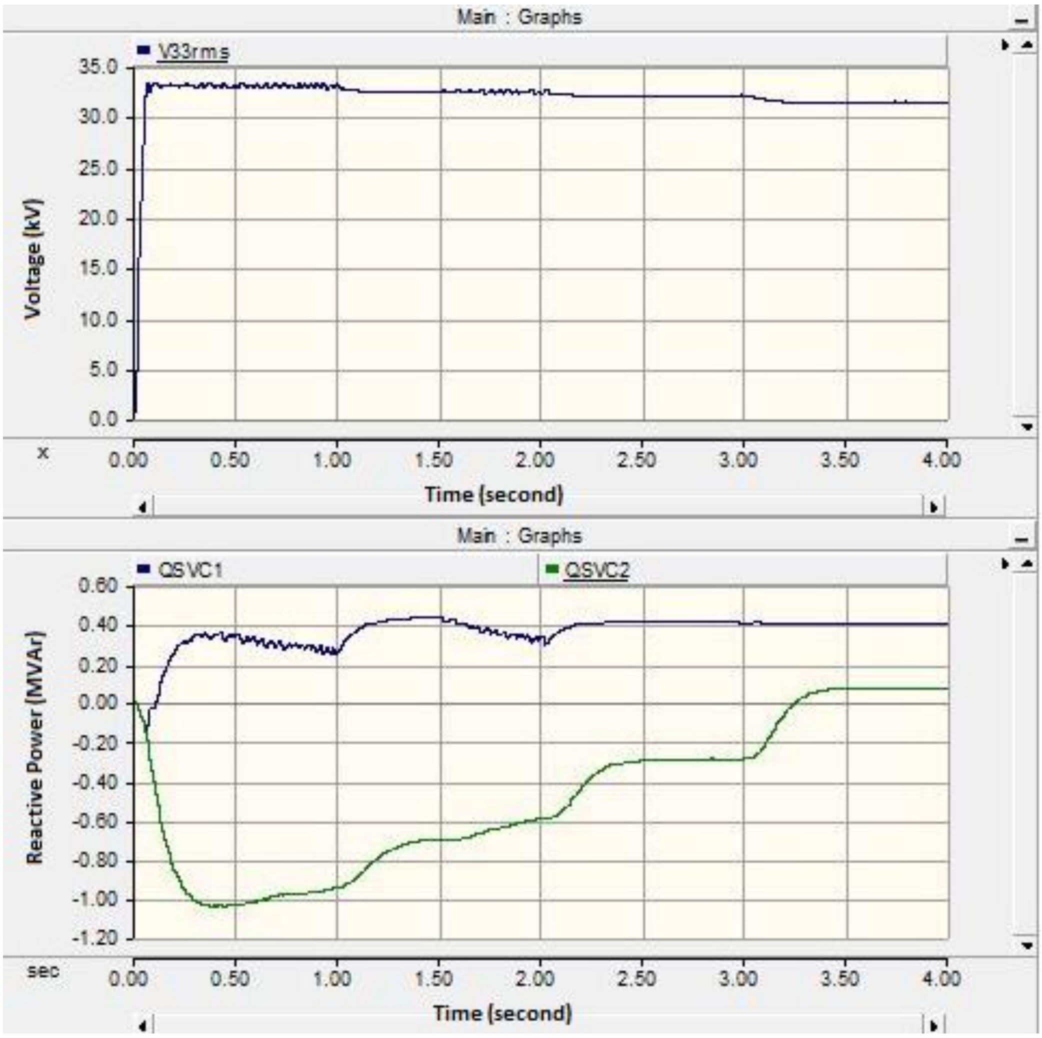


Figure 4.6: *Load sharing for independent operation showing asymmetrical operation and oscillations (simulation)*

4.2 Parallel (Master - Slave Operation)

In parallel mode of operation, two systems share total reactive load, behaving like one 12-pulse SVC system. One of the systems is defined as master (control authority) and the other is defined as slave.

Master behaves like an independent SVC up to some point. It takes necessary measurements from voltage and current transformers. Moreover, it has all the control parameters like K_p and K_i values. After making calculations, required reactive current is determined by the master. Up to this point, there is nothing different from independent mode of operation. What creates difference is the process for dispatching total reactive current between two systems.

Master SVC should determine how much reactive power will be generated / absorbed by each system. These shares depend on the control mode. There are three different control algorithms, namely;

- Asymmetrical load sharing
- Equal load sharing
- Sequential load sharing

Once each system has taken information about how much current they need to generate, they try to reach that current by adjusting firing angles with the help of proportional / integral (PI) controller. On the other hand, each system has to generate their own phase locked loop (PLL) structure from secondary side of their coupling transformers. This is preferred due to the phase difference and any other dissimilarity between two systems. Operational diagram for master-slave operation is given in Figure 4.7. Details of “current dispatch” and “TCR current / Firing angle conversion” blocks for master svc are given in Figure 4.8. Moreover, susceptance to firing angle relation taken from lookup table is presented in Figure 4.9.

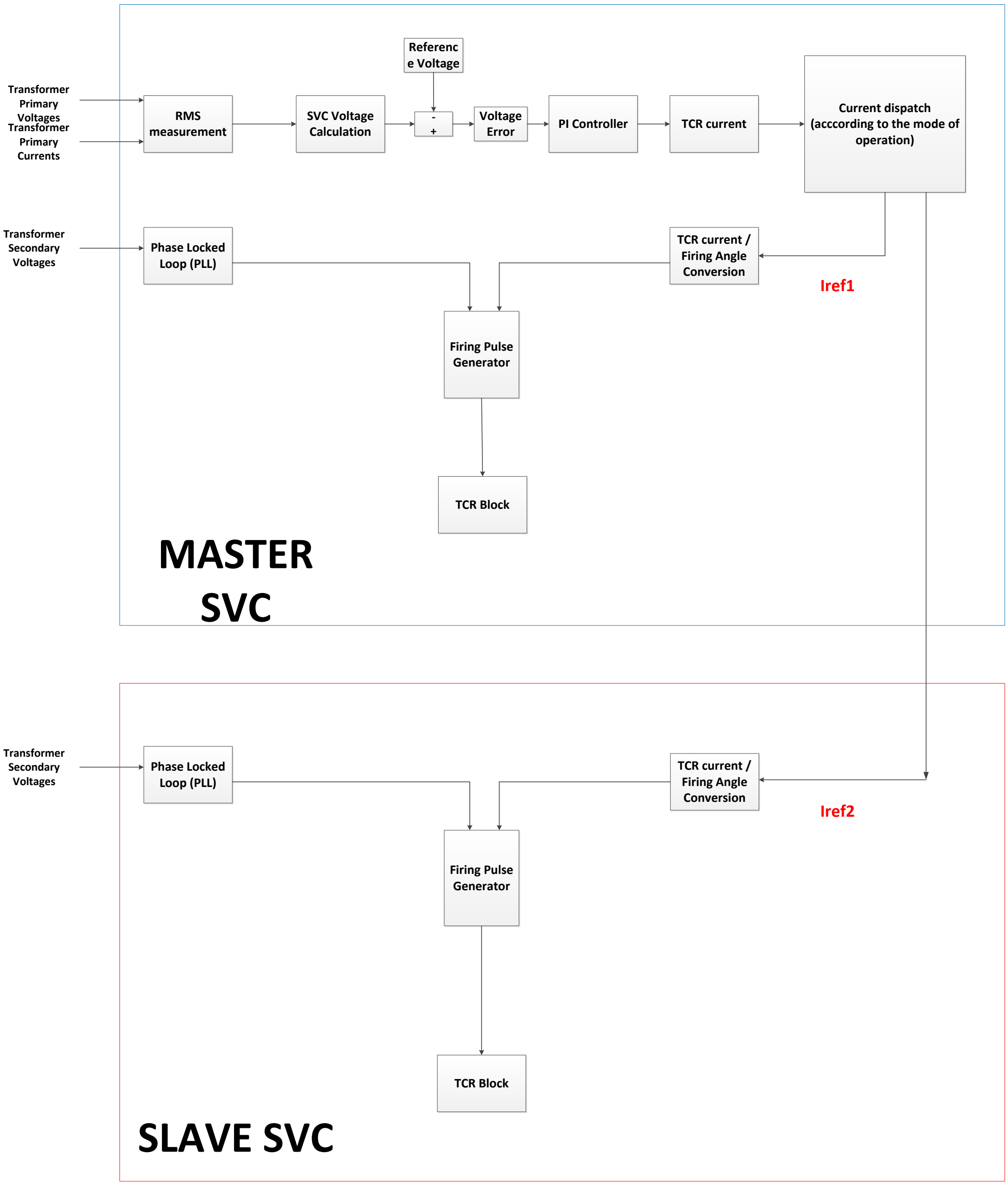


Figure 4.7: *Master-Slave mode operation diagram*

Maximum current carrying capability of the reactors is another important point to be considered. If the required current is greater than the maximum continuous current of TCR, then it damages the system. Thus, reference currents are compared with that limit before current / firing angle conversion.

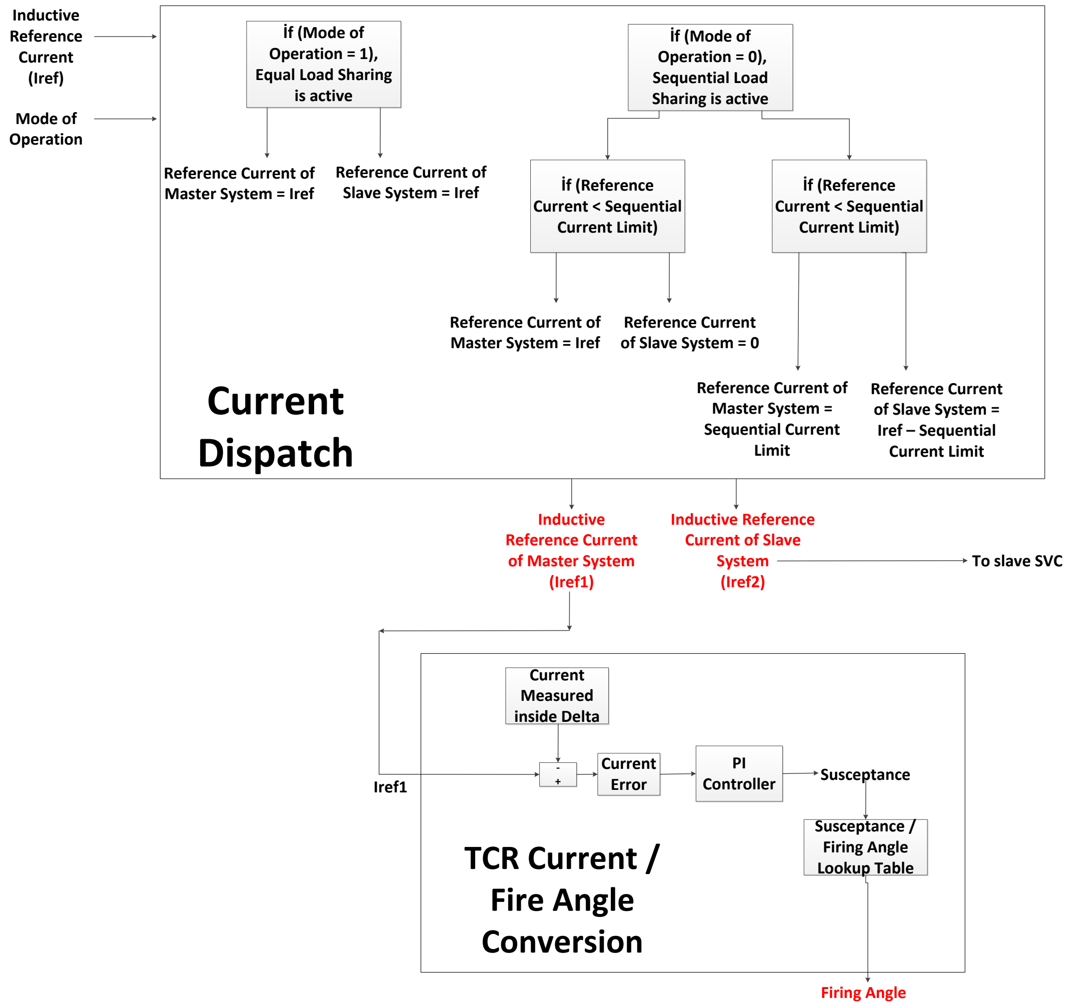


Figure 4.8: *Current Dispatch and Firing angle conversion block*

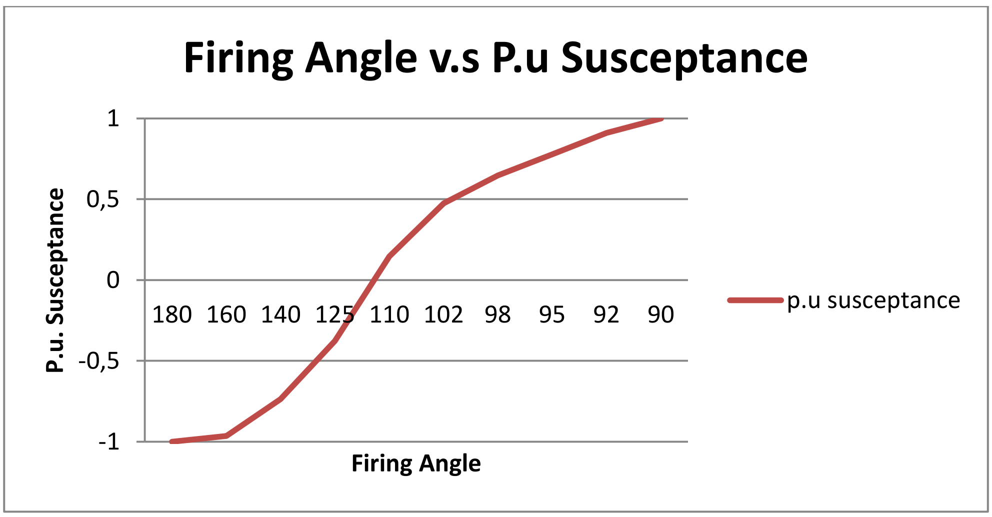


Figure 4.9: *Susceptance / Firing angle conversion graph*

4.2.1 Asymmetrical Load Sharing

Asymmetrical load sharing is kind of an open loop operation. In this mode, control system does not generate any reference current. Instead, reference currents are set externally by the user. Master system just sends that reference current to slave. Hence, this mode is generally used as a test procedure or to see the system situation for a specific reactive power generation.

4.2.2 Equal Load Sharing (Harmonic Cancellation)

In equal load sharing mode the total reactive current generation is dispatched to two systems equally. Thus, both SVC systems generate the same amount of reactive current.

When this mode of operation is realized, 5^{th} and 7^{th} harmonics generated by each system kill each other due to phase difference, resulting in no such harmonic current in the primary side as explained in Chapter 2.

For successive operation of harmonic cancellation, currents should be the same in magnitude. Theoretically, if both systems work with the same firing angles then their currents should be the same. However, in practice there are always dissimilarities. For example, reactance values of two TCR systems may differ from each other. In such a case, working with the same triggering angle yields different amount of currents passing through the thyristor controlled reactor. Hence, 5^{th} and 7^{th} harmonics are not filtered completely. However, as current is chosen as reference systems are not loaded asymmetrically. Thus, overload risk is reduced.

4.2.3 Sequential Load Sharing

In sequential load sharing mode of operation, one of the TCR systems is chosen to be loaded firstly, and the other to be kept as idle. In other words, one is kept unloaded until reactive power requirement reaches a predetermined value. When adjusted capacity of first system is exceeded, other system is triggered.

