DESIGN AND IMPLEMENTATION OF THYRISTOR SWITCHED SHUNT CAPACITORS

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

DESIGN AND IMPLEMENTATION OF THYRISTOR SWITCHED SHUNT CAPACITORS

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This research work deals with the analysis, design and implementation of thyristor switched plain capacitor banks and thyristor switched shunt filter banks. Performances of various thyristor switched capacitor (TSC) topologies are also investigated by simulations. The theoretical findings have been verified by carrying out experimental work on two prototypes implemented within the scope of this research work, one is a wye-connected laboratory prototype and the other is a delta-connected application prototype integrated to some of the SVCs existing in Turkish Coal Enterprise s Plants. The advantages of back-to-back connected thyristor switches over conventional electromechanical contactors are also made clear by conducting an intensive experimental work in the laboratory. A good correlation have been obtained between theoretical and experimental results.

Keywords: thyristor switched capacitor (TSC), shunt filters, reactive power control, harmonics elimination

ÖZ

TRİSTÖR ANAHTARLAMALI ŞÖNT KONDANSATÖRLER TASARIM VE UYGULAMASI

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Bu akademik çalışmada, tristör anahtarlamalı yalın kondansatör bankaları ve tristör anahtarlamalı şant filtre bankalarının analiz, tasarım ve uygulamasından bahsedilmiştir. Çeşitli tristör anahtarlamalı kondansatör (TAK) topolojilerinin performansları da benzetimlerle incelenmiştir. Kuramsal bulgular, bu akademik çalışma kapsamında kurulan iki model üzerinde deneysel çalışmalar yapılarak doğrulanmıştır, biri yıldız bağlı laboratuvar modeli ve diğeri Türkiye Kömür İşletmelerinin Tesislerinde mevcut bazı Static VAr Kompanzatörlere (SVK) eklenen üçgen bağlı uygulama modeli. Ters koşut bağlı tristör anahtarlarının konvansiyonel elektromekanik kontaktörlere göre avantajları da laboratuvarda gerçekleştirilen derin bir deneysel çalışma ile netleştirilmiştir. Kuramsal ve uygulama sonuçları arasında iyi bir bağlantı elde edilmiştir.

Anahtar Kelimeler: tiristör anahtarlamalı kondansatör (TAK), şönt filtreler, reaktif güç kontrolü, harmonik eliminasyonu

To My Family

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INTRODUCTION

1.1 Power Quality Concept

Power quality is defined by International Electrotechnical Commission (IEC) as *the characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters* [4]. It has an increasing importance parallel to the technology improvements. In other words, the increase in usage of power electronic equipments such as motor drives, switchgear applications and arc furnaces causes disturbances in electrical system. Since the power electronic equipments, microprocessor based appliances, induction motors and protection relays are influenced by this disturbance, a great care must be given to keep the utility reliable. In addition, the cost of the power systems are increased because of two reasons. The first one is the damage of the electronic components due to malfunction for some period. The second reason is that the components are selected with higher ratings than usual to overcome these problems.

There are several disturbance types usually encountered in a power system. They can be listed as voltage sag, voltage swell, momentary interruptions, transients, voltage unbalance, harmonics and voltage fluctuations in general [1], [2]. Below, a brief description of each of these can be found.

- **Voltage Sag:** It is defined as rms voltage reduction that causes a short term power loss. In general, it happens due to the loads that demand high current from the main supply such as a fault in a system that draws a high short circuit current from the source.

- **Voltage Swell:** Voltage swell can be defined as the opposite of voltage sag. It is a temporary increase in voltage for a limited amount of time and caused by sudden decrease in total load size. The effect of these two disturbances can be prevented or decreased by a decent voltage regulator.

- **Momentary interruptions:** It is an instantaneous drop on supply voltage. The differences between voltage sag and momentary interruption are their duration and the amount of voltage drop. The latter happens in smaller amount of time with a higher voltage drop.

- **Transients:** Transient can be defined as an increase in supply frequency for a short time duration. The frequency of oscillation can vary from several multiples of supply frequency to hundreds of kHz. Switching transients, capacitor energization and lightning can cause transient.

- **Voltage Unbalance:** It is the presence of negative and zero sequence components in supply voltage. For a balanced three phase supply, the amplitude of each phase would be the same and at the same time, the phase difference between them would be 120^o whereas these quantities do not hold in the unbalanced case. The reasons can be listed as the uneven distribution of single phase loads to each three phases, a short circuit in one phase or unstable utility supply.

- **Harmonics:** Harmonic is a current or voltage waveform whose frequency is an integer multiple of the fundamental frequency. It deteriorates the pure sinusoidal waveform, and causes extra current flowing through the transmission lines that does not contribute any work done. It arises from the nonlinear loads connected to the utility such as switching mode power supplies, variable frequency drives, etc. Harmonics are the most common threat for power quality issues. It can be extracted from the supply voltage or current waveform by fourier analysis.

- **Voltage Fluctuations:** It is described by the intermittent but small variation in rms line voltage. The arc furnaces and cycloconverters can cause this disturbance since they do not operate at the fundamental frequency of the supply voltage.

These electromagnetic disturbances have been categorized as "Short Duration Variations", "Long Duration Variations", etc. in [3]. The latter which typically lasts more than 1 minute is divided into smaller groups which have mainly led to the improvement of Flexible AC Transmission System (FACTS) technology. They are namely sustained interruptions, undervoltages and overvoltages. Sustained interruption is considered as the decrease of the supply voltage to zero for more than one minute. It generally represents a permanent fault in the electrical network. Overvoltage can be caused by a capacitive load which decreases the power factor at the coupling point at the same time. Since the FACTS Devices have an ability to compensate the load by absorbing inductive reactive power from the network, the power factor at the coupling point where the load is connected is improved. As a result, the voltage is reverted and the power quality is increased indirectly. The opposite of the events that cause overvoltages result in undervoltages. In other words, the load is highly inductive this time and causes the supply voltage reduced. Compensation of inductive reactive power by generating capacitive reactive power increases the power factor at the coupling point. Therefore, an increased power quality is achieved indirectly. In the next section, a brief description of FACTS technology and its benefits will be explained.

1.2 Principles of FACTS

Due to the reasons mentioned in previous section, the power quality became a significant consideration. In addition to this, electricity authorities (such as the Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC)) published some standards that suggest limits to the pollution ratio of the electricity to prevent further drawbacks of disturbances. Some of the countries published regulations under the guidance of these standards. As an example, the limits for current harmonics are introduced in Table 1.1 [31].

Table 1.1: Current harmonic limits imposed by Energy Market Regulatory Authority of Turkey

		Medium Voltage $1 < Un \leq 34.5$					High Voltage $34.5 < Un \leq 154$				
Harmonic No		I_k/I_L					I_k/I_L				
		< 20	20–50	50–100	100–1000	> 1000	< 20	20–50	50–100	100–1000	> 1000
Odd Harmonics $(I_h/I_1)(\%)$	3-9	4	7	10	12	15	2	3.5	5	6	7.5
	11-15	2	3.5	4.5	5.5	7	1	1.8	2.3	2.8	3.5
	17-21	1.5	2.5	4	5	6	0.8	1.25	2	2.5	3
	23-33	0.6	1	1.5	2	2.5	0.3	0.5	0.75	1	1.25
	h>33	0.3	0.5	0.7	1	1.4	0.15	0.25	0.35	0.5	0.7
TDD (%)		5	8	12	15	20	2.5	4	6	7.5	10

Even harmonics are bounded to 0.25 times the succeeding odd harmonic.

I_k: Maximum short circuit current at common coupling point

I_L: Fundamental component of maximum load current at common coupling point (15 min average value)

I_h: Harmonic component of load current at common coupling point (3 sec average value)

As well as the statutory obligation, the benefits of FACTS controllers made them an indispensable solution. They are able to remove the disturbances listed in the previous section so that the power carrying capability of the transmission lines is increased and the control of power flow is achieved substantially.

1.2.1 Series FACTS Controllers

The series controller works as a variable voltage supply by changing the impedance of capacitors and reactors. This operation can be achieved by semiconductor switches with self turn-off capability such as thyristors or forced turn-off capability such as gate turn-off thyristors (GTOs). Static Synchronous Series Compensator (SSSC) in [7] and thyristor switched series capacitor (TSSC) in [8] are two examples of the series FACTS Controllers.

Series FACTS controller is more powerful and faster systems to suppress the oscillations and control the power flow than shunt controllers since it has a direct impact on the driving voltage [6]. However, it has more complicated driving algorithm and it has to withstand dynamic disturbance, short circuits or unexpected overloads occurred in the line. Therefore, the ratings of the components have to be chosen higher than the components should normally have to obtain the required power.

1.2.2 Shunt FACTS Controller

The shunt controller works as a variable current supply by changing the impedance of capacitors and reactors. As in the case of series controller, this operation can be achieved by semiconductor switches such as thyristors or switches with forced turn-off capability such as Gate Turn-Off Thyristors (GTOs). Static Synchronous Compensator (STATCOM) in [38] and Static Var Compensator (SVC) which will be examined in this thesis are two examples of shunt FACTS Controllers.

The superior characteristics of this type of controller over series controllers are as follows. They are effective devices to control the voltage around the common coupling point since they have an ability to damp the voltage oscillations [6]. It also have a benefit of serving the connection point independent from the rest of the lines connected to the same point since the distortions of each independent line are reflected to the common coupling point and there is a chance to compensate all the lines at the same time by compensating the common coupling point.

1.2.3 Combined Series and Shunt FACTS Controller

The most beneficial way to control the power flow at the same time to control the line voltage is the combined series and shunt FACTS Controller. Since the series controller injects voltage into the line and the shunt controller injects current into the line, these two controllers can work coordinated or unified depending on the type of the compensation. Note that, if the controller work unified, in other words if the controller are connected to each other with a physical power cable, there can be an active power transition between them through the power link [6]. This helps to balance both active and reactive power in the line.

1.3 Thyristor Switched Capacitor

Thyristor Switched Capacitor (TSC) System is a type of SVC shunt to the line. Single phase consists of a number of back-to-back connected thyristor pair in series to a capacitor and a reactor as can be seen from Figure 1.1. The number of branches in one phase depends on the required precision of the reactive power. Due to its countless benefits including simple design and installation, TSC is preferred in many application areas. Some of them can be listed as supply voltage support, reactive power compensation, harmonics filtration, etc. Among these application areas of TSC, the most common one is the reactive power compensation. TSC simply provides capacitive reactive power to the main electricity so that it reduces or cancels the reactive power demand of the large industrial loads.

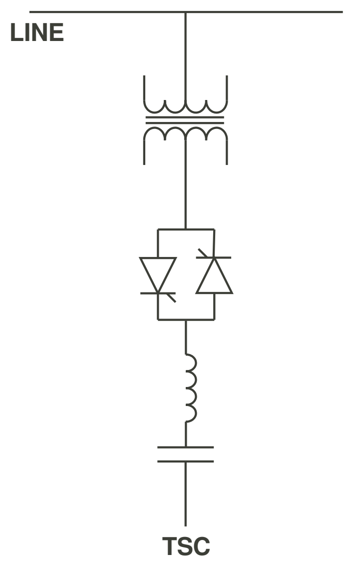


Figure 1.1: General structure of TSC.

TSC has been used since early 70s [9], [10], [11]. It was the only tool to improve the transient stability and to compensate the inductive reactive power efficiently. After investigating the benefits of TSC, many researches have been done about how to improve the transient response of capacitor switching. Since the capacitor draws too much current from the main supply at the instant of turn-on, many methods were improved to obtain a transient-free switching. Some of the researchers tried to obtain this concept without any reactor in series to the capacitor, instead they preferred GTO-Thyristor pairs as in [12]. However, GTO brought more complicated control mechanism and increased the cost. As a result of these researches, the thyristor pair started to be switched on at the instant where the line voltage is equal to the voltage across the thyristor. For the same reason, some other control techniques that support to charge the capacitors before switching on for a better transient response were improved [13], [14] and new zero-crossing detectors were utilized with the improvement of technology [15].

TSC can be configured in many different topology such as delta connected capacitors, star connected TSC, thyristor-diode pairs, etc. The delta connected capacitor banks with different power semiconductor switches are investigated in [26] and [27]. However, there is no practical benefits of using this topology. In [42], these topologies were compared according to the voltage and current ratings of the components.

TSC has been used for many applications in different purposes over the time. With chronological order, it was used for voltage regulation in [16], arc suppression in [17] and reactive power compensation in [18].

Some commercial TSC systems have been built for different purposes in medium and high voltage levels by ABB and Siemens which are the leading companies in application of these system. In these systems, connection to the busbar is generally made through a step down power transformer. The examples of such systems built by ABB and their purpose of installation are listed below. The industry references of Siemens and companies that design commercial TSC systems in low voltage can also be found in Appendix F.

- 150 MVAr TSC for system stability improvement in Zimbabwe [19].

- 94 MVAr TSC for voltage and power quality control in wind power applications [20].

- 115 MVAr TSC for enhancing of power transmission capability in Australia [21].
- Relocatable TSC of 70 MVAr TSC in three stages for the national grid company [22].
- 400 MVAr TSC in three stages for increased power interchange capability between Canada and USA [23].

1.4 Scope of the Thesis

In this thesis, three delta connected TSC systems have been designed and implemented for harmonic filtration and reactive power compensation. The first system has been installed as a lab prototype in TÜBİTAK-UZAY/ODTÜ to filter the 5^{th} harmonic connected to 1 kV busbar. Two of them have been implemented which produces 500 kVAr and 650 kVAr in one step and connected to 1 kV busbar for the purpose of reactive power compensation. They have been installed for the electrical machines in Open-Cast Lignite Mining, Orhaneli/Bursa (BLI) and Yeniköy/Muğla (YLI) administrated by Turkish Coal Enterprise (TKI). These application areas of TSC are the first in literature and had not been studied until now. In Table 1.2, the type of the machines operated in BLI are listed. The reactive power demand of these loads vary between inductive and capacitive region which will be explained next chapter. TSC is used to suppress the inductive reactive power of these loads.

Table 1.2: Electrical Construction Equipment found in BLI, [24].

Type	**Brand**	**Total Number**
Dragline (33 Yd^3)	Bucyrus Erie	1
Electrical Excavator (15 Yd^3)	Marion 191 M	3
Electrical Excavator (10 Yd^3)	PH 1900 AL	4

Transient-free switching concept is the key point of TSC control in this thesis.

From the practical view, the less the transient passes the more the lifetime of the components is. Another important parameter is the frequency characteristics of the TSC. Its behavior has to be in accordance with the load.

There were some important design constraints that have to be followed due to the administrative purposes. For example, the duration of the project was limited to 7 months and it had a restricted budget. Therefore, the design had to be completed as soon as possible. In addition, the place where TSC has been installed has a harsh environment since BLI is an open cast. As a consequence, the design parameters were examined in details so that a robust system was obtained.

In Chapter 2, TSC model is described theoretically. The most common application areas are mentioned, and the critical points in each area are explained. Then the details of control mechanism are examined and the reasons of the importance of transient-free switching concept are stated by mathematical equations. At the end of this chapter, the possible hybrid combinations of the systems are mentioned with their benefits.

In Chapter 3, the practical TSC design is examined. The selection criterions of each components are explained. The special design parameters defined for this thesis and their calculations are given. The practical considerations and the protection techniques are also stated according to the related standards. The implementation of control system defined in Chapter 2 is explained with its detailed circuit diagram. There are several considerations that occurred when the theoretical design is started to be implemented. One of the consequences is given at the end of chapter under the name of cabinet design.

Chapter 4 presents a comparison between simulations and the field datas. These data taken in 22400 sample/sec are processed and the results are shared through this chapter. The three critical waveforms especially determine the design direction. These are the voltage waveform across the thyristor, voltage waveforms across the capacitor and the current waveforms through the reactor. Each phases (turn-on with capacitors are discharged, turn-on with capacitors are charged and self turn-off) are examined carefully for these two components. Lastly, the performance of TSC is presented.

Chapter 5 gives a comprehensive summary of this thesis.

CHAPTER 2

PROBLEM DEFINITION AND PRINCIPLES OF TSC

2.1 Introduction

TSC is a widely used compensation device in industrial areas. The ease of implementation and the reliable operation make it a fundamental reactive power control mechanism. Furthermore, its application area is not limited to reactive power control only. With a careful engineering, it can be used for harmonic filtration and terminal voltage regulation as well as large induction motor starting [5][6]. These concepts will be briefly described in the following section.

From the cost-performance view, slowly fluctuating loads can be compensated by mechanically switched shunt capacitor or filter banks. On the contrary, the operation that needs frequent switching for the rapidly fluctuating loads is necessary to use TSC since the maintenance cost of a mechanical switch is more than the cost of a semiconductor switch. In addition, the reliability issue and the response time should be considered while choosing a suitable switch since overvoltages or some additional harmonics caused by the mechanical switch can be vital [25].

Possible configurations of TSC are shown in Figure 2.1. In an ideal design, each phase consists of back-to-back connected thyristors in series with a capacitor. To achieve more effective operation, each phase includes parallel combination of switched capacitors so that the reactive power can be increased or decreased step by step by turning on/off necessary number of capacitors in each phase at a time (Figure 2.2). As a result, switching performance is increased and smooth voltage and current waveforms are obtained.

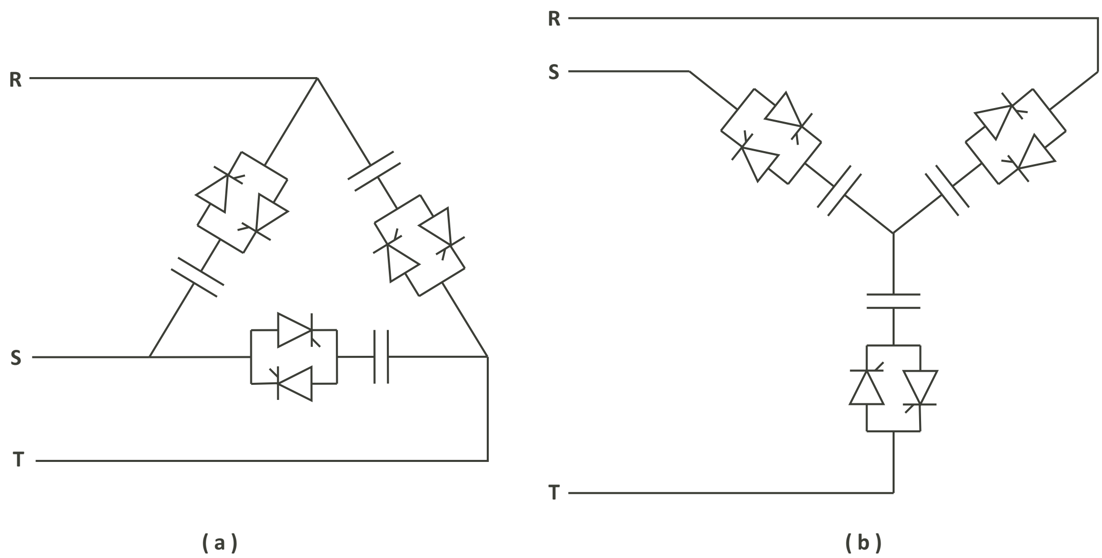


Figure 2.1: Various configuration of Thyristor Switched Capacitor Circuit (a) Delta Connection, (b) Wye Connection.

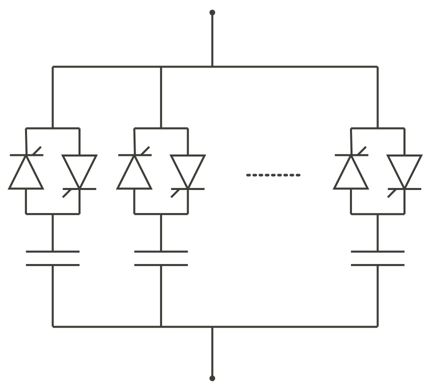


Figure 2.2: Representation of an ideal TSC branch. Each phase may include more than one thyristor/capacitor combination to increase the reactive power variation. The number of branches depends on the reactive power required.

There is one more topology worth to mention since it has some advantages over classical configurations in several application areas. As can be seen from Figure 2.3, capacitor banks are connected in delta. To increase the benefits of this connection type, thyristor/diode or thyristor/GTO pairs are introduced as switching devices instead of antiparallel connected thyristor pairs [26], [27]. However, careful design of its control mechanism is strictly required since there becomes a considerable stress on the capacitors and the semiconductor switches during turn on/off process which also shorten the lifetime of the materials. Otherwise, the whole system might be exposed to an overcurrent in milliseconds which can damage the insulation of the materials. Moreover, in some variations of this configuration, forced commutated semiconductor switch is necessary to achieve a transient free switching which will be described in Section 2.3. This makes the whole control system even more complicated.

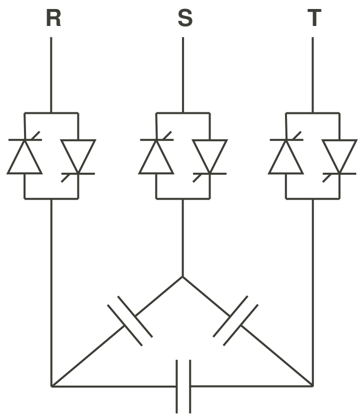


Figure 2.3: Alternative Arrangement of TSC: Delta Connected Capacitor Banks.

In the remaining sections of this chapter, the application areas, especially TSC used for harmonic filtration, will be explained in details. The transient free switching concept and its necessity will be expressed both theoretically and practically. Lastly, the combinations of TSC with other systems which can be frequently seen in industrial applications are mentioned briefly.

2.2 Application Areas

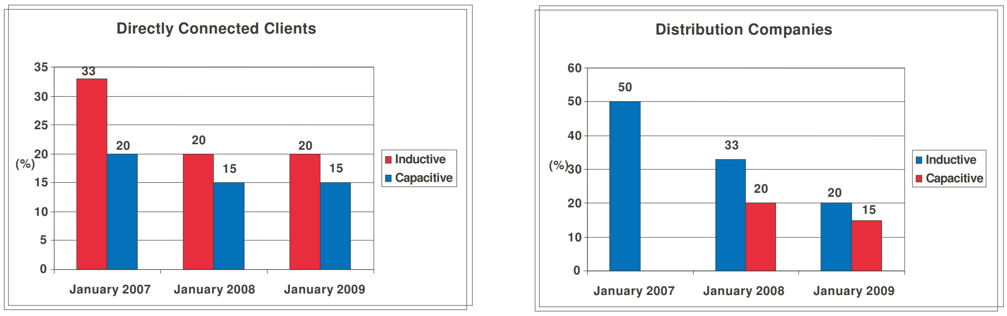
When capacitor switching is considered, reactive power control comes to mind at first. Since the use of medium or large size motors and transformers creating lagging reactive power is increased dramatically in industrial areas over years, the need for capacitive reactive power is inevitable. Also the appreciably quick response of capacitors after being switched on makes TSC a useful and relatively cheaper reactive power compensator. However, TSC can also be used in many other areas such as mitigation of harmonics and terminal voltage stabilization. The remaining topics of this section major in these application areas.

2.2.1 Reactive Power Control

Reactive power control started to be an issue to increase the quality of active power transferred to the utility in early 70s. The importance of power quality concept has been dramatically increased since then and various solutions to this problem has been produced. Some standards were published to increase the power quality and to give a unique understanding to the tolerance of power pollution. According to Turkish Energy Market Regulatory Authority (EPDK), the regulations are given in Electricity Transmission System Supply Reliability and Quality Regulation [28] and Electric Market Network Regulation [29]. The requirements are defined clearly in these regulations and penalties are given to the companies whose do not fulfill these requirements. In Figure 2.4, the limits are determined as monthly average of the consumption. In January 2009, the maximum ratio of capacitive reactive power to active power was accepted as 15% and the limits are 20% for the ratio of inductive reactive power to active power. As also can be seen from this figure, EPDK raises the bar every year and makes the requirements more and more difficult to be satisfied in parallel with the technology. Therefore, the need for reactive power compensators becomes crucial.

TSC is used for reducing or totally compensating the inductive reactive power produced by the load. Since TSC has on/off working principle, in other words single capacitive admittance is connected to or disconnected from the system, the total reactive power that the system needs should be carefully determined so that there is not too much excess capacitive reactive power produced by TSC. In order to avoid this, the system design should be handled delicately so that the reactive power contribution is optimum.

After the decision of reactive power demand, the necessary capacitance needs to



(a) (b)

Figure 2.4: The Limits Defined by EPDK (a) Directly Connected Clients to the Utility, (b) Distribution Companies

be calculated according to this amount of reactive power. The formula is given below:

$$C = \frac{Q}{V^2 2\pi f}, \tag{2.1}$$

where Q is the required reactive power, V is the rms of the line voltage and f is the system frequency. Since the admittance is constant through an operation, the current varies linearly with the applied voltage. Figure 2.5 shows the $VvsI$ characteristics of TSC operating in a varying system voltage. Therefore, the current ratings of the remaining components must be considered accordingly if the applied voltage is known.

As mentioned in Section 2.1, TSC consists of parallel combination of switched capacitors. According to [30], the reactive current should be generated by binary system design so that the maximum error in reactive current is small and the number of stages in a system is minimum. In other words, if there are three different capacitors of 1, 2, and 4 per unit in size, there will be only three branches in one phase consisting of a capacitor and a thyristor pair to create seven different combination. Otherwise, to obtain the same error in the same amount of combination, seven branches in one phase with the same capacitances are necessary. The mentioned case is shown in Table 2.1 as

Note that, the required amount of stages would be 7 in the case where the equal

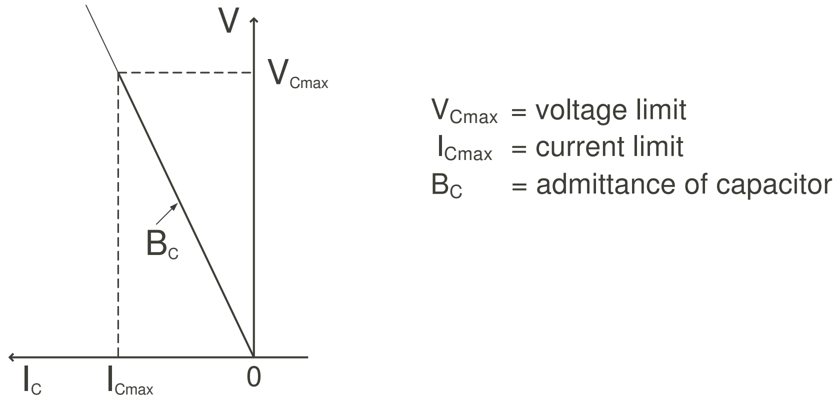


Figure 2.5: Operating $V - I$ area of a single TSC [6].

Table 2.1: Reactive Current Generation in a Design with Binary System

BRANCH 1	BRANCH 2	BRANCH 3	TOTAL REACTIVE CURRENT GEN (P.U.)
P.U. CAPACITANCE			
1	2	4	
X			1
	X		2
X	X		3
		X	4
X		X	5
	X	X	6
X	X	X	7

capacitances were used in order to obtain the same number of reactive power generated with the same error in each step. This means that the result of two different approaches are connected to each other with the formula of $(2^n - 1)$ where n shows the number of branches in binary system design and the result of this formula gives the number of branches in equal stage design.

2.2.2 Harmonic Filtration

A pure sinusoidal voltage is conceptual quantity since an ideal environment is required to generate it. Once it is obtained, only linear loads, the current drawn by which follows the envelope of the voltage waveform, can keep the waveform incorrupted. On the contrary, the industrial areas are full of rectifiers, variable frequency drives, switching mode power supplies, etc. These loads deteriorate the quality of power and deviate the voltage and current waveforms from pure sinusoidal. As a result, there becomes a nonsinusoidal waveform with plenty of additional waveforms in different frequencies superimposed upon it. These different frequencies are harmonics and they appear as multiple frequencies of the fundamental frequency. To ensure the power quality, harmonics need to be filtered out.

IEEE have proposed standards about harmonics and recommend a limitation in harmonic generation [31]. These standards led to strict regulations published by electricity authorities in most of the countries. In Table 1.1, the effective limits to the various harmonics, depending on the size of the utility, accepted by EPDK are shown. Therefore, for some industrial applications, the harmonic filtration has a higher significance than the reactive power compensation.

In an ideal TSC design, each branch consists of a capacitor and a back-to-back connected thyristor pair. However in real life applications, this is not the case. Because a discharged capacitor behaves as a short circuit at the beginning of the turn-on process, the inrush current component through the thyristors is too high such that di/dt is higher than its rating and can cause a failure in these switches. To overcome this problem, a series inductor should be connected to each branch. This inductor works for a current limiting purpose in some applications, and it has a filtering purpose for some other cases. These subjects will be deeply analyzed in Section 2.3. In this subsection, the TSC will be covered from the view point of harmonic filtration. Besides, the purpose of the series reactor in frequency tuning will be explained.

TSC is sometimes designed as a detuned filter or a tuned filter to the lowest harmonic that the load generated. If the main purpose is filtration of one specific harmonic, then the tuned filter would be a good choice. However, practical considerations to use a passive filter should be taken into account. A malfunction in one of the capacitors, temperature and aging cause the tuning frequency shifted upwards. Therefore, the harmonic filters are tuned as a detuned filter in practical applications which means that the tuning frequency is chosen below the harmonic frequency (approximately 10%).

The tuning frequency can be determined by the following formula:

$$f_t = \frac{1}{2\pi\sqrt{L_f C_f}}, \tag{2.2}$$

where L_f and C_f are the filter inductance and capacitance respectively. When a filter is tuned to a distinct frequency, in frequency domain, the resonance values of the filter need to be taken into consideration. There are two types of resonance that can occur during an operation. The first one is the series resonance which is the main design purpose of harmonic filters. The series connected capacitor and inductor impedances in one phase become the same due to waveforms at different frequencies. In this case, the resulting impedance turns out to be only resistive and a significant current flow is expected though the filter. The next type is the parallel resonance which appears at the frequency just below the series resonance frequency and becomes crucial in a filter design as every filter can face with this problem. This time, the reactance of the capacitor becomes equal to the system total shunt inductive reactance (when the transformer, source and line impedances are included). As a result, a significant current flows through the transmission lines and the critical equipment may be damaged, such as connection points and semiconductor switches.

A typical frequency diagram of a detuned filter (tuned to 225 Hz) is shown in Figure 2.6. The frequencies that create parallel and series resonances are clearly shown on this figure. If the system has some critical harmonics below the tuning frequency, the parallel resonance of the filter can excite these harmonics. Therefore, harmonic spectra of the system should be carefully examined in order not to cause a resonance that increases the current passing through the circuit components dramatically. The following figures are obtained by using OrCAD simulation program.

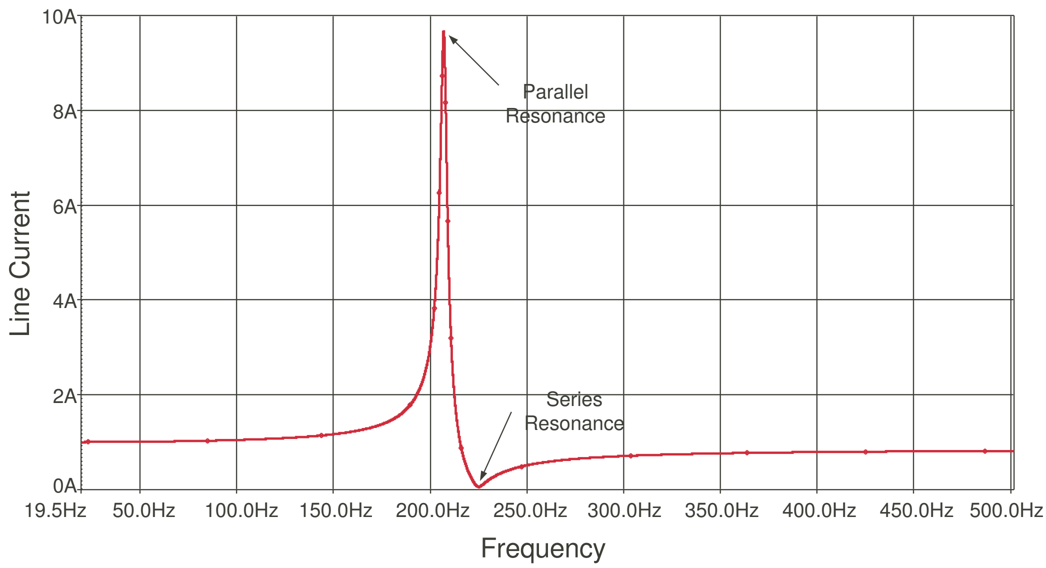
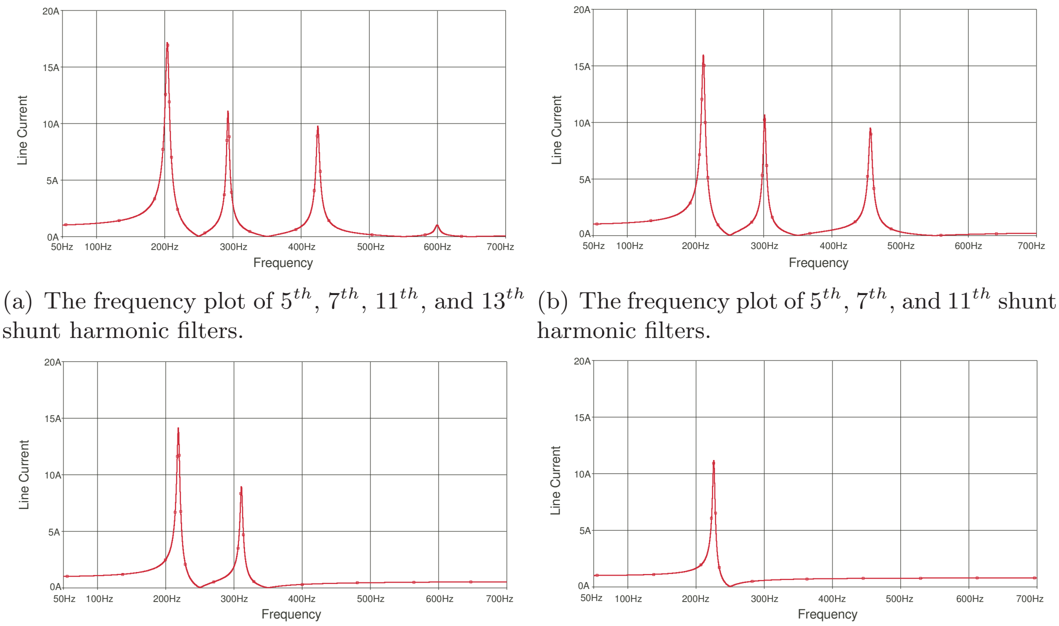


Figure 2.6: Frequency diagram of a 3ϕ power system consisting of 300 MVA power supply, 1 MVA 34.5/1 kV Transformer ($U_k = 5.2\%$), 160 kVAr 5^{th} harmonic filter. 1 A is injected to the system as a harmonic source on the load side.

If the system suffers from a multiple number of harmonics, in other words if the total load of a plant generate harmonics at various frequencies which of them exceed the limits given in the standards, then several filters may be connected as shunt filters. In this case, the resulting frequency spectrum of the filters differ from the one in Figure 2.6. It should be noted that the mentioned configuration is only suitable for passive harmonic filters (passive harmonic shunt filters are briefly studied in [32], [1]) and not for switched filters. Since how many stages are turned-on or off is usually determined by the reactive power need, there may be some times that a critical harmonic filter is not in operation and the system may suffer from harmonic problems. In addition, at the parallel resonance frequencies, the increase in the amplitude of the inter harmonics should be the main consideration as the amplitude of the resonance is higher than the one in a single filter. Figure 2.7 illustrates the switching performance of this kind of shunt filter structure. The filters are turned off one by one starting from the highest harmonic number. The change in the frequency plot each time a filter is turned off should be examined.



(a) The frequency plot of 5^{th}, 7^{th}, 11^{th}, and 13^{th} shunt harmonic filters.

(b) The frequency plot of 5^{th}, 7^{th}, and 11^{th} shunt harmonic filters.

(c) The frequency plot of 5^{th}, and 7^{th} shunt harmonic filters.

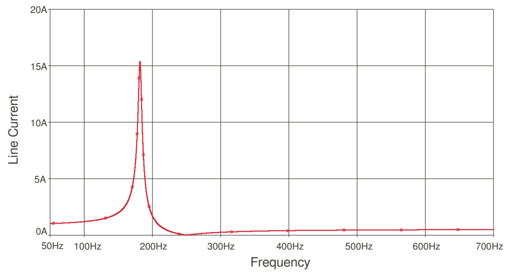
(d) The frequency plot of 5^{th} harmonic filter.

Figure 2.7: The frequency characteristics of several harmonic filters connected in parallel. The system structure is the same as Figure 2.6 except that the filters are tuned to the harmonic frequencies this time.