Sequential load sharing has the advantage of keeping one system as spare. In order to see the affects; sequential limit, the limit above which second SVC system is fired, is set to 485 amperes which nearly corresponds to 1.2 MVAr. 4^{th} and 5^{th} harmonic filters are off for both systems. Then, reference voltage is changed from 33kV to

32.7kV with the steps of 100V. According to changing values of required reactive current, shares of systems are tabulated in Table 4.1 below. Moreover, waveforms are shown in Figure 4.8. In Figure 4.8, "$İ_{ref}$" represents the total inductive reactive current requirement. "ref1" and "ref2" are the current references for master and slave systems respectively.

As seen in Figure 4.10, reference current of master SVC follows total reactive current requirement up to its sequential limit. Then, the difference between total reactive current requirement and the sequential limit is sent to slave SVC as its reference current.

Table 4.1: *Sequential mode of operation*

Reference Voltage	**Required Inductive Reactive Current**	**Generation of Master SVC**	**Generation of Slave SVC**
33kV	147.74 A	147.74 A	0
32kV	375 A	375 A	0
31kV	658.24 A	485 A	173.24 A
30kV	905.3 A	485 A	420.3 A

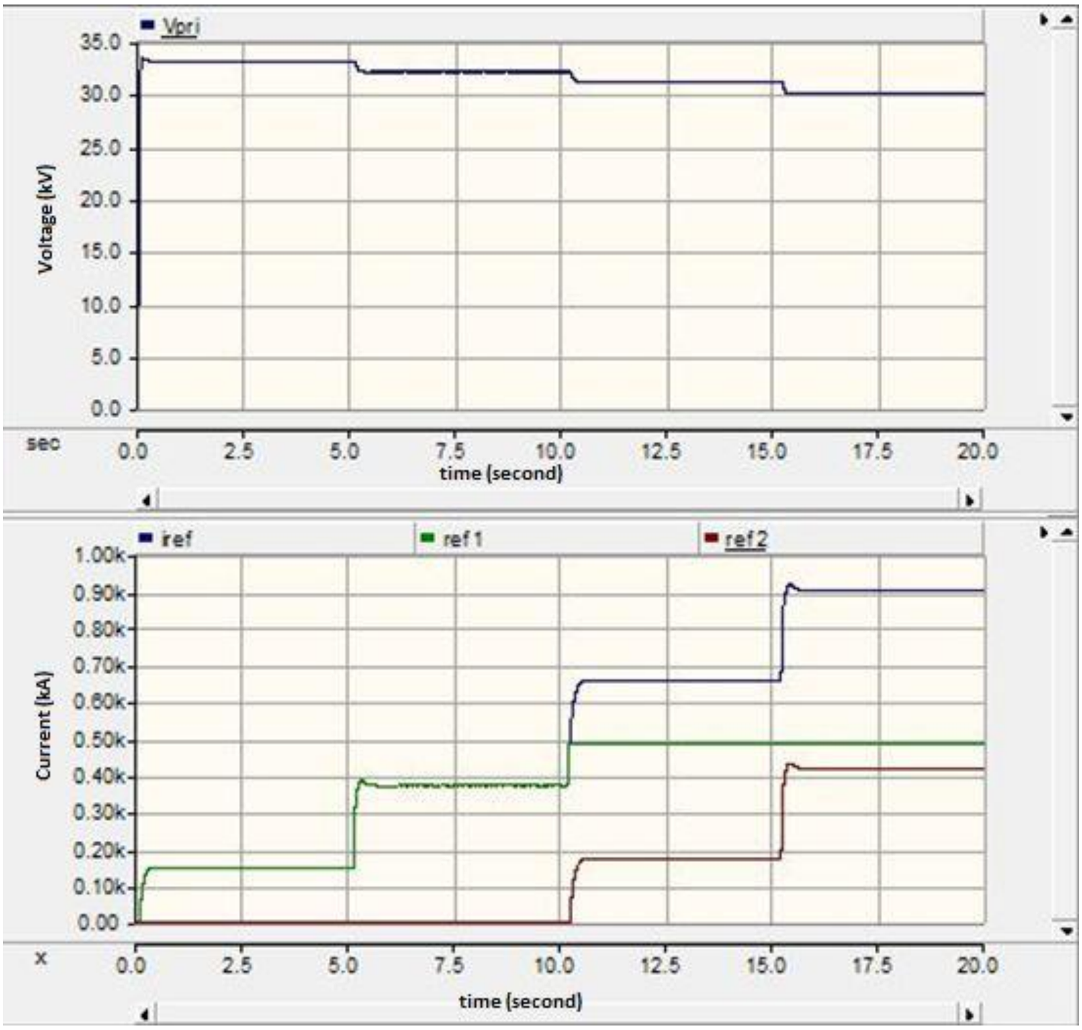


Figure 4.10: *Change of reference currents according to the reference voltage (simulation)*

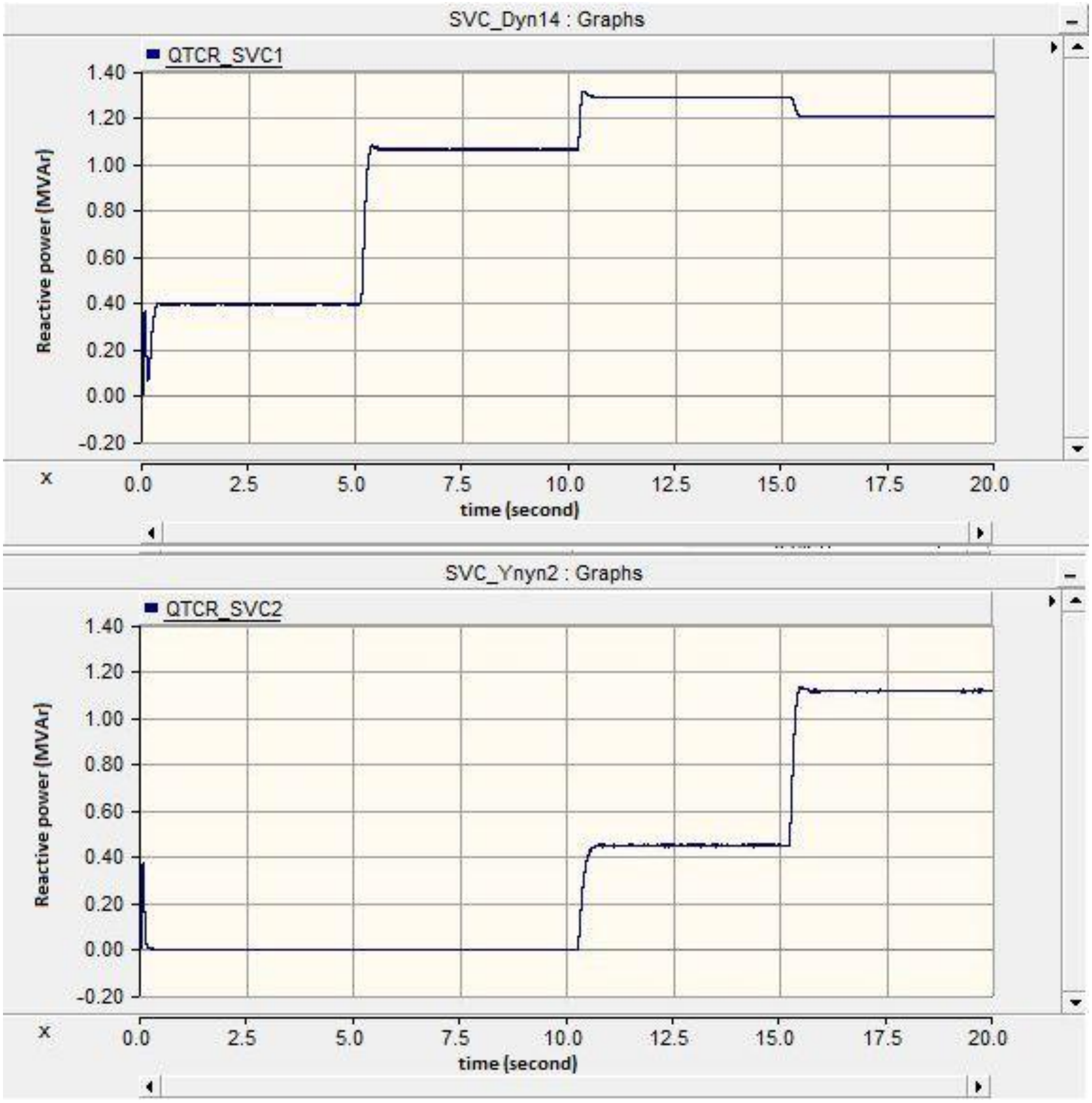


Figure 4.11: *Variation in reactive power generations of two TCR systems (simulation)*

Figure 4.11 shows how reactive power generation changes for sequential load sharing mode of operation. As expected, slave system (the lower graphic) does not operate until the reactive power requirement is more than the sequential limit. It is also important to note that the reason why QTCR1 decreases when the reference voltage is decreased to 30kV is because the power generation of TCR depends on the voltage. Thus, although the current of TCR in the master SVC stays constant decrease in voltage level causes the reactive power to be lower.

4.3 Comparison of 12-Pulse Control Strategies

12-pulse control strategies (equal load sharing and sequential load sharing) are both successful on regulating the mains voltage. However, they have different load dispatch characteristics. Hence, their power quality performances are not identical. In order to see the advantages and disadvantages of both systems, they are compared in terms of three performance criterion, namely;

- Dynamic response
- Harmonic current reduction
- Active power losses

4.3.1 Dynamic Response

During SVC operation, transients such as voltage sags and swells may occur. Compensation systems should be able to react well against these changes. Main objectives are fast response and small overshoot. However, there is a trade-off between these goals and optimization is required.

In order to check dynamic response quality, voltage reference is changed with the steps of 3kV (nearly 10% of the nominal voltage) and response curves are obtained. Results are compared for control methods, equal load sharing and sequential load sharing. Then, response curves are improved by adjusting four control parameters to finalize the responses. Two of these parameters are K_p and K_i for voltage reference settlement and the other two K_{pc} and K_{ic} for reference current settlement.

As comparison, it is observed that both control methods result in the same characteristics. This is because they have the same control algorithm except the dispatch equations for reference current. Different equations do not change reaction time.

Firstly, the results for over-damped response are obtained. Over-damped response has the advantage of not having overshoot; however, its reaction time is quite large. Results for over-damped response are represented in Figures 4.12 and 4.13.

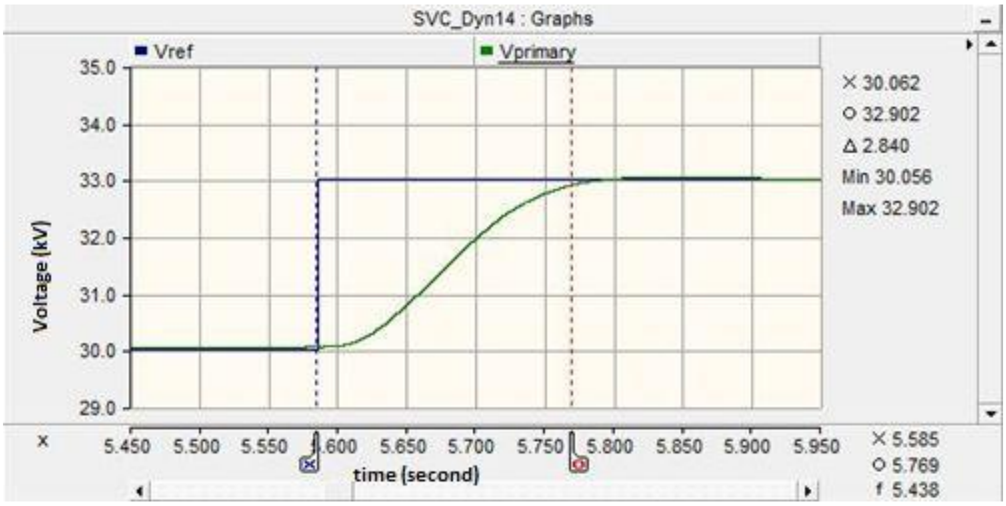


Figure 4.12: *Over-damped response curve from 30kV to 33kV (simulation)*

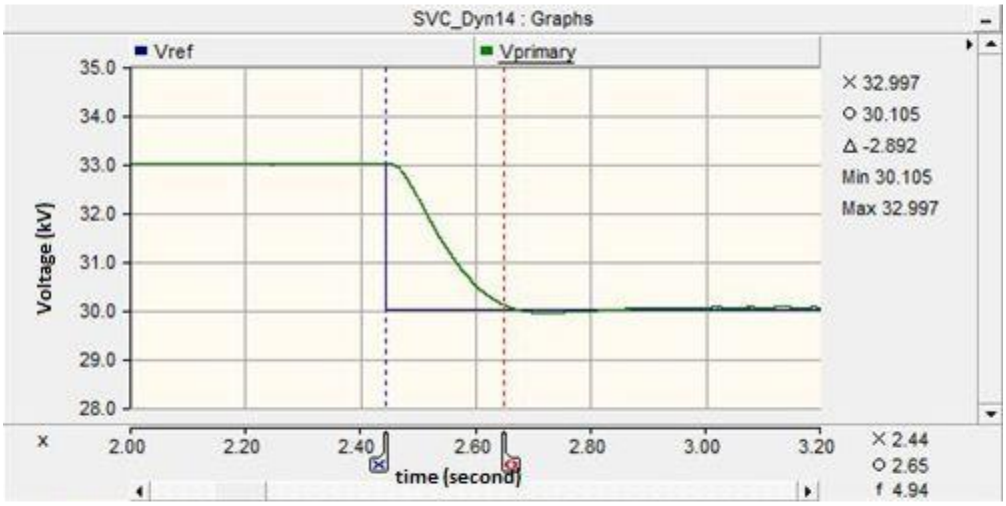


Figure 4.13: *Over-damped response curve from 33kV to 30kV (simulation)*

For over-damped response parameters are 0.8, 0.1, 1e-4 and 4e-6 for K_p, K_i, K_{pc} and K_{ic} respectively. Although there is no overshoot, response time is nearly 200 ms with these controller parameters. 200 ms is a very large value since it is expected that the system should react such changes during 3 or 4 cycles meaning 50 to 64 ms. Then control parameters are changed to decrease response time. When parameters are set as 250, 3, 8e-4 and 8e-6 underdamped response is obtained with nearly 30ms of response time. As seen in Figures 4.14 and 4.15, response is oscillatory so it has stability problems.

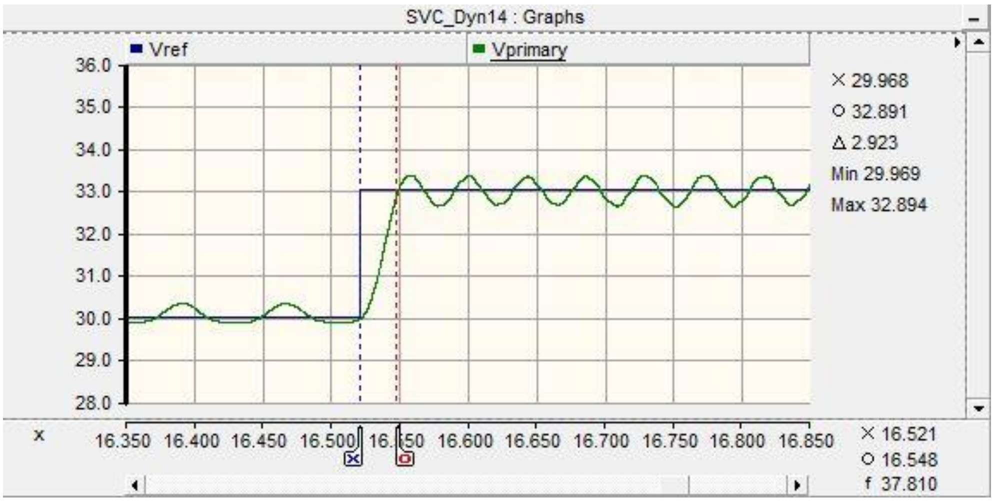


Figure 4.14: *Under-damped (and oscillatory) response curve from 30kV to 33kV due to unproper parameter settings (simulation)*

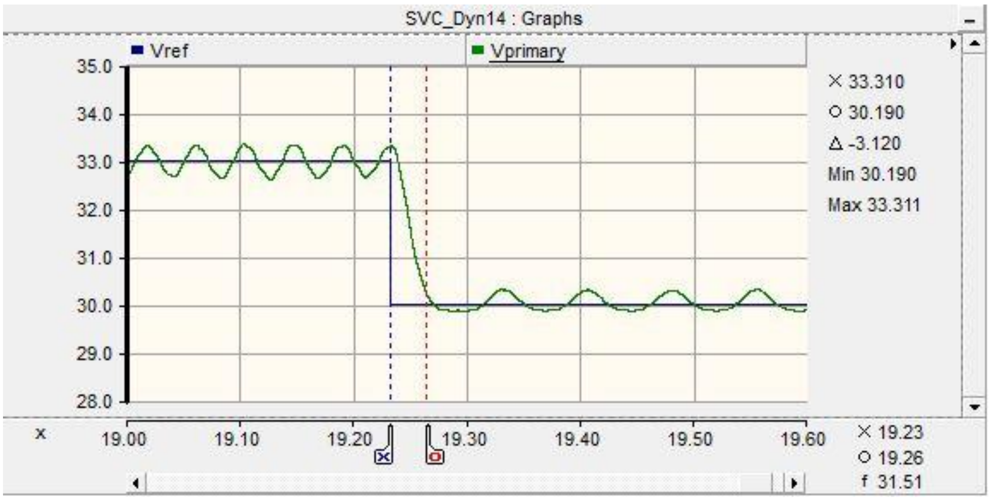


Figure 4.15: *Under-damped (and oscillatory) response curve from 33kV to 30kV due to unproper parameter settings (simulation)*

At the end, control parameters are adjusted to have a critically damped response. When parameters are 250, 0.7, 8e-4 and 8e-6; critically damped response is achieved with results given in Figure 4.16 and Figure 4.17.

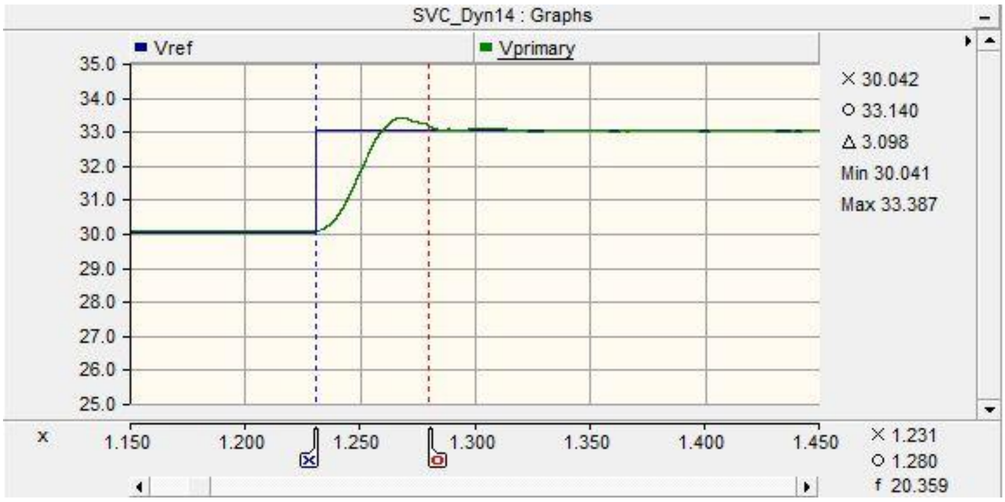


Figure 4.16: *Critically damped response curve from 33kV to 30kV (simulation)*

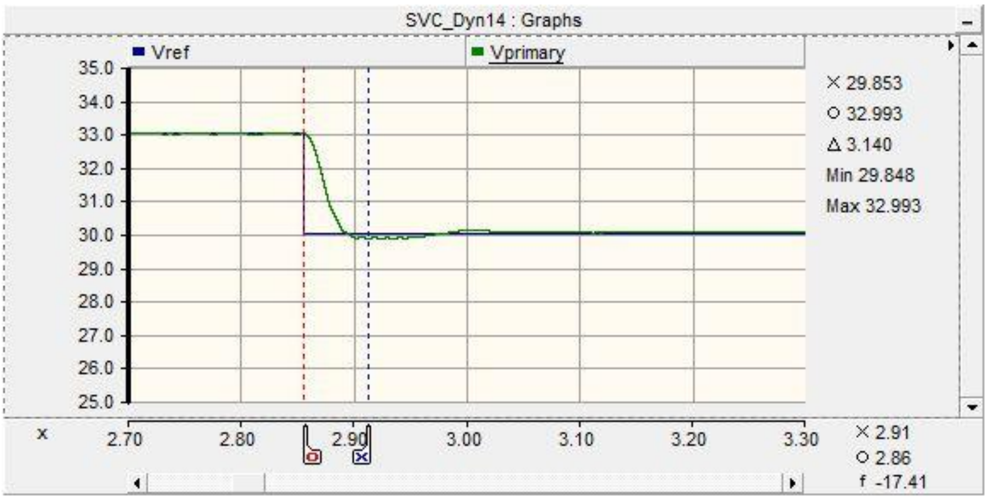


Figure 4.17: *Critically damped response curve from 33kV to 30kV (simulation)*

For critically damped response, reaction time (considering 5% of settling time) is about 50ms. On the other hand, its overshoot is nearly 10% of the step value. Positive and negative step changes result is very similar results.

4.3.2 Harmonic Current Reduction

As explained in Chapter 2, due to its working dynamics SVC systems behave like current sources and they generate current harmonics. In previous chapters, damages caused by current harmonics and corresponding penalty limits are also explained. The most problematic harmonics generated by TCR are low order (3^{rd}, 5^{th} and 7^{th}) harmonics (see Table 2.2).

3rd harmonic component of the current in balanced operation is basically eliminated by using appropriate configuration for TCR. If Y-connected TCR structure is used, then 3rd harmonic causes problems even in balanced firing. However, delta-connected structure eliminates this probability since 3rd harmonic currents in balanced operation flow inside the delta. In order to prove this functionality, TCR is fired at 94 degrees and results are obtained in PSCAD. In figures 4.18 and 4.19, current harmonics with fundamental component are tabulated.

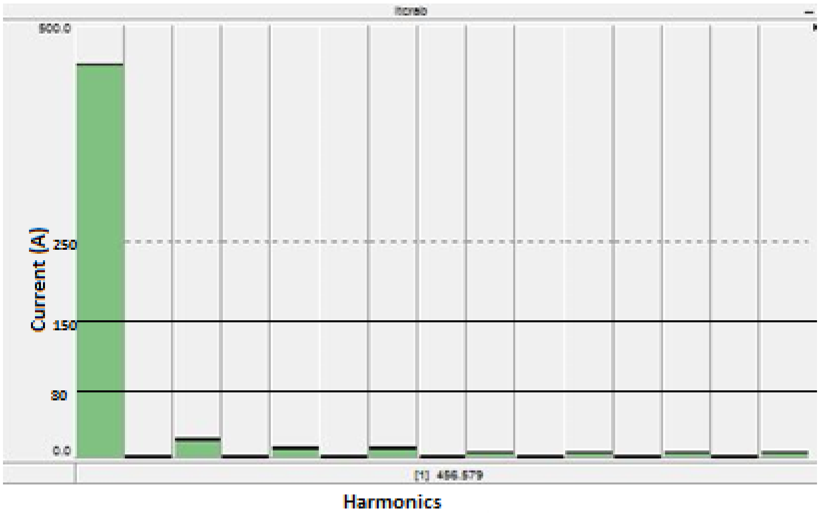


Figure 4.18: *Harmonic currents inside delta for balanced operation (simulation)*

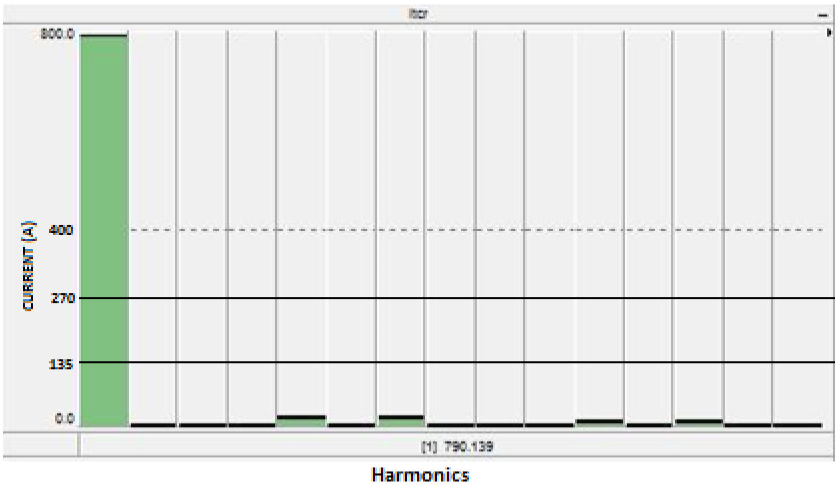


Figure 4.19: *Harmonic currents going out of delta for balanced operation (simulation)*

These figures prove that if TCR phase branches are triggered at the same angles, then no significant 3rd harmonic current will appear out of the delta. On the other hand, in case of an unbalance then 3rd harmonic current flows out of delta and it should be filtered.

When TCR block is fired with 5 degrees of difference between triggering angles (95, 100, and 105 degrees) then the current composition inside TCR delta and outside of the delta is shown in Figures 4.20 and 4.21 respectively. According to these figures, 3rd harmonic current goes out of delta with significant amount. It is measured that for 705 amperes of fundamental current component, 3rd harmonic magnitude is about 35 amperes going out of delta. This corresponds to 5% of fundamental current.

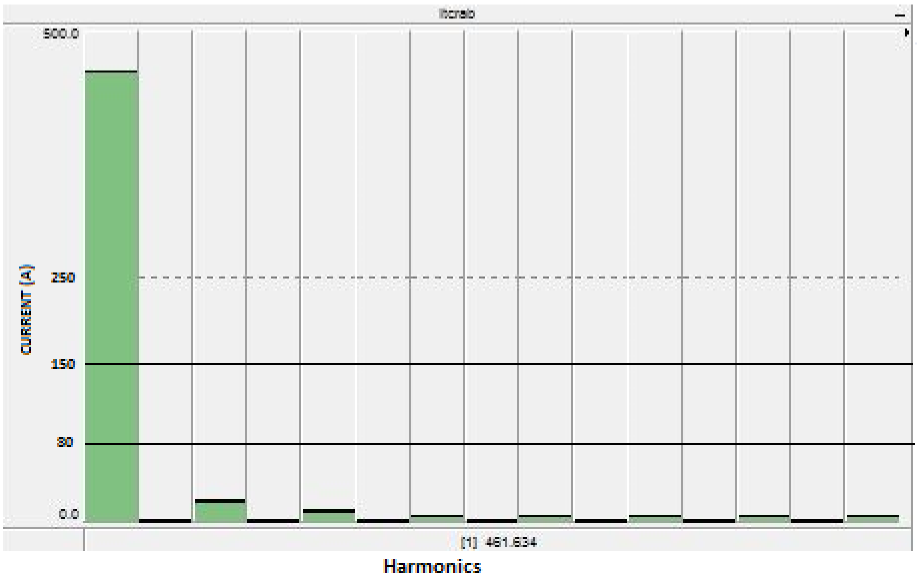


Figure 4.20: *Harmonic currents inside delta for unbalanced operation (simulation)*

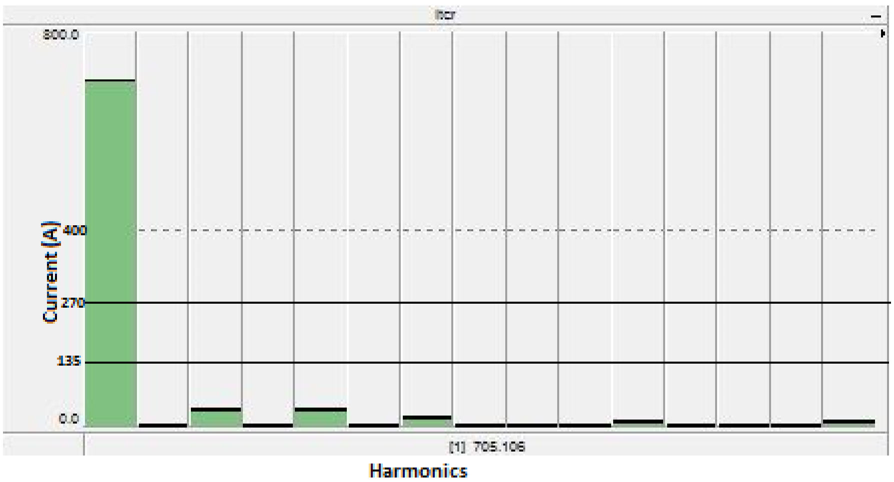


Figure 4.21: *Harmonic currents going out of delta for unbalanced operation (simulation)*

3rd harmonic filter is used to filter out this component. After filtration, 3rd harmonic current is measured about 4 amperes for a 406 amperes of fundamental component and this means 0,98 % of fundamental component (see Figure 4.22). Thus, 3rd harmonic filter is useful and it will filter out any 3rd harmonics during unbalanced operation.

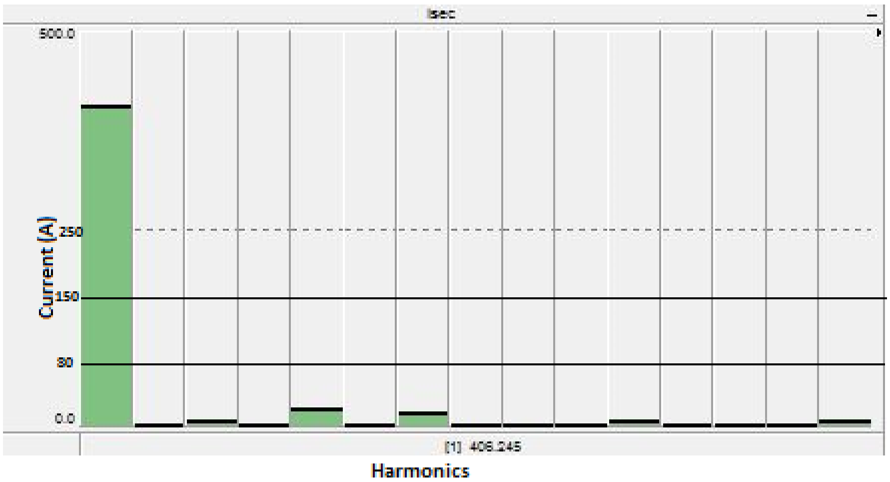


Figure 4.22: *Harmonic currents measured from transformer secondary after 3rd harmonic filtration (simulation)*

The next most problematic harmonics are 5th and 7th harmonics. As explained in chapter 2, the main objective of 12-pulse configuration is to filter out 5th, 7th, 17th, 19th,… harmonics. In order to test this functionality, 5th harmonic filters are switched off and reference voltage is set to 33kV. In this situation, harmonics at TCR branch, transformer secondary and point of common coupling (PCC) are measured for two different control methods: sequential load sharing and equal load sharing. For sequential load sharing mode, sequential limit is set to 500kVAr at 1kV side which corresponds to 288 amperes in line. For this specific condition total reactive power generation is nearly 1.9 MVAr; thus, the slave TCR is loaded with 1.4MVAr. On the other hand, for equal load sharing mode both TCR systems are loaded with nearly 1MVAr.