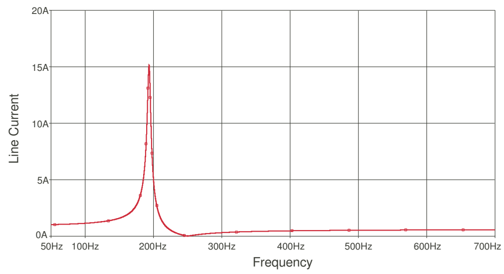
Unlike the above case, when TSC stages are chosen to filter the same frequency harmonics, the filters work more efficiently. The reactive power compensation is achieved, which is the main purpose, at the same time whichever stage is on, the required harmonic is filtered out without any distortion in frequency characteristics. It is obvious from Figure 2.8 that switching thyristors on and off has no effect on neither parallel resonance amplitude, nor series resonance frequency. Therefore it can be concluded that harmonic filtering has a second importance in a TSC design to obtain a stable operation. This characteristics of TSC is valuable if and only if it is used for one specific harmonic filtration.

2.2.3 Terminal Voltage Regulation

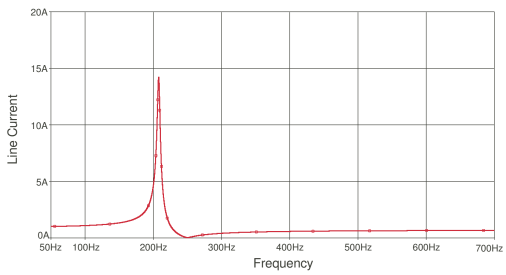
Many electronic devices are exposed to voltage variations due to the change in load type or load number connected to the electricity network. The varia-



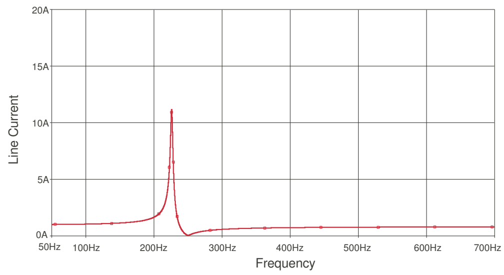
(a) The frequency plot of 5^{th} harmonic filter with four branches on.



(b) The frequency plot of 5^{th} harmonic filter with three branches on.



(c) The frequency plot of 5^{th} harmonic filter with two branches on.



(d) The frequency plot of 5^{th} harmonic filter with one branch on.

Figure 2.8: The frequency characteristics of 5^{th} harmonic filters connected in parallel. The system structure is the same as Figure 2.6 except that the filters are tuned to 5^{th} harmonic frequency.

tions appear as voltage dips, rapid fluctuations in amplitude, or even voltage avalanches. As a result, some faults occur at critical parts of the electronic devices since their operating principle depends on the zero crossing of the voltage and current waveforms. In addition, high voltage may cause a breakdown of the insulation. Therefore, the voltage at the supply end must be kept constant to avoid all these problems.

If the single phase Thévenin equivalent circuit of a power system is represented by Figure 2.9(a), the variation in voltage amplitude can be expressed as:

$$\mathbf{\Delta V} = \mathbf{V_S} - \mathbf{V_L}, \tag{2.3}$$

where $\mathbf{V_S}$ is the voltage at the source end, $\mathbf{V_L}$ is the voltage at the load end. When we assume that $(R_s + jX_s)$ is the source impedance, the voltage difference can also be expressed in terms of load current $\mathbf{I_L}$ as:

$$\mathbf{\Delta V} = \mathbf{I_L}(R_s + jX_s), \tag{2.4}$$

Let's assume that the load is inductive as can be seen in Figure 2.9(b). So the apparent power of the load can be expressed as:

$$\mathbf{S_L} = \mathbf{V_L I_L^*}, \tag{2.5}$$
$$= P_l + jQ_l, \tag{2.6}$$

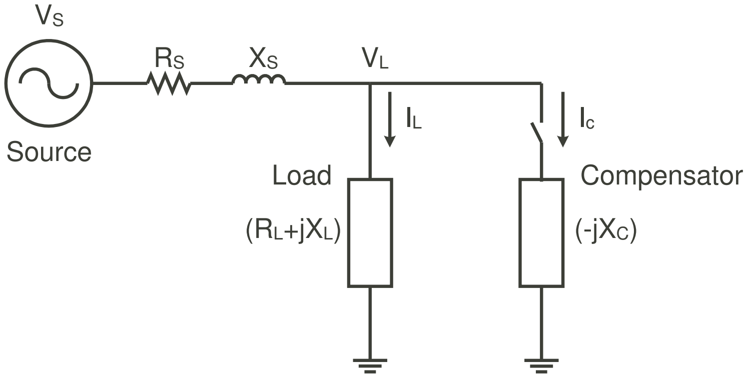
Combining 2.5 and 2.6, the resultant load current $\mathbf{I_l}$ is equal to:

$$\mathbf{I_l} = \frac{P_l + jQ_l}{V_l}, \tag{2.7}$$

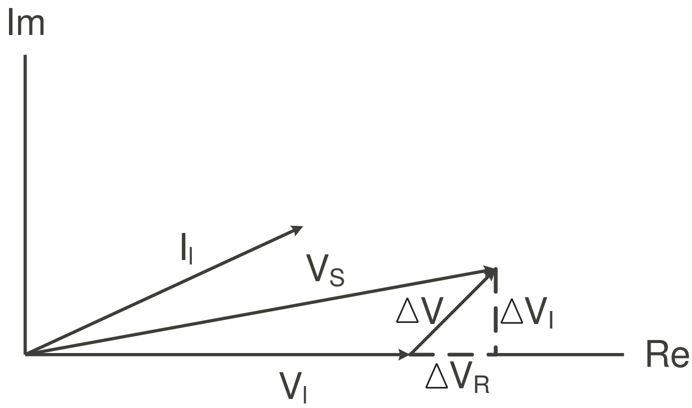
Now, the voltage difference $\mathbf{\Delta V}$ becomes equal to the following equation :

$$\begin{aligned} \mathbf{\Delta V} &= \left(\frac{P_l + jQ_l}{V_l}\right)(R_s + jX_s), \\ &= \left(\frac{P_l R_s - Q_l X_s}{V_l}\right) + j\left(\frac{P_l X_s + Q_l R_s}{V_l}\right), \\ &= \Delta V_R + \Delta V_I, \end{aligned} \tag{2.8}$$

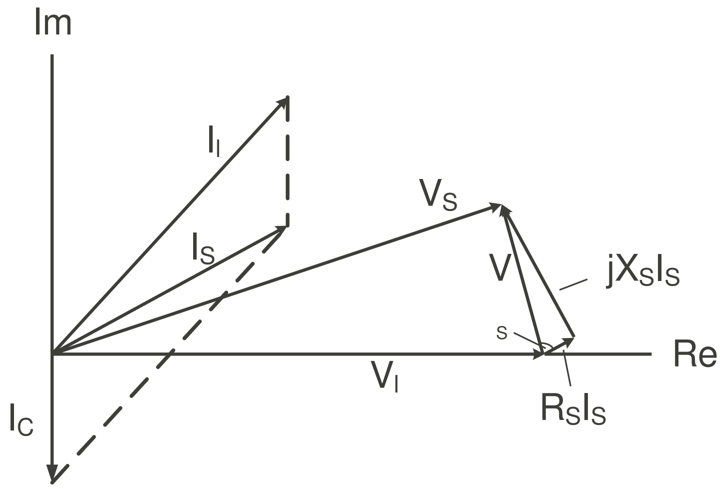
As can be seen from 2.8, the difference includes both real and imaginary components. It means that the load voltage is affected by the real and reactive power of the load. If the total reactive power demand is changed by connecting a shunt TSC which works as capacitive (purely reactive), then the load voltage can be adjusted in such a way that the voltage difference between the source and the load terminals becomes zero. This case is illustrated in phasor diagram in Figure 2.9(c). Note that, by changing the reactive current of the load, the phase of the load voltage also changes, but the amplitude of it remains equal to the supply voltage. Therefore, the compensation of the reactive power and the regulation of the terminal voltage cannot be achieved at the same time by a purely reactive compensator [5].



(a)



(b) Phasor diagram of Source Voltage, Load Voltage and the Load (=Source) Current.



(c) Phasor diagram of Source Voltage, Load Voltage, Source Current, Load Current and the Compensator Current.

Figure 2.9: (a) Equivalent circuit representation of an electrical system and phasor diagrams (b) without compensator, (c) with compensator for zero voltage difference.

2.2.4 Induction Motor Starting

High current demand of an induction motor during start up has been a problem since late 70s when the induction motor usage started to increase. This surge current causes voltage dips and flicker in a power system and exceeds the disturbance limits defined by the electricity authorities. To prevent these results, many methods are developed. Among these methods, the most considerable one is the switched shunt capacitor since the rest of them requires a decrease in starting torque. Using a switched shunt capacitor in medium and large size motor starting is a well-known practice with proven benefits over years.

In this application, mechanical switches are preferable over semiconductor-based ones since the switching occurs only a couple of times in one start up. In addition, large motors are not stopped often as its inertia requires a vast amount of real power each time it is started. However, the reliability of semiconductor technology and maintenance-free operation make the semiconductor switches such as thyristors preferable every time. Besides, its cost is reduced due to the developing technology, so the only drawback is eliminated. Therefore, TSC is a suitable and effective solution for reducing the voltage disturbances in the induction motor starting.

The total capacitance is divided into several equal capacitor branches to ensure that the voltage stays stable as much as possible and smooth transitions occur during the entire motor acceleration. Each stage is turned on and off one by one whenever the motor reaches the speed which doesn't cause a higher voltage disturbance than expected. In [33], it is claimed that the entire capacitor banks are turned on until the current speed reaches 87% of the rated speed.

Due to the economical considerations, in motor starting applications, capacitors are involved to work under stress. The rated voltage is chosen to be suitable for a phase to ground connection, however they are installed to the network phase to phase. Since an increase in rated voltage is proportional to the square of the effective power, it takes only 1/3 as many units as necessary to obtain the same reactive power. Capacitors can withstand this overstress as it lasts only a couple of cycles. However, at least 5 minutes should pass before reenergizing the capacitors to ensure that they are fully discharged [34]. This application directly restricts the frequent switching of a motor during start-up. In addition, it requires a controllable switching to ensure that the overstressed capacitors do not get damaged by a high inrush current component.

2.3 Switching Performance of TSC

The key parameter in TSC design is the transient-free switching concept. It means that switching occurs without any distortion or oscillation in current and voltage waveforms. This could be true only for the ideal system which does not include any inductance and whose single phase consists of a capacitor parallel with an anti-parallel connected thyristor pair. However under practical circumstances with several parallel stages on a phase, the capacitor/thyristor combination draws extremely high inrush current component. This situation is illustrated in Figure 2.10. When the last stage (the branch consisting of C_1 as capacitor and S_1 switch as thyristor pairs) is turned on, it draws current from other branches that are already charged and still conducting as well as the supply. As a result, the amplitude of initial current becomes too high to damage the semiconductor switches. According to [36], the peak value of overcurrents because of these switching transients should not exceed $100I_N$ (I_N is the rated rms capacitor bank current). It is also stated that the inrush transient current can be calculated as:

$$\hat{I_S} = \frac{U\sqrt{2}}{\sqrt{X_C X_L}}, \tag{2.9}$$

where

$$X_C = 3U^2\left(\frac{1}{Q_1} + \frac{1}{Q_2}\right) \times 10^{-6}. \tag{2.10}$$

Here,

$\hat{I}_S$ is the peak value of the inrush current, (A);

U is the phase to ground voltage, (V);

X_C is the series- connected capacitive reactance per phase, (Ω);

X_L is the inductive reactance per phase between the capacitor banks, (Ω);

Q_1 is the output reactive power of the capacitor to be switched in, (MVAr);

Q_2 is the sum of the output reactive power of the capacitor banks which are already energized, (MVAr).

As also can be seen from 2.9, the more inductive reactance series to the capacitors, the less the peak of the inrush current component. Therefore each branch includes additional series inductor in order to limit the inrush current, in other words in order to keep the di/dt rating of the thyristor within the acceptable limit. The resulting equivalent circuit becomes an LC circuit (Figure 2.11). It is therefore inevitable to expect an oscillation between these storage devices.

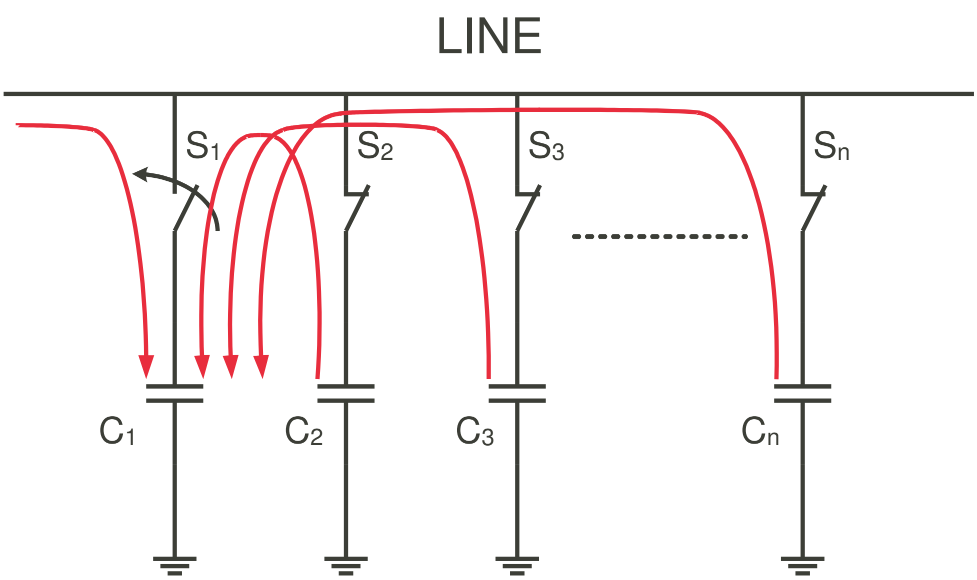


Figure 2.10: The illustration of inrush current paths drawn by the stage turned on lastly. The rest of the stages are already conducting and charged to the supply voltage.

In the following sections, switching performance of a practical TSC will be represented with mathematical expressions and figures. The necessary conditions

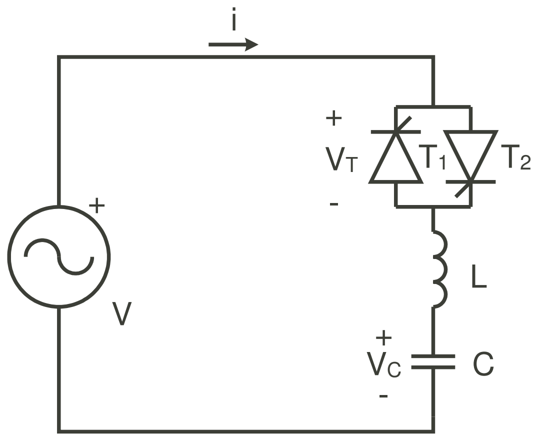


Figure 2.11: Single phase representation of TSC.

for transient-free switching will also be investigated.

2.3.1 Switching Transients

The single phase equivalent circuit of one-stage TSC in Figure 2.11 will be taken as reference to the rest of this section, the multiple stage analysis can be done similarly. To simplify the equations, ignore the small resistance coming from the inductor coil and the transmission line since it has minor effect over the peak values of any resulted waveforms. The mathematical representation of this simplified circuit when the thyristors are in transition is as follows:

$$v(t) = \hat{V} \sin(wt + \alpha), \tag{2.11}$$

where $v(t)$ is taken to be the source voltage and α is the phase difference. To observe the switching transients, the simplified mathematical model of overall TSC system has been used. The thyristor is supposed to be an ideal switch, and the series inductor and capacitor are supposed to be ideal storage devices. Since $i(t) = C\frac{dv_C(t)}{dt}$, and $v_L(t) = L\frac{di(t)}{dt}$, the overall system equation (when the stored charge of the capacitor is represented by V_{co}) can be written as:

$$\frac{d^2i(t)}{dt^2} + \frac{1}{LC}i(t) = \frac{w\hat{V}}{L}\cos(wt+\alpha), \tag{2.12}$$

with the initial conditions:

$$\begin{aligned} &i(0) = 0, \\ &\frac{di(t)}{dt}|_{t=0} = \frac{\hat{V}}{L}\sin\alpha - \frac{V_{co}}{L}, \end{aligned} \tag{2.13}$$

The solution to the ordinary differential equation in 2.12 is as follows:

$$\begin{aligned} i(t) = \; & \tfrac{wC\hat{V}}{1-w^2LC}\cos(wt+\alpha) - \sqrt{LC}\left[\tfrac{V_{co}}{L} - \hat{V}\left(\tfrac{1}{L} + \tfrac{w^2C}{1-w^2LC}\right)\sin\alpha\right]\sin(\tfrac{1}{\sqrt{LC}}t) \\ & -\tfrac{wC\hat{V}}{1-w^2LC}\cos\alpha\cos(\tfrac{1}{\sqrt{LC}}t) \end{aligned} \tag{2.14}$$

The details of how to derive this result can be found in Appendix A. To simplify the above equation, let

$$\begin{aligned} &n = \frac{1}{w\sqrt{LC}} = \sqrt{\frac{X_C}{X_L}}, \\ &\Longrightarrow \frac{1}{1-w^2LC} = \frac{n^2}{n^2-1}, \\ &B_c = wC, \\ &w_o = \frac{1}{\sqrt{LC}}, \\ &\Longrightarrow n = \frac{w_o}{w}, \\ &\hat{I}_1 = \frac{n^2}{n^2-1}B_c\hat{V}, \end{aligned}$$

assign as new variables. Here w_o is natural frequency of oscillation as mentioned before and n is equal to the per-unit natural frequency. Therefore, the final equation to represent the single phase TSC is shown below:

$$\begin{aligned} i(t) = \; & \hat{I}_1\cos(wt+\alpha) - nB_c\left[V_{co} - \tfrac{n^2}{n^2-1}\hat{V}\sin\alpha\right]\sin(w_ot) \\ & -\hat{I}_1\cos\alpha\cos(w_ot), \end{aligned} \tag{2.15}$$

2.15 shows that there are some components oscillating at the natural frequency of filter. These are the last two terms of the equation on the right hand side. The amplitude variation of this component can be found in Figure 2.12.

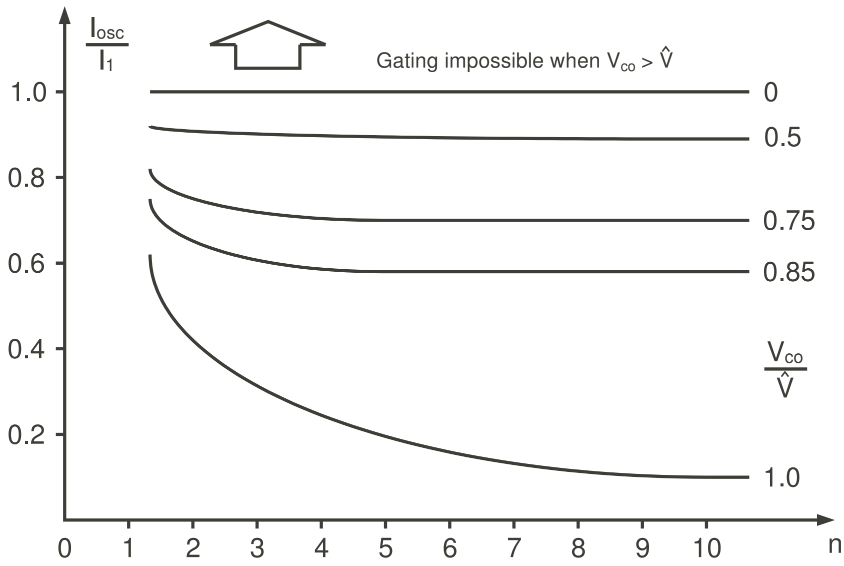


Figure 2.12: Amplitude of oscillatory current component - thyristors gated when $v = V_{co}$, [35].

2.3.2 The Concept of Transient Free Switching

The transient-free switching concept is highly important because of several reasons. First of all, the capability of thyristor should be taken into account. The rate of increase in current through the thyristor can not be more than its di/dt ratings otherwise the thyristor gets damaged irreversibly. The other reason is that the oscillating current pollute the electrical system and causes supply voltage distortions. As a result, the power quality decreases. As also mentioned in Section 2.3, capacitors can not withstand a peak of the inrush current higher than 100 times its rated current, hence a great care must be given to switching performance.

To be able to perform a transient-free switching, the oscillatory components in 2.15 must be vanished. There are two conditions to examine before determining a control strategy for transient-free switching. The first one is when the capacitors are discharged or have not been energized yet. In this case, there is no current flowing through the circuit and the supply voltage can be directly seen across the thyristors. From 2.11 at $t = 0$, this case can be represented by the following equations:

$$\begin{aligned} \sin\alpha &= \frac{V_{co}}{\hat{V}} = \frac{0}{\hat{V}} = 0, \\ &\Longrightarrow \alpha = 0^o, \\ &\Longrightarrow \sin\alpha = 0 \;\; \& \;\; \cos\alpha = 1. \end{aligned} \tag{2.16}$$

Hence, 2.15 becomes:

$$i(t) = \hat{I}_1 \cos(wt) - \hat{I}_1 \cos(w_o t). \tag{2.17}$$

This result corresponds to $I_{osc}/I_1 = 1$ in Figure 2.12 which means that the amplitude of the oscillatory current component is equal to the amplitude of the fundamental current component. It is obvious from 2.17 that the peak value of i(t) is always smaller than $2\hat{I}_1$. Therefore initiating a switching of a fully discharged capacitor should not be preferred if otherwise is available.

The second condition is when the capacitor is charged to the source voltage initially. At $t = 0$ the following condition holds:

$$\sin\alpha = \frac{V_{co}}{\hat{V}}. \tag{2.18}$$

Solving 2.15 and 2.18 together, the graph in Figure 2.12 is derived. The closer the initial capacitor voltage to the source voltage, the better the transient characteristics can be obtained.

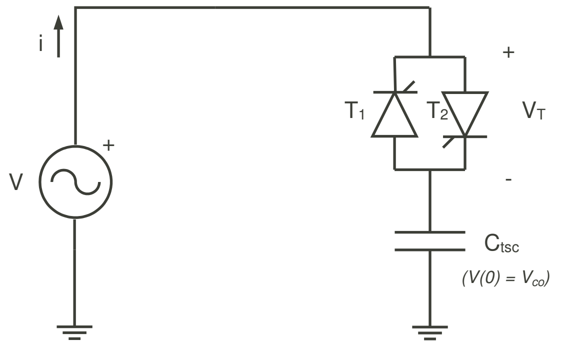
In ideal case whose circuit diagram can be seen from Figure 2.13(a), the transitions occur smoothly. In other words, when the thyristors are switched on, the current starts to flow through the capacitors without any transients. Its waveform directly follows the source voltage (Figure 2.13(b)) with a phase difference 90^o leading. At the same instant, the capacitor voltage begins following the source voltage since the thyristor does not hold any voltage on itself when it is conducting. Attention needs to be given to the voltage waveform across the thyristor before switching on. Before the gate signals are sent, thyristors are exposed to capacitor's charged voltage in addition to the source voltage. Therefore, the voltage waveform oscillates between zero and two times the peak of the source voltage, Figure 2.13(c). Here, an important result arises that will be explained in details in Chapter 3. The ratings of the thyristor must be chosen carefully so that it can withstand the voltage at least two times as much as the source voltage.

As stated above, if the entire components were ideal, everything would be easy. However, to be able to design a system that can continue working for years without any problem, every possibility and every nonlinear behavior should be considered. For example, the Thévenin equivalent circuit of a practical TSC can be seen in Figure 2.14(a). It includes the source inductance, the transformer leakage inductance and series resistance, and the inrush limiting reactor and its internal resistance in addition to the capacitor and thyristor pairs. These parameters can be calculated by the following equations:

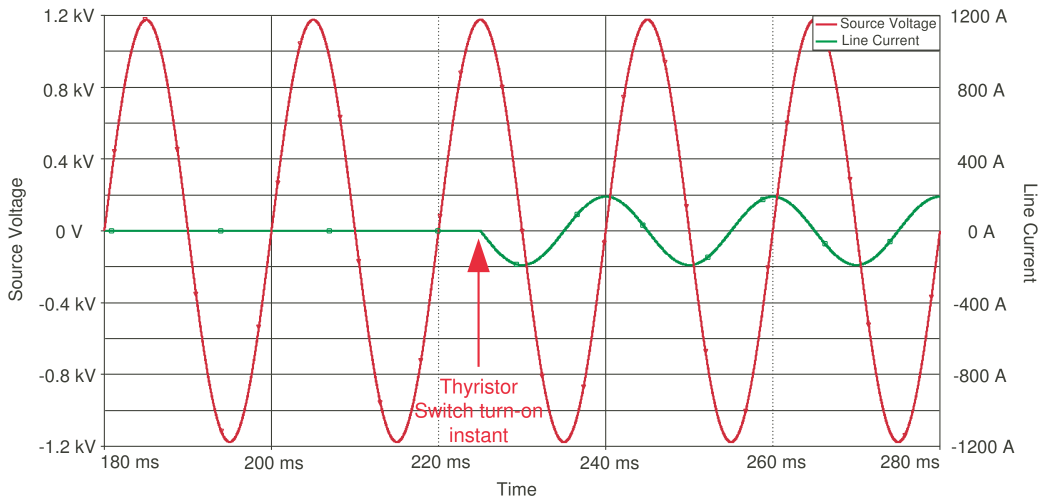
$$L_s = \frac{V^2}{2\pi f S}. \tag{2.19}$$

Note that if the calculations are made regarding to the primary side, the resulted impedance must be reflected to the secondary side by including the transformer ratio. This means that the impedance must be divided by $(N_1 : N_2)^2$ (N_1 and N_2 are represented the transformer's primary and secondary side ratio respectively). In 2.19, the source resistance could be taken into account, however it is negligible and does not affect the behavior of the overall system.

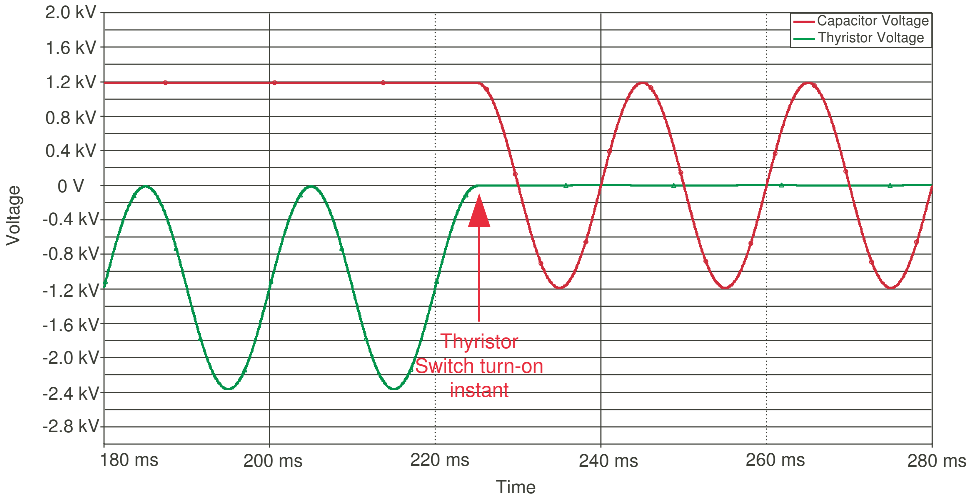
On the other hand, the transformer has appreciable leakage inductance and resistance that come from its long coils. The calculation can be made according to both primary side or secondary side. The impedance reflection rules must be applied in case the calculation is made on the primary side. The series resistance



(a) Circuit for analysis of TSC in ideal circumstances.



(b) Supply voltage and phase current waveforms after the switching occurs.



(c) Capacitor voltage and thyristor voltage waveforms after the switching occurs.

Figure 2.13: The behavior of an ideal TSC. Capacitors are initially charged.

is known as copper loss of the transformer and for a typical transformer, it is approximately 1% of its power rating. The formula below explain how to obtain the leakage inductance:

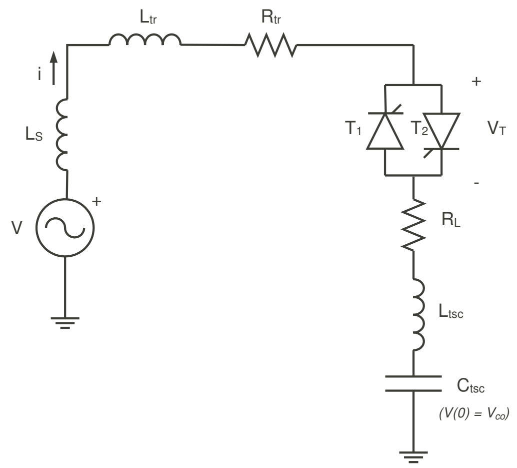
$$L_{tr} = \frac{V^2 U_k}{2\pi f S}. \tag{2.20}$$

where U_k is the transformer's short circuit impedance rating (If the transformer's secondary terminal is short circuited line to line, primary terminal voltage increases from zero volts to a level at which $U_k V_{secondary}$ appears at the secondary terminal). The inrush limiting reactor or a filter reactor is determined depending on the tuning frequency and can be calculated by 2.2. In this equation, there are three unknowns. The capacitance is derived from the required reactive power of the system as mentioned in Section 2.2.1. The tuning frequency is chosen according to the system overall frequency characteristics and also explained in Section 2.2.2. From these values, the inductance can be obtained. Its internal resistance can be obtained by 2.21 where Q is called the *Quality Factor* of the inductor. It can be easily seen that Q represents the ratio of inductive reactance at tuned frequency to its internal resistance. The quality factor of an ordinary inductor can be found in its datasheet.

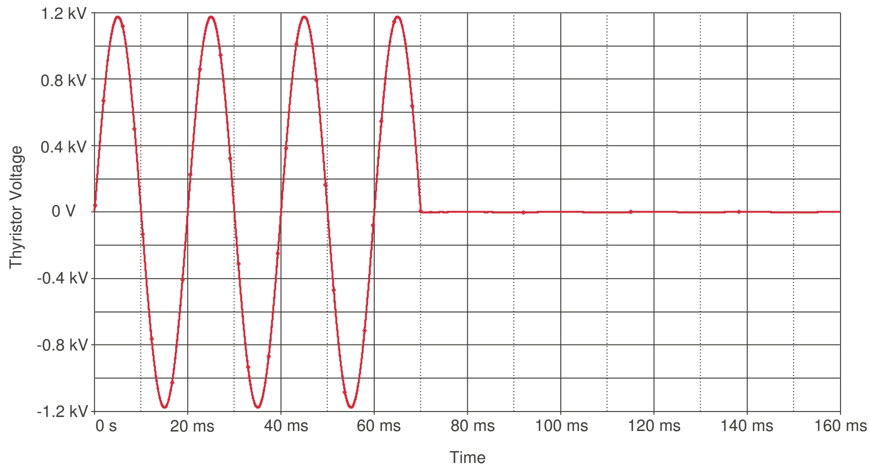
$$R = \frac{wL}{Q}. \tag{2.21}$$

In Figure 2.14(b), the initial condition of capacitor is zero volts. Therefore, thyristor carries only the supply voltage. After switching on, the voltage across the thyristor drops to zero (or almost zero as it has a small internal resistance that creates negligible voltage drop) and, the capacitor and inductor in series start to be charged. However, there is a current flowing back and forth between these two storage devices at the tuning frequency until the stable point is found and current flow becomes smooth (Figure 2.14(c)). The series resistance R_L helps this oscillation to damp out and to reach a stable point. If the circuit did not include any resistance, then the oscillations would continue forever.

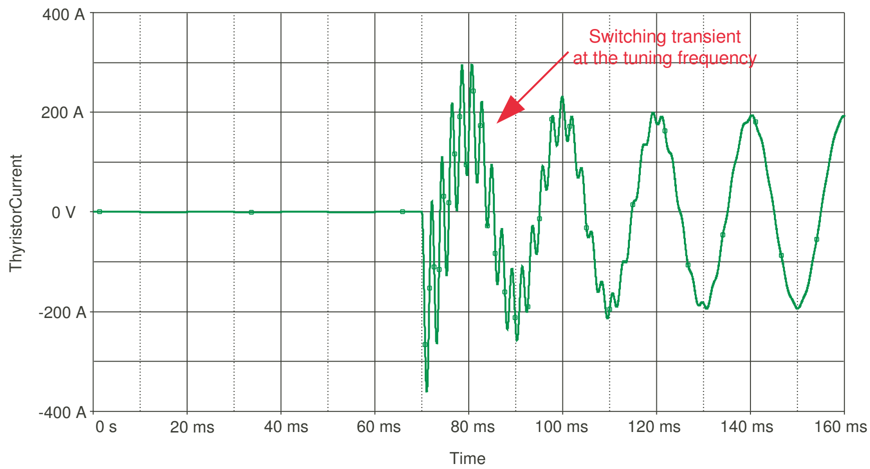
If the nonlinear behavior of thyristor is also taken into account, then some other



(a) Circuit for analysis of TSC in practical circumstances.



(b) Thyristor voltage waveform after the switching occurs.



(c) Thyristor current waveform after the switching occurs.

Figure 2.14: The behavior of a practical TSC. Capacitors are initially discharged.

components parallel to the thyristor must be established to protect the thyristor from overvoltage at the turn-on instant. These topics that requires safety issues will be discussed in next chapter.

2.4 Possible Hybrid Configurations

TSC is usually utilized with another compensator or filter system because of several reasons. First of all, TSC has a discrete reactive power capability. In each stage, the reactive power increase has a stair-like behavior. Increasing the stage number may help improving transitions and obtaining a more precise reactive power compensator. However, the economical considerations do not allow to have more than couple of stages as each stage includes one thyristor pair, one capacitor and one inductor which make the overall system too expensive to build.

As mentioned in Section 2.2.2, the main purpose of TSC is not designing it for harmonic filtration. Therefore, it would be beneficial to use TSC and a harmonic filter that compensate the reactive power and filter the main harmonics at the same time. A passive or an active filter can be chosen depending on what kind of filtration is necessary. TSC and active filter combination will be explained later. However, using a passive filter is also a common practice since it has a high cost/efficiency performance. Remember that a passive filter stays connected to the main bus line and there is no way to control its behavior unless it is disconnected physically.

The last and maybe the most important reason to use a hybrid configuration is the need for inductive reactive power as well as capacitive reactive power. The motor drives and long underground cables produce leading reactive power. Especially the usage of underground cables has been increased because of its countless advantages. For example, the esthetical appearance of streets and places are not disturbed by unnecessary overhead cable and their installation hardware. Moreover, they are not exposed to the atmospheric events and they are much more safer in city centers. As explained before, EPDK has strict regulations over the limits of both inductive and capacitive reactive power. Even the capacitive limit is lower than the inductive limit, therefore precautions should be taken to secure staying within the limits.

In the following sections, current configurations are summarized. Section 2.4.1 explains the method proposed in the field application part of this thesis. Therefore, its details are left to the subsequent chapters.

2.4.1 Thyristor Controlled Reactor and TSC

Thyristor Controlled Reactor (TCR) and TSC combination is the most common compensating system used in industrial areas. The principle of operation of TCR is based on the control of reactor current by displacement of the thyristor's firing angle. Firing angle means the angular delay from the zero crossing of source voltage to turn on the thyristor so that the mean voltage across the thyristor is controlled. The maximum conduction of a TCR can be obtained by 90^o gating angle. The gating angle varies between 90^o and 180^o, outside this period, the conduction can not be initiated.

The circuit diagram of TCR and its utilization with TSC to the main bus line are shown in Figure 2.15(a) and Figure 2.15(b) respectively. The split arrangement of TCR reactors are due to the protection of the thyristor in case of a reactor fault. The purpose of TCR is not only supplying inductive reactive power, but also smoothing the reactive power TSC produces. For example, there are two-stage TSC with a capacity 2 per unit each and a TCR with 4 per unit in total. When there is a load with 3 per unit demand, two stages of TSC must be on and at the same time, TCR must produce 1 per unit reactive power not to overcompensate the load.

In Figure 2.16, the resultant $V - I$ characteristics of TCR and TSC operating together is shown. Two stage TSC is sampled in this figure each of which has an impedance of B_C and the full capacity impedance of TCR is represented by B_{Lmax}. The operating point of the overall system can be any place inside the hatched area. The reactance of each system changes by the supply voltage.