If sequential load sharing mode is used, then the harmonic components at the point of common coupling are given in Figure 4.23. However, with the use of equal load sharing mode, the results are tabulated in Figure 4.24. Results for 5th and 7th harmonic components are also tabulated as the percentage of their rated components in Table 4.2.

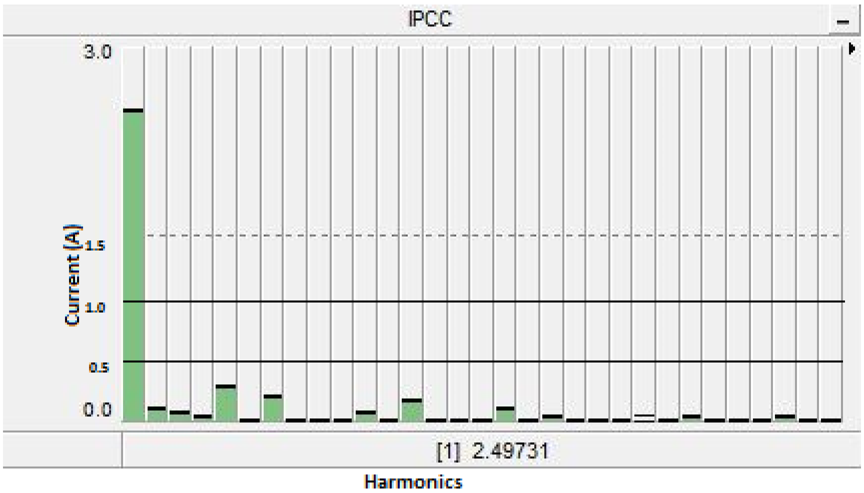


Figure 4.23: *Current harmonics at PCC with sequential load sharing (simulation)*

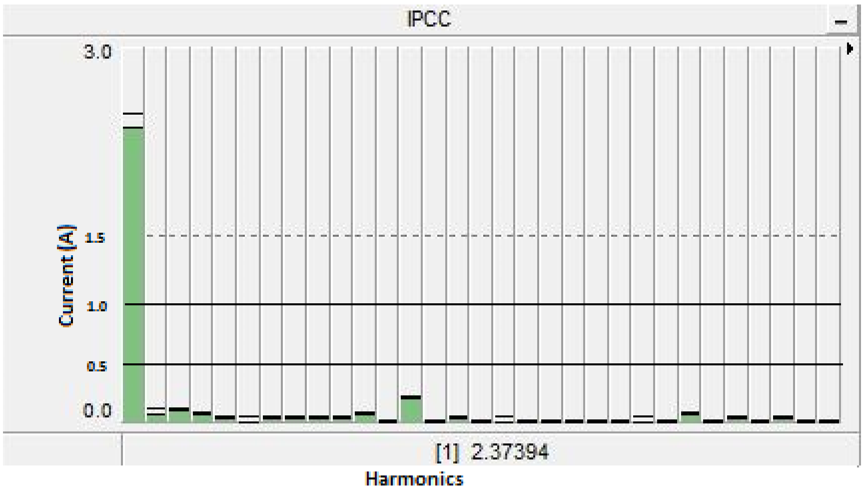


Figure 4.24: *Current harmonics at PCC with equal load sharing (simulation)*

Table 4.2: *Maximum harmonic currents at PCC as the percentage of their rated current when reference voltage is set to 33kV*

Control method	**5th harmonic current**	**7th harmonic current**	**17th harmonic current**	**19th harmonic current**
Sequential load sharing	%2.4375	%0.8982	%0.2	%0.0956
Equal load sharing	%0.075	%0.0973	%0.0411	%0.045

This is an expected result since in order to eliminate 5th and 7th harmonics, current magnitudes should be as close as possible. The same situation is analyzed with 10% difference between the reactor values of TCR systems. Although there is an increase in harmonic content, resultant harmonics are less than 2% for each component (see Figure 4.25) as expected. Even though systems try to produce the same current in terms of fundamental magnitude, their firing angles differ. This brings different harmonic content. Figures and the table clearly shows that equal load sharing has much better harmonic reduction performance than sequential load sharing mode.

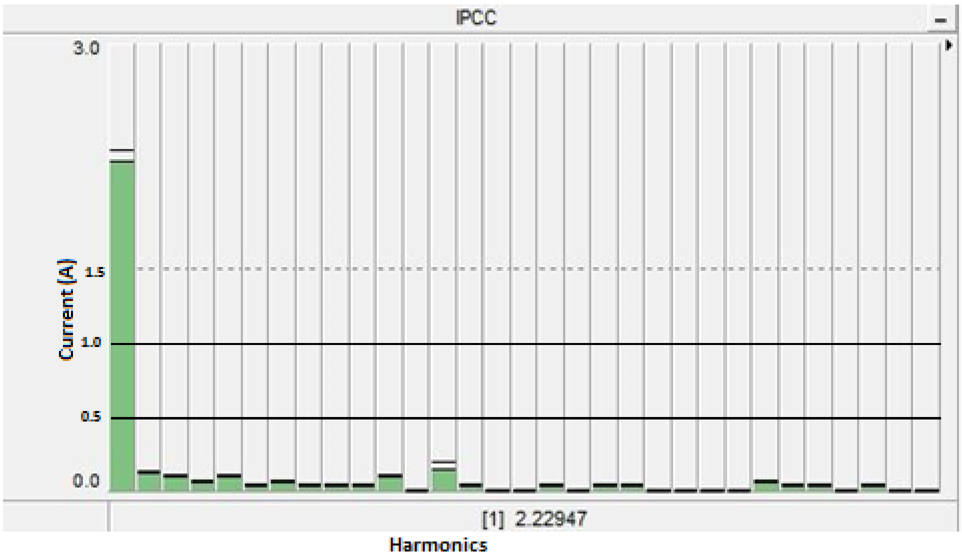


Figure 4.25: *Current harmonics at PCC with equal load sharing for unbalance (simulation)*

4.3.3 Active Power Losses

Theoretically SVC systems do not have active power consumption. However, in reality their active power requirement is not zero as there are reactor losses, transformer losses, thyristor losses etc.

In order to see the power consumption of each system as well as the total active power requirement, 12-pulse configuration is run under different voltage references. As the reactive power requirement is changed, power loss of each system is also changed and results are recorded. For sequential mode of operation, sequential limit is set to 1MVAr.

Voltage reference is changed from 33kV to 31.5 kV with the steps of 500V. Active power consumption of each SVC system and the total loss is shown in Figure 4.26 and 4.27 respectively.

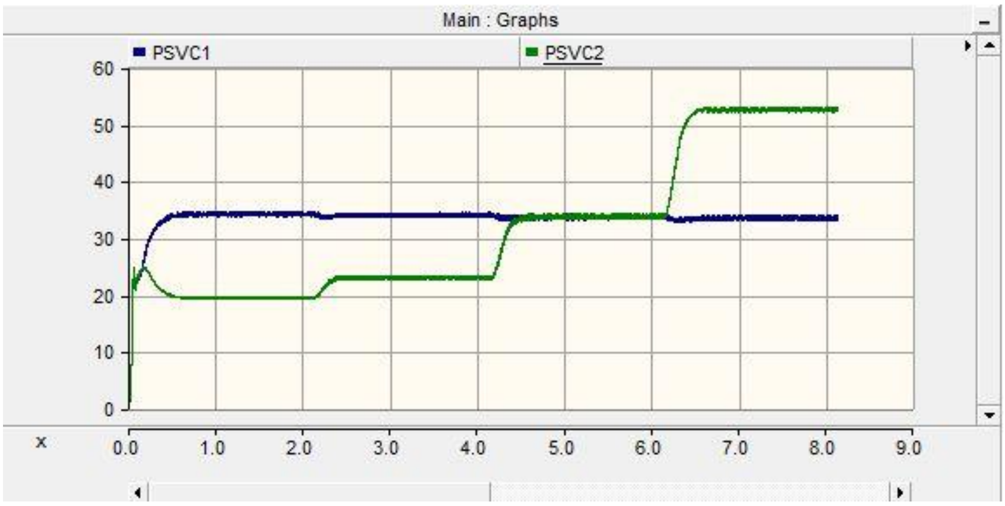


Figure 4.26: *Losses for each system under sequential load sharing mode of operation (simulation)*

Figure 4.26 shows that the power losses for master SVC is constant since its reactive power generation is not changed during the operation. As the total requirement increase, losses of the slave also increase. Looking at Figure 4.27, total loss variation according to reference voltage is given.

On the other hand, for equal load sharing mode both SVC systems has the same power losses and the total loss behavior is represented in Figure 4.28.

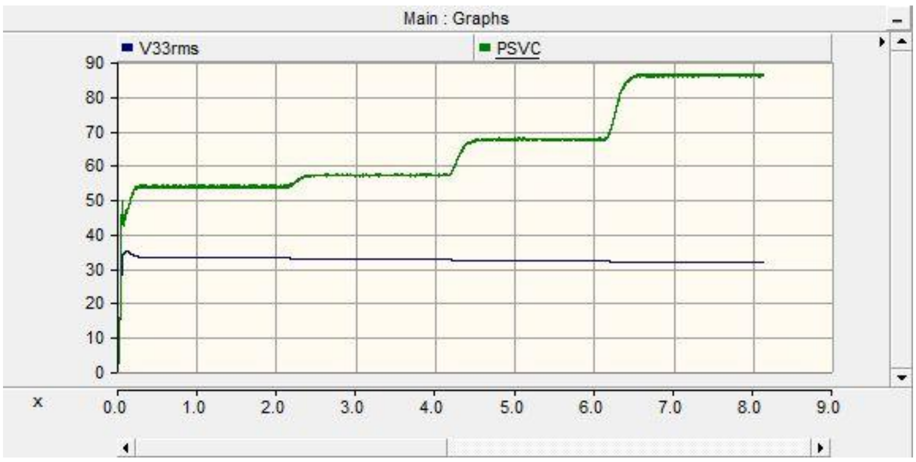


Figure 4.27: *Total Losses under sequential load sharing mode of operation (simulation)*

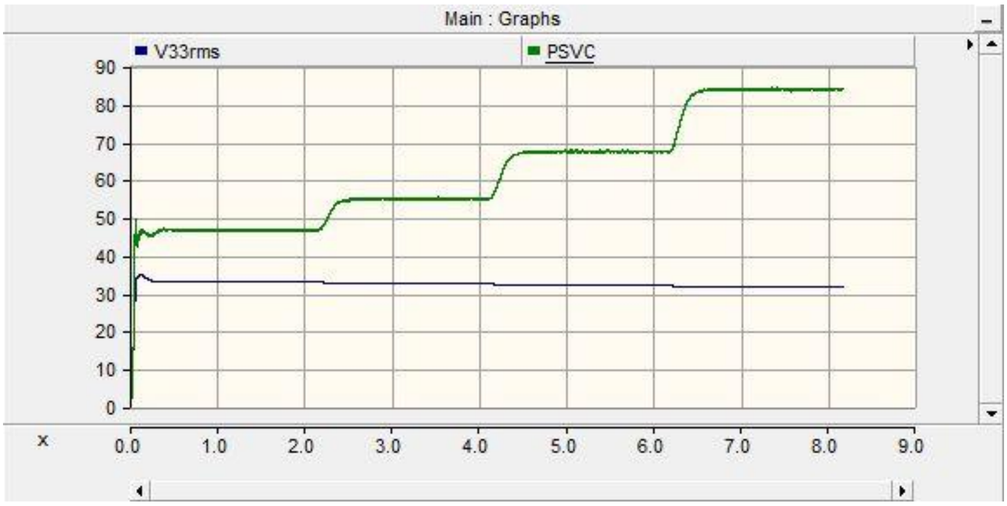


Figure 4.28: *Total Losses under equal load sharing mode of operation (simulation)*

Finally, relationship between power losses, mains voltage and reactive power generation of TCR is investigated in detail. In Figure 4.29, power losses are recorded for different reference voltages. Although each mode has different voltage limits, the figure gives idea about their common operating points. Moreover, Figure 4.30 represents the relationship between total inductive reactive power generation of TCR systems and power losses. In figures results for equal load sharing (ELS) and sequential load sharing with three different sequential limits 500, 1000 and 1500 (SLS-500, SLS-1000, SLS-1500) are shown. Both figures prove that equal load sharing mode always results in lower power losses. This is mainly because of the fact that losses are proportional to the square of the current. Thus, dividing the current equally decreases total loss. Losses of sequential load sharing mode has nearly the same value with equal load sharing mode when the total reactive power requirement is double of sequential limit, means system is working like equal load sharing mode.