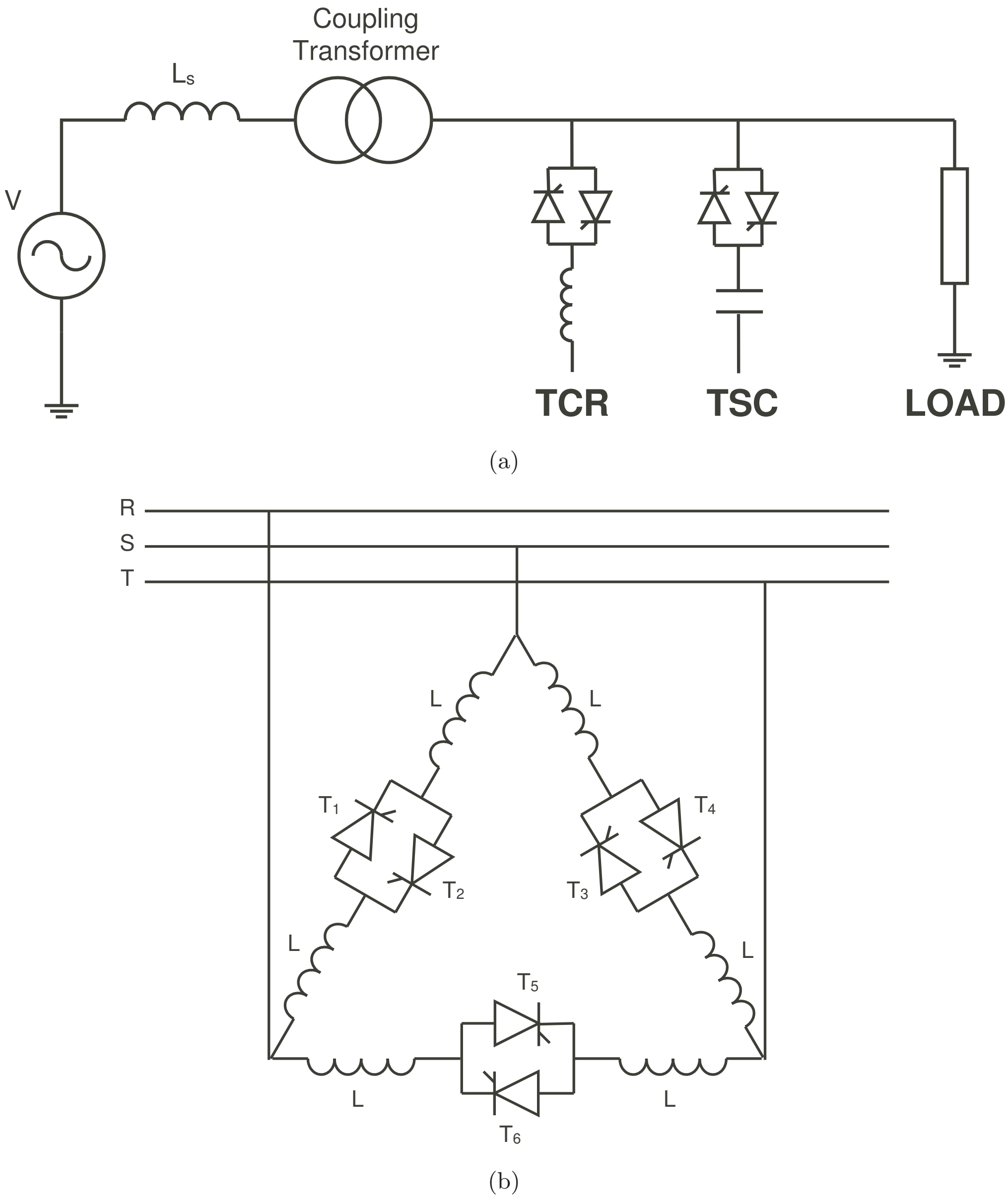


Figure 2.15: (a) Single line system diagram of TCR and TSC connected in parallel. (b) 3ϕ Circuit representation of TCR.

The sizing of a hybrid system is an important subject to work on. Systems are combined to get benefit of each of them and to build a more efficient system. If the sizing of each system is not calculated correctly, some extra reactive power capability of systems prevent an optimum utilization of power switches and the cost of components is increased since the current and voltage ratings must be chosen higher to achieve the design requirements. In addition, the losses of a single TCR can be reduced by an optimum system sizing.

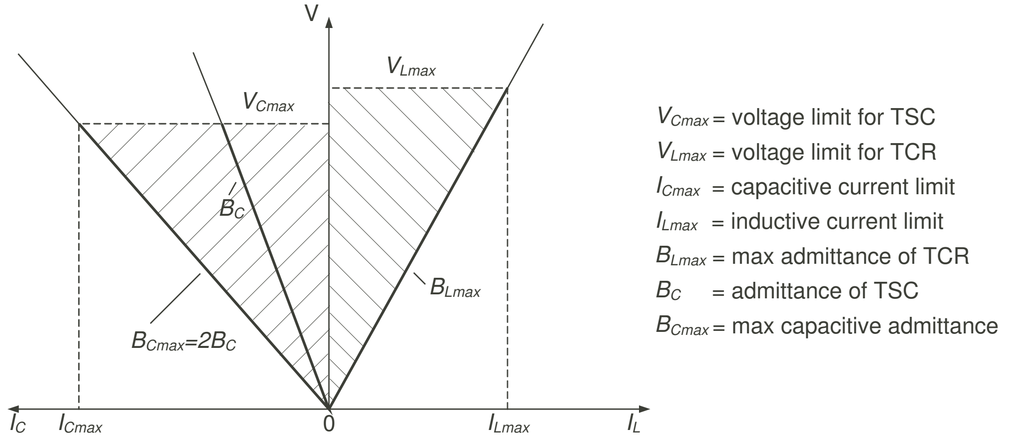


Figure 2.16: The $V - I$ characteristics of TSC and TCR combination, [6]

In Figure 2.17, there is a load that operates in inductive and capacitive area symmetrically. According to [40], the following formula must hold in order to confirm that an optimum capacity usage is obtained.

$$Q_L + Q_{TCR} + Q_{TSC} = 0. \tag{2.22}$$

Since TCR is related to only the capacitive part of the load, and TSC is related only the inductive part of the load to compensate, each of these regions of the load determines the reactive power generation capability of each system. Since the load is symmetrical in Figure 2.17, the power generation of each system must be equal to exploit the components efficiently.

2.4.2 Static Synchronous Compensator and TSC

Static Synchronous Compensator (STATCOM) already has an application area when it is combined with a passive filter. However, it is more advantageous to install a shunt TSC because of several reasons. The purpose of this idea comes from the efficient utilization of system components and its size. Since the passive filter can not be turned off automatically, in no load condition, STATCOM must still be conducting to compensate the excess capacitive energy produced by the

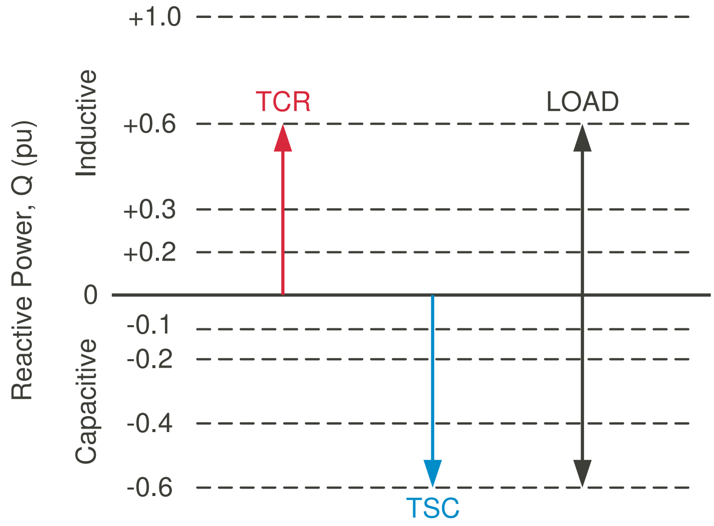


Figure 2.17: Power generation capability of TSC and TCR for optimum system performance.

passive filter. In this case, more capacity is needed to compensate the same load.

The converter used for reactive power control has two types, namely voltage source converter (VSC) and current source converter (CSC). The principles of VSC based STATCOM are listed in this section briefly and will be referred as STATCOM for simplicity. The details of CSC based STATCOM can be found in [38].

The connection diagram and the basic six-pulse circuit configuration of a STATCOM can be seen in Figure 2.18(a) and Figure 2.18(b) respectively. It is connected in parallel to TSC and the utility. The converter uses forced commutated semiconductor switches such as GTOs, IGBTs and IGCTs. The capacitor operates as DC voltage source and helps regulating the bus voltage. In steady state operation, the voltage generated by the converter is in phase with the supply voltage so that there is only reactive power flowing through the system. Then the reactive power generation is expressed by the following formula,

$$Q = \frac{(V_1 - V_2)}{X} V_1. \tag{2.23}$$

V_1 is the system voltage, V_2 is the voltage produced by the converter, and X is the transformer leakage inductance. When the produced voltage increases above the system voltage, the converter generates reactive power. When opposite of this event happens, the converter absorbs the reactive power as a result.

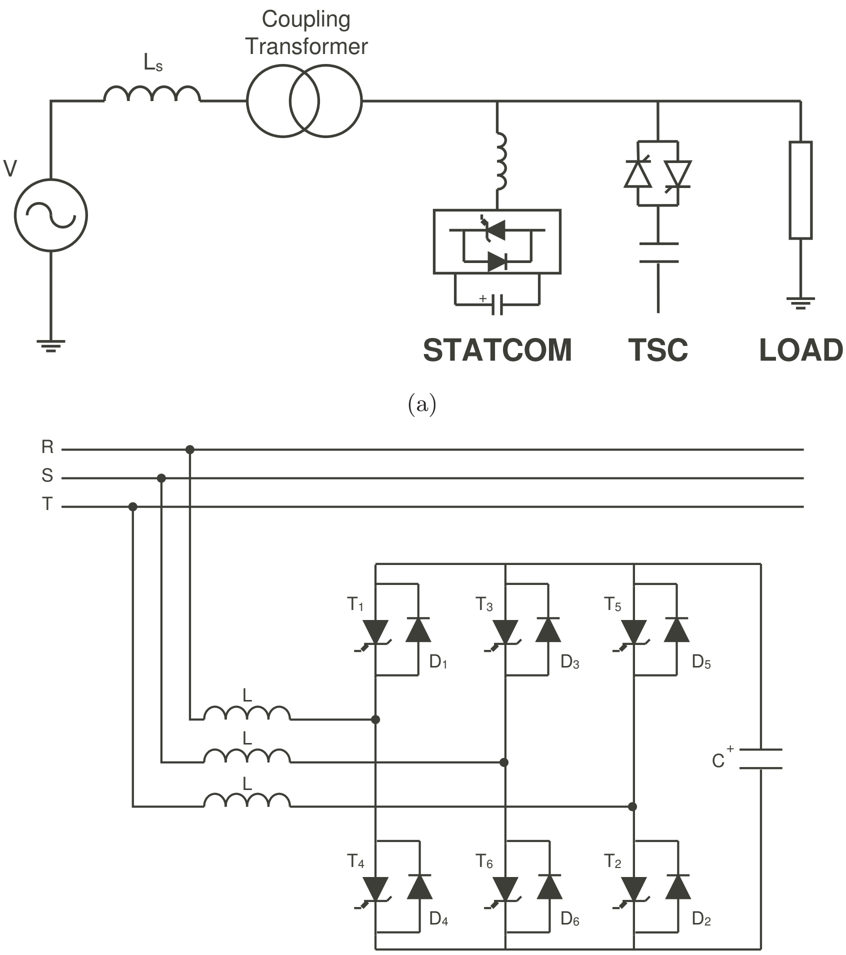


Figure 2.18: (a) Single line system diagram of STATCOM and TSC connected in parallel, (b) 3ϕ Circuit representation of VSC based STATCOM.

In Figure 2.19, a typical $V-I$ characteristics of STATCOM and TSC operating together is shown. The angled lines can be explained by the contribution of TSC since the it has a constant impedance. The hatched area again shows where the operating point can be.

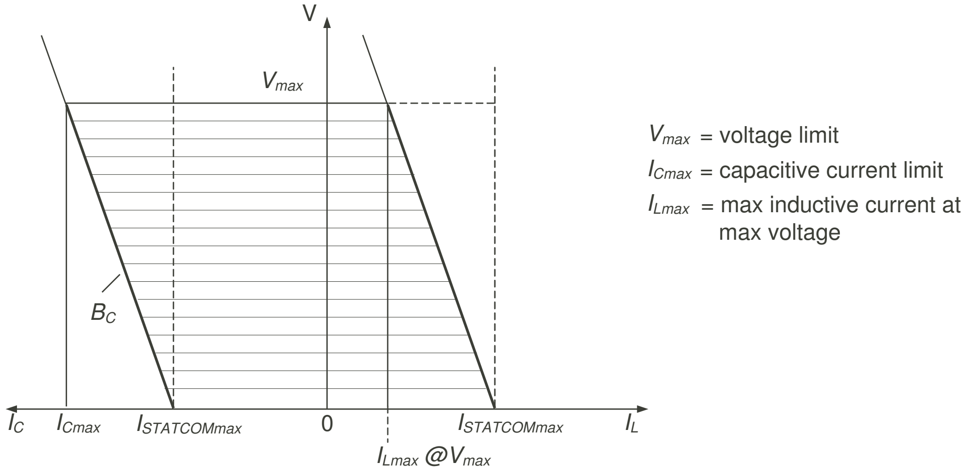


Figure 2.19: The $V - I$ characteristics of TSC and STATCOM combination, [6]

As mentioned in previous section, sizing of a combined system is crucial to stay within the optimum performance limits and to reduce the STATCOM losses considerably. In Figure 2.20, the load oscillates between capacitive and inductive region. However, the inductive power requirement to compensate the capacitive part of the load is somewhat higher than the reverse case. As it is known that STATCOM is the only source of inductive reactive power, the size of almost symmetrical STATCOM can be determined by the load's need directly. The following formula helps determining the STATCOM's capability:

$$Q_{STATCOM} = Q_{CSC} + Q_F, \qquad (2.24)$$

where Q_F is the shunt capacitors connected to CSC terminals. According to 2.22 and 2.24, the required capacitive reactive power can be calculated. Since TSC can be turned on and off in case of necessity, STATCOM does not have to compensate the capacitive power TSC is given to the system when the load operates in capacitive part. As a result, smaller size STATCOM is sufficient to perform the same duty.

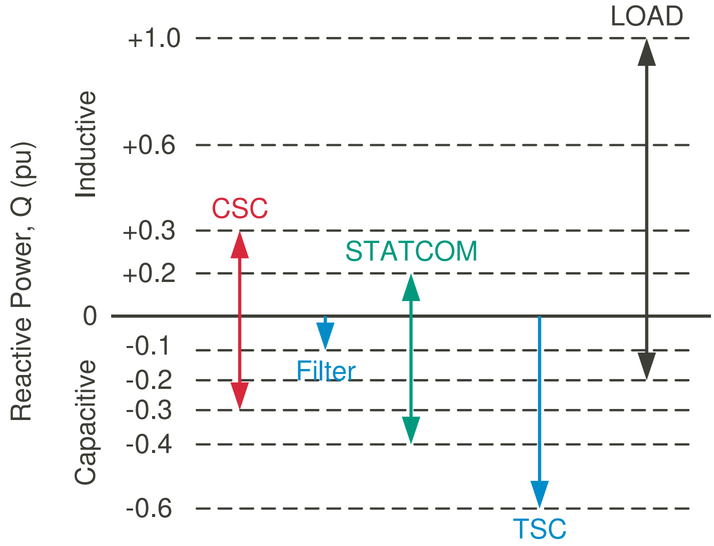


Figure 2.20: Power generation capability of TSC and CSC based STATCOM for optimum system performance.

2.4.3 Active Power Filter and TSC

Nonlinear loads such as diode or thyristor rectifiers, arc furnaces are common in industrial areas and they are major source of harmonic currents. Active Power Filter (APF) works as a harmonic filter which can eliminate not only a specific harmonic, but also the harmonics with any frequencies other than the fundamental frequency at the same time. The principle of operation of an APF is that it decomposes the oscillating current component out of the total current that the load draws from the supply system and produces harmonic current component that cancels the harmonic component of the nonlinear load.

APF also has an ability to compensate the reactive power of the load, however this purpose forces the semiconductor switches (such as IGBT) used in the converter and their power ratings must be increased. This solution to supply all the reactive need is not preferable since the cost versus efficiency ratio is increased. Instead of this, TSC can be connected to be the main reactive power supply.

Figure 2.21(a) shows the single line diagram of shunt TSC and APF to the power system. Voltage source converters (VSC) or current source converter (CSC) can be used to regulate the voltage. For the DC voltage supply, again a capacitor parallel to the converter is connected. In Figure 2.21(b), VSC based APF is shown. The reactors connected in series are for transforming the voltage created by the converters to current source given to the bus line. As can be noticed that the circuit topologies of APF and STATCOM are similar to each other, but their control mechanisms are different.

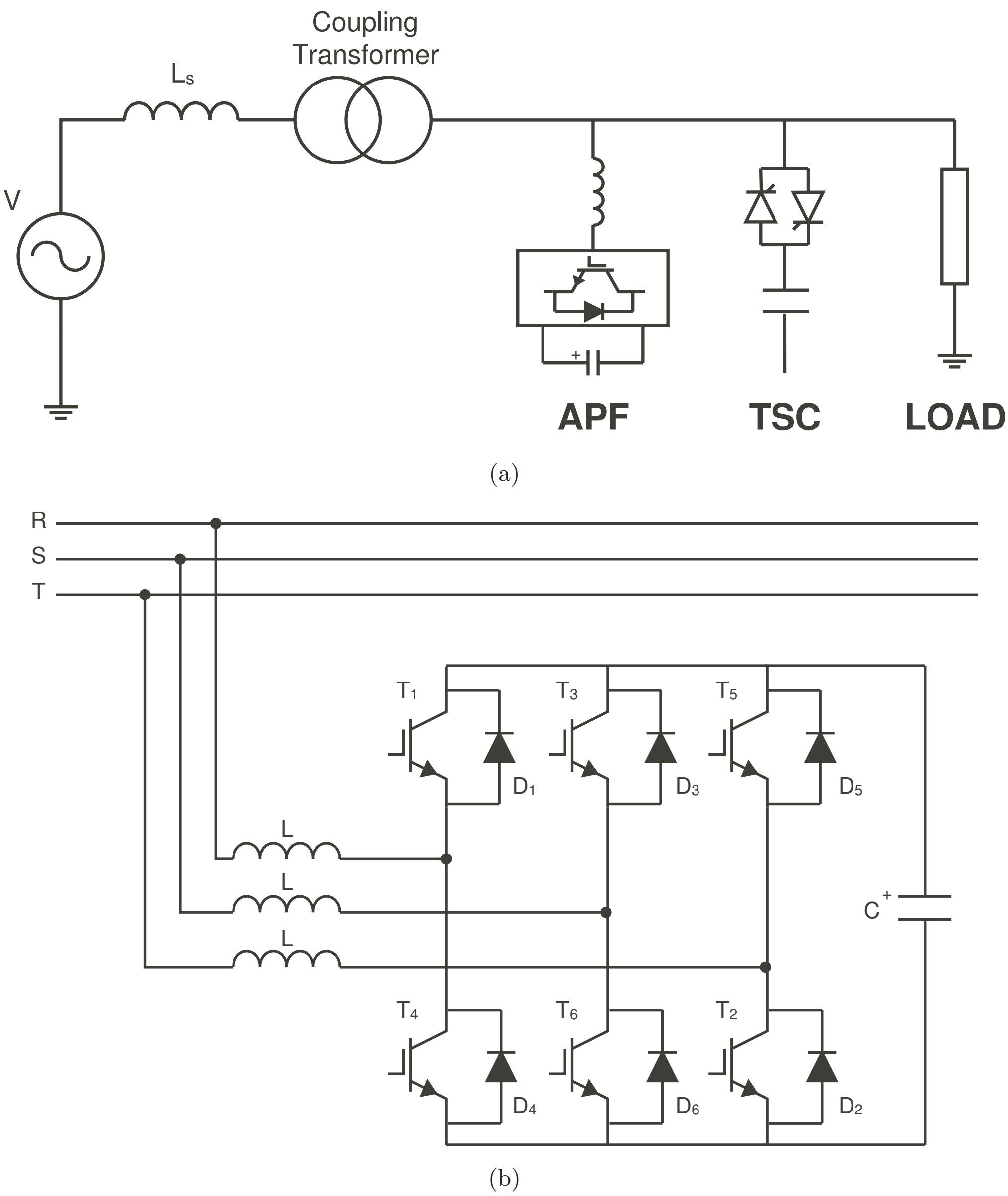


Figure 2.21: (a) Single line system diagram of APF and TSC connected in parallel. (b) 3ϕ Circuit representation of APF.

It should be noted that if the power system contains voltage harmonics as well as harmonics coming from the source, it is impossible to create an optimal conditions for whole electrical system. Therefore, one mission must be performed one at a time to obtain an efficient compensation, [39].

2.5 Discussions

In this chapter, the following conclusions can be drawn:

- The main purpose of a TSC is to generate (capacitive) reactive power so as to compensate the load.
- It is not efficient to use the TSC as a harmonic filter unless it filters only one type of harmonics.
- TSC should be built with several stages to give more accurate response at the expense of decrease in dynamic response.
- The main advantage of a TSC is controlled connection of capacitor to and controlled disconnection from the supply. Therefore a transient-free switching concept has been studied to prevent the inrush current component.
- The hybrid topologies can be very useful in order to obtain an optimum reactive power compensating system.

The frequency response of TSC for several conditions has been given in this chapter. There are two main points that should be considered, series and parallel resonant frequencies. As the filter frequency is adjusted according to the series resonant frequency, sometimes the latter can be forgotten. However, the parallel resonant frequency can result serious damages not only on the filter components but also on the whole system's key components. Therefore the load that will be compensated should not include any harmonics at the parallel frequency.

It has been demonstrated that there are several issues to be considered before energizing occurs in order to obtain a transient-free switching. First of all, the timing of switching must be when the voltage across the thyristor drops to zero to avoid a substantial inrush current. Besides, the capacitors must be charged to the supply voltage beforehand. In practical case, the latter condition can be hard to satisfy. In such a case, it should be kept in mind that the most important parameter to consider is the thyristor's capability to withstand the rate of increase in current. The methods and their result have been carefully examined in this chapter.

Among the available topologies given along this chapter, the most efficient one is when the each phase branches are connected in delta. Note that, only the capacitors connected in delta model is not a practical solution since it has more drawbacks than advantage as explained.

Several compensating or filtering system can be combined together in order to get a better overall response. Each system fulfills their own duty and at the same time, they help to each other. For example, a tuned TSC can also filter the harmonics that TCR created and TCR can help TSC preventing its discrete reactive power contribution. Some of the common hybrid types have been defined and explained briefly.

Up until now, the system description, the basic operation principle and the important design considerations of TSC are given so that a complete practical TSC and its control mechanism can be implemented in the next chapter.

CHAPTER 3

ANALYSIS AND DESIGN OF TSC

3.1 Introduction

Determining the load characteristics is the initial step of a design process. The size of the system and the ratings of the components depend on a careful analysis of requirements of the load. In this thesis, a TSC is designed which is connected in parallel to an existing TCR. Just to remember that TCR does not contribute the compensation by absorbing inductive reactive power only, but also it helps TSC to have a smoother response as mentioned in Section 2.4.1. The load can be defined as the electrical excavators in open-cast lignite mining in Orhaneli, Bursa. The types of these loads are defined as lagging or leading regarding their power demand from the supply and listed in Table 3.1. At first glance, the required capacitive reactive power seems to be provided by passive shunt filters or plain shunt capacitors. However, when the load variation is examined in time, it can be seen that the rapidly fluctuating load can only be compensated by a dynamic system (Figure 3.1).

In Figure 3.1, the raw data is taken by a mobile monitoring system defined in [41] and processed by MATLAB running on Windows XP. Computations are made to observe the general characteristics of the load, such as real and reactive power variations, current and voltage change, as well as the response of the built system. As can be seen from this figure, the load oscillates rapidly between inductive and capacitive regions depending on the field's condition. Therefore, a hybrid system or a system capable of providing both inductive and capacitive

Table 3.1: Type of the excavators and their reactive power requirement.

	Motor and Driver	Reactive Power Demand
Power Shovel A	DC motors fed from 4 quadrant, 6 pulse Thyristor Converters with neutral thyristors	Inductive and Capacitive
Power Shovel B	DC motors fed from 4 quadrant, 6 pulse Thyristor Converters	Inductive and Capacitive
Power Shovel C	Ward-Leonard Drive, Induction Motor on the supply side	Inductive only
Dragline	Ward-Leonard Drive, Synchronous Motor on the supply side	Inductive and Capacitive, depends on the field exciter settings

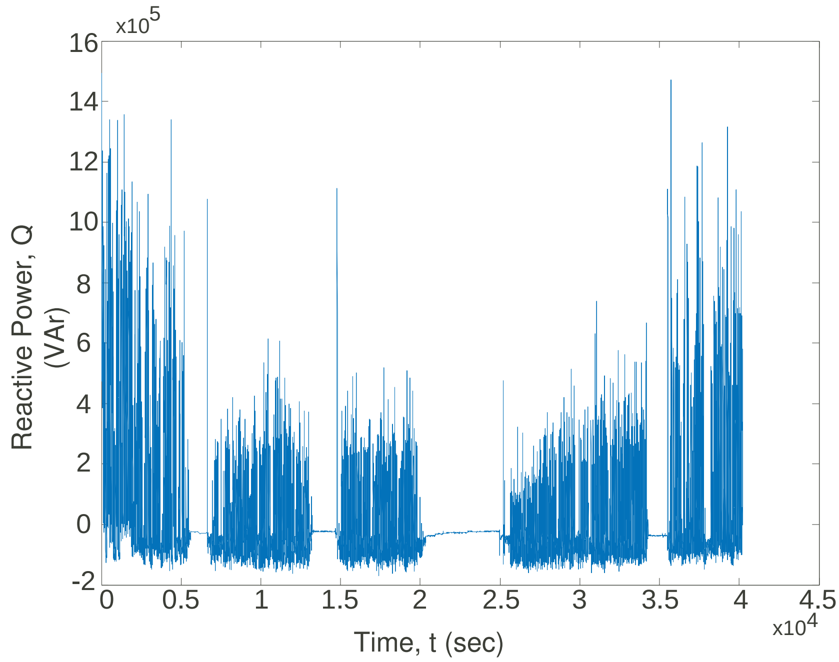


Figure 3.1: Load Characteristics of excavators in Orhaneli, Bursa.

reactive power with a decent response time is necessary to improve the power factor of the load. In this case, TSC and TCR combination has been chosen to fulfill this task.

The design process starts with the choice of the capacitor. The points mentioned in the subsequent section needs to be carefully followed. Next, the important points in selection of an inductor which is used for current limiting purposes in this thesis is introduced. Then, the most important part which is the choice of the power semiconductor switched is explained in details. In the remaining part of this chapter, the critical parts of the control system are defined and the cabinet design to implement TSC system is given.

3.2 Selection Criterion of Circuit Topology

In Section 2.1, the basic circuit topologies have been mentioned. For simplicity, thyristors have been the only semiconductor devices in every branches. However, many other configurations (such as delta or wye connection of capacitors or semiconductors) can be obtained. The cons and pros of each topology depend highly on the application areas. To gain a little simplicity may increase the cost of the system or the stress on each devices.

In [42], different circuit configurations are discussed in details by giving their operating conditions. The current ratings of the components are obvious results of delta or wye configurations. In addition to this, some critical parameters are defined through this research such as thyristor and capacitor peak voltages, the maximum turn-on time with a completely discharged capacitor, the stored charges on the capacitors when the switches turned off, etc.

In this thesis, the circuit diagram of TSC is preferred as in Figure 2.1(a). The current through the thyristor is chosen to be more important criteria than the voltage across it, since the change in current affects the system greatly and it is tried to be kept within acceptable limits. On the other hand, the voltage variation is rare and small, and the cost of the thyristor does not differ so much when the operating voltage is within the medium voltage level. Some conclusions can also be made based on the results given in [42] about the reason of selection of delta configuration. Delta connected system has one of the best capacity factor (C_f) which is equal to the inverse of the peak thyristor voltage and the rms thyristor current product among the rest of the topologies.

3.3 Selection Criterion of Capacitors

The choice of the capacitor group is an important start of a TSC design and there are several critical points that should be considered during this process. After the analysis of load behavior, the size of the system is determined initially. Since capacitors are the main storage element to supply this necessary reactive power, the capacitance is determined by 2.1. Note that there are one more storage device series with the capacitor and on the contrary, it absorbs the reactive power whenever current transmits through. It is the inrush limiting reactor or filter reactor and in situations where the system's total reactive power is the critical issue, its characteristics must be taken into consideration and capacitor must be designed to supply more reactive power than necessary to cover the effects of this inductor. Otherwise, this effect may be neglected as the value of the inrush limiting reactor is small comparing to the value of the capacitor.

Table 3.2: Reasons for the voltage rise of the TSC capacitors in practical situation.

Type of the Voltage Rise	Results
Harmonic current	Voltage is induced depending on the amount of the harmonics.
Increase in supply voltage	Max % 10 of the supply voltage.
Series reactor	Stored energy of the reactor induced extra voltage on the capacitor depending on the size of the reactor.
Reactance of the produced reactor	The manufacturer produces the reactors with a tolerance. Max % 5 of the ordered reactance.

The voltage rating of the capacitor must be chosen at least the peak of the supply voltage. Since the capacitors are switched off at the peak of the supply voltage (either positive peak or negative peak) due to the thyristor self-turn off ability, they remain charged to this peak value for a while. This situation is illustrated in Figure 3.2. In addition to this, the series reactor must also discharge its stored power through the capacitor. As a result, the capacitor voltage may increase some more. Therefore, leaving a margin after calculating possible causes of increase (Table 3.2) in voltage would be a reliable choice. It should be remembered that the power calculated in rated voltage is not equal to the power in operating voltage. The reactive power capability depends highly on the applied voltage. When the voltage decreases, the reactive power supplied to the system also decreases by the square of voltage ratio. This relationship can be shown as:

$$\frac{Q_1}{Q_2} = \left(\frac{V_1}{V_2}\right)^2, \tag{3.1}$$

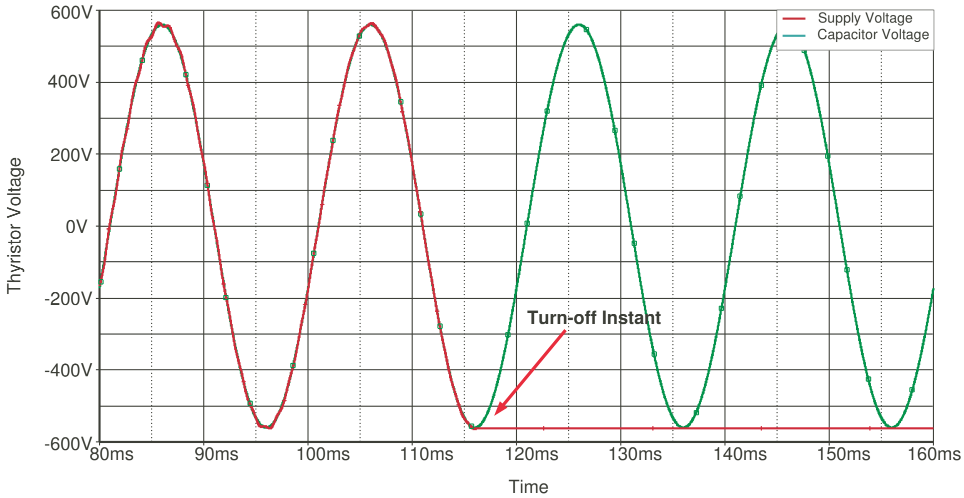


Figure 3.2: Voltage variation during switch-off process.

In the implementation part of this thesis, the rated voltage of the capacitors is chosen to be $1.5kV$ although the operating line to line voltage is $1kV$. The capacitors are single phase with two bushings since they are connected inside a delta configuration. The rated power in $1.5kV$ is $400kVAr$ which makes the capacitance approximately $566\mu F$ in $50Hz$.

3.3.1 Discharge Methods

After switching the thyristors on, capacitors become fully charged in milliseconds. For safety, the capacitors must be discharged after disconnection from the network during a maintenance. The time that passes during discharge depends on the manufacturer if the duration is not specified, however at least 10 minutes should be given to self-discharge of the banks. Later, the terminals of the capacitors should be grounded one by one and each terminals should be shorted together in case of a failure in discharging devices. In some cases, the readings of the voltmeters from the terminals do not reflect the truth although they show zero voltage since there can be stored but opposite polarity charges in capacitors. These trapped charges may cause serious damages. Therefore, grounding should take place before every close contact with the capacitors.

Self-discharge can be obtained by two ways, either connecting a discharge resistor internally, or a reactor parallel to the capacitor banks. The former would be a better choice to prevent any damages caused by trapped charges as each capacitor has its own discharge device. In the following sections, the design and purpose of these devices will be described in more detailed way.

3.3.1.1 Discharge Resistor

Connecting a resistor to each capacitor unit separately is a reliable and necessary way to keep the capacitor discharged when the system is turned off. The resistor is connected in parallel to the capacitor and help it to turn the stored energy into heat by free wheeling. The connection scheme is shown in Figure 3.2.

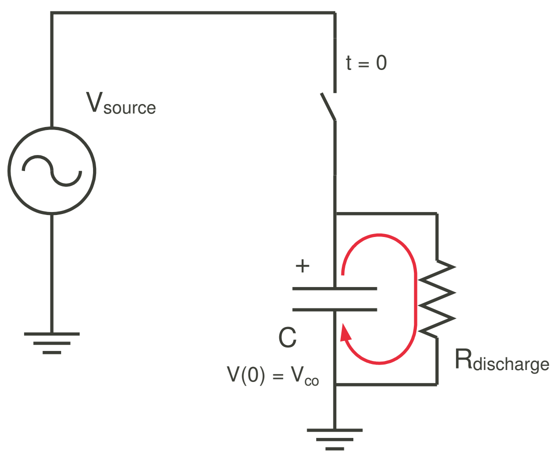


Figure 3.3: Discharge resistor connection diagram.

The discharge resistor should also be included in a system model in order to see what really happens in real life. Since the amount of the stored charge on the capacitor before switching on depends entirely on the time duration passed after switching off. The magnitude of a suitable resistor can be calculated for a single phase unit according to the equation given in [36] as,

$$R \leq \frac{t}{C \ln(U_N \sqrt{2} / U_R)}, \tag{3.2}$$

where

U_N is the rated voltage of the capacitor unit, (V);
U_R is the permissible residual voltage, (V);
t is the time to discharge from $U_N\sqrt{2}$ to U_R, (s);
R is the discharge resistance, $(M\Omega)$;
C is the capacitance, (μF);

and the time to discharge the capacitor should not be more than 10 minutes to obtain a residual voltage of $75V$. In this thesis, the discharge resistor is chosen to be $0.4M\Omega$ by the manufacturer. This makes the discharge time to be equal to 12.5 minutes for $1.5kV$ rated voltage. If the operating voltage of $1kV$ is taken into account, the discharge time drops to approximately 11 minutes. This means that, before working on the terminals of the capacitor, make sure that at least 11 minutes has passed after switching off the system.

3.3.1.2 Discharge Reactor

External discharge devices such as a reactor can be used in special occasions. For example, when the discharge has to occur fast in limited amount of time, the discharge reactor would be preferred over resistor. Note that there is no need to connect a discharge reactor instead of resistor in TSC design since it is better to keep the stored charge in capacitors during operation as much as possible in order to achieve a transient free switching. Otherwise recharging of the capacitors before switching occurs would be necessary or a small amount of transient has to be undertaken.

The reactor is connected in parallel to the capacitor banks as well, Figure 3.4(a). The safety requirements are applied to the connection place of the reactor, such as creepage distance and all the possible insulation necessities have to be considered beforehand. Because of the economical considerations, two reactors are usually connected line-to-line instead of connecting three of them for each phases as shown in Figure 3.4(b). During operation, only the magnetizing current passes thorough the reactor which is considerably smaller than the current thorough the capacitor. However, a significant current flow is expected during a discharge. Therefore there is one drawback of using reactor. It has limited number of discharge capability since the coils of the reactor gets overheated after several times of usage in specific time.

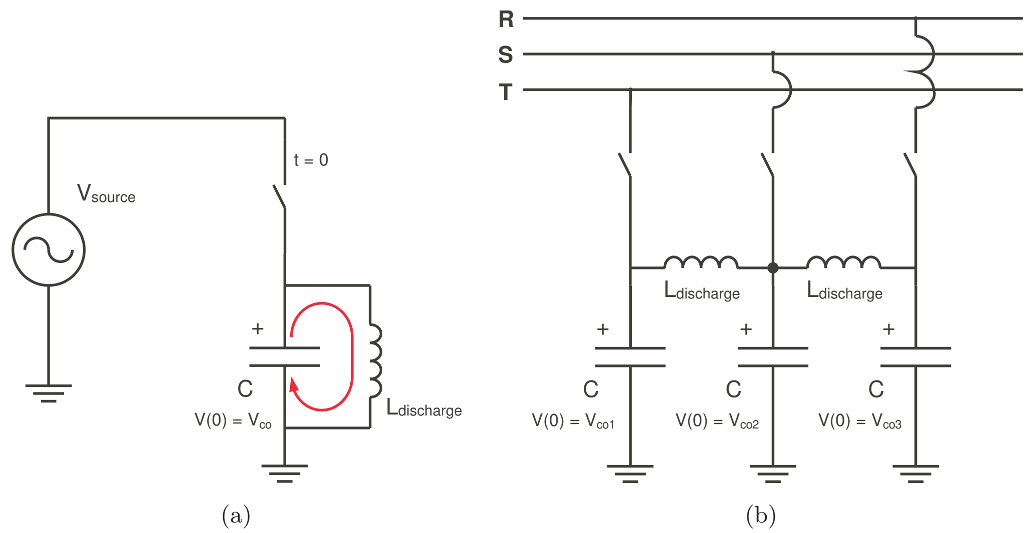


Figure 3.4: Discharge reactor connection diagram (a) parallel to each capacitor, (b) across two phases.

3.3.2 Unbalance Detection Technique

Detection of an overcurrent or overvoltage in capacitor banks caused by a failure in a capacitor element is an important application for safety. In Figure 3.5, the internal view of a capacitor is shown. As can be seen from this figure, capacitor is composed of several small capacitor elements connected in series or parallel whose number depends on its voltage and current ratings. A breakdown in one of these elements can cause the whole group of elements fail which results in an increase in voltage for the rest of the groups. Therefore the healthy capacitors may also fail because of the excessive voltage across their terminals.

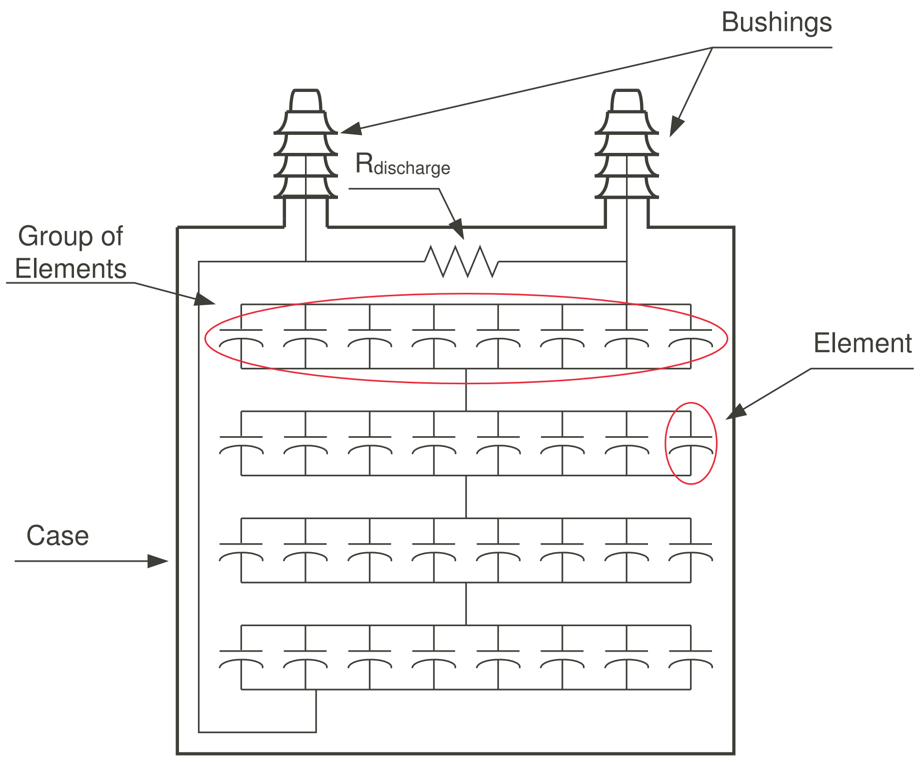


Figure 3.5: Capacitor internal structure.

There are several types of unbalance protection. They are listed in [37] with their detailed circuit diagrams. The most common protection type is current unbalance between neutrals. The connection scheme is shown in Figure 3.6. A change in one of these capacitances causes a voltage difference between the neutral points of stars and a current starts to flow along this path. In steady state, very small amount of current passes through the current transformer between neutrals. On the other hand, a high current flow is expected during a failure which can easily be sensed by the transformer. This technique has an important advantage. It is not affected by the system disturbances or an unbalance in the electrical network. Therefore a reliable protection is achieved by this technique to distinguish the internal failure of the capacitor.

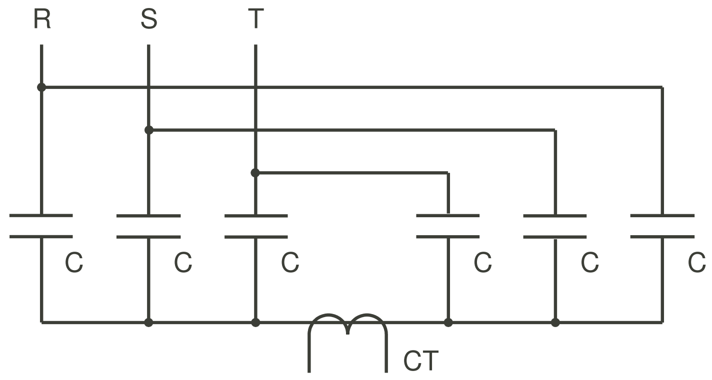


Figure 3.6: Double-star connection for unbalance protection.

As mentioned in Section 3.2, in this thesis, the circuit diagram is chosen to be delta connected branches each of which includes a series combination of capacitor, reactor and the thyristor. There is not any applicable protection technique for this type of connection. Therefore, the safety is achieved by inserting an internal fuse and by monitoring the voltage and current waveforms of each capacitor.

3.4 Selection Criterion of Inductor

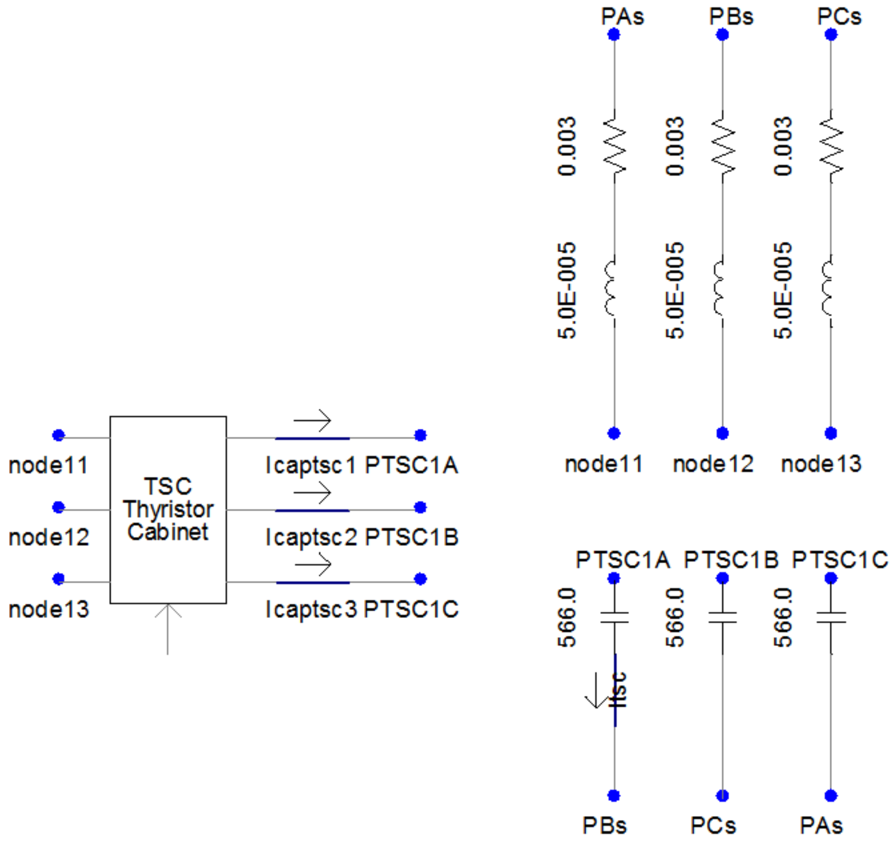
The inductor selection is made according to the tuning frequency. Just like the design of a passive harmonic filter, the inductance can be easily calculated by 2.2 if the tuning frequency and the capacitance are already known. As mentioned in Section 2.2.2, the inductor is utilized to limit the inrush current component or to filter certain harmonics. TSC is not a beneficial system to eliminate the harmonics, besides it brings some disadvantages. For example, the inductor increases the inductive reactive power when the inductance increases with a decrease in tuning frequency. Therefore, a bigger capacitor must be selected to achieve the same reactive power supply.

To order a special design reactor, the ratio of harmonic components which are expected to pass thorough the reactor have to be given to the manufacturer since they create extra burden on the reactor. The reactor is designed to be capable of withstanding this overload current. It can be extracted into its harmonic contents by EMTDC-PSCAD simulations. The circuit is modeled as shown in Figure 3.7. Since the capacitor and reactor values are known from the previous sections, and the internal resistance of the reactor can be found from 2.21, the simulation can be performed. The thyristors are placed between reactors and capacitors which are shown in black box and will be mentioned in the following section in details. In Figure 3.7(b), the fft block and its connection scheme are shown. FFT block helps the current to be extracted to its various frequency components. It calculates up to 31 harmonics, here only the first 15 is analyzed. For this thesis, the ratio of the resultant harmonic to the fundamental current component is listed in Table 3.3. From this table, it is concluded that the 5^{th} harmonic is the dominant one.

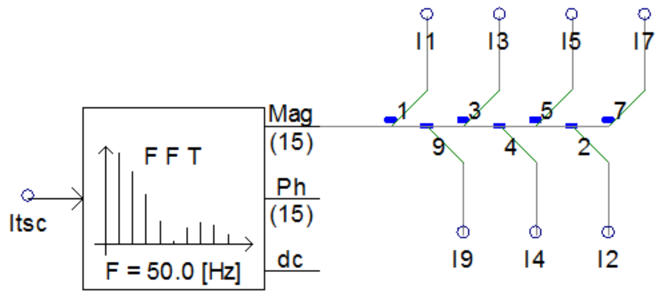
Table 3.3: Ratio of harmonic current component to the fundamental frequency

Harmonic Order	%
1	100
3	1.99
4	1.89
5	6.12
7	1.07
9	0.35
11	0.66

In this thesis, the reactor is used to limit the inrush current. The tuning frequency is chosen to be approximately $950Hz$, therefore the inductance is calculated as $50\mu H$. The rated voltage is the line-to-line system voltage $(1kV)$ assuming there is a failure in capacitor and the system voltage is seen across the reactor terminals. The frequency characteristics of the overall system is shown in Figure 3.8. As can be seen from this figure, there are 5^{th} and 7^{th} passive harmonic filters which already existed in the system to help the filtration of the



(a)



(b)

Figure 3.7: PSCAD model of the (a) TSC circuit, (b) harmonic extraction.

load current and TCR harmonics. The parallel resonant frequency of the TSC falls on the 8^{th} harmonic component (around 415 Hz) since it is known that the load does not include harmonics at this frequency. As a result, safe operation of TSC has been achieved.

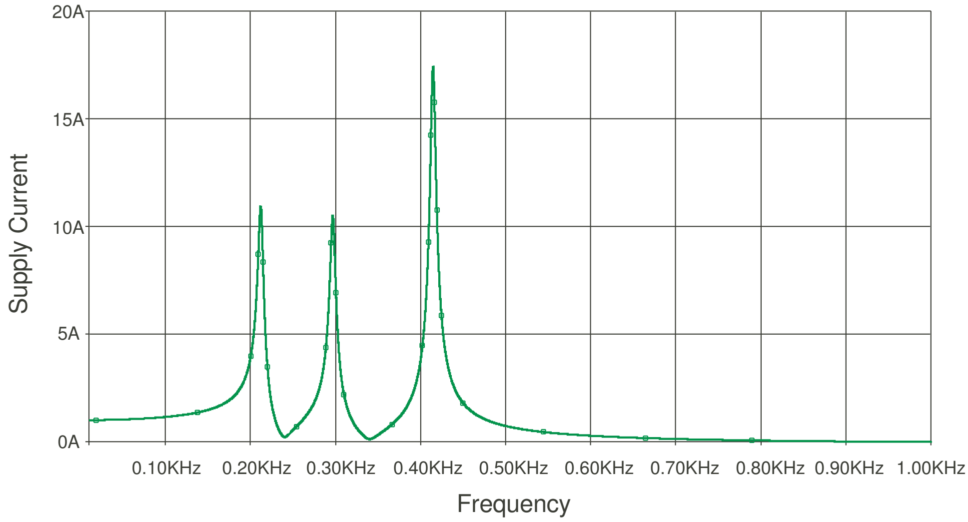


Figure 3.8: Frequency characteristics of TSC and the passive filter located in TKİ, Orhaneli/Bursa. The passive filters are tuned to 5^{th} (240 Hz) and 7^{th} (340 Hz) harmonics.

3.5 Selection Criterion of Power Semiconductor Switches

With a development in technology, power semiconductor switches started to vary over years. As a result, more efficient and faster switches have been produced for different application areas, such as IGBT, IGCT, GTO, etc. For capacitor switching, thyristor is more preferable because of several reasons. First of all, thyristor has a high endurance limit to high current and voltage involving applications. In addition to this, thyristors are generally used in AC applications to control the current flow. Since when a firing pulse is sent to the thyristor's gate once, it stays turned on until the current crosses zero, i.e. until the current changes its polarity, and turns itself off afterwards. Therefore, there is no need to control the turn-off process, it would be enough to stop sending the firing pulses to its gate and wait for a negative bias. Lastly, the supply frequency is 50 or 60Hz depending on the country. This means that the switching frequency is not required to be very high to control the current.

Selection of a thyristor is a long way and needs to be carefully followed. The main criteria is the reverse bias voltage blocking capability. In TSC system, this value is at least twice of the supply voltage since after the capacitor is fully charged, the thyristor sees the sum of the capacitor and supply voltage during off period. The next criteria is the rated rms current of the system. The max surge current should also be calculated in case of a short circuit. The thyristor needs to withstand the inrush current at least until the protective device cuts the current off.

Although the thyristor seems to be sensitive to overvoltages, and break down so easily, the current has also severe effects on thyristor. For example, the rate of increase in current is an important parameter. The firing signal has a function such that it helps the current to pass evenly thorough the anode of the thyristor. When the firing signal is sent to the gate, a small amount of time has to be waited to allow the charge to span the gate evenly before the current reaches its peak value as can be seen in Figure 3.9. The arrows show the propagation directions of the gate signal. Notice that there are transmission paths for guidance to enable the signal spread more efficiently. If the time of increase in current is greater than the spanning time of the charges, then the current has to pass in one point only and the thyristor gets burned since the charge density at that specific point becomes too high. Therefore, the $di(t)/dt$ rating of the thyristor should be considered and simulations involving the worst cases should be examined before choosing a suitable thyristor.

The surge current should be calculated beforehand as well as the value for one cycle of surge current value. The latter corresponds to the i^2t value and should be determined for the selection of the protective device (such as fuses) or for the decision of existing device if it ensures an adequate protection or not.

The gating current is calculated according to the V_{GT} vs I_{GT} graphs which can be found in product's datasheet. The main purpose is to implement a pulse which has a high amplitude with short duty cycle which is approximately 1 A with a frequency of 1kHz and 20% of duty cycle in this thesis. It is important to apply the firing pulse as fast as possible to guarantee that the thyristor is fully on before the current reaches its peak value. Note that the power of the pulse applied to the gate has a limitation, otherwise the thyristor gets burned.

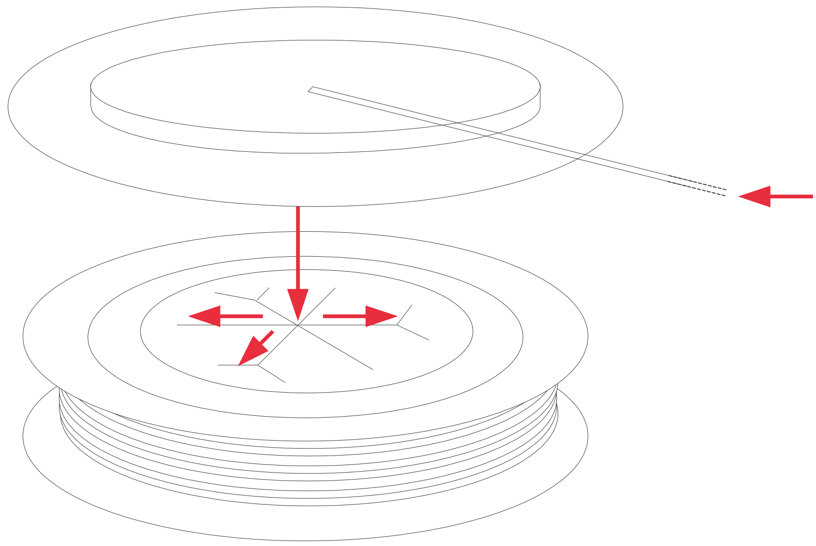


Figure 3.9: Thyristor gate triggering.

In this thesis, the thyristor whose part number is DCR1950C52 in Dynex Semiconductor is utilized. The datasheet of this thyristor is given in Appendix B. The rest of the subsections include the auxiliary devices that must be included in a thyristor based design.

3.5.1 Design of Snubber Circuit

Snubber circuit, connected in parallel to the thyristor pair as shown in Figure 3.10, is a passive circuit that consists of series combination of a resistor and a capacitor. When the thyristor is turned off, the charges stored during the conduction period are extracted as reverse recovery current. Snubber circuit works as a path for this current and helps it to dissipate its energy on the resistor. Otherwise, the stored energy causes a high voltage overshoot and generate a rapid increase in voltage that can damage the thyristor. In addition, RC snubber circuit has an ability to limit the rate of increase in voltage and prevents the thyristor to exceed its dV/dt rating as the voltage of the parallel capacitor can not be altered so quickly. The waveform that shows the thyristor turn-off process is given in Figure 3.11. Here Q_s is the stored charge, I_{RRM} is the peak value of the reverse recovery current and V_{RM} is the peak reverse voltage. From this figure, it can be easily seen that the reverse voltage has an overshoot because of the recovery current.

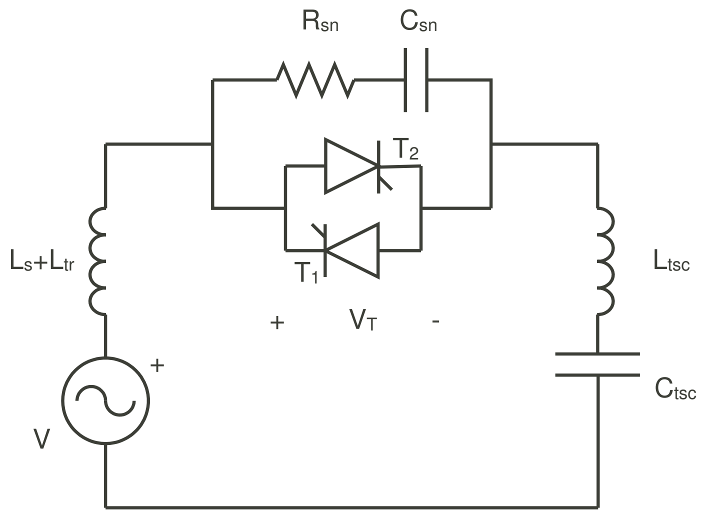


Figure 3.10: Equivalent circuit for snubber design for TSC.

An approximate calculation for the snubber values can be made by the formulas and procedures in [44]. To be able to follow this application note, the reverse recovery characteristics of the thyristor have to be known.

In this thesis, the snubber resistance and capacitance values are 220Ω and $220nF$ respectively. Since there is not an available formula to find the exact snubber values, they are chosen by transient domain analysis of OrCAD simulation program so that the response to the reverse recovery process is optimum (the peak of the voltage rise has been kept below 5% of the peak thyristor voltage). Alternatively, an approximate calculation for the snubber values can be made by the formulas and procedures in [44]. To be able to follow this application note, the reverse recovery characteristics of the thyristor have to be known. There are some facts that should be considered during the trial-error process. First of all, an increase in snubber capacitor causes a decrease in peak dynamic voltage at the expense of an increase in conduction losses. Besides, a dramatic increase in snubber resistor value causes an increase in dV/dt and peak dynamic voltage.

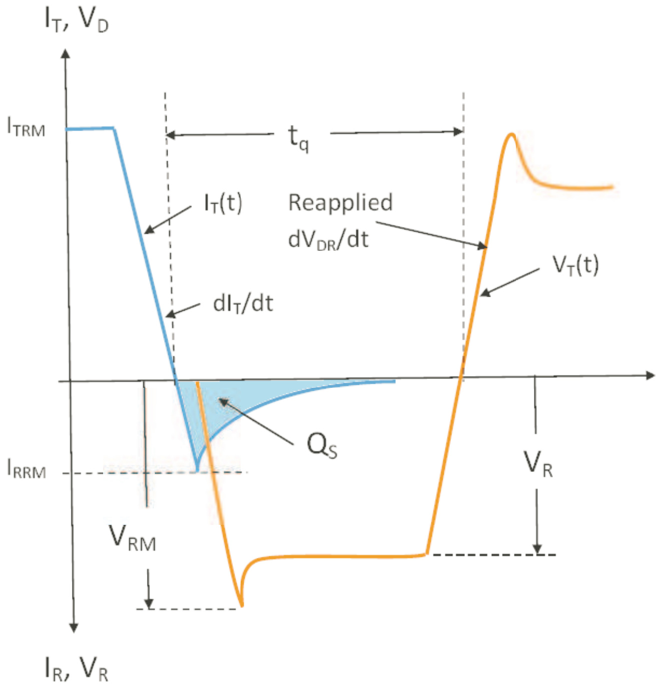


Figure 3.11: Thyristor turn-off waveforms, [43].

On the contrary, the damping effect can be increased by increasing the resistance value at the same time. Therefore to obtain the optimum solution, some negative results must be undertaken to some degree.

3.5.2 Design of Heatsink

The temperature of the thyristor increases during the conduction period as the thyristor has an internal resistance. The current passing through this resistor reveals heat energy and unless this heat is removed, the temperature of the case keeps increasing. There are several cooling methods to prevent this problem. These method differ from each other by their ability to remove the heat.

The selection of the cooling type depends on the heat generated. To calculate the average power created inside the thyristor, the on-state power dissipation curve in its datasheet should be taken as reference since the internal resistance is nonlinear. According to the level of heat generation, the suitable type of cooling method should be preferred. The most common cooling methods are the natural and forced air cooling. The connection of this type of heatsink varies from thyristor to thyristor. It can be connected to the anode or cathode side of the thyristor. In some cases where the power dissipation is high, the heatsink can be attached from both sides of the thyristor terminals. The natural air flow achieves the heat exchange and keeps the temperature of the thyristor constant in the former case and a fan is connected to remove the heat around the heatsink in the latter for a faster response. One of the important parameter in mounting is the junction to case thermal impedance and it should be kept as small as possible. Coating some silicone grease (a thermally conducting material) to fill the microscopic gaps between the case and the heatsink is a way to reduce this impedance. The impedance between the heatsink and the ambient air can also be reduced by increasing the area of the heatsink. The total thermal resistance can be summarized as follows:

$$R_{eq} = R_{jc} + R_{ch} + R_{ha}, \tag{3.3}$$

where R_{jc} is the junction to case, R_{ch} is the case to heatsink and R_{ha} is the heatsink to ambient resistance.

Another cooling method is the water cooled heatsink which has a decent heat exchange capability. It is useful for two kind of applications. One is for the high current and high power assemblies. It can also be preferred for its size since it occupies a smaller place comparing to the air cooling method. However, it is costly and less reliable to assemble it in a system. Since the recycled water must be pure water in order not to be ionized by friction, it has a risk to freeze easily and, if there is a problem with the pipes where the water is circulating, it has a risk to leak and makes the pressure drop inside the pipes.

In this thesis, a heatsink of type EM in Dynex Semiconductor company is preferred as shown in Figure 3.12. To be able to determine the mean power dissipation of thyristors from the curve in thyristor's datasheet, the mean on-state

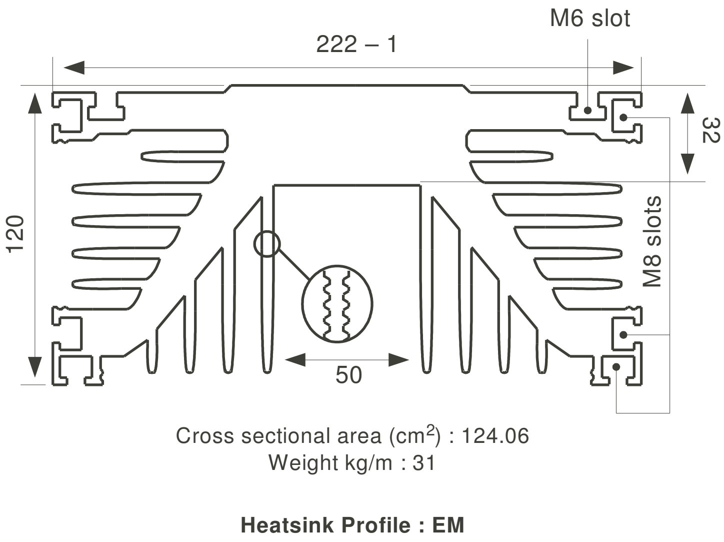


Figure 3.12: Heatsink profile for the reduction of junction temperature.

current value must be calculated first. The rms current is found to be $196A$ by PSCAD simulation program. Therefore the peak value of the sinusoidal current becomes $\sqrt{2}I_{RMS}$ which is approximately $277A$. As a result, the current passing through the thyristor can be represented by $277\sin(\theta)$. Since the thyristors are connected back-to-back, the positive half cycle passes through the forward thyristor and the negative half cycle passes through the backward thyristor as shown in Figure 3.13. By using 3.4, the average value is calculated as $176A$. This result gives a mean power dissipation of approximately $50W$ which can be easily compensated by a natural cooled heatsink.

$$f_{avg} = \frac{1}{b-a}\int_{x=a}^{b} f(x)\,dx, \tag{3.4}$$

3.6 Design of Control Systems

The most important part of a TSC design is its control system. There are several reasons to claim this argument. First of all, the control system must ensure the transient free switching concept mentioned in Section 2.3.2. The whole purpose

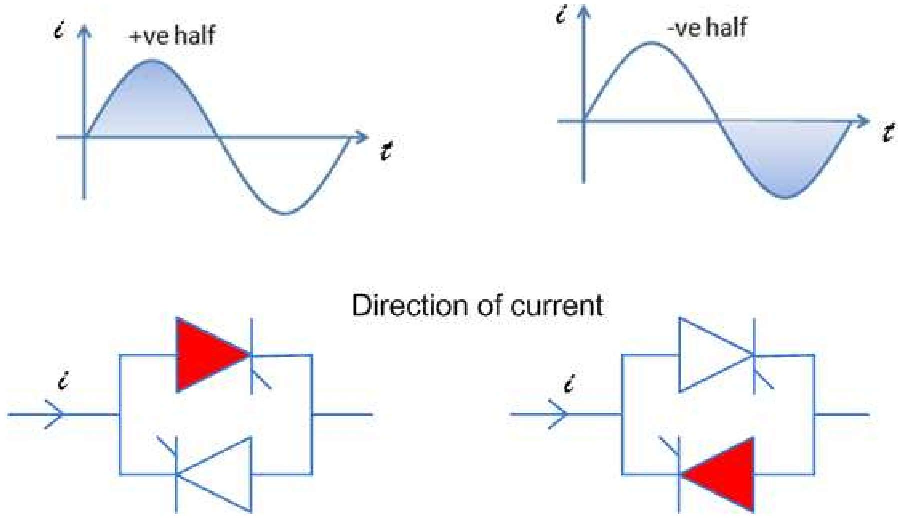


Figure 3.13: The current distribution of back-to-back connected thyristors in the steady state.

underlying the design process is the transient concept, otherwise the TSC system would be useless since it brings harmonics and very high inrush current that can disturb or damage the whole network. Secondly, the capacitor switching is an dangerous process in high voltage and high powers. The increase in capacitor current can be so sharp and the amplitude can climb up to several kA s in case of a failure or a gating in wrong place. Therefore, the protective devices must be chosen accordingly, such as high speed fuses and the control system must preserve a fast detection of a failure.

In this thesis, the control system consist of several stages. The decision and detection mechanisms are built in some analog cards. The block diagram is shown in Figure 3.14. Some of these cards are already installed to the system for the control of TCR and will be briefly described in this section. TSC uses these signals that the control cards sent to implement its own control system which means that it operates in parallel to TCR.

The first one is the Power Monitoring (QM) unit. It has a potentiometer calibrated to the system's total reactive power capability. It takes the reactive power of the network and compares with the system's capacity. If the network

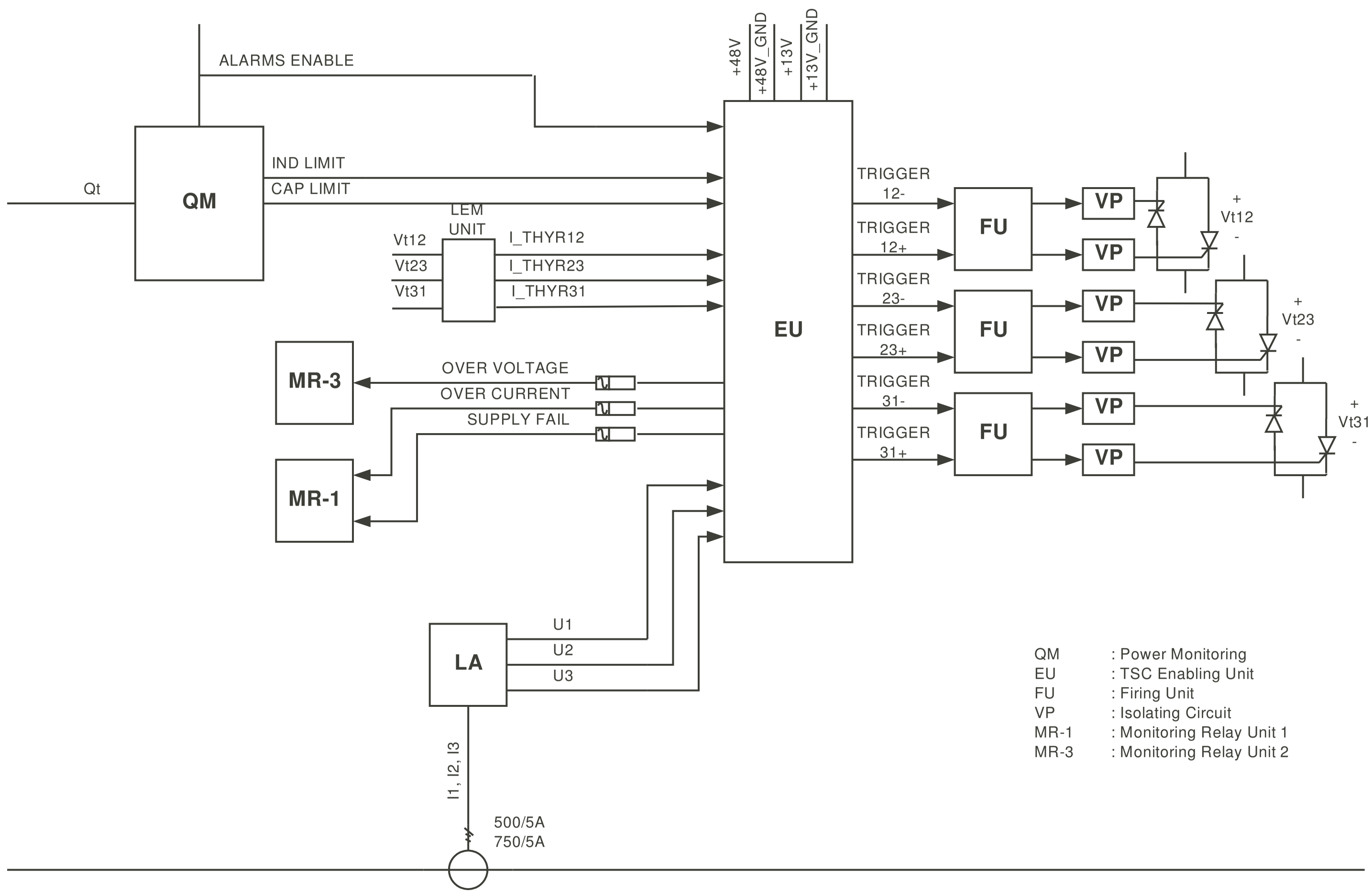


Figure 3.14: Block diagram of TSC control scheme.

stays in inductive or capacitive region even the whole available capacity is used, it warns the control system by sending *inductive* or *capacitive limit* signal to the related cards.

The next card is the Monitoring Relay Units (MR). The main purpose of this unit is to define the type of the failure and takes the necessary precautions. These can be to ring the alarm or, if the failure is severe, to send directly the "open the main circuit breaker" comment to interrupt the current flow.

The connections of these control units mentioned above with the TSC control mechanism and the tasks of each control card dedicated only for TSC will be explained in following sections in details.

3.6.1 TSC Enabling Unit

TSC Enabling Unit (EU) is the brain of TSC control system. Every decisions and internal checking are made inside this card. Therefore, it would be better to analyze the unit by splitting it into its subunits each of which is responsible for a distinct tasks. The circuit diagram and the definition of input-output (IO) data drawn by Schematic File of P-CAD 2002 Software can be found in Appendix C. In Figure 3.15, the picture of practical EU card is shown.

EU has its own power supply that converts the $48V$ to $\pm 15V$ to be isolated from the rest the system. $15V$ is also used to provide power to PLC relays that carry the error signals from the EU card to the mother board. These relays help to convert the signal level suitable for mother board. Before the power supply, there is a high pass filter which is also advised by the manufacturer.

The current on the line and the voltage across the thyristors are kept under control by this unit. It takes these values, amplify to detect more accurately and compares with a set value. If the current exceeds this value, then a signal named "overcurrent" is sent to the microcontroller to stop sending any firing pulse. The same procedure is applied to the voltage. When an overvoltage occurs, the thyristors should not be fired since the increase in current would be severe in that case as mentioned previously. The high voltage rated thyristor can

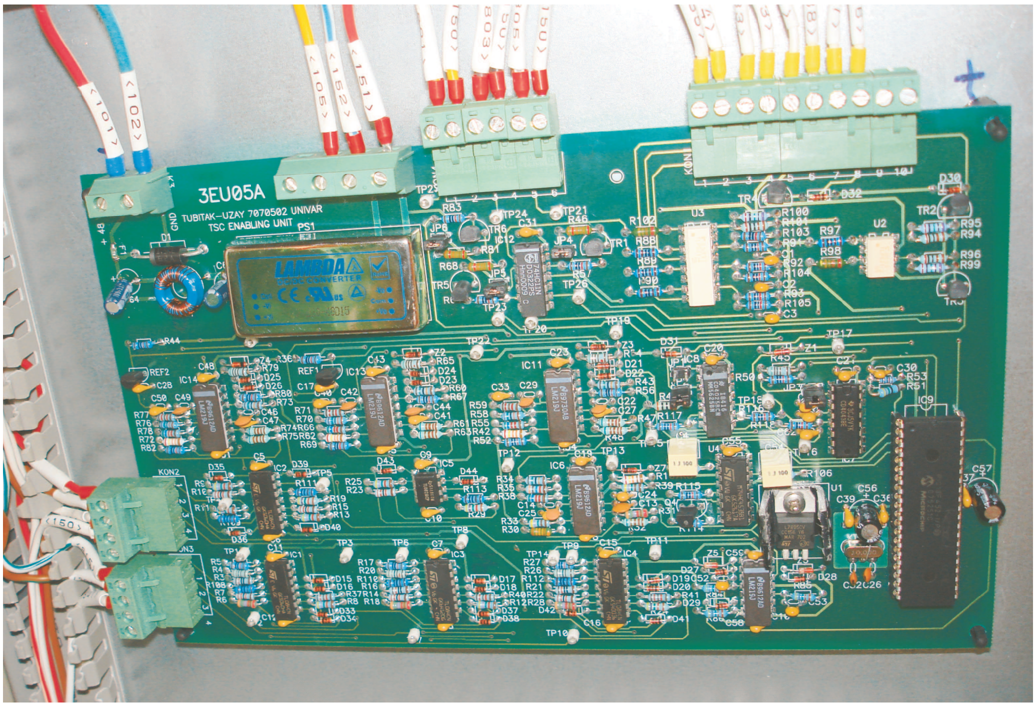


Figure 3.15: The view of EU control card designed for TSC.

withstand the small variations due to the change in supply voltage or overloaded capacitor banks. Otherwise, an error signal that opens the main circuit breaker is sent until the system voltage drops to normal values or capacitors are discharged to a safe region. The supply of the EU unit is also checked internally. If any of these three faults occur, the microcontroller prevents the firing pulses sent to the gates. And according to their priority, warning signal is sent to one the the MR cards mentioned in the above section.

In another place, the firing signals are produced by using the voltage across the thyristors. When the voltage waveform passes the zero crossing point, a signal that enables the firing pulses is created. This control is done for each phases independently. There is one more condition that has to be received before sending the firing pulses. These are the signals coming from the QM card, "inductive and capacitive limits". If the "capacitive limit" signal is received, it means that the TSC must be turned on to balance the need for capacitive reactive power or vice versa. After the enable firing signals under the name of

"ENB_A, ENB_B and ENB_C" are collected in the microcontroller's input pins and checked if there is a fault condition or not (named "EN/DIS" in the input pin), then microcontroller starts to sent firing pulses in $4kHz$ with a duty cycle of 20% to each gate.