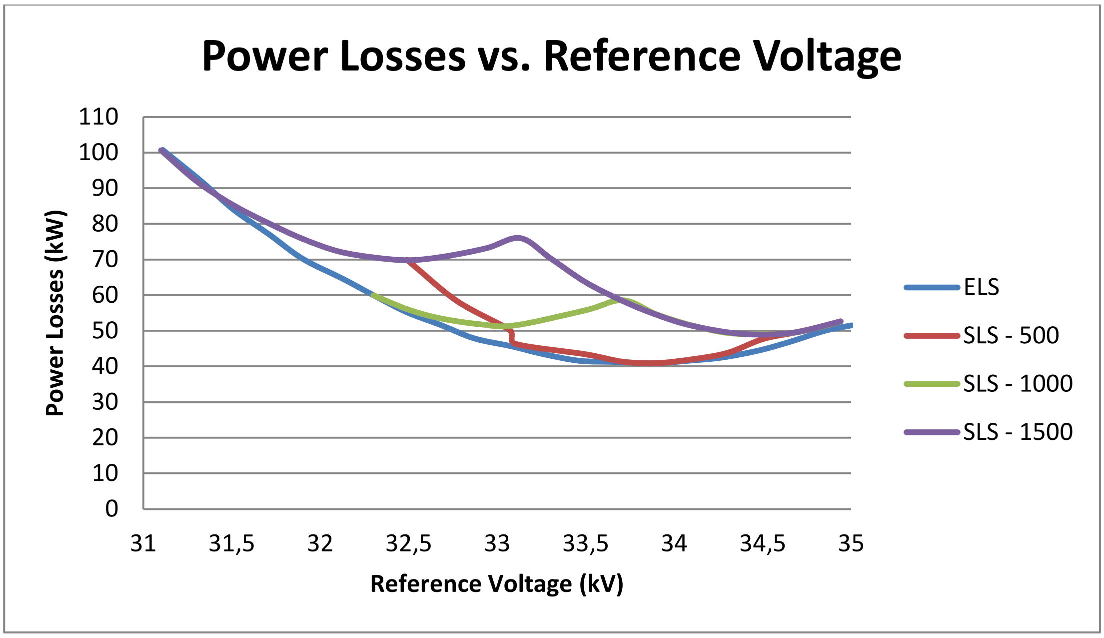


Figure 4.29: *Power losses according to reference voltage (simulation)*

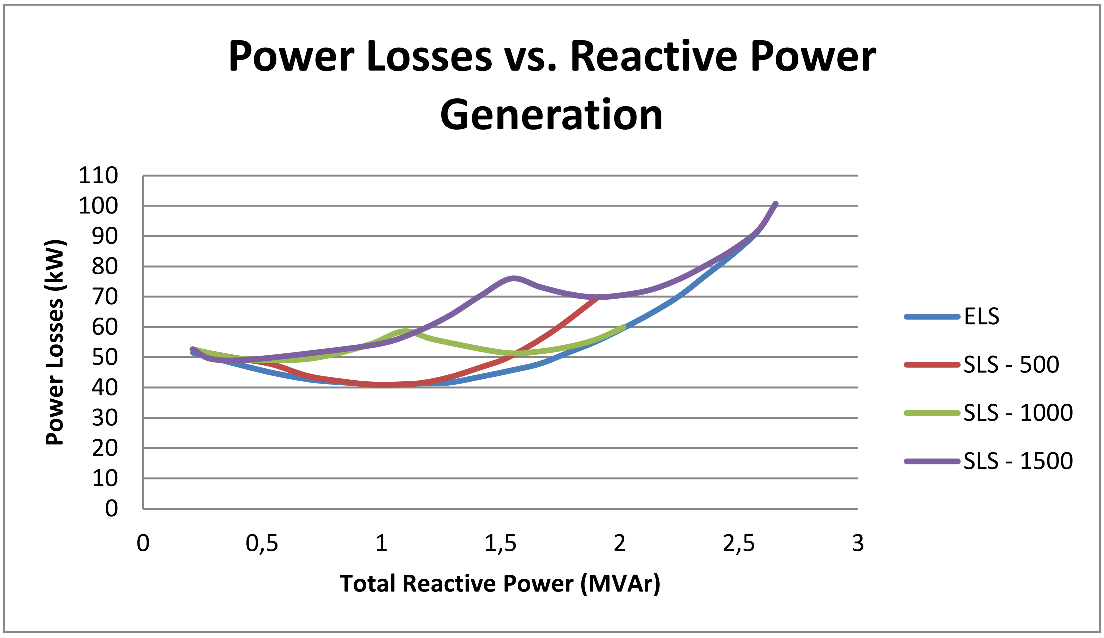


Figure 4.30: *Power losses according to total reactive power generation (simulation)*

CHAPTER V

FIELD IMPLEMENTATION

5.1 Installation of Proposed SVC System

After design process, SVC system is shipped to Saudi Arabia. Civil work including pour, placement of containers and coupling transformers, and channel excavation for cables are all completed by KACST team. Moreover, they prepared connections for auxiliary supply. Figure 5.1 shows one of the containers ready for work. Then; for cabling between containers and other outer equipment, de-ionized water cooling system preparation, and commissioning the system field work is conducted between at 28^{th} of February and 21^{th} of March.

Figure 5.1: *SVC master system container*

Saudi Electricity Company (SEC) made the connection between SVC system and grid according to regulations. For this, they installed insulators on the pole. Surge arresters and 33kV XLPE cables are connected to mains with the help of these insulators. Figure 5.2 shows how they connected XLPE cables to the insulators.

De-ionized water cooling system is installed according to design (see Figure 5.3 and 5.4). On the other hand, coupling transformer connections are completed as seen in Figure 5.5. SVC system with delta – Y coupling transformer is selected as master.

Figure 5.2: *PCC connections*

Figure 5.3: *De-ionized Water cooling system – heat exchanger*

Figure 5.4: *De-ionized water cooling system panel*

Figure 5.5: *SVC container, coupling transformer and heat exchanger*

1kV side power equipment has already been installed before shipment. In the field, 1kV cables are connected to distribution panel and ground connections are completed. Thyristor panel, harmonic filter panel and TCR reactors are seen in Figure 5.6 (a), Figure 5.6 (b), Figure 5.7 (a), and Figure 5.7 (b). Then, the designed system has taken its final form (see Figure 5.8).

(a): *Thyristor panel*

(b): *1kV side of container*

Figure 5.6: *(a) Thyristor panel and (b) 1kV side of container*

(a): *Harmonic filter panels*

(b): *Harmonic filter reactor and capacitor connections*

Figure 5.7: *(a) Harmonic filter panels and (b) Reactor capacitor connections*

Figure 5.8: *SVC platform (front view)*

5.2 Implementation of Control Strategies and Harmonic Performance

Field installation process took nearly one week. Then, SVC system is commissioned step by step. First of all, each system is commissioned independently. Then, equal load sharing mode is investigated. Sequential load sharing mode is also performed and finally, asymmetrical load sharing situation is observed.

Voltage, current, and reactive power measurements are taken for each step. For all these steps measurements are taken. “Circutor Power Analyzer – AR5” is used as measurement device. All measurements are based on 5 second averages.

5.2.1 Independent Mode of Operation

For independent mode of operation, measurements can be classified in two main groups, namely creating voltage profile for a single SVC system, and investigating operational harmonics. Balanced and unbalanced situations are considered separately. For balanced condition, measurements are taken from one phase only. On the other hand, three phase information is taken for unbalanced condition.

Firstly, TCR is triggered from zero conduction to full conduction with the steps of 10 degrees . In order to be more precise near full conduction, another measurement is taken at 100 degrees. Two different scenarios, with all filters active and only 3rd harmonic filter active, are followed. Result is shown in Figure 5.9 and Figure 5.10.

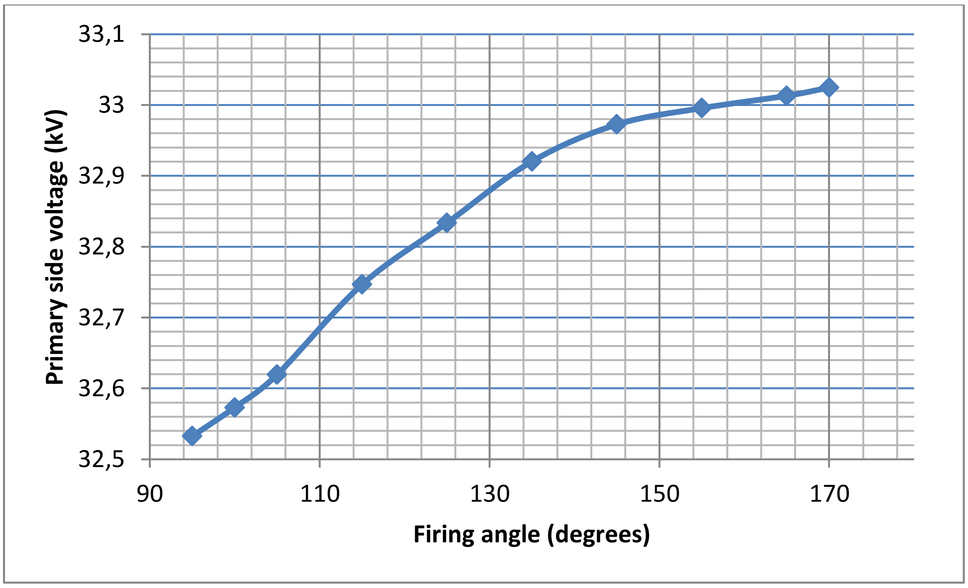


Figure 5.9: *Voltage versus firing angle relationship with harmonic filters (field data)*

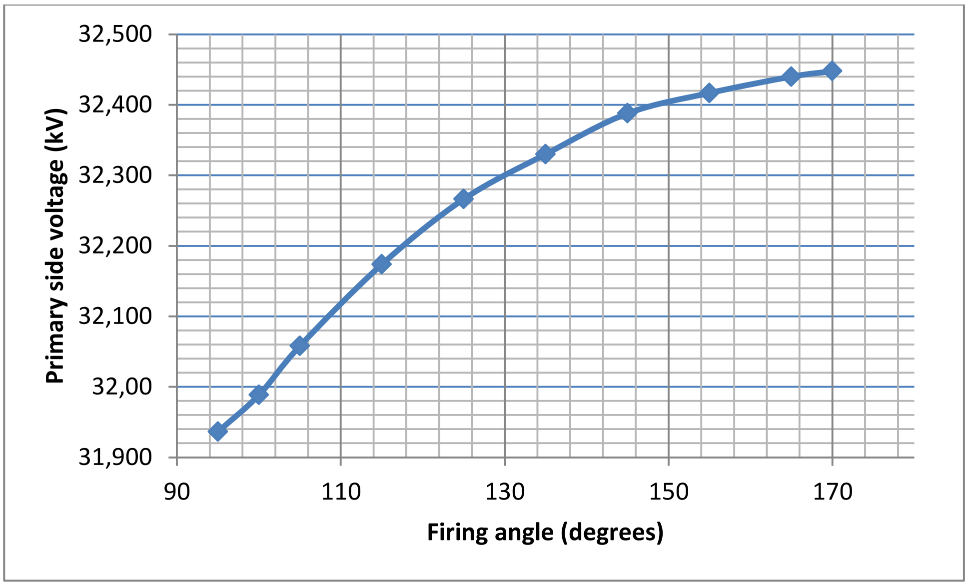


Figure 5.10: *Voltage versus firing angle relationship with one filter only (field data)*

According to figures, for this specific measurement period under full load TCR effect on the 33kV bus voltage is nearly 0.5kV.

In order to investigate harmonics during balanced and unbalanced operation, current measurements on TCR line are taken. 3rd, 5th, 7th, 17th, and 19th harmonics are observed. All harmonic information is given as the percentage of rated current, i.e. 866 amperes (see Figure 5.11).

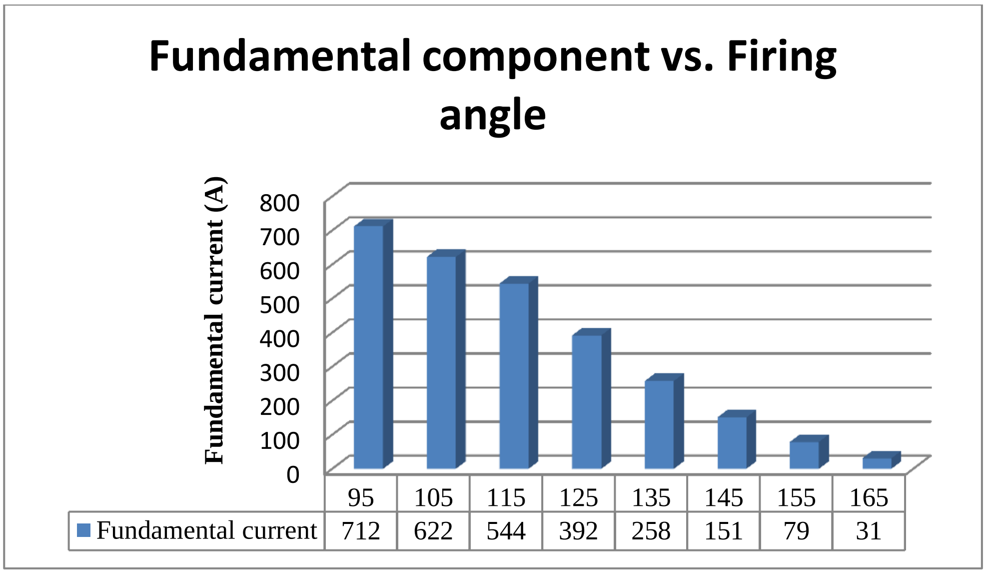


Figure 5.11: *TCR fundamental current (line) versus firing angle relationship (field data)*

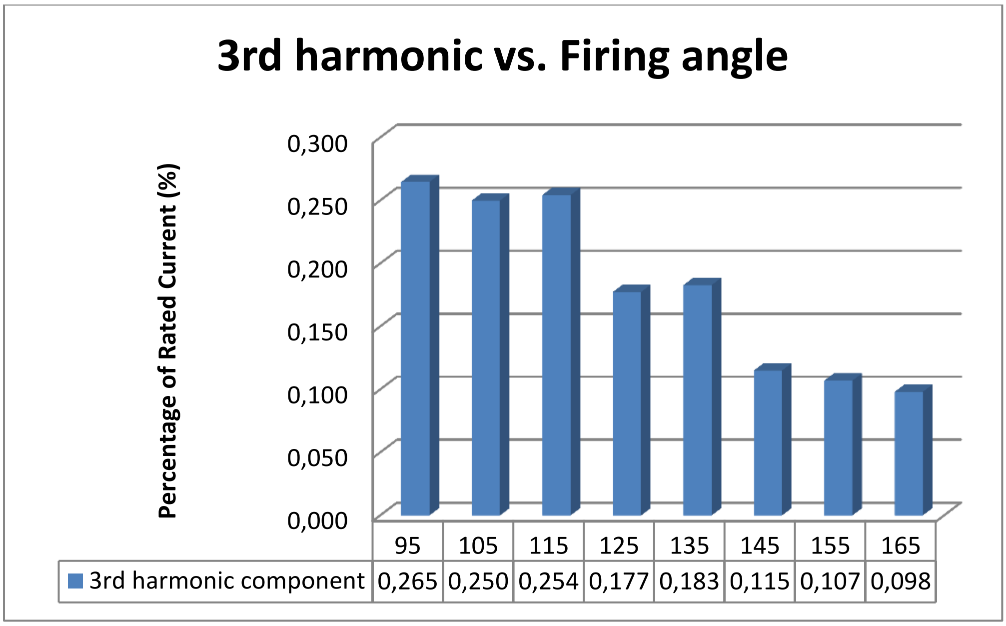
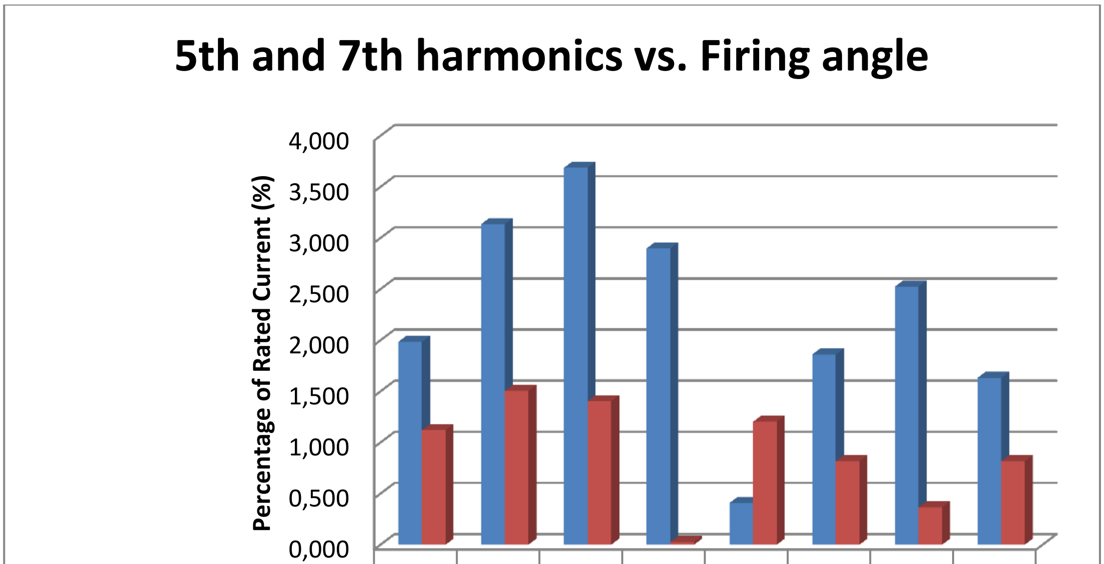


Figure 5.12: *3^{rd} harmonic current versus firing angle relationship (field data)*

3^{rd} harmonic current measured from outside of delta is shown in Figure 5.12. According to the figure, 3^{rd} harmonic current is less than 0.3 % of rated current. In ideal situation, for delta connected structure it is expected to be zero in balanced operation; however, dissimilarities between phases, firing angle mismatches, source voltage unbalance cause this result.