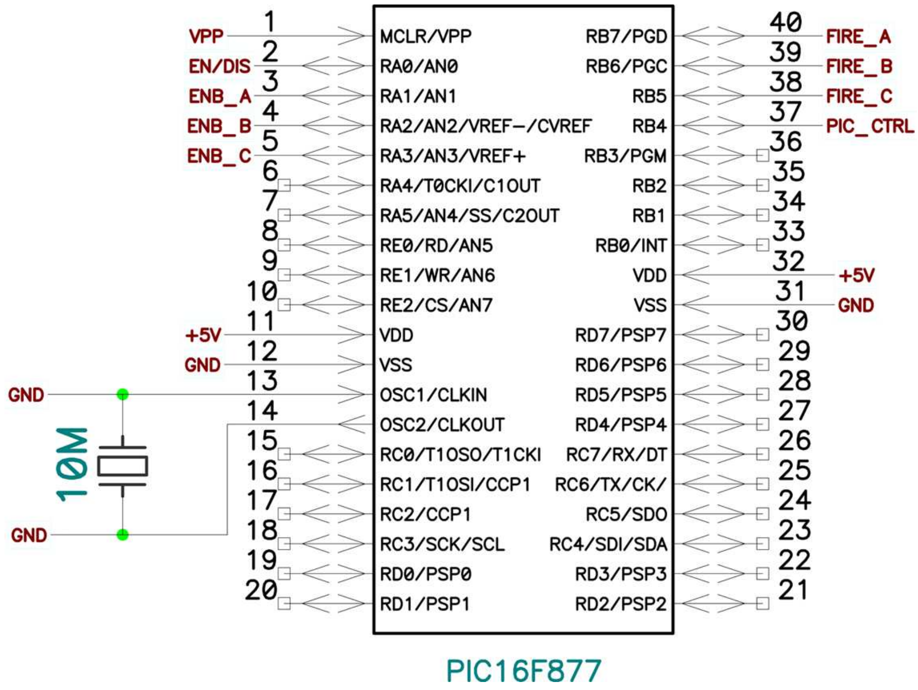


Figure 3.16: The connection scheme of the microcontroller, type PIC16F877.

As can be seen from Figure 3.16, the input pins and their purposes are explained above. The output pins perform two tasks. The obvious one is the sending firing signals to each phase independently. The second task is the internal check of the microcontroller itself. The output pin named "PIC_CTRL" stays high during normal operation. If an error resulting from the malfunction of the microcontroller occurs, this control pin cannot send high signal anymore and helps EU card to detect it. The rest of the used pins are supply voltages and clock signals necessary for regular operation.

3.6.2 Other Supportive Units

Supportive units mean that there are some electronic cards whose duties are only to change the state of the signal or to increase its power, or maybe to isolate. They don't have the ability to control or to make a decision about the process. The purpose of these units will be explained in this section and how important they are even they have simple tasks.

The first one is the "LEM Current-Voltage Convertor Unit" (LA). Along the line, there are current transformers to monitor the line current whose ratios are $500/5A$. LA card basically takes the current from the secondary of transformer ($5A$) and converts it to voltage without any scale up or down ($1:1$ ratio). Since the control cards carry current in mA scale, the only aim of this process is to make the signal suitable for a control card.

The next unit is named as "Firing Unit" (FU). Its benefit is to increase the power of the firing pulses in order to meet the turn-on criteria of the thyristor which can be found in the product's datasheet. Note that the graphs shown in this datasheet sometimes show the DC current range applied to the gate. In this situation, max applicable gate power should be taken into account and the power of the applied pulse should be calculated by considering the duty cycle. The rate of increase in gate current is also an important parameter as well as the power of this pulse. The faster the current spread over the gate, the better the current propagation is achieved. In this thesis, a current whose amplitude is around $1A$ is implemented to the thyristor's gate in $15V$.

The last supportive unit is the "Thyristor Drive Unit" (VP). The most important component on this unit is the pulse transformer. The speciality of this component is that it is designed to transmit a fast rice and fall timed and constant amplitude pulses. It is used to interface the low voltage control circuit to the high voltage gates of thyristors. This means that it provides a type of isolation between high and low voltage sides.

3.7 Key Points in Design of TSC Cabinet

There are several considerations that should be examined carefully before starting to build a TSC cabinet. The first and the most basic criteria is that all the components of the system should be easy to reach, since some components might be taken apart in case of a relocation or a fault in some parts of the system. Otherwise the cabinet would be too heavy to carry easily since it consists of all the TSC components. In addition to this, the time that must be spent to disassemble the cabinet components would be too long which yields loss of labour.

If the control units of TSC are preferred to locate inside the cabinet in order not to extend the route of the signals, the cabinet must contain high and low voltage equipment at the same time. In this case, the interaction between these equipments must be prevented, otherwise the low voltage side would not operate as it is expected due to the Electromagnetic Interference (EMI). The best way to prevent this interaction is to place a shield made by a conducting material (such as sheet metal) around the low voltage components.

Other important parameters in cabinet design are the clearance and creepage distance and should be taken into account for safety. The clearance distance is the shortest distance between two conducting material or between a conducting material and an exposed conductive material thorough the air whereas the creepage distance represents this shortest distance along the surface of the insulation. The former occurs due to the ionization of the air, the latter occurs due to the deterioration on the surface of the insulation which is called "tracking".

During the conduction period, heat is generated by all the TSC components. The main sources of this heat are the thyristors and the reactor. Despite the thyristors have their own heatsinks, interior side of the cabinet must be suitable to remove this heat from the heatsinks. Therefore, after the power dissipation is calculated for each components, enough space must be provided and some ventilation holes must be opened if necessary to prevent any increase in temperature. In addition, the operating temperature must be kept over an acceptable lower limit during cold weather. In this thesis, an air conditioner has been installed inside of the container to find a solution for every month of the year. Since the most basic rule of a reliable operation is to stay in acceptable temperature limits of each component, the temperature of the cabinet should be kept under control all the time (such as placing some temperature sensors close to the most critical parts or observing the components by a thermal imaging camera regularly).

As can be interpreted from the above discussion that the cabinet design is an independent design from TSC design that needs a lot of care. Some 3-dimensional programs such as AutoCAD can be used to predict future problems and take precautions before they arise. Otherwise, many days must be spent to find an optimal layout.

3.8 Discussions

In this chapter, the selection criteria of the TSC components and some safety requirements are explained in details. Even if a TSC system seems to be easy to design, the application to real life should be conducted carefully since it brings many considerations. Besides, if the selected components are special designs for the manufacturer, the safety requirements and some standards should be examined and the critical parts should be carefully determined. In order to obtain a reliable design and a coordinated operation of the components, all of the particular characteristics of each components must be known in details. This also helps to understand the possible problems and detect their place easily. Before selecting any of the components of the TSC, the circuit topology must be chosen first. The current and voltage ratings of each components are the basic determining causes. The ease of implementation is also an important parameter in selection of circuit topology. Note that some sacrifices must be made in order to obtain an optimal solution. Therefore, the importance of the parameters depending on the utilization area must be taken into account.

The selection of the capacitor requires some knowledge about the load characteristics since the capacity of the TSC is determined by its capacitors. In this chapter, some basic calculations to produce the required reactive power and some safety requirements are mentioned. The most conspicuous issue is the discharge of the capacitor. During a maintenance, capacitors must be fully discharged in order not to cause any damages.

Capacitor switching is a critical design that must be conducted carefully, and for medium voltages, the design procedure gets even harder and more dangerous. Since an increase in inrush current component can be very sharp during turn-on process, there becomes a need to limit this increase in order not to exceed the ratings of the components and not to cause a disturbance for the entire network. Therefore, a reactor series to the TSC capacitor is placed for each branch to smoothen the inrush current. There can be some other application areas for this reactor, however they are not so rational as explained through this chapter. There is one important consideration for selection of TSC reactor. The percentage of harmonic current components must be predefined since the coil of the reactor heats up more for higher frequencies and the insulation is made accordingly.

Among the components given along this chapter, the most critical one is the power semiconductor switch. Thyristor has been found to be the most suitable switch for this application. The detailed explanation of its selection criteria has been given through this chapter. The considerations in its utilization vary greatly as well as the considerations in its protection. The design of its snubber and the selection of its heatsink have been introduced and explained particularly.

The control system of TSC in order to achieve a transient free switching mentioned in previous chapter has been studied in this chapter. Briefly, the voltage across the thyristor is kept under control and the firing signals are sent during zero crossing of this voltage waveform. In addition, the key points in cabinet design have been introduced and some important considerations have been mentioned for safety. Note that, in order not to meet any problems after the installations of the cabinet, a 3-dimensional model should be plotted and all the steps mentioned in this chapter should be followed one by one.

The design procedure of TSC and the safety requirements for its real life application have been given theoretically through this chapter so that each components can be chosen according to the needs and their combination can be achieved. Next chapter will be the application of all these knowledge and the practical TSC construction will be introduced. The graphs formed by the field data will be compared to the graphs resulted from the theoretical simulations.

CHAPTER 4

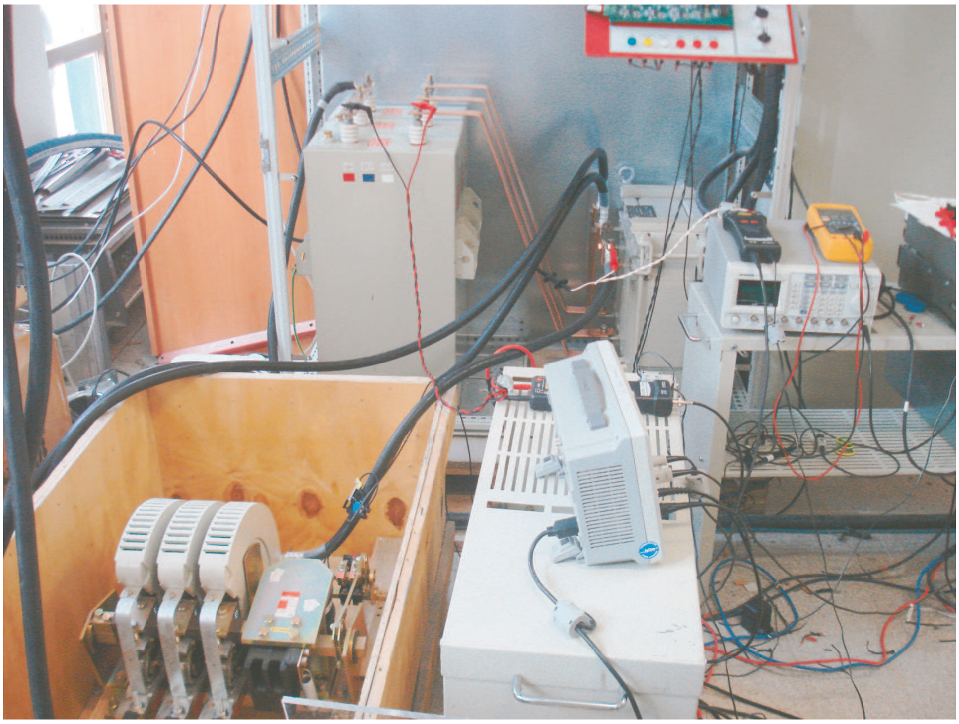
EXPERIMENTAL RESULTS

4.1 Introduction

The operation principles and the design rules described in Chapters 2 and 3 are verified by conducting an intensive experimental work. For this purpose, two prototypes have been developed. The first one is a laboratory prototype consisting of a single stage shunt LC filter tuned to 225 Hz. The second one is an application prototype consisting of a shunt capacitor connected in series with an inrush current limiting reactor. The experimental data recorded on these prototypes will be presented in this chapter.

4.2 Laboratory Prototype

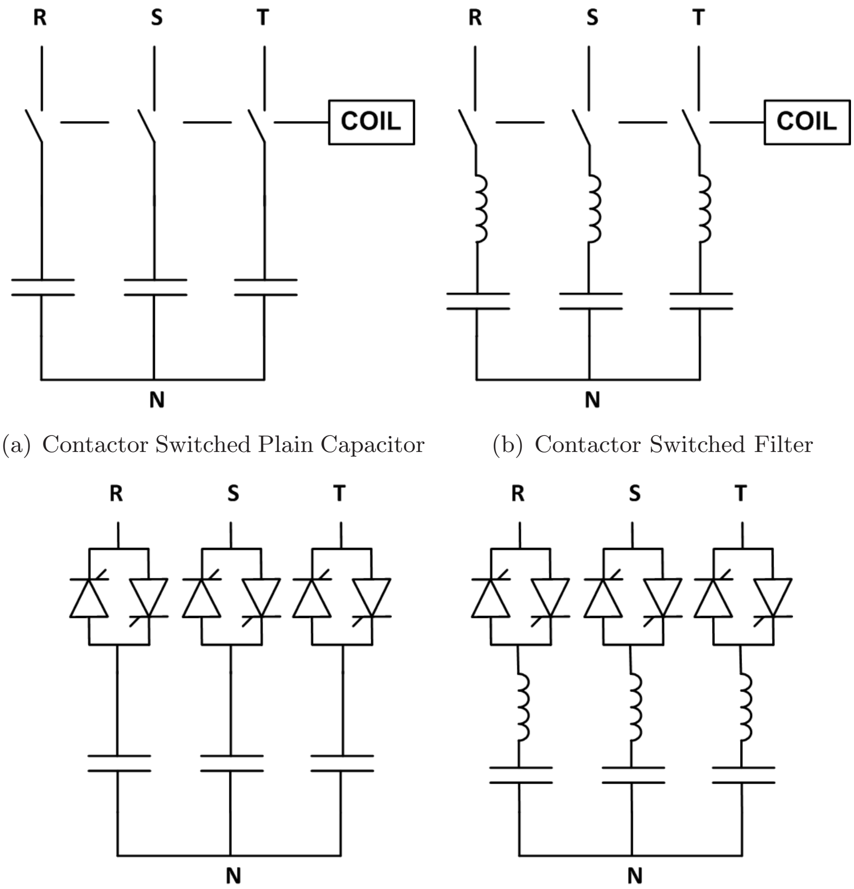
A single-stage shunt TSC has been built as a laboratory prototype as shown in Figure 4.1. The objective of designing and implementing the laboratory prototype are primarily to verify the theoretical findings given in Chapter 2 experimentally in the laboratory and secondarily to make a comparison between the performances of contactor switched and thyristor switched capacitors with and without filters. Four different cases as shown in Figure 4.2 have been configured and their results have been examined. Since the performance of the most preferred delta connection will be tested in the field on the application prototype, wye connected TSC topology is preferred for the laboratory prototype. Note that the common node of the capacitors are connected to the neutral point of the transformer as can be seen from Figure 4.2.



(a) Contactor Switched Shunt Filter

(b) Thyristor Switched Shunt Filter

Figure 4.1: Laboratory prototype of Thyristor and Contactor switched shunt filter.



(a) Contactor Switched Plain Capacitor

(b) Contactor Switched Filter

(c) Thyristor Switched Plain Capacitor

(d) Thyristor Switched Filter

Figure 4.2: Circuit representations of four different switching scheme.

The capacitor units used in the laboratory prototype are designed to form a delta connected bank and having a capacitance of 510 μF / unit. Therefore each capacitor can produce 271 kVAr at rated voltage and frequency (1.3 kV, 50 Hz). However in the laboratory prototype, three units are connected to form a wye-connected capacitor bank. The resulting wye-connected capacitor bank can therefore produce only 156 kVAr at rated operating voltage and frequency (1 kV l-to-l, 50 Hz). When they are connected in series with filter reactors (981 μH/phase wye) in order to adjust tuning frequency to 225 Hz, the resulting three phase fifth harmonic filter bank can produce 153 kVAr at rated voltage and frequency (1 kV l-to-l, 50 Hz).

In the following sections, the resulting current and voltage waveforms of all configurations in Figure 4.2 will be examined in details. In addition, the advantages and disadvantages of these configurations will be discussed.

4.2.1 Contactor Switched Plain Capacitor

The performance of the system in Figure 4.2(a) will be examined in this subsection for the time periods in which the contactor switched plain capacitor is connected to and disconnected from the busbar. The system has been connected to the low voltage side of 34.5/1 kV 800 kVA transformer having $5\%U_k$. The leakage inductance of the transformer is calculated to be 200 μH / phase wye. Since the transformer is operated at no load, excluding the contactor switched plain capacitor, on its low voltage side, the transformer leakage inductance behaves just like an inrush current limiting reactor during the connection of shunt capacitors to the transformer's secondary. Tuning frequency of the shunt capacitors together with transformer's leakage reactance is found to be 500 Hz. Therefore it is not expected to have a large inrush current component through the capacitors at the instant of their connection to the transformer's secondary.

In commercial low voltage applications, contactors with auxiliary contact is used to overcome the transient problems. Auxiliary switch is closed initially to damp the inrush current component since it has a series resistance. 3 ms later, the main contactor is closed and all the current is transferred to these contacts. Since the response time of an ordinary contactor is much more than 3 ms as will be seen next sections, a special contactor design is necessary to manage this transition.

4.2.1.1 Connection to the Busbar

Figure4.3 shows the voltage and current waveforms obtained experimentally. It is seen from Figure 4.3(d) that the peak of the inrush current is nearly 15 times the peak of the steady-state current owing to the existance of a considerable inrush current limiting inductance. It is worth to note that the associated standard [37] permits an inrush current component up to 100 times the peak of the rated capacitor current. This inrush current component leads to the production of a voltage overshoot superimposed on the transformer's secondary voltage and hence the capacitor voltage as can be observed from Figure 4.3(a) and 4.3(c). Its magnitude is nearly 2.2 times the peak value of the rated voltage. This is not desirable because the loads sensitive to such disturbances and connected to the same busbar would be affected seriously by the switchings of plain capacitors.

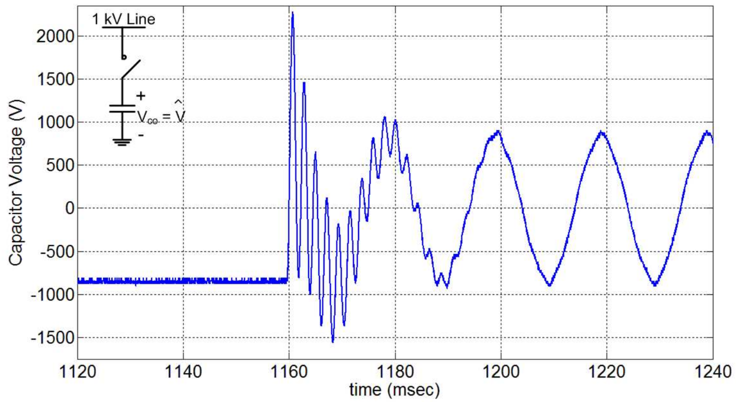
If one considers an ideal system in which there is no inrush current limiting element (reactor or resistor), then the value of $n = \frac{w_o}{w}$ as defined in Section 2.3.1 would go to infinity. Therefore the oscillating current component in Equation 4.1 goes to infinity.

$$\begin{aligned} i(t) = \quad & \hat{I}_1 \cos(wt + \alpha) - \overbrace{nB_c \left[V_{co} - \frac{n^2}{n^2 - 1} \hat{V} \sin\alpha \right] \sin(w_o t)}^{\infty} \\ & - \hat{I}_1 \cos\alpha \cos(w_o t), \\ & \Longrightarrow i(t) \longrightarrow \infty. \end{aligned} \tag{4.1}$$

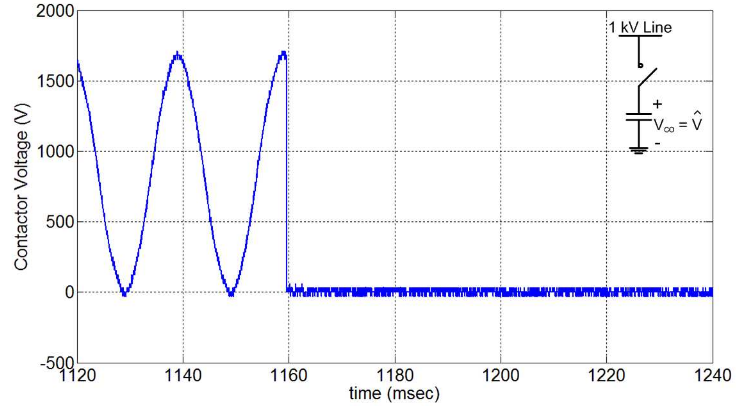
The situation would be much worse if there were more than one parallel capacitor banks connected to the same busbar. For this case, the outrush currents delivered by the initially charged capacitor banks (Figure 2.10) cause an increase in the inrush current component of the initially discharged capacitor bank which is connected to the same busbar.

Switchings of the capacitor banks produces oscillating current component and hence oscillating voltage component as can be observed from Figure 4.3. The frequency of oscillations is the tuning frequency (Equation 4.1). The current and the voltage records in Figure 4.3 show that the oscillation takes place at 500 Hz as expected.

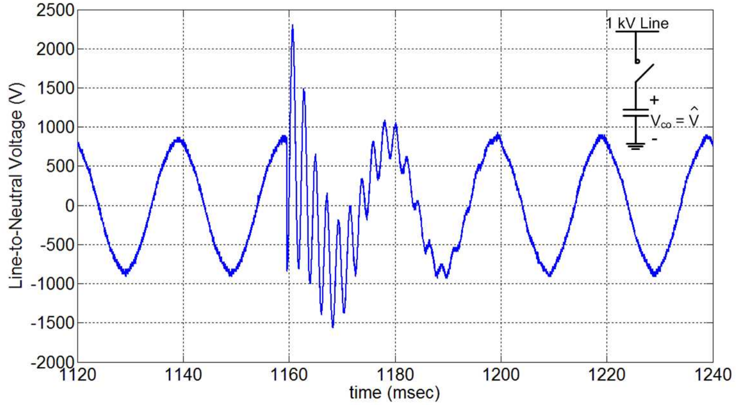
Furthermore, the magnitude of the switching transients depend on the initial charge of the capacitor as well as on the switching instant. Figure 4.3(b) represents the worst case. It means that the capacitors are initially fully-charged and the turn-on has been occurred when the voltage across the contactor is maximum (two times the line-to-neutral voltage). At the switching instants, the capacitors are subjected to this voltage difference which results in 2 kA inrush



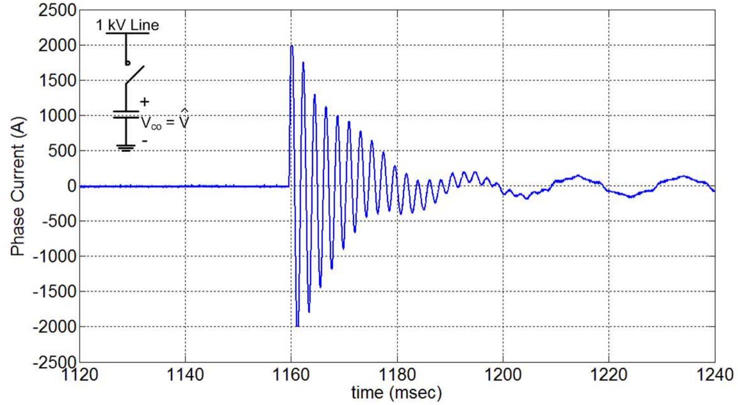
(a) Voltage Waveform across the capacitor



(b) Voltage Waveform across the contactor



(c) Line-to-neutral voltage



(d) Current Waveform through one phase

Figure 4.3: Resultant Waveforms of the turn-on transient with contactor when the capacitors are initially charged.

current.

Line-to-line voltage is also affected by this inrush current component. The distortion can be clearly seen in Figure 4.4. The peak value of line-to-line voltage increases approximately 60% above its nominal value. This means that any client connected to the 1 kV busbar will be exposed to this distortion. As a result, the critical components may be damaged if they do not have a reliable protection facilities.

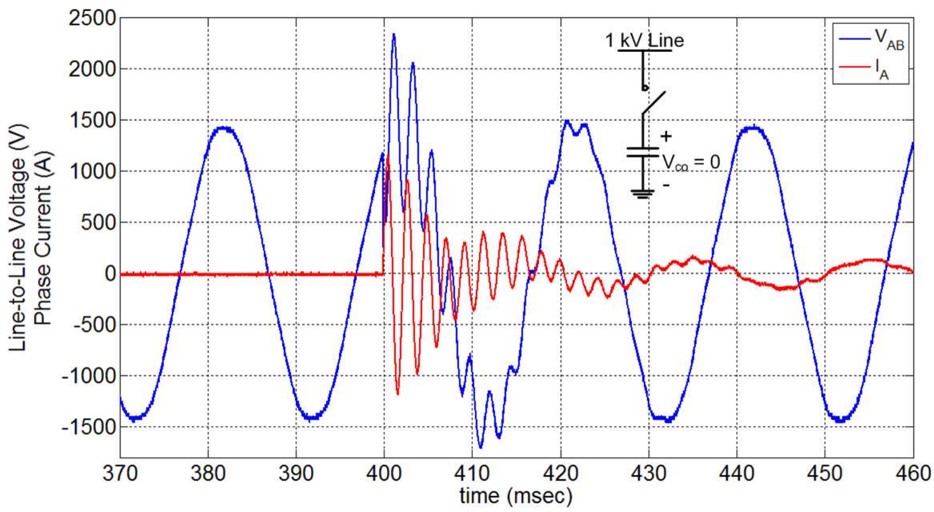


Figure 4.4: Resultant line-to-line voltage and phase current of the turn-on transient with contactor when the capacitors are initially discharged.

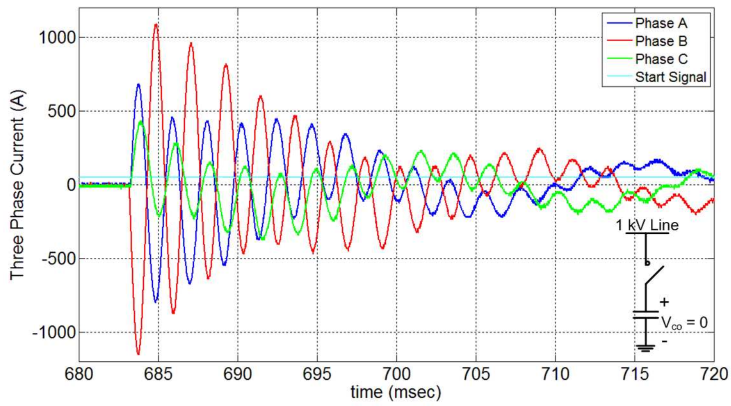
As can be seen from Figure 4.5(a), all three poles of the contactor are closed and opened simultaneously, therefore the connection of the capacitors to the busbar occurs at random voltage value across the contactor. For a fully charged capacitor, the closing instant can occur when the voltage magnitude across the contactor becomes two times the line-to-neutral voltage and results in very high inrush currents as mentioned before. Therefore it is recommended in [37] that there must be usually 3-10 minutes between consecutive switchings to ensure that capacitors are discharged to 10% of its rated voltage.

One of the main disadvantages of contactor-based switching is the delay after the start signal is sent. It took 150-200 msec to initiate the conduction in these experiments as can be seen in Figure 4.5(b). This time delay can only be avoided by using semiconductor switches instead of electromechanical ones.

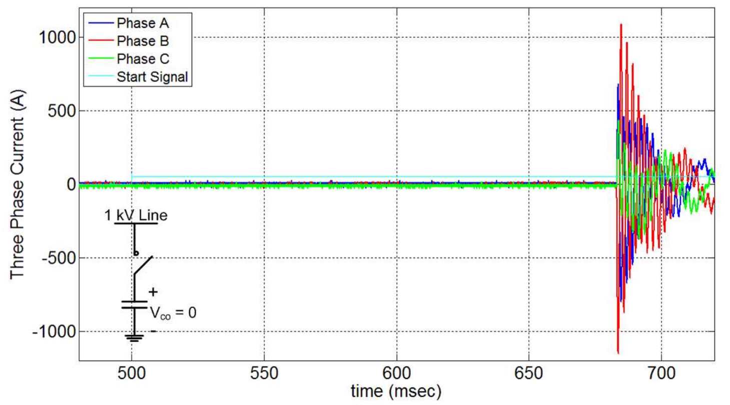
Figure 4.5(c) shows the rms values of the three phase transient currents. The transient damps out eventually and the settling time is seen to be 3 cycles in this figure. In other words, before the system gives its rated output power, at least 3 cycles must pass. Therefore, it would be wrong to assume that the system operates in full performance whenever the contactor is closed.

4.2.1.2 Disconnection from the Busbar

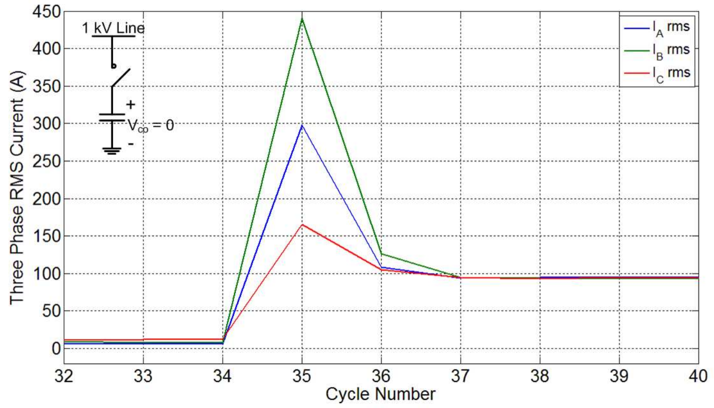
Disconnection has been occurred without any spike or transient during these experiments as can be seen from Figure 4.6. The energy of the reactor is partly dissipated on arc resistance between contactor terminals of the same phase and partly charges the capacitor to a value higher than the peak voltage. Since the phase current drops to zero before naturel zero crossing of the sine wave (Figure 4.6(d)), capacitor is left charged to the peak of line-to-neutral voltage as shown in Figure 4.6(a) or to a higher value, therefore the contactor is exposed to the sum of the line-to-neutral voltage and capacitor voltage (Figure 4.6(b)). The transitions are smooth, therefore turn-off transient does not create any distortion in line-to-neutral voltage waveform (Figure 4.6(c)). It can therefore be concluded that the turn-off performance of a contactor switched system is much better than its turn-on performance.



(a) Three phase current waveform at the turn-on transient

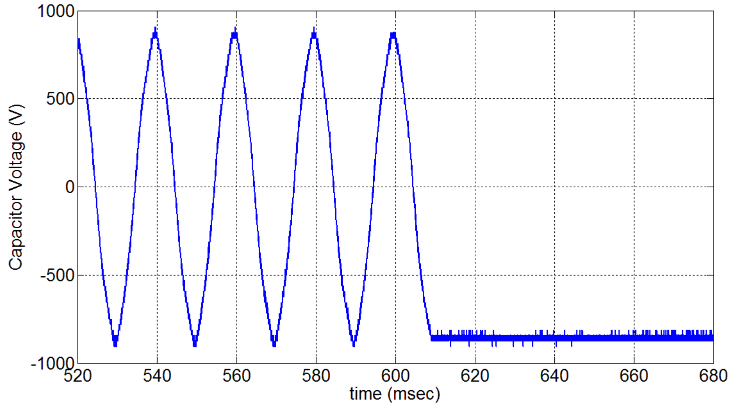


(b) Response time of the contactor switched system

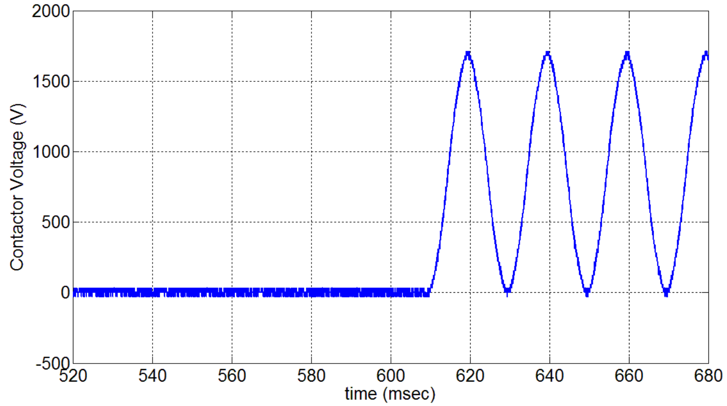


(c) Settling time of the contactor switched system

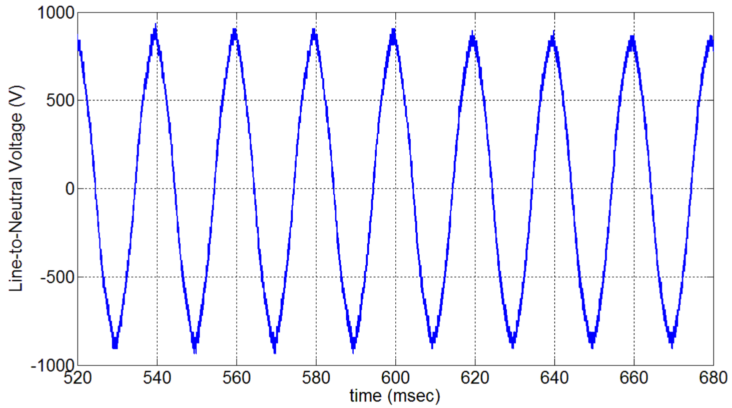
Figure 4.5: Resultant 3ϕ phase current waveform, the response time and the settling time of the turn-on transient with contactor.



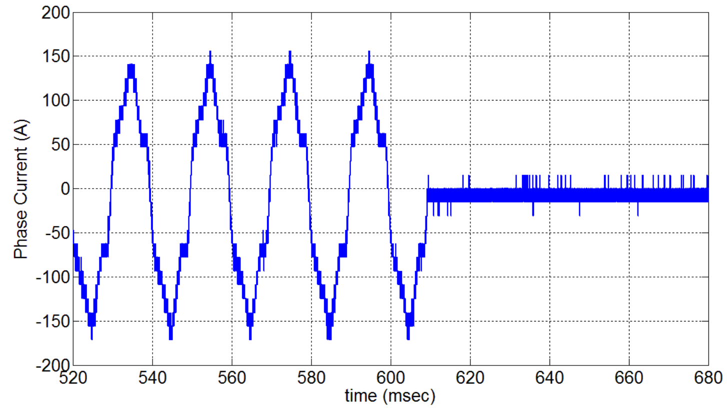
(a) Voltage Waveform across the capacitor



(b) Voltage Waveform across the contactor



(c) Line-to-neutral voltage



(d) Current Waveform through one phase

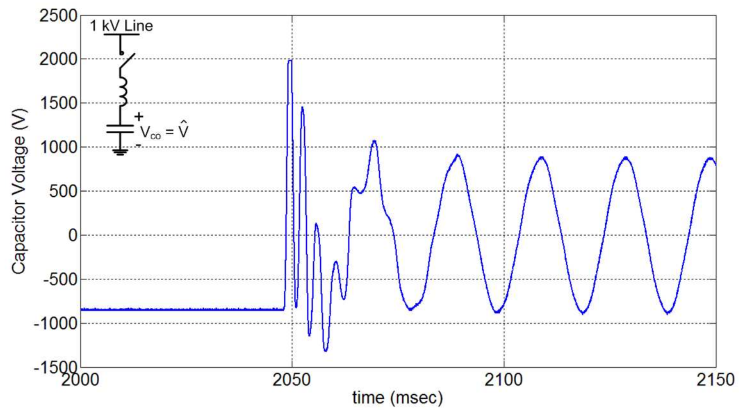
Figure 4.6: Resultant Waveforms of the turn-off transient with contactor.

4.2.2 Contactor Switched Shunt Filter

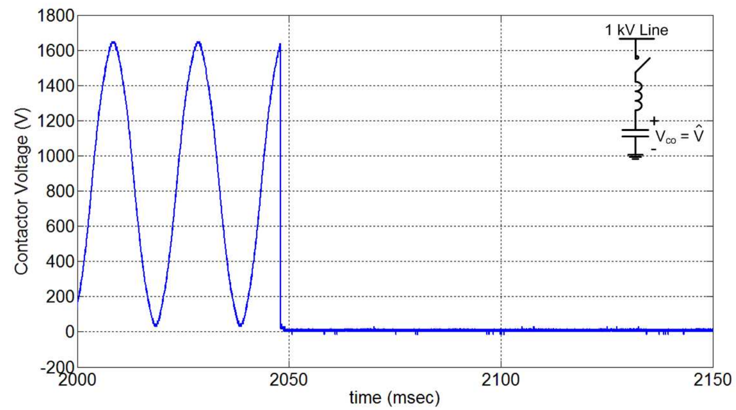
The case shown in Figure 4.2(b) has been studied in this section. A filter reactor is placed between the contactor and the capacitor. The system is designed to filter out the fifth harmonics, therefore the tuning frequency has been chosen to be 225 Hz.

4.2.2.1 Connection to the Busbar

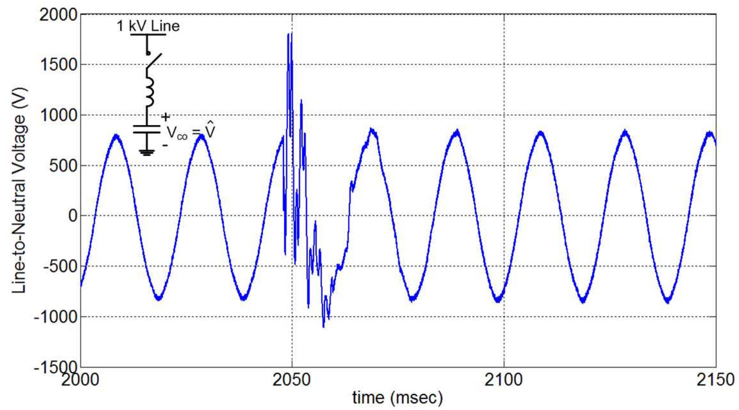
Similar conclusions can be drawn for the contactor switched filter since the switching instant is not controllable. As can be seen from Figure 4.7(b), the worst case is obtained once again and the contactor is closed at twice the peak value of the line-to-neutral voltage. A comparison of waveforms in Figure 4.7 with those of Figure 4.3 shows that by designing the shunt element as a tuned filter bank, switching transients are reduced to a certain extend and naturel frequency of oscillation are considerably ruduced. The capacitor voltage shown in Figure 4.7(a) has climbed up to 2 kV and the distortion of line-to-neutral voltage due to this surge current is less disturbing as can be seen in Figure 4.7(c). Since the standards allow the transient overvoltages on the capacitors up to two times the peak value of the capacitor's nominal voltage, e.g. a capacitor having a rated value of 700V can easily withstand this transient. In addition, there is one more important difference between the waveforms of contactor switched plain capacitor and filter. It is the frequency of oscillating current component. As can be determined from Figure 4.7, oscillation takes place at a frequency of 250 Hz for the first cycle and then the oscillation frequency gradually decreases to 200 Hz. Although the tuning frequency of passive shunt filter is 225 Hz. This is because the leakage inductance of the coupling transformer operating at no load causes the effective value of filter inductance to be increased from 981 to 1181 μH (981+200 μH) and hence the tuning frequency from 225 Hz to 205 Hz. This fact can not explain completely variations in oscillation frequency from 250 Hz to 200 Hz. The iron core of the input filter reactor is saturated because of the large inrush current component (2 kA) passing through their coils for the first cycle of the oscillating current component. The magnetic saturation owing



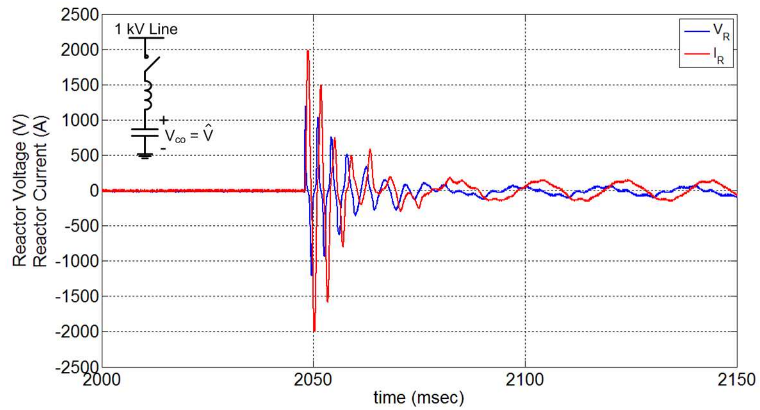
(a) Voltage Waveform across the capacitor



(b) Voltage Waveform across the contactor



(c) Line-to-neutral voltage



(d) Current and Voltage Waveform of the reactor

Figure 4.7: Resultant Waveforms of the turn-on transient with contactor when the capacitors are initially charged.

to high inrush current causes a considerable reduction in the self inductance of iron core filter reactor as will be discussed in Section 4.5.

The line-to-line voltage is again affected considerably by the switching transients. Although the peak of the transient current is not too high as compared to the worst case, the distortion on the l-to-l voltage is inevitable. This is the major drawback of contactor switched filter banks. Therefore it is not recommended for frequent switchings of filter banks.

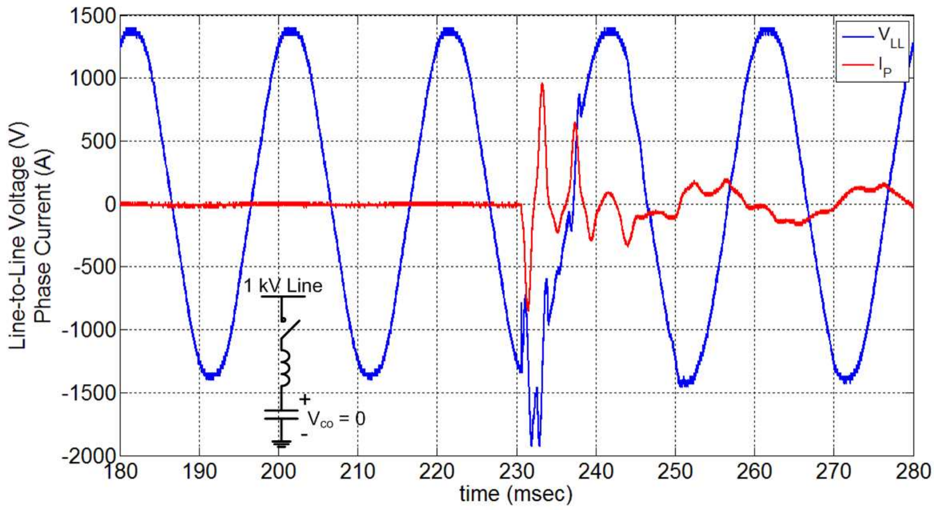


Figure 4.8: Resultant line-to-line voltage and phase current of the turn-on transient with contactor when the capacitors are initially discharged.

Figure 4.9 shows the rms values of the phase currents. The settling time becomes 4 cycle for this case. Note that the lower frequency of oscillations do not mean that the transient will last shorter.

4.2.2.2 Disconnection from the Busbar

During disconnection from the busbar any distortion in the voltage or current waveforms is not observed. The reason mainly relies on the reactor current since it vanishes slowly. Although a forced turn-off occurs, the stored energy on the reactor can be easily dissipated in the arc resistance of the contactor.

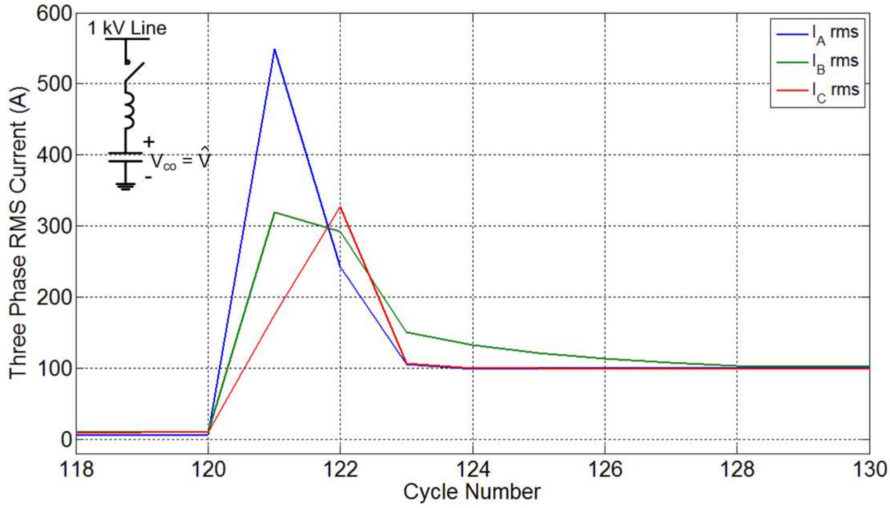
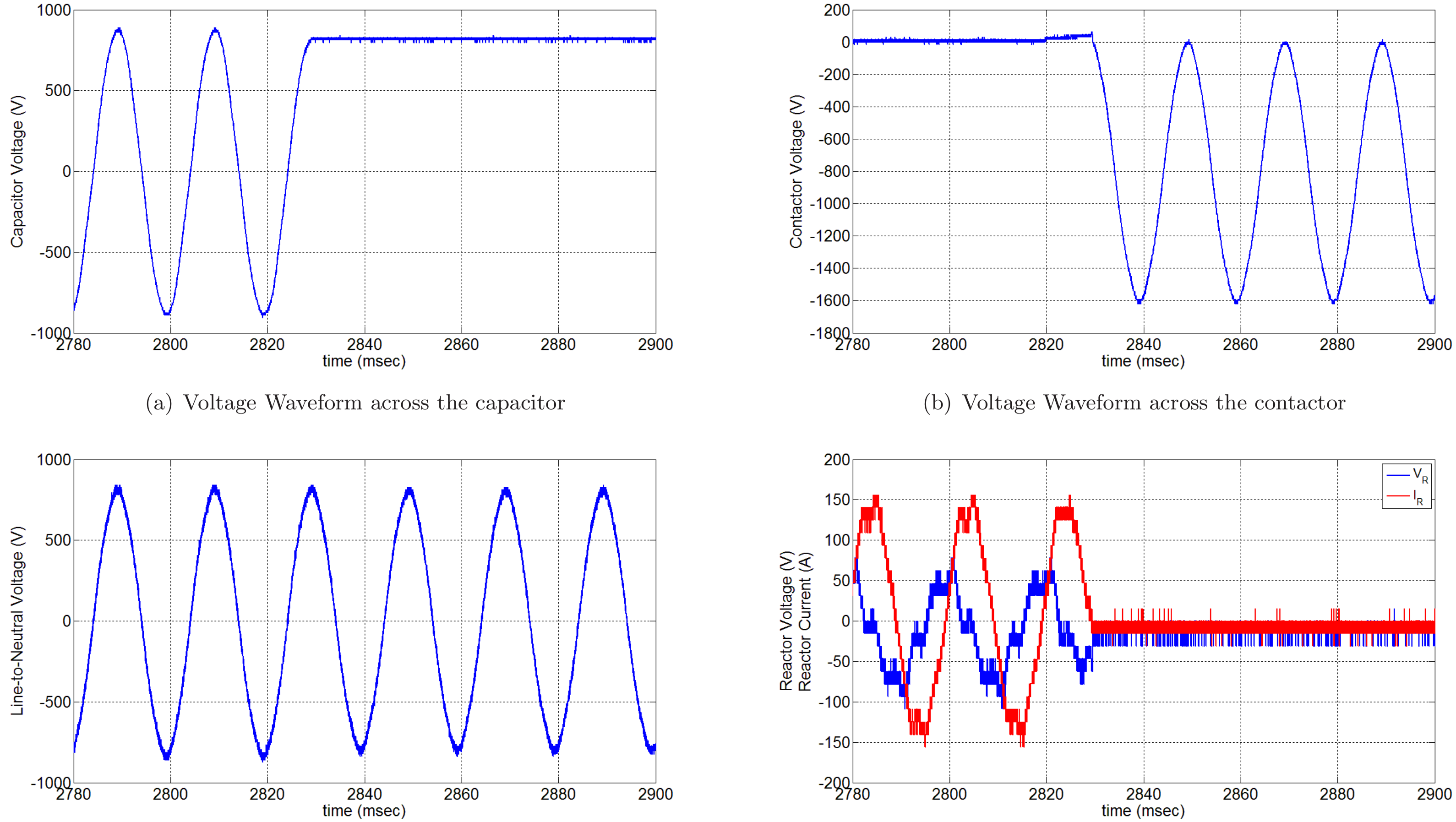


Figure 4.9: Resultant settling time of the turn-on transient with contactor.

The vacuum contactor could be unable to dissipate this energy and would cause significant transients.



(a) Voltage Waveform across the capacitor

(b) Voltage Waveform across the contactor

(c) Line-to-neutral voltage

(d) Voltage and current Waveform of the reactor

Figure 4.10: Resultant Waveforms of the turn-off transient with contactor.

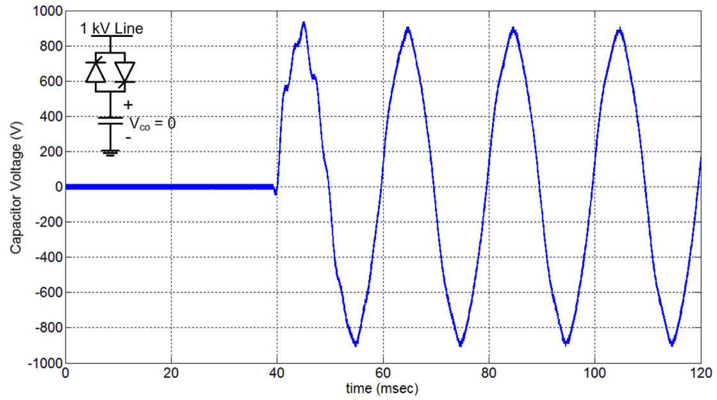
4.2.3 Thyristor Switched Plain Capacitor

The case shown in Figure 4.2(c) has been studied in this section. The benefits of controllable switching will be expressed by representing the current and voltage waveforms of each component. Similar results have been obtained from the systems built in BLİ and YLİ, therefore the field data mentioned in the rest of the chapter can be referred.

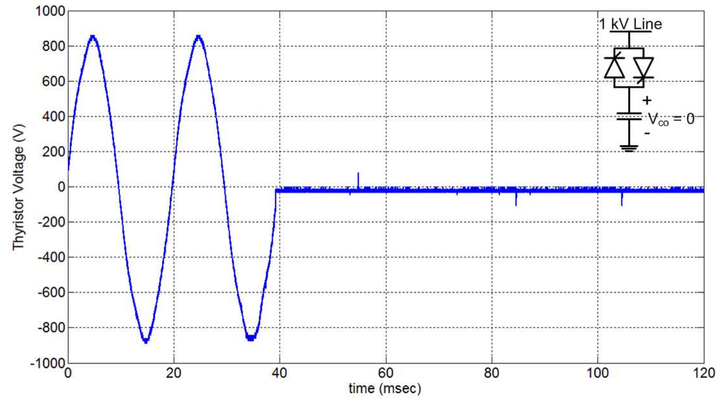
4.2.3.1 Connection to the Busbar

There is a great difference between the transient responses of contactor and thyristor switched plain capacitors. The current only increases up to 210 A even if there is not any reactor that limits the inrush current during turn-on process as can be seen in Figure 4.12(d) and there are negligible distortions on the capacitor voltage and line-to-neutral voltage waveforms (Figures 4.12(a) and 4.12(c) respectively). The switching occurs where the voltage across the thyristor switch is zero. Therefore the capacitor does not draw high amounts of current as it is exposed to zero voltage difference at the instant of turn-on.

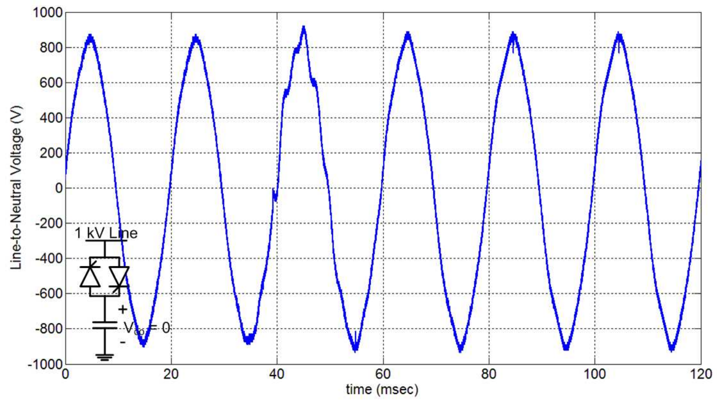
Figure 4.11 shows the switching instant when the capacitors are initially discharged. According to the Figure 2.12, the amplitude of oscillatory current component is equal to the amplitude of fundamental current component and it is independent from the series reactance in the system. Therefore, the transient free switching can not be achieved with the capacitors fully discharged. However the amplitude of transient current (Figure 4.11(d)) only rises up to 300 A which means that it still has a decent transient response comparing to the contactor switched plain capacitor's performance. Again the distortions of the capacitor voltage and line-to-neutral voltage is negligible.



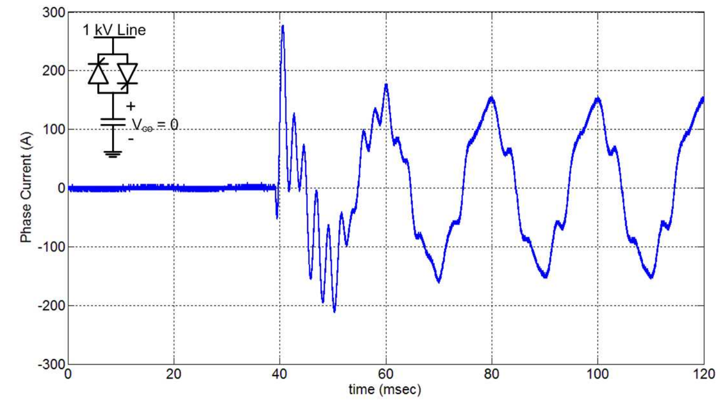
(a) Voltage Waveform across the capacitor



(b) Voltage Waveform across the thyristor

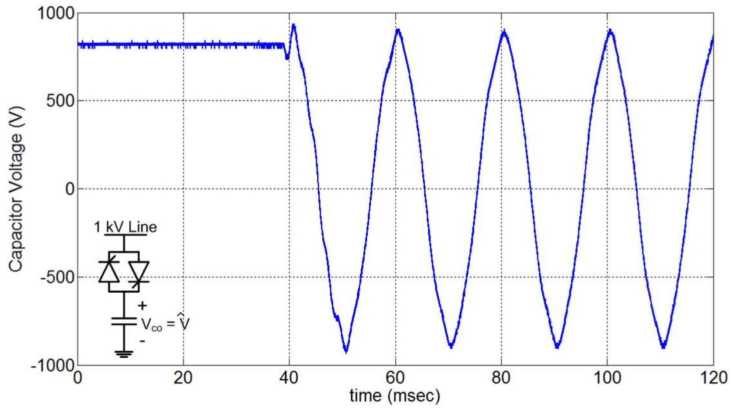


(c) Line-to-neutral voltage

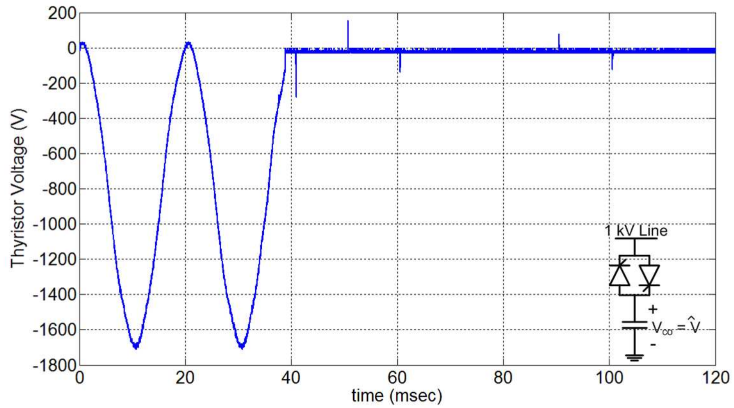


(d) Current Waveform through one phase

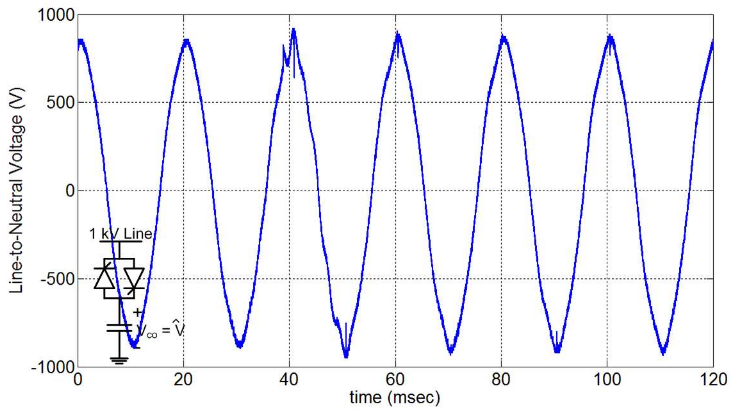
Figure 4.11: Resultant Waveforms of the turn-on transient with thyristor when the capacitors are initially discharged.



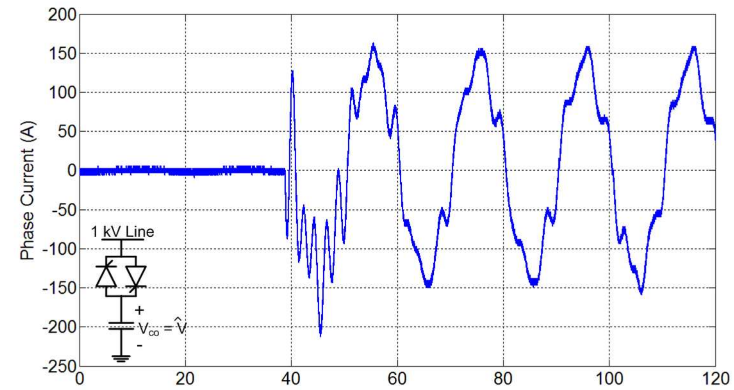
(a) Voltage Waveform across the capacitor



(b) Voltage Waveform across the thyristor



(c) Line-to-neutral voltage



(d) Current Waveform through one phase

Figure 4.12: Resultant Waveforms of the turn-on transient with thyristor when the capacitors are initially charged.

This transient has also negligible effects on the line-to-line voltage which makes the coupling point more clean for all other clients connected to the same bus-bar. The same conclusion can be drawn for the switching transient when the capacitors are initially discharged.

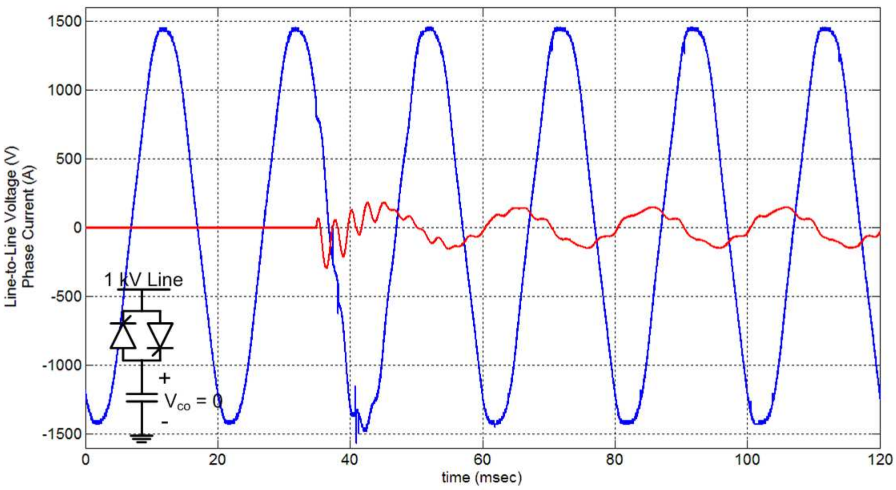


Figure 4.13: Resultant line-to-line voltage and phase current of the turn-on transient with thyristor when the capacitors are initially discharged.

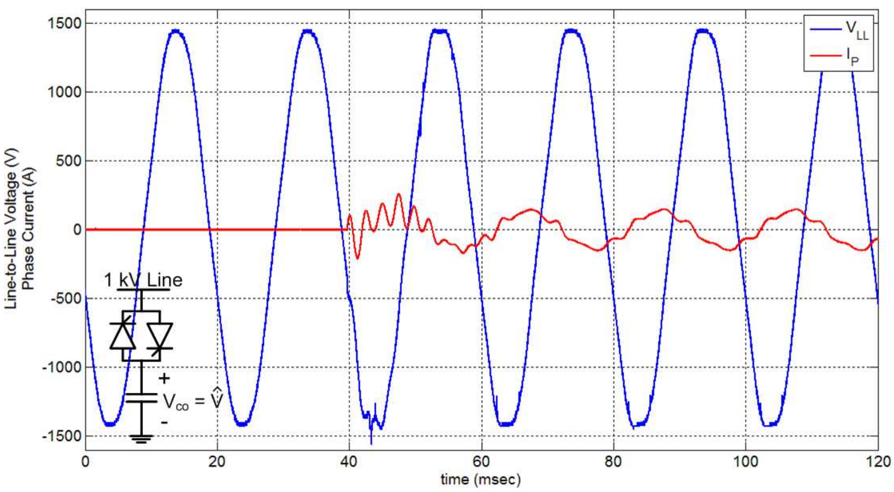


Figure 4.14: Resultant line-to-line voltage and phase current of the turn-on transient with thyristor when the capacitors are initially charged.

The oscillatory current component still exists on the transient waveform due to the transformer leakage inductance as can be observed from Figure 4.16(a). The frequency of oscillation is again expected to be the corner frequency of the leakage inductor and the series capacitor. The Figure 4.16(b) reveals the response time of the thyristor switched system. In 15 msec, the first phase initiates conducting. This value is superior comparing to the 200 msec delay in contactor switched cases. However, settling time stays at 3 cycles which can be observed from the rms values of phase currents in Figure 4.16(c).

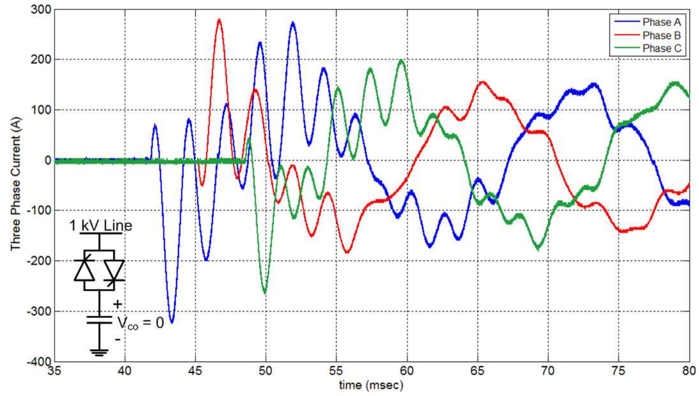
As can be seen from Figure 4.15(b), the delay for initiation of conduction can reduce to 2 ms. In thyristor switched configurations, the delay time depends on the instant when the start signal is sent to the control unit. Figure 4.15(c) shows the settling time when the capacitors are initially discharged. It can be observed that the duration is decreased to two cycles.

4.2.3.2 Disconnection from the Busbar

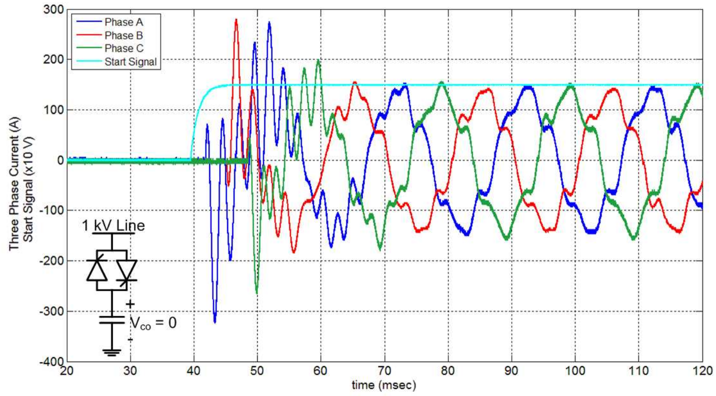
Disconnection occurs naturally due to the nature of thyristor switches. Since the thyristor continues to conduct until its current drops below a certain level called *latching current*. Therefore there is not any distortion occurred during turn-off period and each phase turns off independently. The three phase capacitor voltages are shown in Figure 4.17. They are charged to different voltage polarities depending on the polarity of line-to-neutral voltage at the turn-off instant. A slight difference between the capacitor trapped charges can be expected due to the reactance of the transformer.

4.2.4 Thyristor Switched Shunt Filter

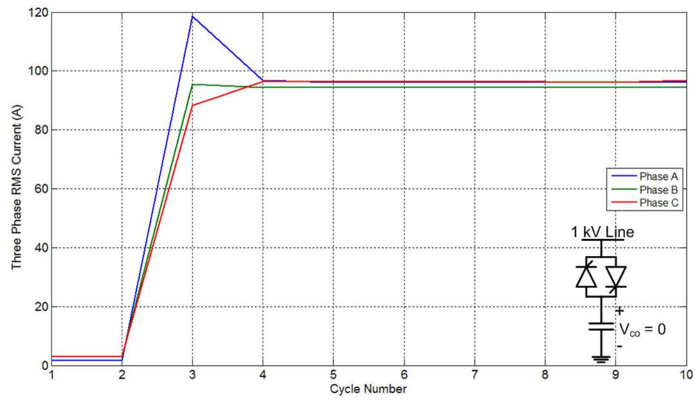
The case shown in Figure 4.2(d) has been studied in this section. The system is again designed to filter out the fifth harmonic, therefore it is tuned to 225 Hz. The optimum responses have been recorded in this experiment.



(a) Three phase current waveform at the turn-on transient



(b) Response time of the thyristor switched system

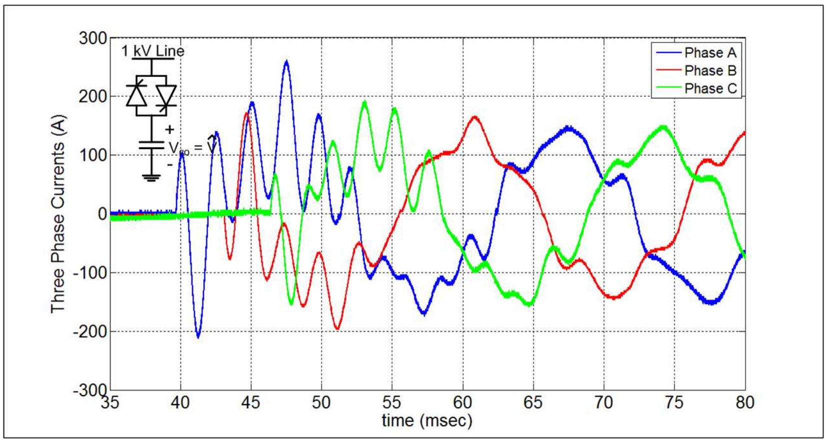


(c) Settling time of the thyristor switched system

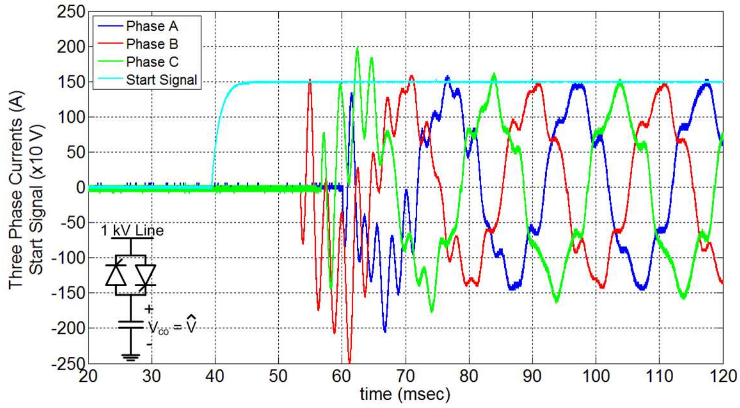
Figure 4.15: Resultant 3ϕ phase current waveform, the response time and the settling time of the turn-on transient with thyristor.

4.2.4.1 Connection to the Busbar

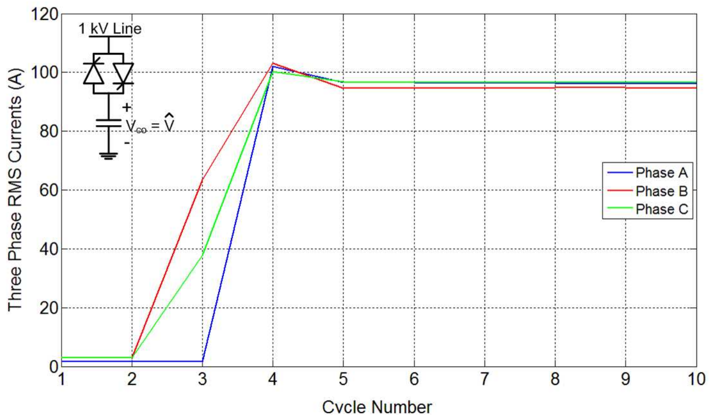
The waveforms shown in Figure 4.19 are obtained when the capacitors are initially charged to almost the peak value of the line-to-neutral voltage. Therefore,



(a) Three phase current waveform at the turn-on transient



(b) Response time of the thyristor switched system



(c) Settling time of the thyristor switched system

Figure 4.16: Resultant 3ϕ phase current waveform, the response time and the settling time of the turn-on transient with thyristor.

the conditions for transient free switching mentioned in Chapter 2 hold for this experimental setup. The current waveform seen in Figure 4.19(d) has an oscilla-

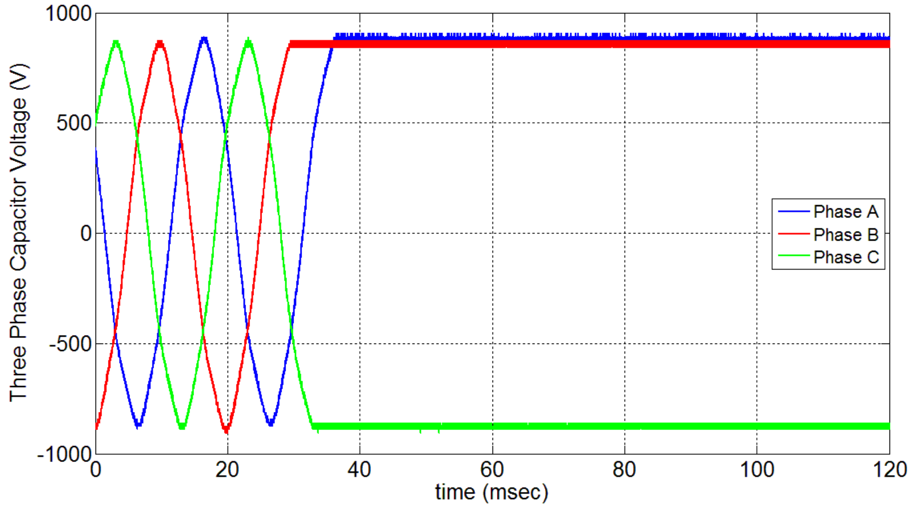
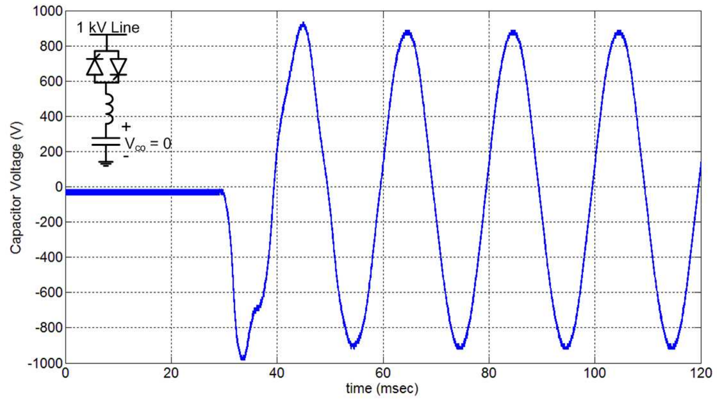


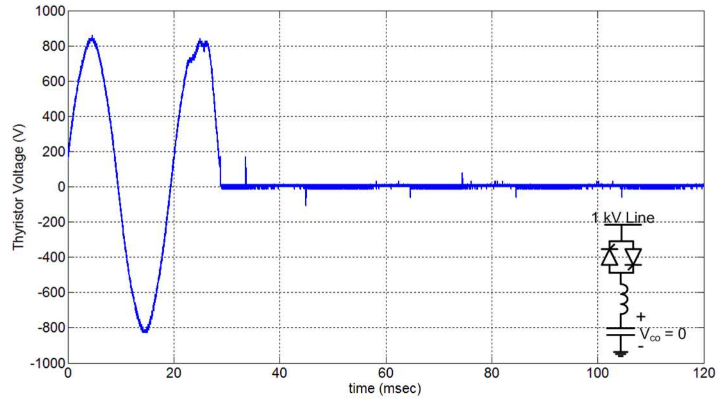
Figure 4.17: Resultant 3ϕ Capacitor Waveforms of the turn-off transient with thyristor.

tory current component inevitably due to the reactor in series with the capacitor. The back and forth energy transfer between reactor and capacitor has to take place for a limited amount of time. However, the frequency of oscillation is small and the peak value does not exceed 220 A.

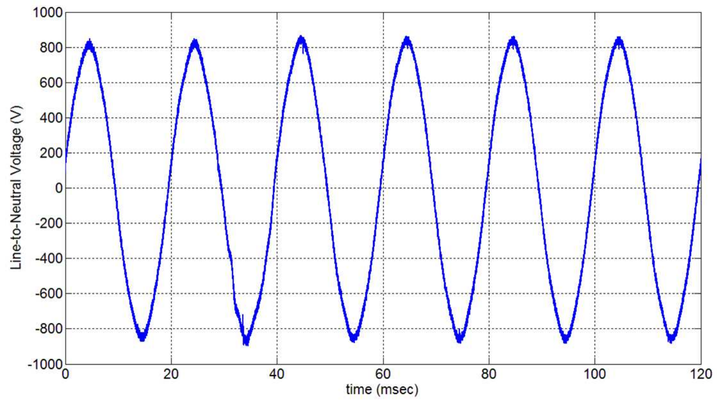
The same comments can be made for the switching of initially discharged capacitor bank. As explained in Subsection 4.2.3.1, the amplitude of the oscillatory current component is expected not to change since it is equal to the fundamental component of the current. This result can be verified by Figure 4.18(d).