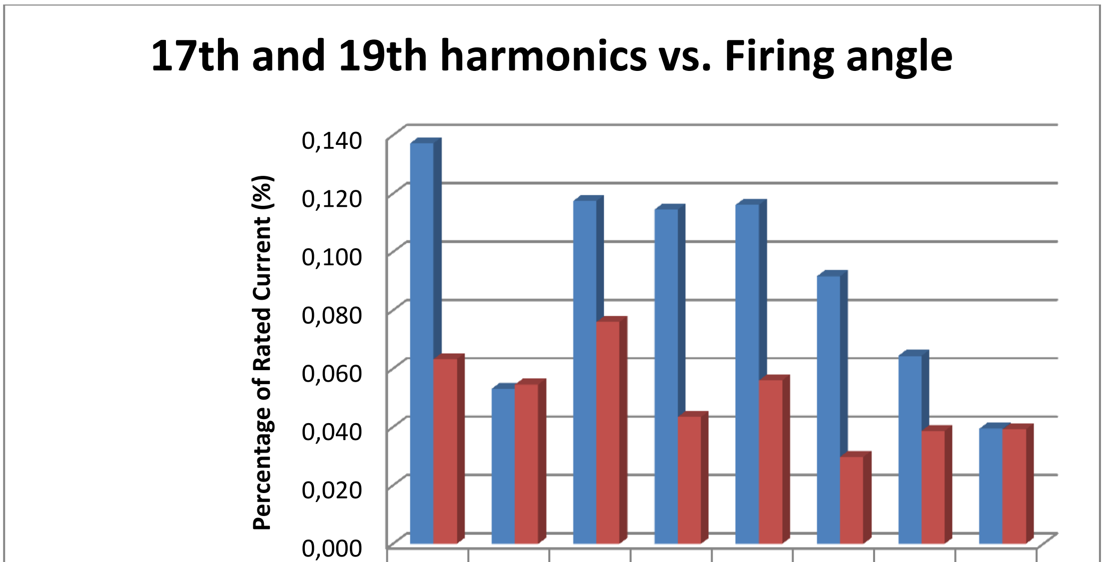
5^{th} and 7^{th} harmonics are dominant harmonics for 6-pulse scheme as explained in previous sections. Their variation with firing angle is represented in Figure 5.13. On the other hand, 17^{th} and 19^{th} harmonics are other harmonics under interest of the study. Their variation is also shown in Figure 5.14. According to figures, each harmonic component has different characteristics relating to the firing angle.

Finally, TCR harmonics for unbalanced operation is measured. Firstly, firing pulses with 5 degrees of difference are created for operation near full conduction. When thyristors are triggered with 95-100-105 degrees, current and voltage harmonics are as given in Figure 5.15. In the figure, RS (L1)-ST (L2)-TR (L3) phases are shown separately. Then, the measurement is repeated when firing angles are 120-130-140 degrees (Figure 5.16).



	95	105	115	125	135	145	155	165
5th harmonic component	1,984	3,135	3,686	2,899	0,408	1,860	2,524	1,632
7th harmonic component	1,121	1,504	1,403	0,027	1,203	0,817	0,366	0,817

Figure 5.13: *5^{th} - 7^{th} harmonic currents versus firing angle relationship (field data)*



	95	105	115	125	135	145	155	165
17th harmonic component	0,137	0,053	0,117	0,115	0,116	0,092	0,064	0,039
19th harmonic component	0,063	0,055	0,076	0,043	0,056	0,030	0,039	0,039

Figure 5.14: *17^{th} - 19^{th} harmonic currents versus firing angle relationship (field data)*

During investigation of unbalance, 4^{th} and 5^{th} harmonic filters are disabled to see effects more clearly. As the figures are raw outputs of PQ analyzer device (AR5), values are shown as the percentages of fundamental component. This means, for unbalance scenario I, 3rd harmonic current is about 17.8 amperes even though it differs a little from phase to phase. 5th and 7th harmonics are 25 and 13 amperes respectively. On the other hand, for scenario II, 3rd harmonic current is about 10 amperes. 5th and 7th harmonic components did not change much they are still nearly 26 and 13 amperes. Results prove that if thyristors are fired with different angles, 3rd harmonic current becomes comparable with 5th and 7th harmonics in line. This 3rd harmonic magnitude gets bigger as unbalance situation happens for lower firing angles.

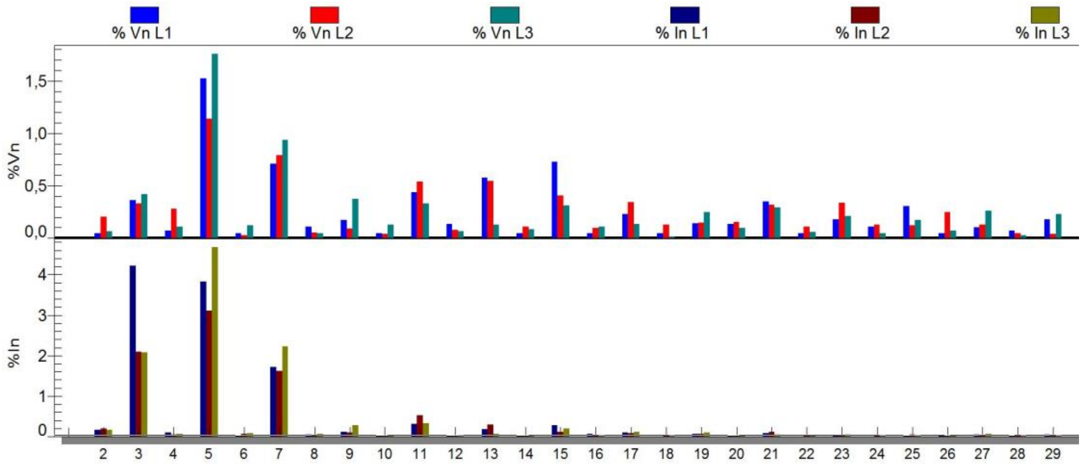


Figure 5.15: *Current / voltage harmonics for unbalance of 95^0-100^0-105^0in RS-ST-TR phases (field data)*

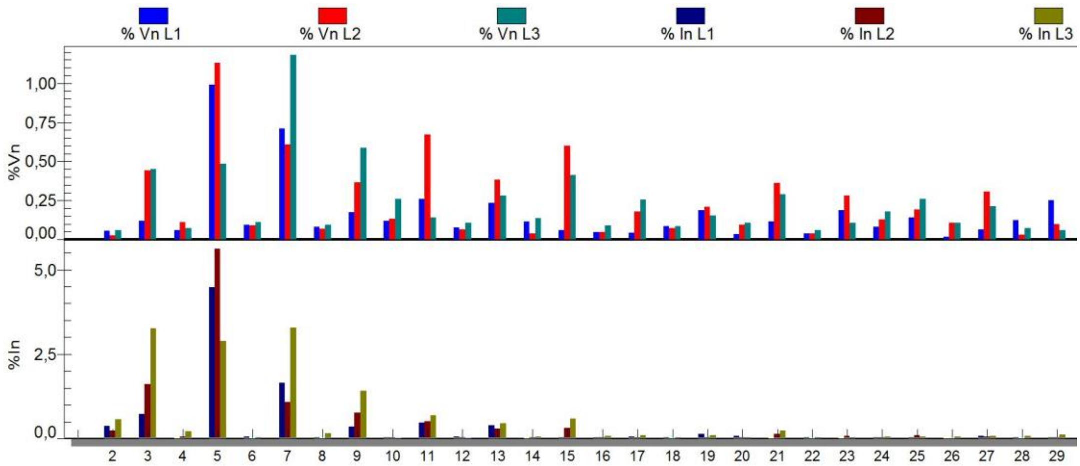


Figure 5.16: *Current / voltage harmonics for unbalance of 120^0-130^0-140^0 in RS-ST-TR phases (field data)*

5.2.2 Sequential Mode of Operation

When both SVC systems are enabled and mode is selected as sequential load sharing, voltage control mode (closed loop) is operated. Measurements are taken from two points, primary side of master SVC and point of common coupling (PCC). Two different sequential limits (500kVAr and 1MVAr) are applied and firstly, for a specified total reactive power generation harmonics are observed. Then, voltage reference is changed step by step from 32.2 to 31.8 kV. When total inductive reactive power generation is nearly 700kVAr, resulting current and voltage harmonics are given in Figure 5.17 and 5.18 for 500kVAr sequential limit. Likewise, Figures 5.19 and 5.20 are for 1MVAr limit.

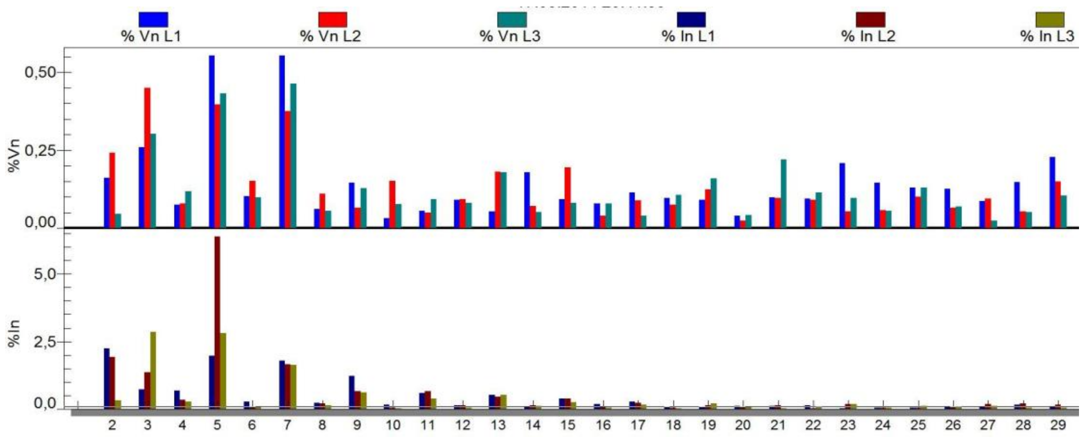


Figure 5.17: *Current / voltage harmonics at primary side of master with 500kVAr sequential limit (field data)*

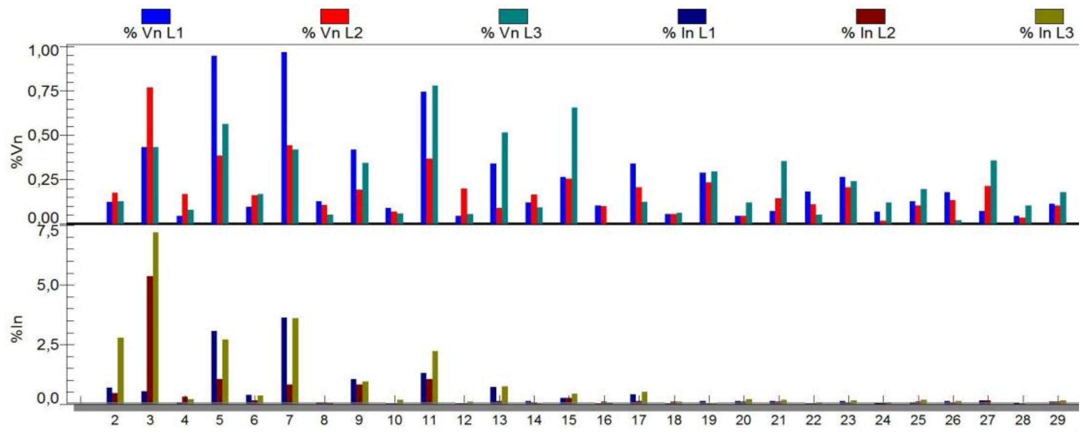


Figure 5.18: *Current / voltage harmonics at PCC with 500kVAr sequential limit (field data)*

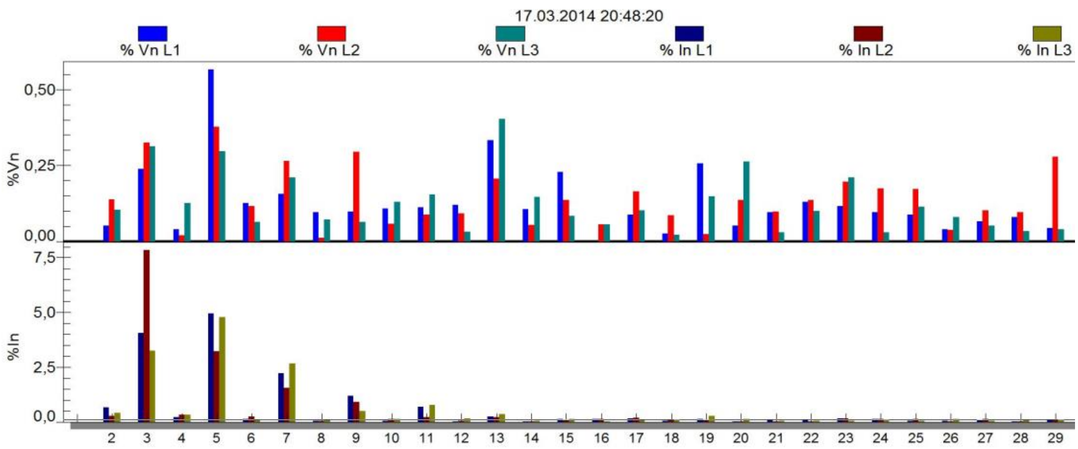


Figure 5.19: *Current / voltage harmonics at primary side of master with 1MVAr sequential limit (field data)*

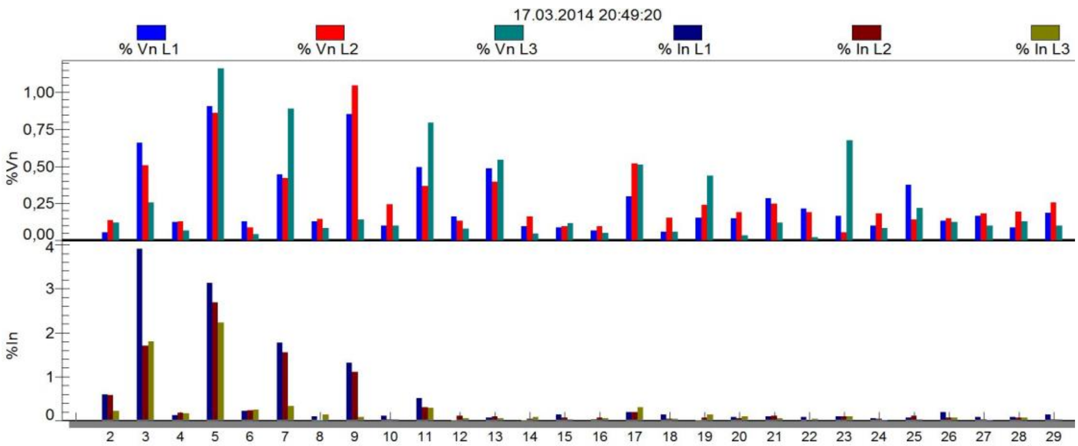


Figure 5.20: *Current / voltage harmonics at PCC with 1MVAr sequential limit (field data)*

Although specific harmonics (5^{th},7^{th},17^{th},19^{th}) are reduced at PCC side, reduction rate is not satisfying with sequential mode of operation. For 1MVAr sequential limit, it seems harmonics are lower. It is because of the fact that the reactive power generations of two systems are closer to each other.