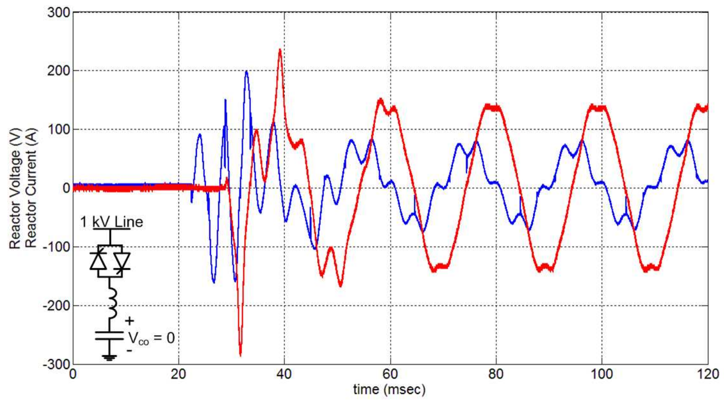
(a) Voltage Waveform across the capacitor



(b) Voltage Waveform across the thyristor

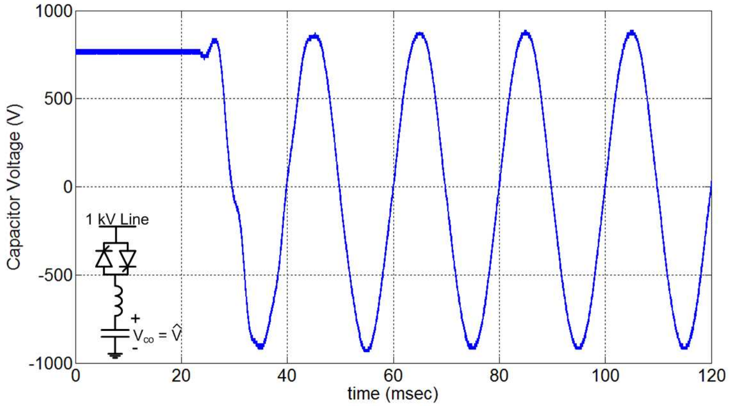


(c) Line-to-neutral voltage

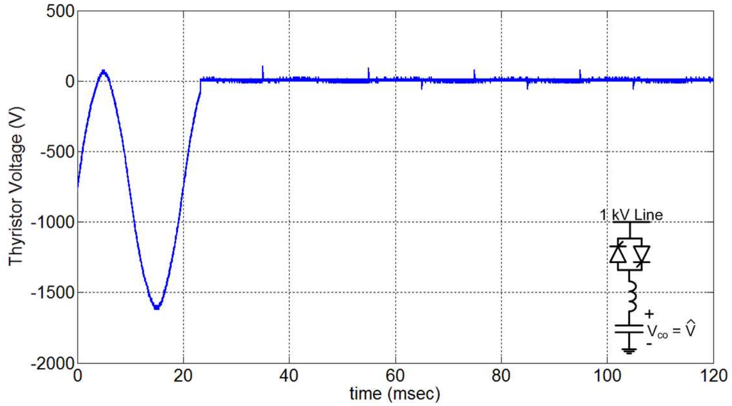


(d) Current and Voltage Waveform of the reactor

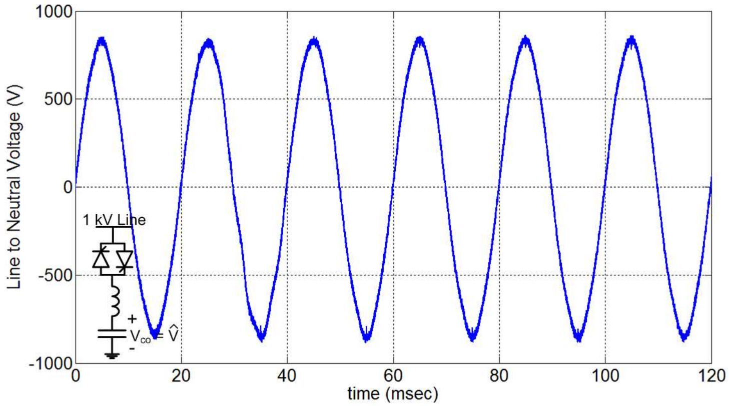
Figure 4.18: Resultant Waveforms of the turn-on transient with thyristor when the capacitors are initially discharged.



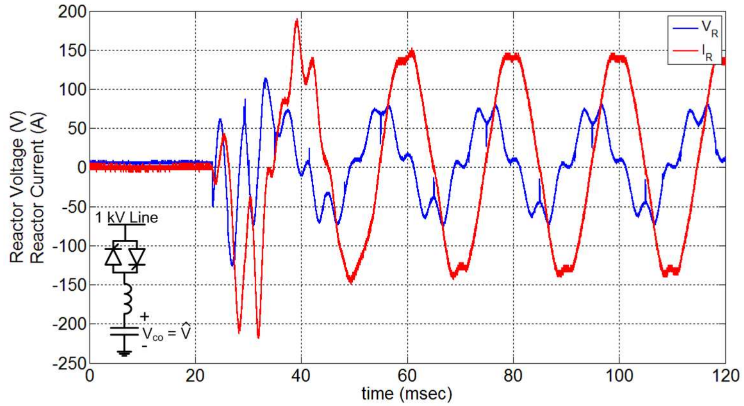
(a) Voltage Waveform across the capacitor



(b) Voltage Waveform across the thyristor



(c) Line-to-neutral voltage



(d) Current and Voltage Waveform of the reactor

Figure 4.19: Resultant Waveforms of the turn-on transient with thyristor when the capacitors are initially charged.

Line-to-line voltage distortion shown in Figure 4.21 is smaller than the one in previous case and not even comparable with the contactor switched cases. Figure 4.23 shows the rms values of the phase currents. Thyristor switches do not affect the settling time of switching transients. It should be remembered that the settling time has increased when the shunt capacitor is equipped with a series reactor for either inrush current limiting, detuning or tuning purposes.

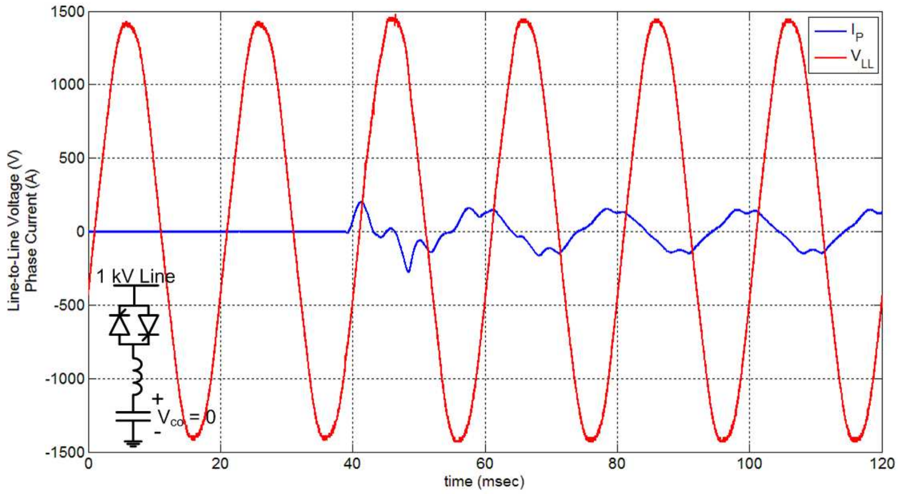


Figure 4.20: Resultant line-to-line voltage and phase current of the turn-on transient with thyristor when the capacitors are initially discharged.

The voltage and current waveforms of back-to-back connected thyristor pair are as given in Figure 4.24. Since the residual voltage on the capacitors after disconnection from the busbar may exceed peak value of the supply voltage owing to the presence of the filter reactor as described in Section 3.3, the filter bank is energized by applying triggering pulses to the forward and backward thyristors earlier than the zero-crossing of the anode-cathode voltage of each thyristor. In the experimental setup, firing circuits are activated when the thyristor voltages tends to be lower than $\pm 50V$ out of 1.65 kV peak. This avoids the risk of misfiring at wrong instant for the purpose of transient-free switching. Triggering pulses of forward and backward thyristors during the energization of the filter bank are also given in Figure 4.24. It is seen from Figure 4.24 that both the forward and backward thyristor receive their firing pulses simultaneously and

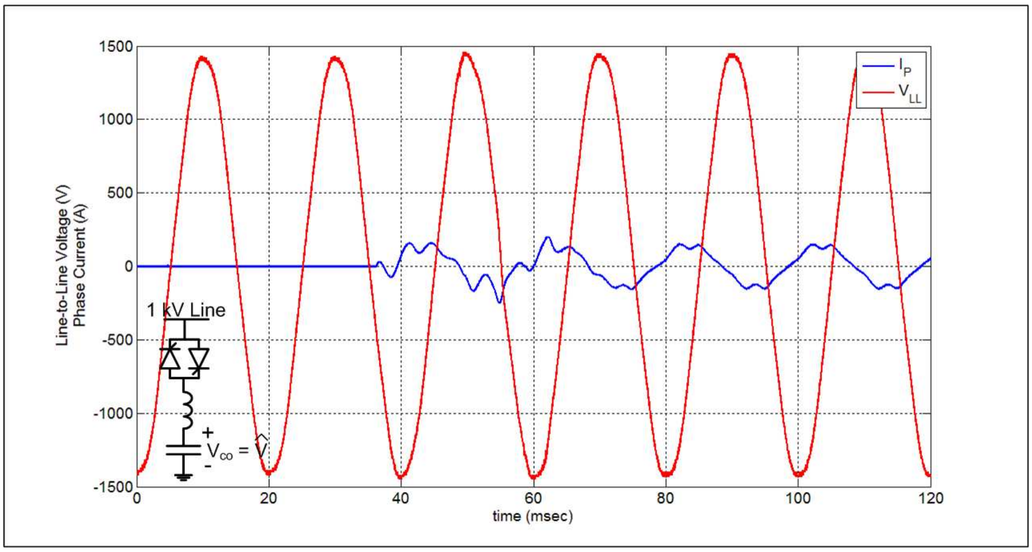


Figure 4.21: Resultant line-to-line voltage and phase current of the turn-on transient with thyristor when the capacitors are initially charged.

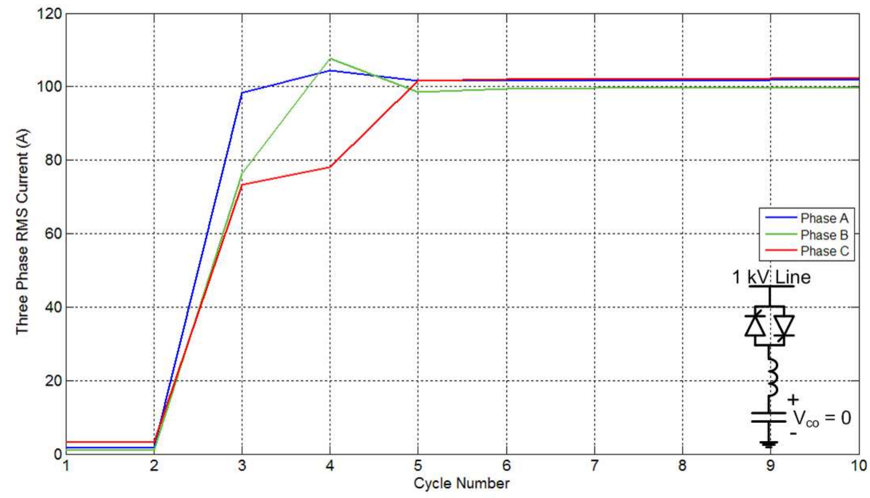


Figure 4.22: Resultant settling time of the turn-on transient with thyristor.

continuously whenever the control circuit sends a signal to the firing circuits to energize or to keep the filter bank connected to the busbar. Each firing pulse is a 4 kHz pulse train with 12% duty cycle. Simultaneous application of firing pulses to backward and forward thyristors also prevents the filter current from

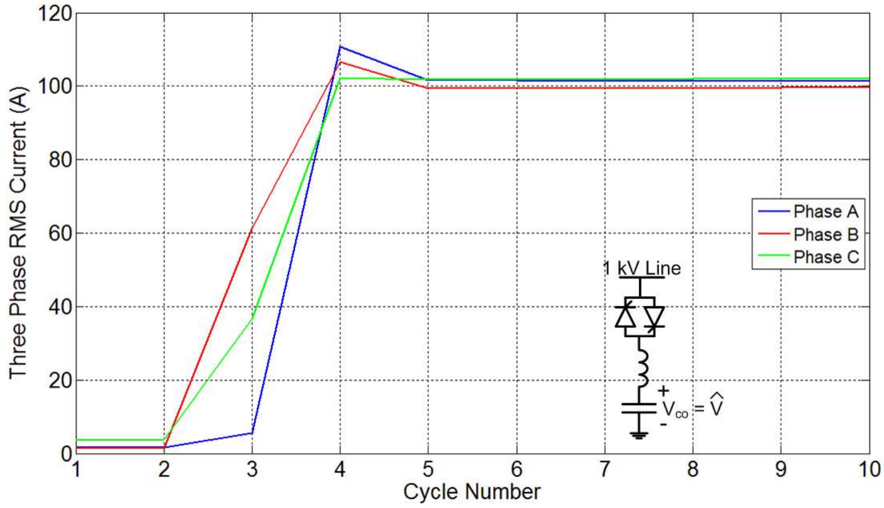


Figure 4.23: Resultant settling time of the turn-on transient with thyristor.

having notches during the transition from the positive to the negative half cycles. This is more apparent from waveforms given in Figure 4.25 The waveforms of Figure 4.25 have been recorded on the laboratory prototype for steady-state operation.

4.2.4.2 Disconnection from the Busbar

The same conclusions can be made for the thyristor switched shunt filter turn-off process since it depends highly on the semiconductor switch type. The voltage across the capacitors are shown in Figure 4.26. They remain charged until the discharge resistor dissipates the stored energy.

4.3 Application Prototype

Single-stage shunt TSC has been installed for open cast lignite mining of Turkish Coal Enterprice in Orhaneli, Bursa (BLI) and in Yeniköy, Muğla (YLI). The sizes of each system are 500 kVAr and 650 kVAr respectively. They have been installed in April, 2008 and have been working since then without any problem.

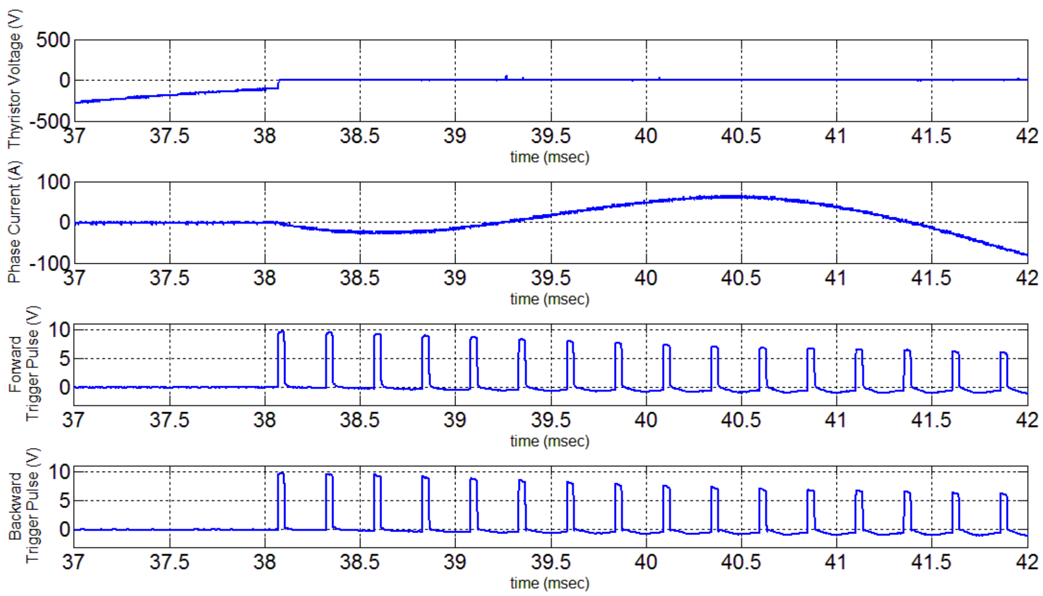


Figure 4.24: Firing pulses, voltage and current waveforms of a back-to-back connected thyristor pair at the instant of switching.

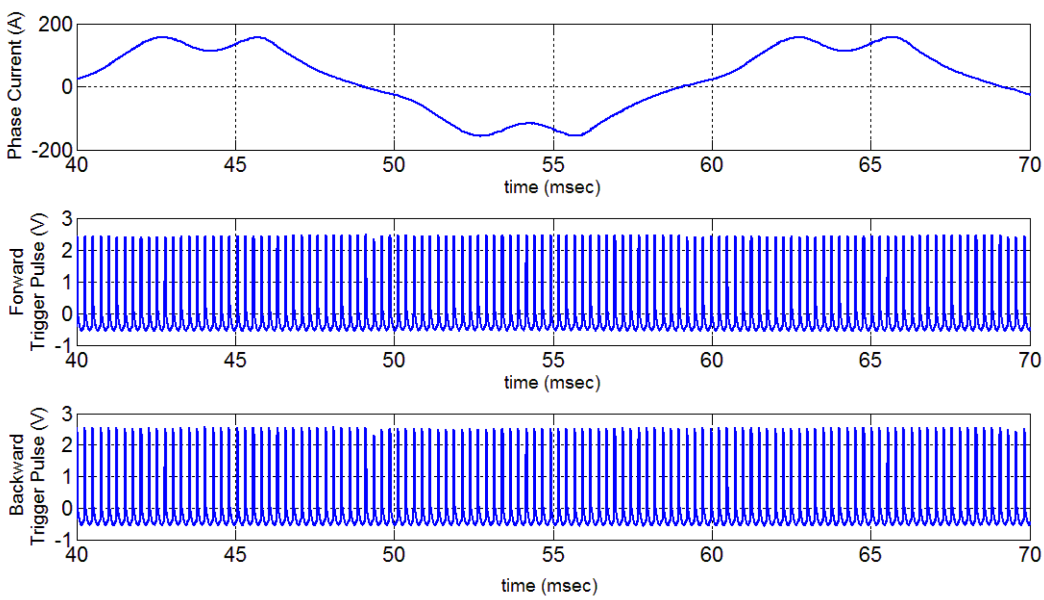


Figure 4.25: Firing pulses and current waveforms of a back-to-back connected thyristor pair during steady-state.

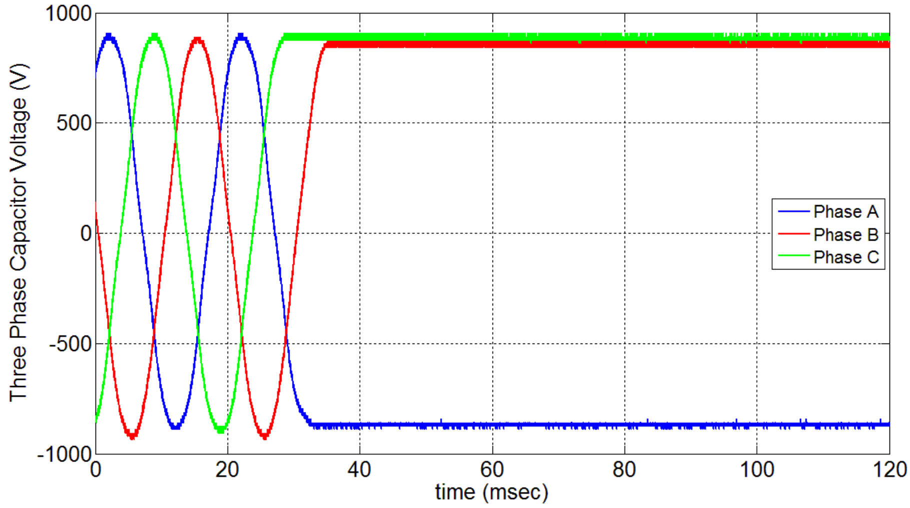


Figure 4.26: Resultant 3ϕ Capacitor Waveforms of the turn-off transient with thyristor.

The load characteristics is rapidly fluctuating and oscillating between inductive and capacitive reactive powers as can be seen in Figure 3.1. The power meter connected by Turkish Electricity Distribution Corporation to monitor the electricity demand was reading around 6% of inductive reactive power to active power ratio. After the installation of TSC, this value has been dropped to 1%.

Figure 4.27 and 4.28 show the single line diagram of both systems. As can be seen from these figures, TSC has been integrated in parallel to the existing TCR + Passive Filter system. The main transformer, circuit breaker, current transformers, cables and their values used in these system are clearly shown. The passive harmonic filter tuned to 4^{th} harmonic has been removed after the installation of TSC.

The details of each component behavior and the possible worst cases will be introduced in the rest of the chapter. The performance parameters will also be explained for some of the critical components and the waveforms will be examined for both turn-on and turn-off process separately. In addition, the degree of harmonic current component passing through the TSC branches will be discussed despite the TSC is not a main harmonic source when fired correctly.

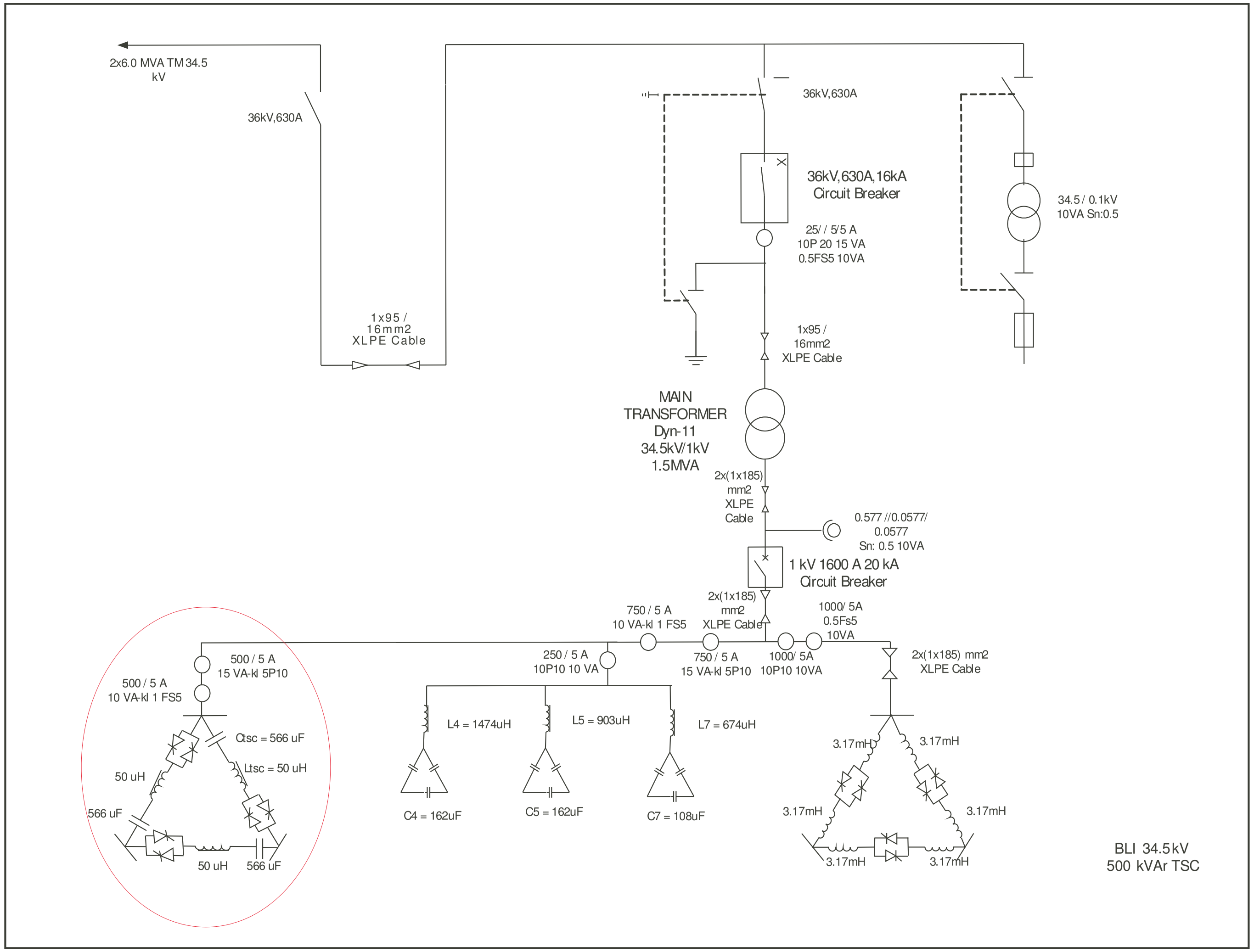


Figure 4.27: Single Line Diagram of the electrical network installed in BLI.

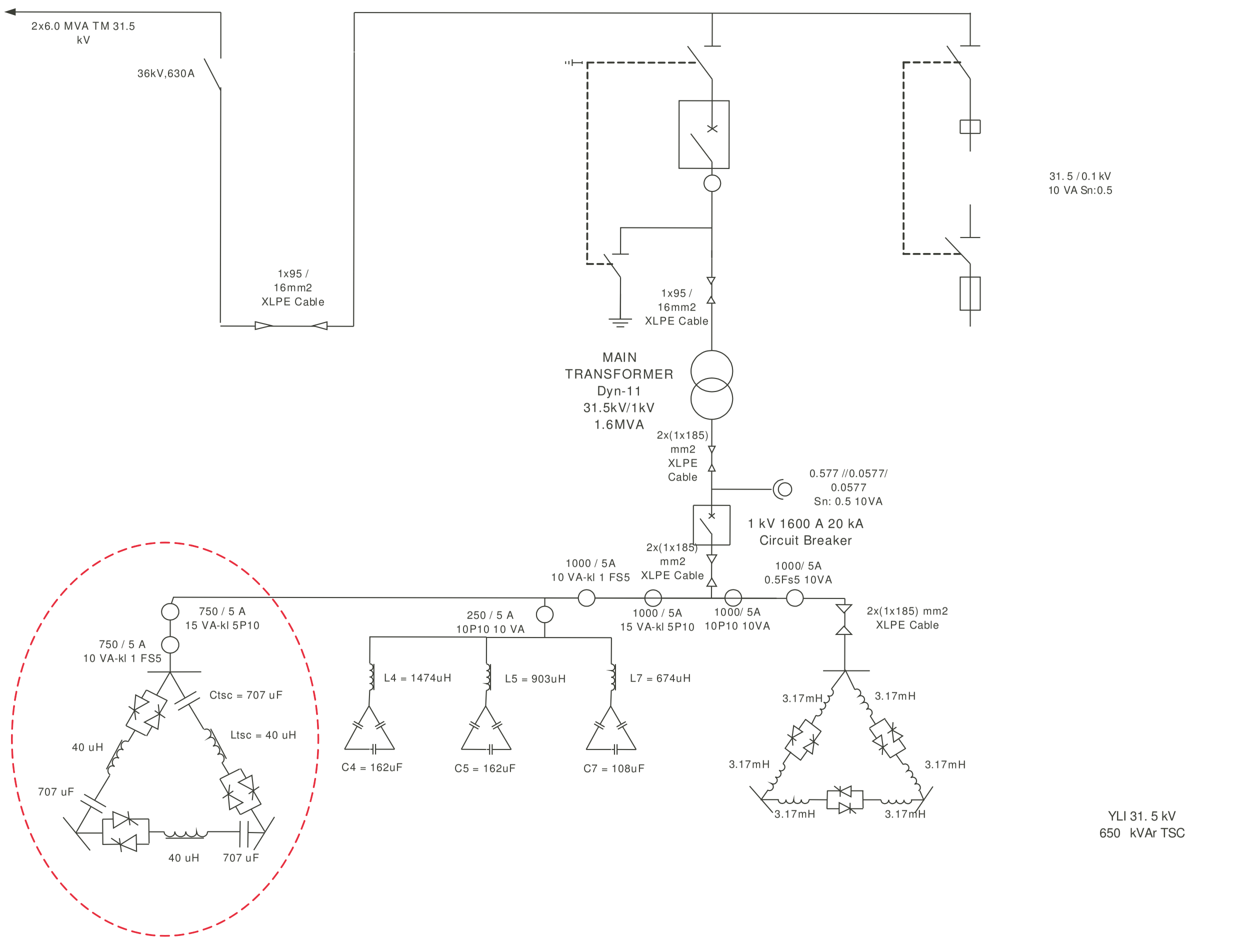


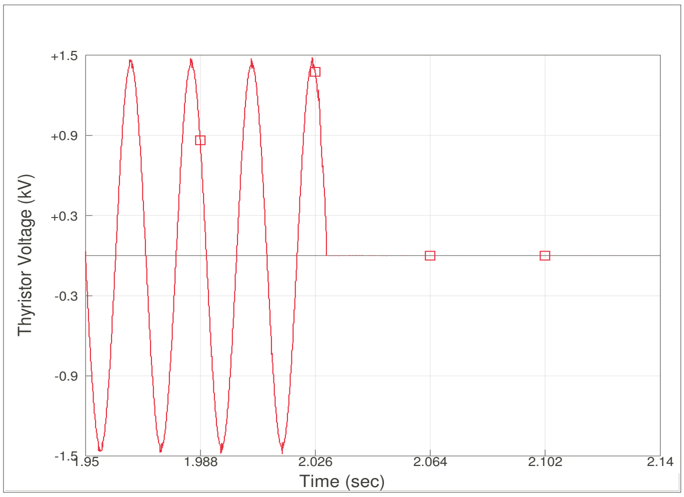
Figure 4.28: Single Line Diagram of the electrical network installed in YLI.

Experimental results will be presented as well as the theoretical simulation results so that the unexpected effects caused by real life circumstances can be seen clearly. The field data has been taken by the mobile monitoring units described in [41] and recorded for several hours and days in different sampling rates. The simulation results were obtained by PSCAD/EMTDC (2001) software program. Only the results for the system in BLI will be introduced in this thesis since the results for YLI have so much in common. The PSCAD model of the whole system is given in Appendix D.

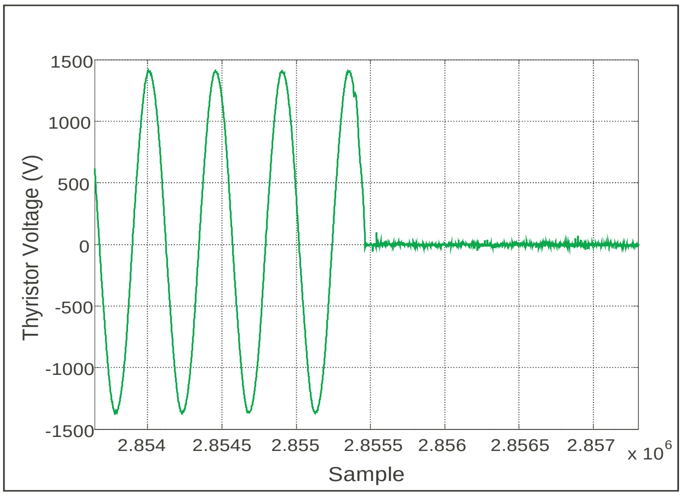
4.3.1 Voltage Waveforms of Thyristor

At the instant where the thyristor has not been energized, the voltage waveform across the thyristor follows the supply voltage waveform since the rest of the components (such as reactor and the capacitor) have not stored some energy yet, the thyristor is the only component that holds this voltage. This situation is illustrated in Figure 4.29 for one phase of thyristor. Since TSC is connected in delta, the $1kV$ rms voltage with a peak value of approximately $1.4kV$ is oscillating across the thyristors. After the thyristors are switched, they keep little amount of voltage as expected because of their small internal resistance. During this period, mean power dissipation is around $50W$ where the mean on state current is approximately $175A$. This conclusion can be made by the datasheet of thyristor given in Appendix B. Since the power dissipation is not very high, natural air cooling method with a single-sided heatsink is preferred as mentioned in Section 3.5.2.

Figure 4.30 shows the waveform when the thyristor is switched off after a certain transition period (a period needed to fully charge the capacitors) has passed. This time, the thyristor must withstand the DC voltage across the charged capacitor in addition to the supply voltage. Since the capacitors are charged at least to the peak value of the supply voltage, the waveform oscillates above or below the zero crossing line depending on the polarity of the capacitor voltage. This is the main point that increases the ratings of the thyristor as the withstand voltage must be at least twice of the supply voltage.



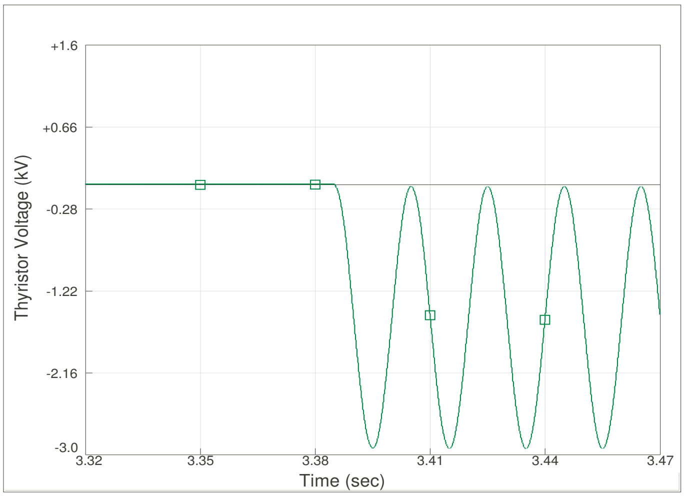
(a)



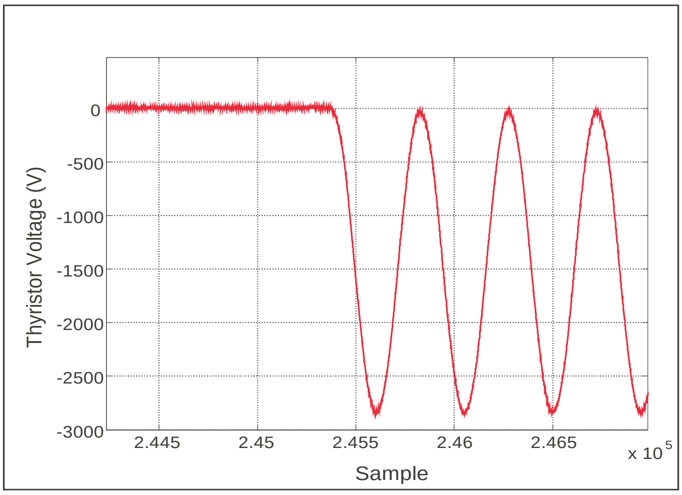
(b)

Figure 4.29: Voltage waveforms across the thyristor connected line-to-line when the thyristors are on and capacitors are initially discharged. (a) Simulations Results, (b) Derived from Field Data.

The last situation shows when the thyristor is turned on after some time. As explained in previous sections, the capacitors consist of internal discharge resistors which decrease the stored energy in time. As can be seen in Figure 4.31, the voltage waveform across the thyristor crosses the zero point and climbs to a lower peak value at the negative side comparing to the previous figure. This means that the capacitors are discharged for some time (the passed time is not enough to totally discharge the capacitor but enough to carry some energy to ground). There is one more important case that should be interpreted from this figure. The thyristors are turned on when the voltages on them cross the zero point



(a)



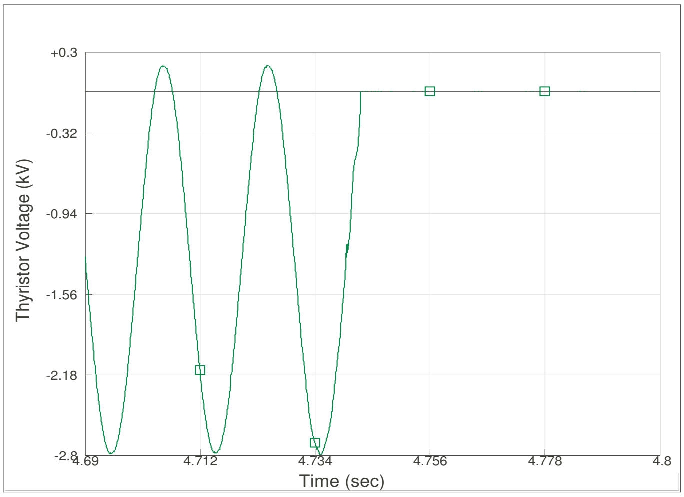
(b)

Figure 4.30: Voltage waveforms across the thyristor connected line-to-line when the thyristors are off and capacitors are initially charged. (a) Simulations Results, (b) Derived from Field Data.

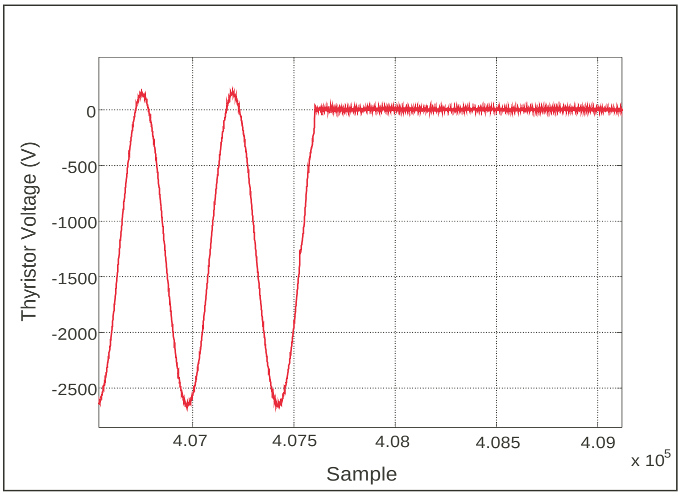
since the optimum firing instant for minimum transient has been concluded to be the zero cross of the thyristor voltage waveform in Chapter 2.