5.2.3 Equal Load Sharing Mode of Operation

In equal mode of operation, the same steps are followed and results are observed as in Figure 5.21 and Figure 5.22 for the same amount of total inductive reactive power generation (700kVAr).

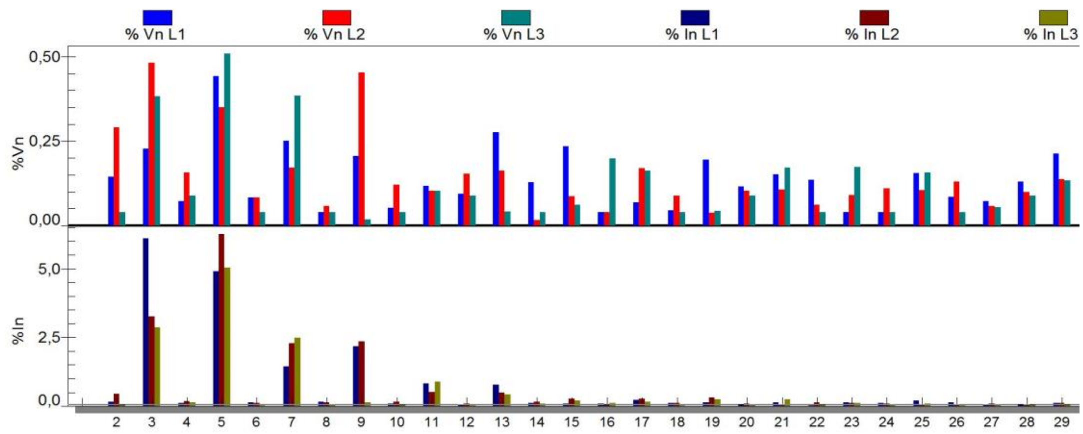


Figure 5.21: *Current / voltage harmonics at primary side of master with equal load sharing (field data)*

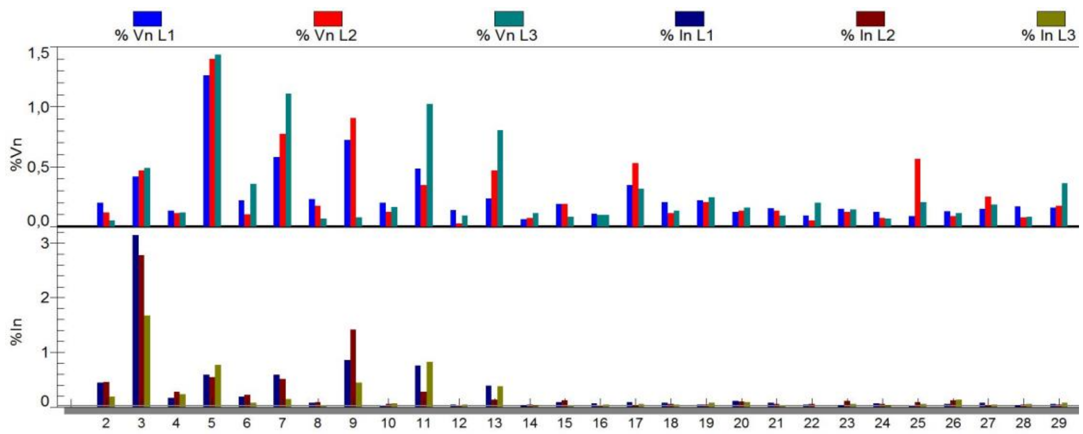
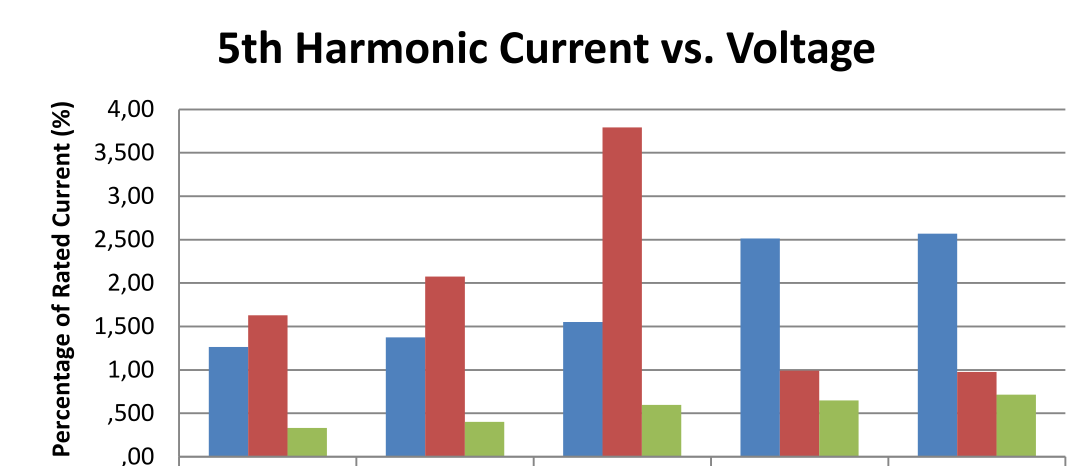


Figure 5.22: *Current / voltage harmonics at PCC with equal load sharing (field data)*

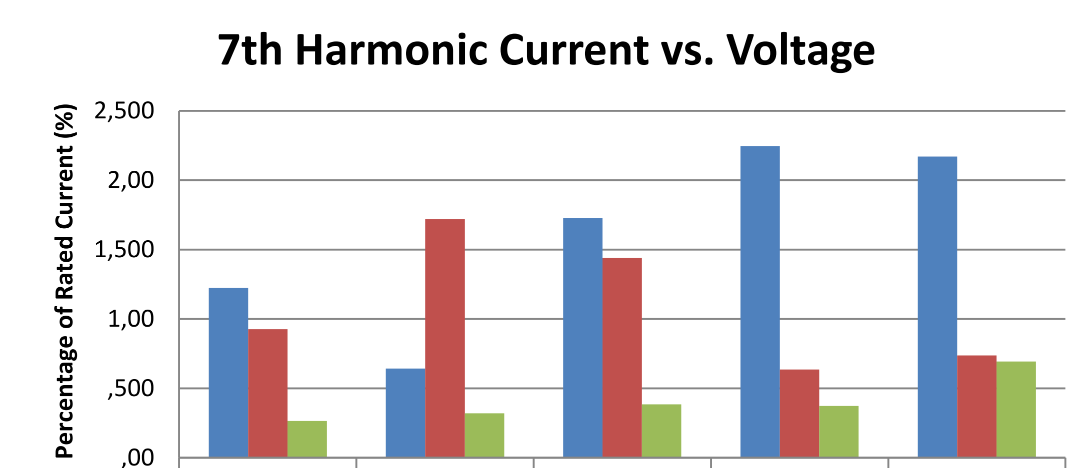
Figures present that, equal load sharing has successful results on eliminating 6-pulse harmonics. For example, although 5^{th} harmonic current is between 5-10 % of fundamental current at primary side of master SVC, it is only about 0.8% at PCC side. The same reduction effects can be seen for 5^{th}, 7^{th}, 17^{th}, and 19^{th} harmonics meaning equal load sharing is effective on eliminating these harmonics.

In order to see the results for different voltage levels, systems are operated in closed loop and voltage reference is changed from 32.2kV to 31.8kV when the voltage level is 32kV without SVC. Variation of 5^{th}, 7^{th}, 17^{th}, and 19th harmonic currents during this process is shown in Figures 5.23 – 5.26. Moreover, total harmonic distortion measurements taken from PQ device during this process are also given in Figure 5.27.



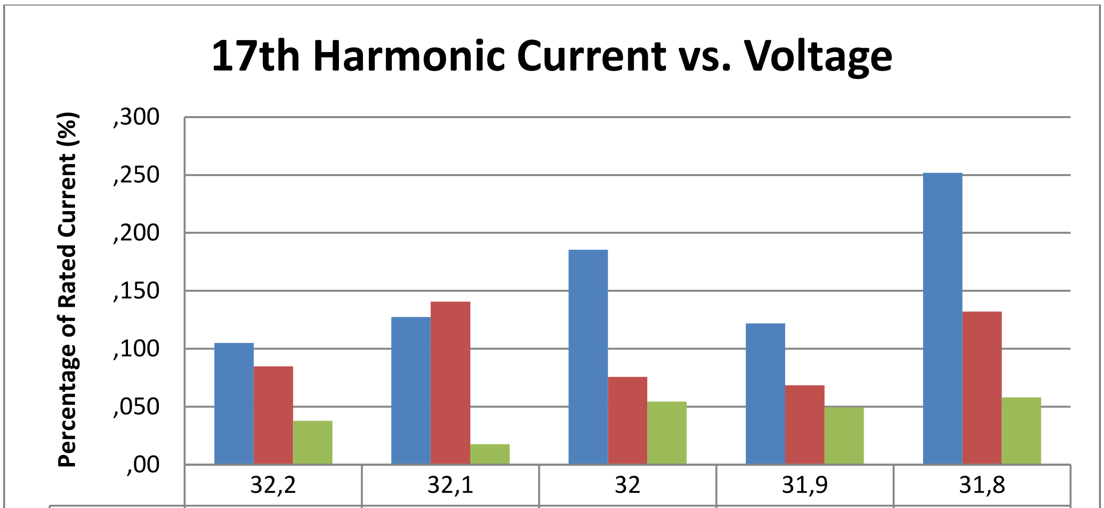
	32,2	32,1	32	31,9	31,8
SLS-500	01,264	01,376	01,551	02,514	02,570
SLS-1000	01,631	02,075	03,791	00,991	00,976
ELS	00,331	00,402	00,598	00,650	00,716

Figure 5.23: *5^{th} harmonic current as percentage of rated current for different voltage levels and control algorithms (field data)*



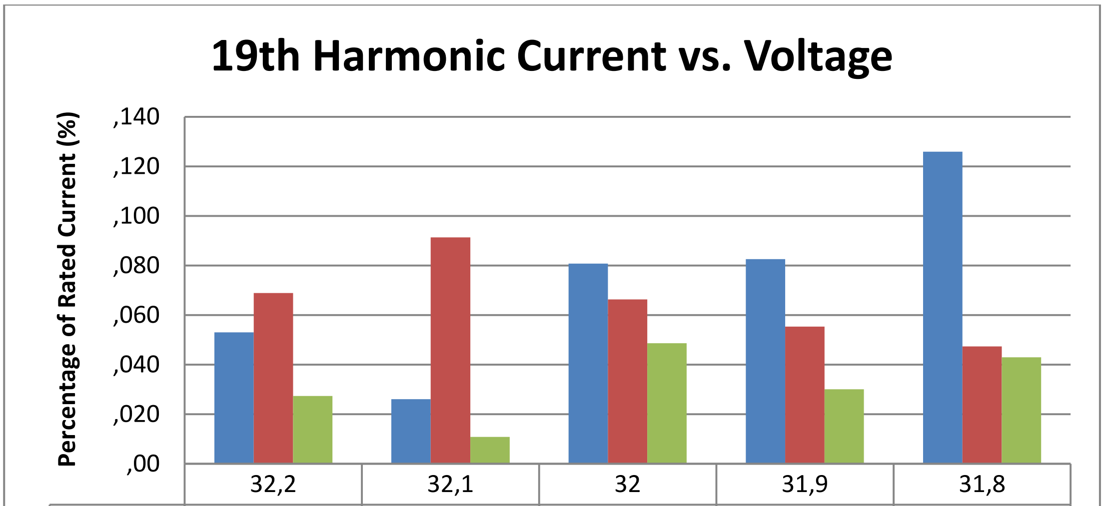
	32,2	32,1	32	31,9	31,8
SLS-500	01,224	00,644	01,726	02,246	02,169
SLS-1000	00,926	01,719	01,440	00,635	00,737
ELS	00,266	00,320	00,385	00,373	00,694

Figure 5.24: *7^{th} harmonic current as percentage of rated current for different voltage levels and control algorithms (field data)*



	32,2	32,1	32	31,9	31,8
SLS-500	00,105	00,127	00,185	00,122	00,252
SLS-1000	00,085	00,141	00,076	00,069	00,132
ELS	00,038	00,018	00,054	00,049	00,058

Figure 5.25: *17th harmonic current as percentage of rated current for different voltage levels and control algorithms (field data)*



	32,2	32,1	32	31,9	31,8
SLS-500	00,053	00,026	00,081	00,083	00,126
SLS-1000	00,069	00,091	00,066	00,055	00,047
ELS	00,027	00,011	00,049	00,030	00,043

Figure 5.26: *19th harmonic current as percentage of rated current for different voltage levels and control algorithms (field data)*

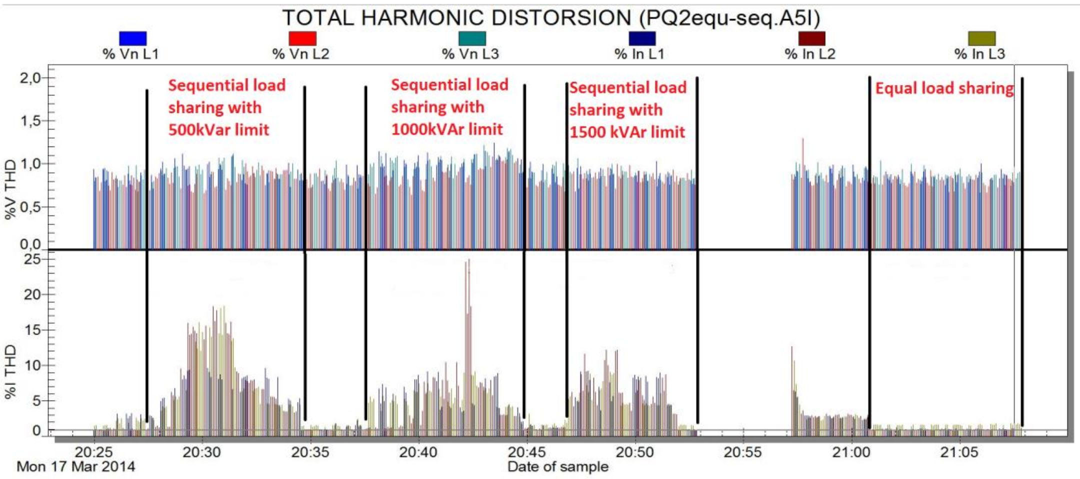
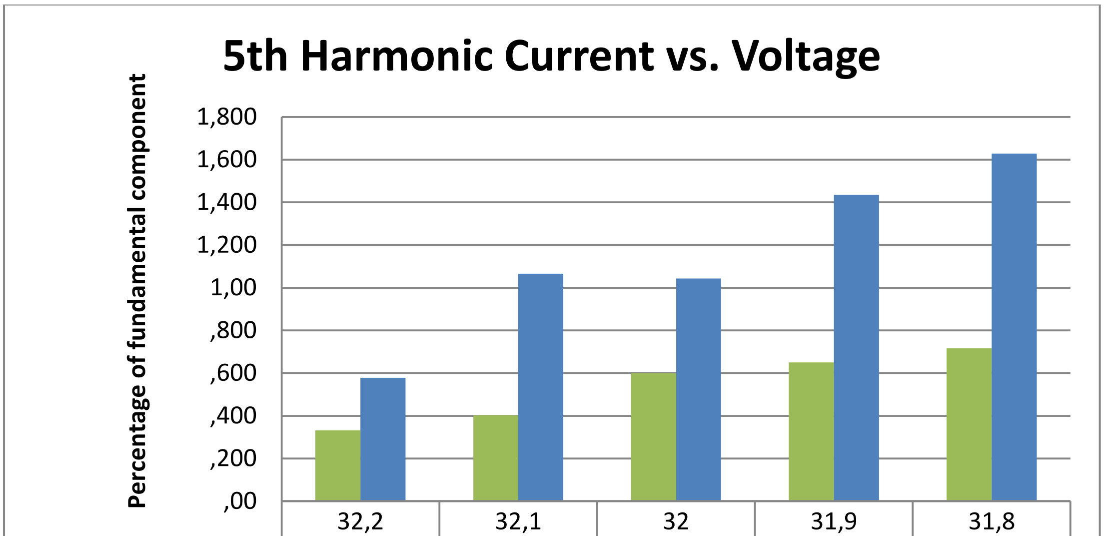


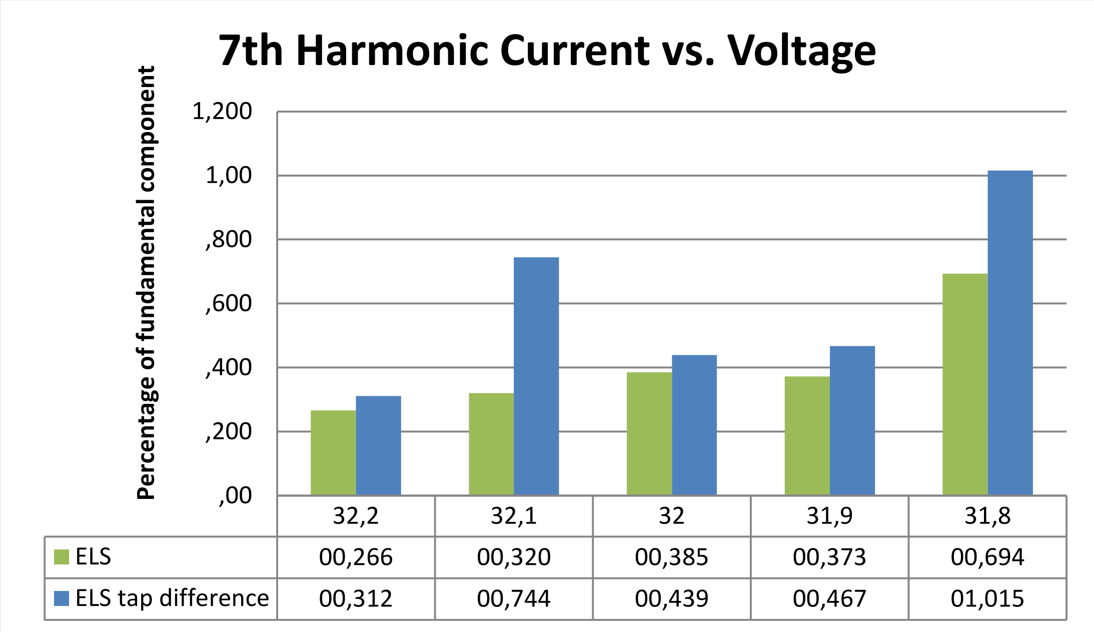
Figure 5.27: *THD of different control algorithms*

Finally, voltage difference created between transformers to see harmonic performance of equal load sharing mode for such dissimilarity. Tap positions are changed and a voltage difference of 8,69 % is created between two couplings. Then for the same voltage levels results are tabulated (see Figure 5.28 and 5.29).



	32,2	32,1	32	31,9	31,8
ELS	00,331	00,402	00,598	00,650	00,716
ELS tap difference	00,578	01,066	01,044	01,434	01,628

Figure 5.28: *Relationship between 5th harmonic current as percentage of rated current for different taps (field data)*



	32,2	32,1	32	31,9	31,8
ELS	00,266	00,320	00,385	00,373	00,694
ELS tap difference	00,312	00,744	00,439	00,467	01,015

Figure 5.29: *Relationship between 7th harmonic current as percentage of rated current for different taps (field data)*

Figures prove that equal load sharing mode of operation has much better harmonic elimination characteristics. However it should be noted that for current loads and operating points sequential load sharing algorithm has also acceptable results in terms of harmonics. Considering short circuit current is as 1kA (given from SEC) and nominal current for the systems (3MVAr in total) as 52.49 A, then according to Table 2.3 harmonic limits are 4 %, 2 %, and 1.5 % for harmonic orders up to 11, from 11 to 17, and from 17 to 23 respectively. Thus, investigating Figures 5.23-5.26, it is clear that even sequential load sharing algorithm has below limits although it has small margin at some points. Moreover, at some operating conditions sequential load sharing modes has similar results with equal load sharing. This is because total inductive reactive power generation is double of sequential limit which yields the systems are working like equal load sharing mode. On the other hand, when simulation results are also considered, it is seen that any dissimilarity between systems (in terms of transformer voltage ratio, reactor values…) decreases the efficiency of harmonic cancellation.

5.3 Dynamic Performance

Dynamic response quality is measured for three phase current change. In order to do the measurement, voltage reference is changed between 32.5kV and 33kV. These are limit values for that specific time. Above and/or below these limits at least one phase is stuck to upper or lower firing angle limit.

There is no difference between control strategies in terms of dynamic performance since the reference currents are generated using the same algorithm, only equations are changed.

As there are two PI controllers (one for reference voltage error and the other for TCR current error) four parameters are tuned one by one and results are achieved as given in Figure 5.30 and Figure 5.31 below. In order to check dynamic response quality, DSP is used. Thyristor currents inside delta which are measured via hall effect current transformer are presented with a triggering pulse. In figures; yellow, green, and purple waveforms show thyristor currents. The blue signal is the instant that voltage reference is changed.

Figure 5.30: *Transient response from 32.5kV to 33kV*

Figure 5.31: *Transient response from 33kV to 32.5kV*

These pictures prove that response time is nearly 4 cycles when going from one limit to another. On the other hand, to see performance in a more clear way, transient response is seen on one phase only. By doing so, new voltage limits become (for phase AB) 32.9 and 32.2kV.

Results for changing reference from 32.9kV to 32.2kV and vice versa is presented in Figures 5.32 and 5.33 below. In figures, phase voltage is seen as red colored and corresponding current is given as yellow. Blue signal is again the triggering instant. Response time is observed to be 4 cycles again.

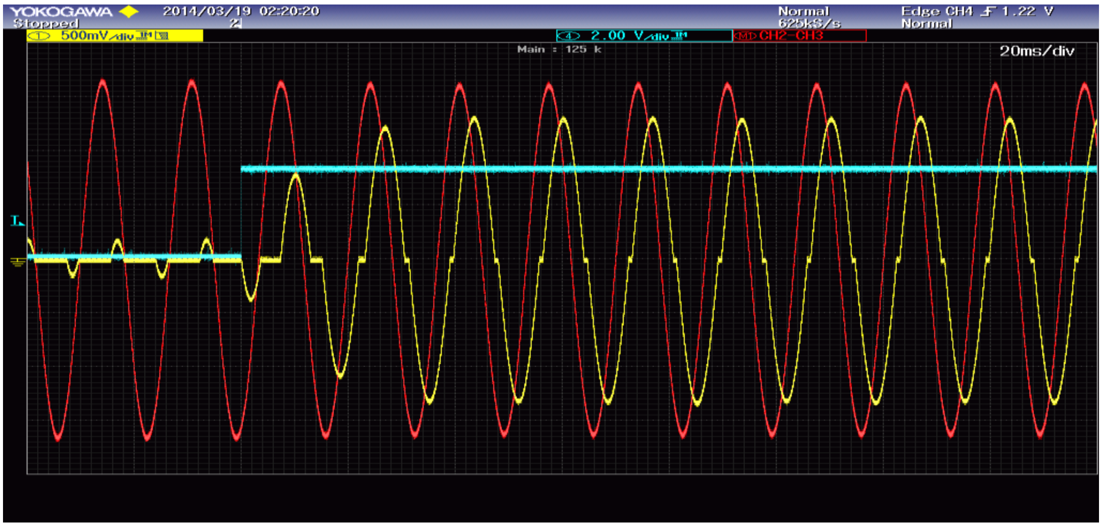


Figure 5.32: *Transient response from 32.9kV to 32.2kV*

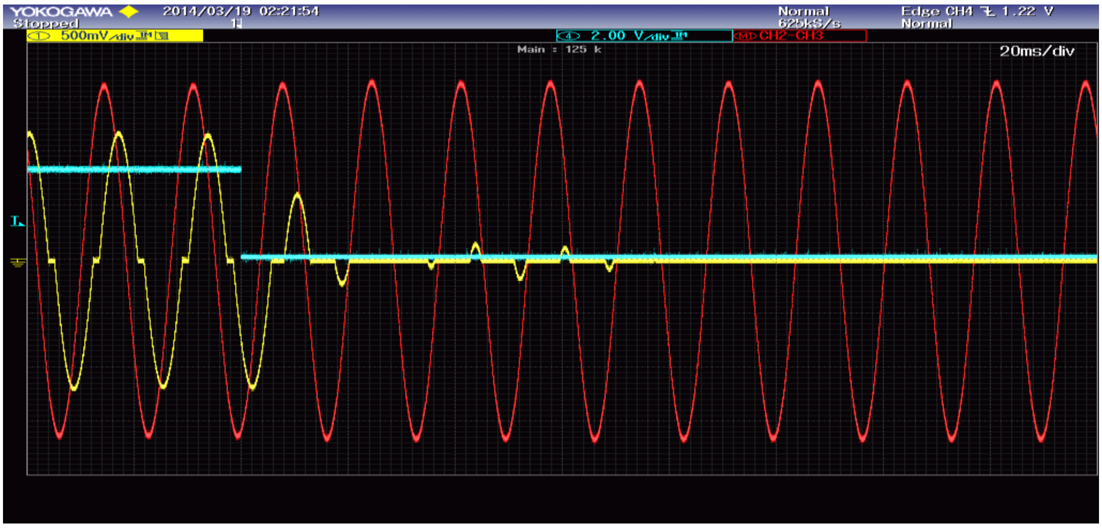


Figure 5.33: *Transient response from 32.2kV to 32.9kV*

5.4 Discussion of Results

As the achievements of simulation work and field measurements following results can be concluded;

- 12 - pulse TCR based SVC system having 3rd and 4th harmonic filter is an effective solution for voltage regulation problems caused by long distribution lines and high load during summer in Dhurma / Saudi Arabia. Moreover, with the use of equal load sharing algorithm the system suppresses harmonics below limits with a safety margin.
- Dynamic response is measured as 4 cycles. Control parameters are adjusted to make the system critically damped to reach an optimum point in terms of fast response and low oscillations.
- Some dis-similarities such as transformer U_k mismatches, source voltage unbalances, reactor value differences, thyristor firing delays, etc… make total filtration of $6n \pm 1$ (n is odd) pulse harmonics impossible; however especially with equal load sharing algorithm, harmonics are suppressed significantly. When harmonic limits are considered (see Table 2.3) sequential load sharing algorithm has also acceptable results. However, equal load sharing has greater safety margin.
- As a comparison of control algorithms, if the systems are intended to be operated in parallel, then although sequential load sharing algorithm has advantage of keeping one system as spare equal load sharing is a better choice. First of all, equal load sharing topology based systems have better harmonic reduction capability. Secondly, power losses are reduced in equal load sharing mode.
- There are some differences between simulation work and field results about the voltage range of SVC system. This is because of some wrong information and assumptions during the modelling of power system. Although from control perspective this does not change anything, especially capacitive power of the system may be required to be increased in the future. In such a case, TSC can be a solution. Adding a TSC parallel to TCR increases capacitive reactive power capability which is good when load is high especially in summer. Moreover, during light load (in winter with capacitive line characteristics) TSC can be shut-down not to reduce inductive reactive power capacity.
- Having two systems to get 12-pulse ability has a disadvantage of being expensive. Based on the same design specs and cost, STATCOM and/or TSC can also be considered as alternatives. In current situation, STATCOM system can be an alternative.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

This master thesis work deals with design, implementation and analysis of 12-pulse TCR based SVC. As a result of collaboration agreement signed between TUBITAK and King Abdulaziz City for Science and Technology (KACST), prototype is designed considering unique requirements and implemented in Dhurma / Kingdom of Saudi Arabia. Within the scope of the project, SVC technology developed by TUBITAK is transferred to KACST Institute in Saudi Arabia. An extended research and demonstration for 12-pulse TCR operation is also achieved, which constituted a basis for the scope of this Thesis.

The developed system is composed of two parallel connected 6-pulse SVC. Systems are designed to be suitable for both parallel and independent operation. Moreover, they are capable of being transferred to another location easily. Each system has its own coupling transformer and harmonic filters as sources of capacitive reactive power. A special control algorithm is developed to share load between systems equally.

Designed system is implemented in Dhurma / Kingdom of Saudi Arabia to solve voltage regulation problems mostly because of irrigation and air-conditioner based loads during summer time.

As results of theoretical work, analysis and field measurements carried out in the scope of this master thesis, following conclusions /contributions can be drawn:

- 12 pulse TCR based SVC system working at voltage regulation mode is designed and implemented. Voltage regulation is done successfully in the meantime $6n \pm 1$ (n is odd) harmonics are suppressed.
- For independent mode of operation; TCR voltage, current, and harmonic performance characteristics are investigated both in simulation environment and reality.
- For two different parallel operation modes (sequential load sharing and equal load sharing) quality of performances are compared in terms of voltage regulation capability, dynamic response, harmonic content, and power losses in simulation environment. It is concluded that, equal load sharing algorithm has better harmonic reduction and power loss performance. If sequential load sharing limit is set to the full capacity of one system then voltage regulation capability is similar for both algorithms. Dynamic performance is also similar for two different control methods.
- For parallel operation modes, field results are collected and it is seen how they respond in the implemented 33kV power system. Although a greater installed capacity is required, due to the agreement signed between TUBITAK and KACST, the total installed capacity is limited to 3 MVAr. With this capacity, it is measured that the voltage can be regulated up to +/-1kV.
- As a result of comparison, it is proven that with the algorithm of equal load sharing specific harmonics (5^{th}, 7^{th}, 17^{th}, 19^{th} harmonics) are suppressed. For current IEEE limits (as explained in chapter 5.2.3) harmonics are all below limits with a safety margin.
- Dynamic response for the two different modes of operation is investigated and optimized by adjusting control parameters. System is set to critically damped response.
- Dissimilarities such as transformer unbalances and reactor variations are investigated in simulations and field work. Their effects on power quality (in terms of harmonic content) are discussed. It is seen that when there is dissimilarity harmonic reduction performance is reduced. However, according to field results, even with nearly 9 % of voltage unbalance between systems, harmonic levels are still below limits.

As further work, whole system can be designed in a way that coupling transformer is also placed in container so that relocation process becomes much easier. For that, coupling transformers may be designed as dry types. However, it will increase power losses. If losses become critical, then transformers can be designed as outdoor but with special platforms connected to control container. By doing so, re-locatability is improved.

Although response time is acceptable (about 4 cycle), feed-forward controller and/or fuzzy logic can be added to further improve these response characteristics. However, in that case stability problems may occur. Parameters should be investigated carefully.

For current situation, control algorithm is designed to share inductive reactive load equally between systems and it is seen that the algorithm is successful. However, if it is required to eliminate corresponding harmonic components completely, another control algorithm having harmonics as its controlled variable can be developed. Moreover, if it is necessary to eliminate higher order harmonics then an active filter may be designed. In order to increase reactive power control capability in capacitive region, a TSC implementation can also be considered.

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