4.3.2 Voltage Waveforms of Capacitor

In ideal case, the capacitors are charged to the peak value of the supply voltage and remain constant at that point after turn-off if they do not have any discharge resistors. However in practical case, there are some parameters that increase or decrease the amount of this stored energy. The most common points and their



(a)

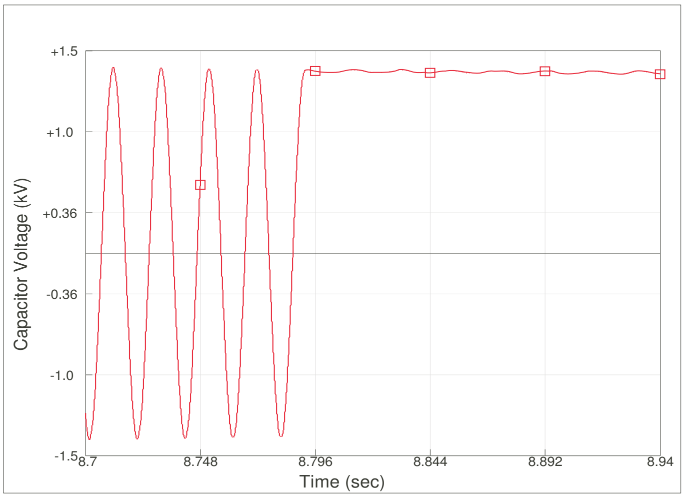


(b)

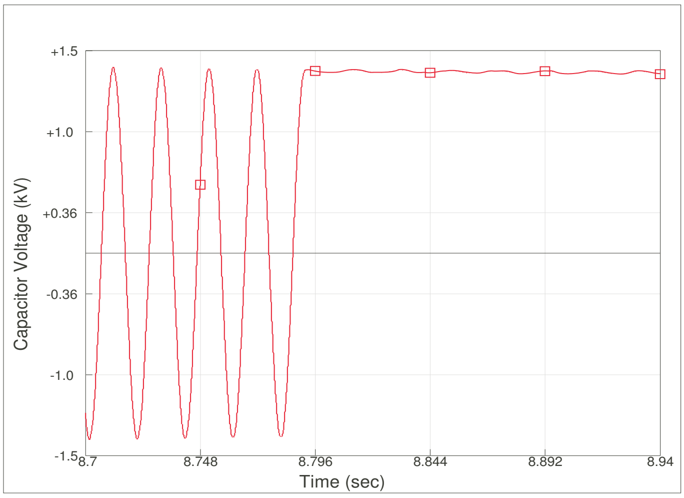
Figure 4.31: Voltage waveforms across the thyristor connected line-to-line when the thyristors are on and capacitors are partially discharged. (a) Simulations Results, (b) Derived from Field Data.

effects are listed in Table 3.2. All of the items listed in Table 3.2 should be taken into consideration to obtain a worst case. The simulation and the real life waveforms of capacitor voltage at the instant of turn-off can be seen in Figure 4.32.

The closest results to the ideal case can be obtained when the conditions in Figure 4.33 are provided. The capacitors are already charged and the turn-on process occurs at the zero crossing point of the thyristor voltage waveform. The presence of this transient is due to several reasons. The first reason can be stated



(a)

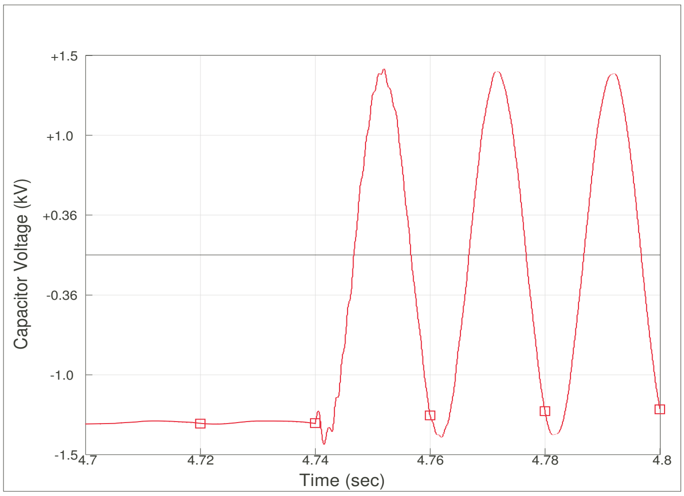


(b)

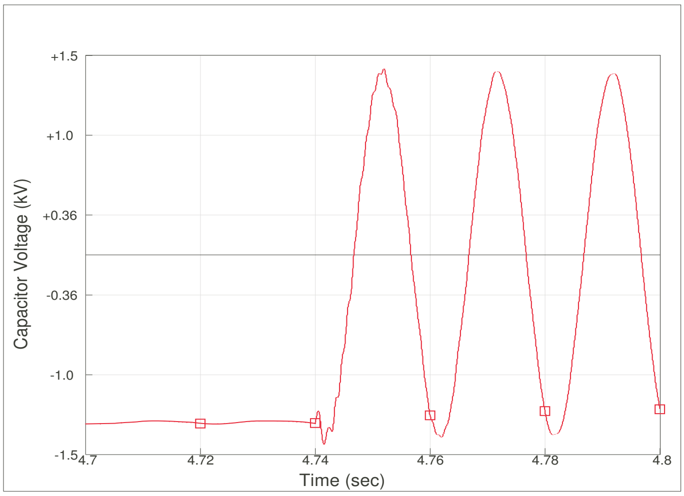
Figure 4.32: Voltage waveforms across the capacitor when the thyristors are off. (a) Simulations Results, (b) Derived from Field Data.

as the occurrence of a series inrush current limiting reactor. The second one is the situation just mentioned above. Because of the overcharged capacitors, the voltage waveform is never able to cross the zero line and continues to oscillate above or below this line. Therefore, the switching must occur when the voltage across the thyristor is around 100 V out of 2.83 kV peak value which makes the transient inevitable.

Figure 4.34 shows the capacitor's first initialization. The deterioration in the first cycle is expected because of the inrush current. Note that this transient is compensated quickly and the steady state is reached for the rest of the cycles.



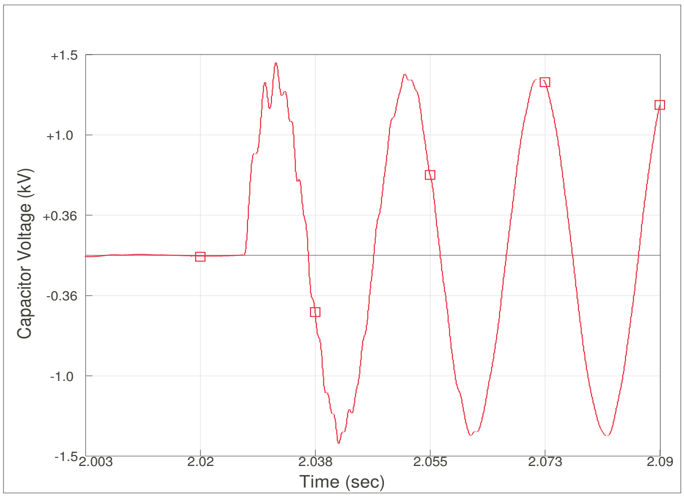
(a)



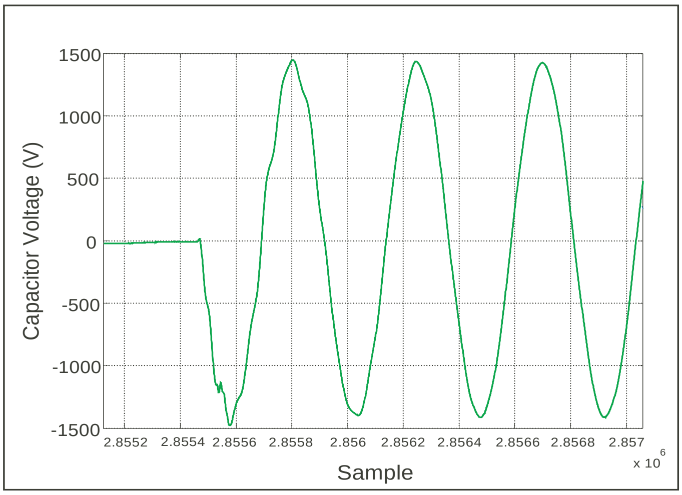
(b)

Figure 4.33: Voltage waveforms across the capacitor when the thyristors are on and capacitors are initially charged. (a) Simulations Results, (b) Derived from Field Data.

This quick response is due to the transient free switching concept mentioned in Section 2.3.2, otherwise the transient would last longer and the system would be exposed to some undesirable harmonics. In other words, if the switching was occurred at a random place, the duration and the size of this oscillation would be greater due to the high amount of inrush current component. This situation will be illustrated next section to show the degree of transient in misfiring of thyristors case.



(a)

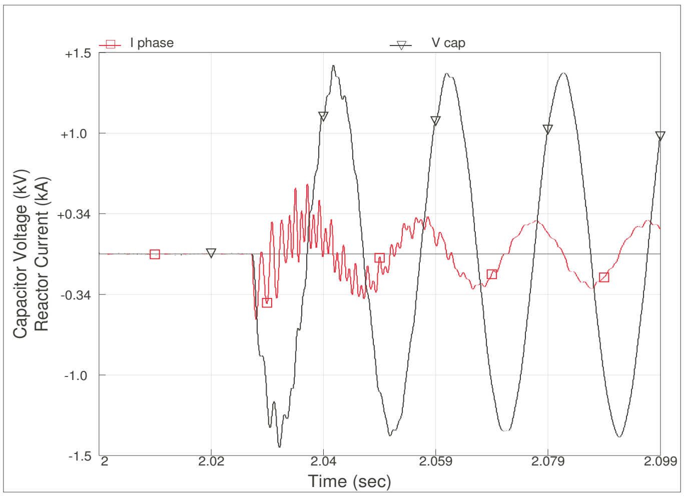


(b)

Figure 4.34: Voltage waveforms across the capacitor when the thyristors are on and capacitors are initially discharged. (a) Simulations Results, (b) Derived from Field Data.

4.3.3 Current Waveforms of Reactor

Remember that there is one specific purpose of the reactor which makes its usage crucial and useful. It is called inrush current limiting reactor and as the name implies it reduces the rate of rise of the inrush current and prevents it to climb up to a high and critical levels. As mentioned in the laboratory prototype experiments, the self inductance of the reactor decreases because of several reasons during transient period. Therefore, the transient is expected to occur more on the phase initially conducting. Below, there are some figures that explain the turn-on and turn-off processes depending on the state of the capacitors. In simulations, single phase reactors are used instead of coupled reactor which can create small difference between the transients of the real values and the simulation results.



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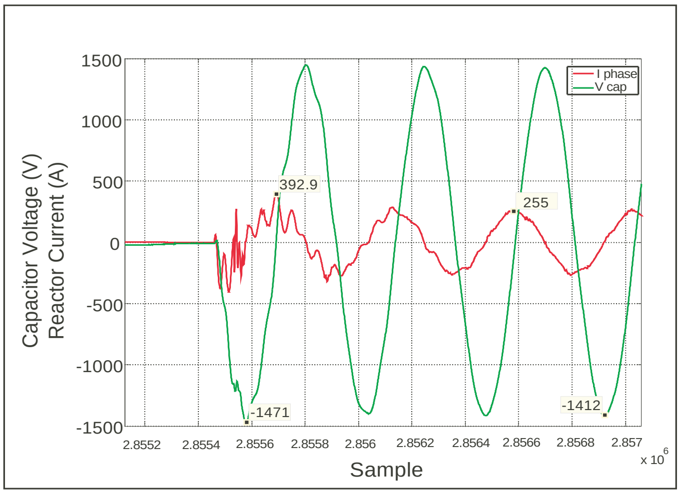
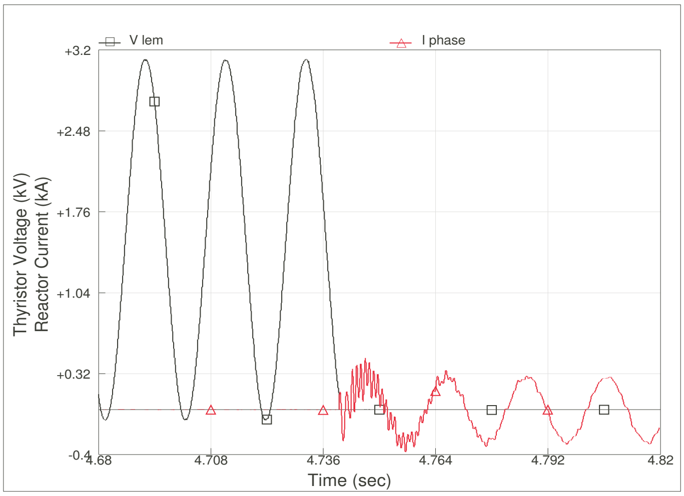


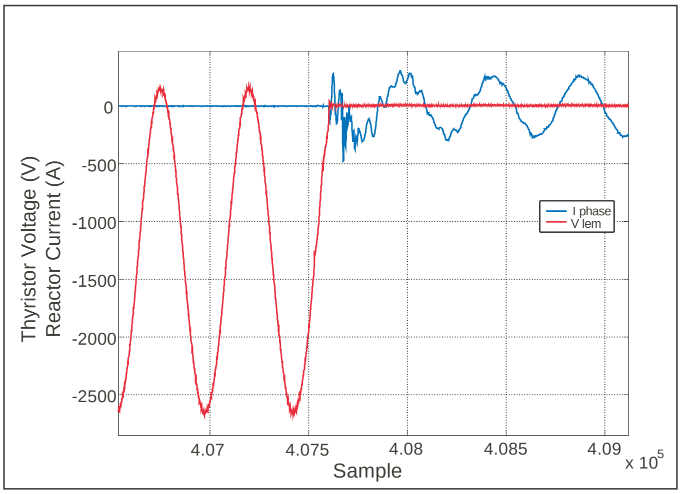
(b)

Figure 4.35: Current waveforms thorough the reactor and capacitor voltages when the thyristors are on and capacitors are initially discharged. (a) Simulations Results, (b) Derived from Field Data.

In Figure 4.35, switching occurs when the capacitors are discharged. In this case, the maximum inrush current is expected. However, the transient disappear in two cycles and steady state is reached quickly. The peak value of the transient is marked on the figure which is $393A$. During the steady state operation, the peak value of current appears to be $255A$ as expected. From these value, the increase in current can be approximated as % 50 above. Capacitor voltage is also affected from this transition and its negative peak value climbs up to $-1471V$ whereas this value is -1412 during steady state. In this case, the change in capacitor voltage can be calculated as % 4.



(a)



(b)

Figure 4.36: Current waveforms thorough the reactor and thyristor voltages when the thyristors are on and capacitors are partially discharged. (a) Simulations Results, (b) Derived from Field Data.

Figure 4.36 explains the transient current in partially charged capacitor case. The oscillatory current component has smaller amplitude and looses its sharp decays. These oscillations would be a lot smaller if the capacitors were fully charged. At the beginning of this transition, thyristor voltage suddenly vanishes as expected.

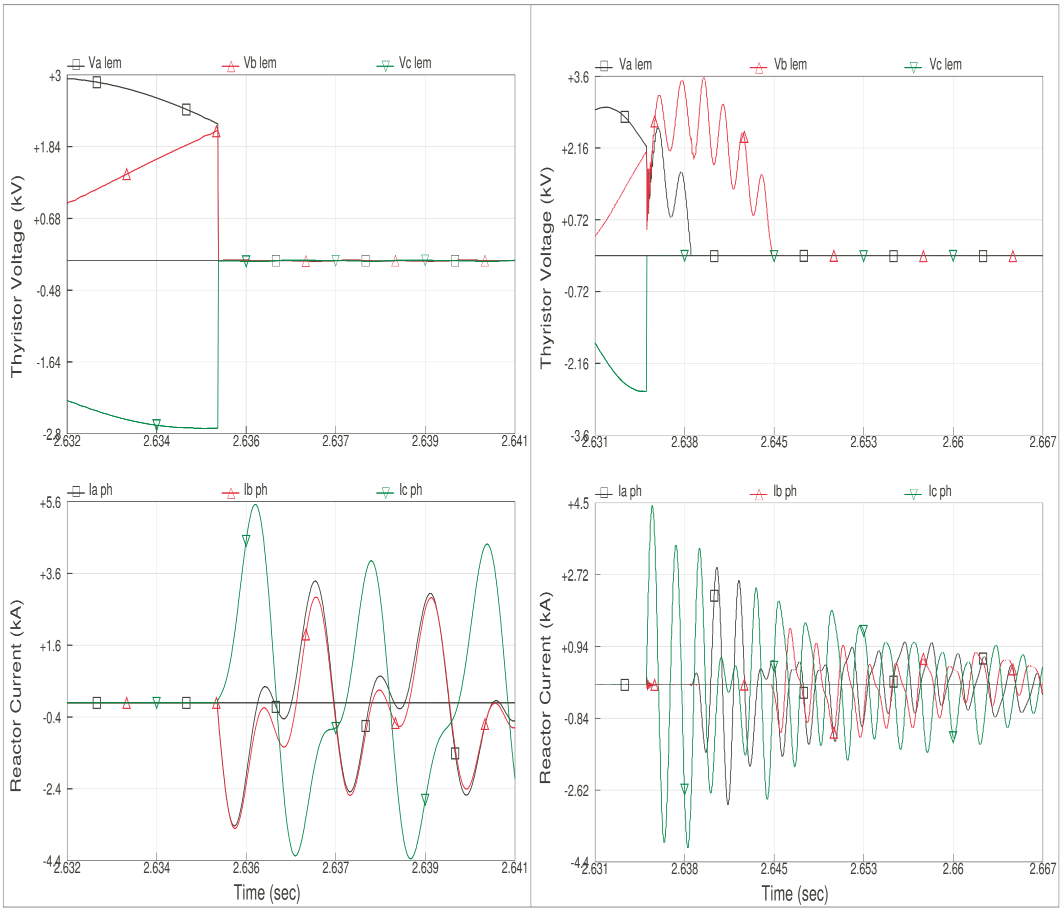


Figure 4.37: Current waveforms through the reactor during a misfire and their effects on the thyristor voltage.

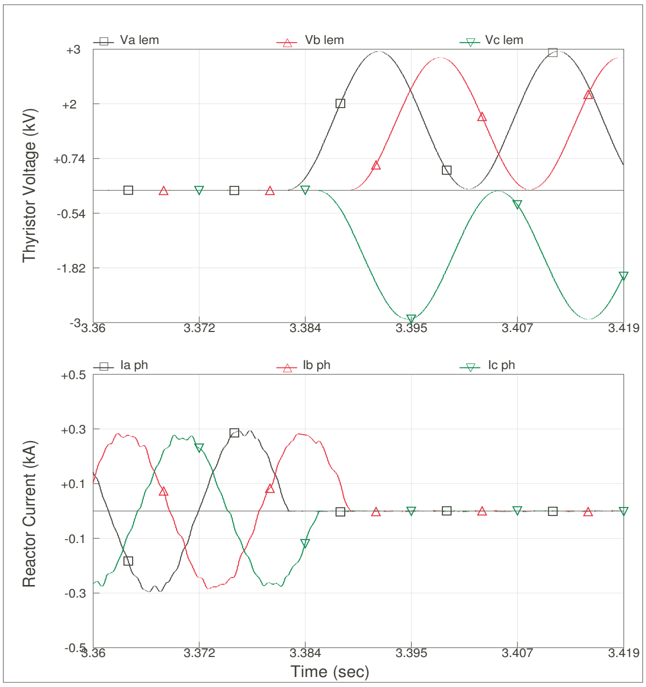
To illustrate a misfired case of a thyristor, the PSCAD simulation program is used. The results of the simulation can be seen in Figure 4.37. On the right hand side of this figure, the case where the thyristors are switched on at the same time can be observed. On the left of the same figure, the firing signal is sent at the peak of voltage across the thyristor for one phase, and the resultant reactor current is observed. For the first case, a peak of $5.6kA$ inrush current is obtained and for the other case (which is more likely to happen in practice), a peak of $4.5kA$ is obtained with a di/dt rating of $7.9A/\mu s$. For both cases, if the surge current can be handled in one half cycle, these amplitude and rate of rise do not harm the thyristor used in this thesis. However, the lifetime of the capacitors and the reactors decrease and a considerable amount of distortion would be given to the supply voltage every time this fault occurs. Therefore, a fast current protection technique must be provided in order to prevent these situations.

Turn-off process occurs less disturbingly. Since the thyristors continue to conduct until its current drops below latching current level if the firing signal is not sent. The turn-off occurs naturally, the current vanishes and the capacitor voltage in addition to the supply voltage appear across the thyristor as in Figure 4.38. There is one point that should be noted that the distortion during steady state is normal since the load includes harmonics and some of the harmonics are attracted by TSC.

4.3.4 Harmonic Analysis

Since TSC behaves like a passive filter during its on period, some of its characteristics are inherited from passive filter, such as harmonic filtration. As a result, TSC attracts the harmonics near its tuned frequency. In addition to this, TSC itself creates some harmonics during its on/off transition time and causes distortions in the main supply. Nonetheless, TSC does not create any harmonics in steady state operation. Therefore, it would be suitable to examine the one cycle behavior of TSC at the instant of switching.

In Figure 4.39, the harmonics created on the phase and line currents are drawn separately for one phase. The data for the first cycle of the transition are processed with fft blocks. As can be seen from this figure, some of the harmonics are diminished in line current whereas they have a considerable impact in phase current. For example, it can be clearly seen that the amplitudes of the harmonics having higher frequencies than 15^{th} harmonic are much more smaller. On the contrary, 2^{nd}, 3^{rd} and 4^{th} harmonics are seem to be amplified on the line current. In [31], the harmonic limits and the word "Total Demand Distortion" (TDD) are defined in details. TDD can be expressed by 4.2 as the ratio of square root of the square sum of the harmonics to the maximum demand load current. Total demand distortion (TDD) for the former figure is found as % 52.6 and for the latter case, it is found to be % 45.5. Although the TDD exceeds the



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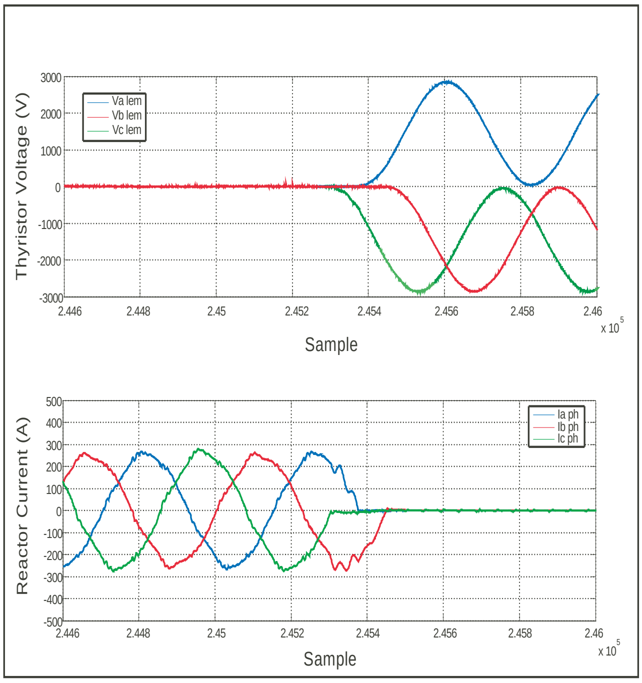
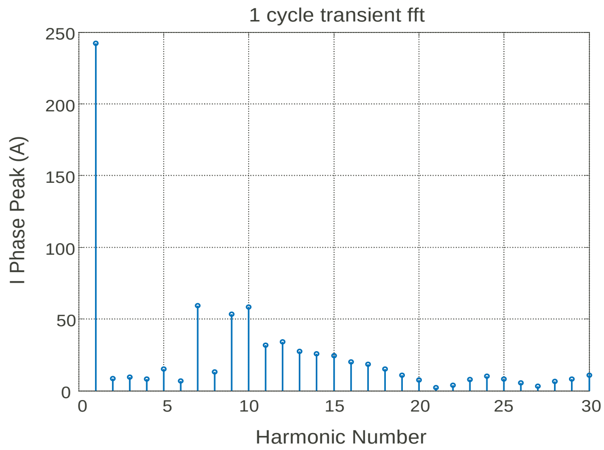


(b)

Figure 4.38: 3 Phase current waveforms thorough the reactor and thyristor voltages when the thyristors are off. (a) Simulations Results, (b) Derived from Field Data.

limits defined by authorities for one cycle, the overall TDD (when its behavior is monitored for a period of time such as 15-30 mins) stays under the limits.



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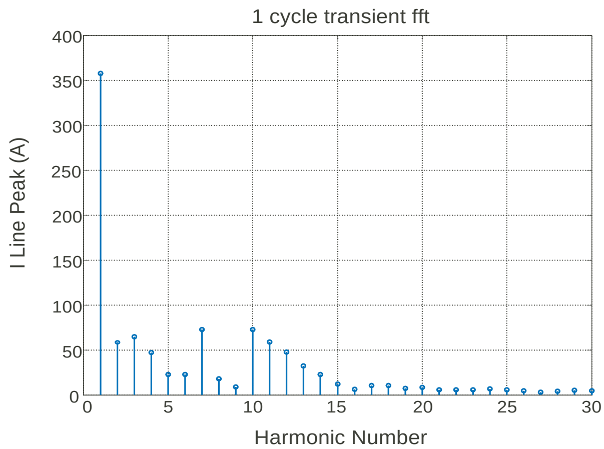


(b)

Figure 4.39: Harmonic spectrum of TSC current during transient for one cycle period, (a) Phase Current, (b) Line Current.

$$TDD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + ...}}{I_1}, \tag{4.2}$$

4.3.5 Reactive Power Compensation Performance

In this section, reactive power compensation performance of TSC system working in parallel to the TCR system will be described. Since TSC itself can only compensate the inductive reactive power and the load that the system is built for fluctuates between inductive and capacitive regions, complete load compensation can be seen by the operation of two systems together. The load characteristics and the systems response are shown in Figure 4.40. According to the reactive power demand for a period of time (small fluctuations do not affect the TSC on/off state), whenever the "TSC ON" signal is received by the control system of TSC, it gets into conduction immediately. Note that, there exist two passive filters for 5^{th} and 7^{th} harmonics with a total of $250kVAr$ reactive power capability. At the instants where TSC is off, the capacitive reactive power in the figure comes from these filters.

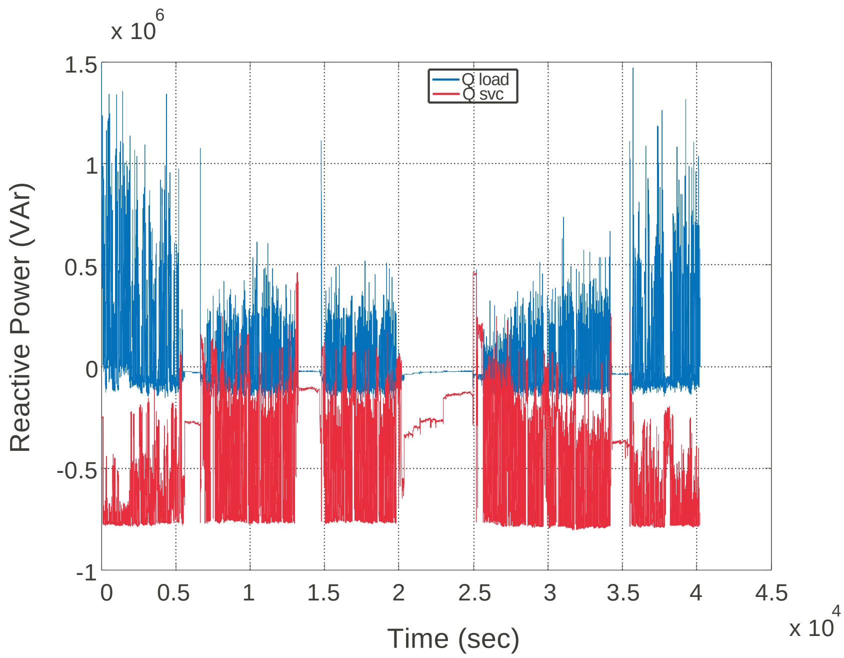


Figure 4.40: Reactive power compensation performance of TSC working in parallel to TCR.

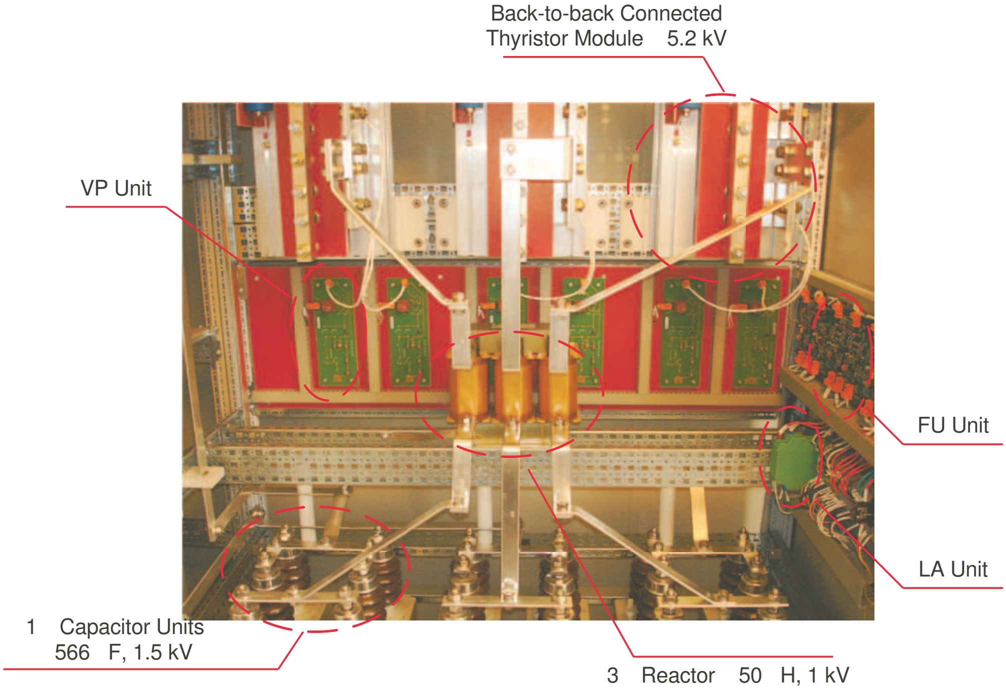
The response time of TSC depends on the delay time in QM unit. Whenever it receives the "TSC ON" signal (named "inductive limit" internally), QM unit checks if this signal last for 2 more seconds. In other words, it checks if the coming signal is not just a noise or temporary fluctuation. Then firing signals are sent to the thyristors, and in less than $20ms$, TSC is turned on completely and contribute to the load compensation.

4.4 TSC Cabinet Interior Equipment

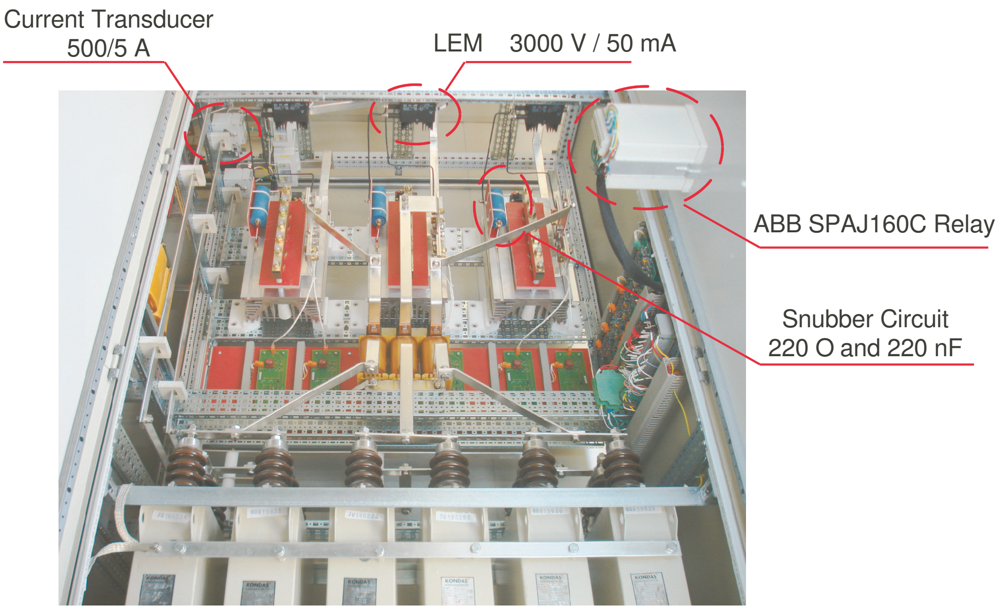
TSC cabinet design and its critical points are explained in Section 3.7 in details. How the components are organized inside a $120x200x60cm$ (width x height x depth) cabinet are shown with practical application pictures in this section. The minimum distance between any live parts or between live parts and the conductors is adjusted to 5 cm. The dielectric breakdown strength of air is 33kV/cm for standard conditions, however it decreases with sharp edges, humidity, atmosphere pressure, etc. Therefore, 5 cm air gap would be a suitable choice. Nevertheless, the cabinet is tested by megger for 1 minutes in 6 kV AC voltage and confirmed that it passed the test successfully.

In Figure 4.41(a), the general view of the cabinet installed in BLI is shown. The components are marked on this picture to introduce the layout of the interior. As can be clearly seen, the 3ϕ coupled reactor is placed between the thyristors and the capacitors. There are six capacitor units two of which are connected in parallel to obtain the designed output power. Note that there are 3 bushings on each capacitor unit despite they are single phase capacitors. The reason is that the manufacturer assumed the capacitors connected in wye, and that there is a possibility to apply an unbalanced protection by twin capacitors as explained in Section 3.3.2. Last item in this picture is the thyristor stack. It consists of one snubber circuit laid on the heatsink, two back-to-back connected thyristor squeezed between the clamp and the heatsink. The heatsink is live conductor that carries the phase current. Therefore gate signals are protected by a shrinkable tube with high isolation. The rest of the items show the control cards whose duties are already explained in previous chapters.

Figure 4.41(b) shows the missing components in the previous picture. Across the thyristor, there exists a voltage transducer which has a conversion ratio of $3000V/50mA$. LEM is chosen in this part since it can also measure the DC voltage on the capacitors. In addition, there are three sets of current transducer with a conversion ratio of $500/5A$ which are used for TSC's own protection. Lastly, unbalanced protection relay is placed on the cover of the cabinet. The information of the current for three lines separately are carried to the input



(a)



(b)

Figure 4.41: Picture of practical cabinet design of TSC. (a) View 1, (b) View 2.

channels of this relay. The trip signal is sent by this relay if it detects an unusual current behavior (the rated values are preset on the controller cabinet of the relay).

4.5 Discussion

In contactor or thyristor switched applications with inrush current limiting, detuning or tuning reactors, the three phase series reactor has usually a common magnetic core especially in low voltage applications. If the designer does not apply the transient free switching strategy, a large inrush current component starts to flow through the reactor coils just at the switching instant. This large current may saturate the magnetic core of the reactor, thus resulting in a lower value for self inductance and hence a drift in the tuning frequency. On the other hand, if the poles of the contactor are closed or the thyristor switches are triggered into conduction at different time instant, especially for three phase four wire systems, the self inductance current carrying coil of the three phase reactor bank reduces by a factor of 1.5. This will cause a further drift in the tuning frequency. In view of these findings, it is recommended to use air core reactors instead of iron core reactors on a common magnetic circuit in contactor or thyristor switched shunt filter applications without having transient free switching strategy.

CHAPTER 5

CONCLUSIONS

This research work deals with the analysis, design and implementation of thyristor switched plain capacitor banks and thyristor switched shunt filter banks. Performances of various TSC topologies are also investigated by simulations. The advantages of back-to-back connected thyristor switched over conventional electromechanical contactors are made clear by conducting an intensive experimental work in the laboratory. The theoretical findings have been verified by carrying out experimental work on two prototypes implemented within the scope of this research work, one is a wye-connected laboratory prototype and the other is a delta-connected application prototype integrated to some existing SVCs.

Following conclusions can be drawn from the results of this research work:

- A plain capacitor bank should be equipped with an inrush current limiting reactor in many applications as recommended in standards ([36]).
- Switching of shunt capacitors with or without inrush current limiting reactor, detuning or tuning reactor may cause transient overvoltage component at the common coupling point which may be harmful for other industrial loads supplied from the same busbar or may lead malfunctioning of these industrial loads.
- If frequent switching of plain capacitors or shunt harmonic filters are required in some industrial applications, it is recommended to use back-to-back connected thyristors instead of conventional contactors or circuit breakers.

- Delta-connected TSC topology is shown to be the most advantageous circuit. Third harmonic current component and its multiples will circulate within the delta-connected circuit. Delta connection reduces the thyristor current by a factor of $\sqrt{3}$.

- Transient-free switching can be obtained only by the use of back-to-back connected thyristor switches.

- Three phase four wire wye connected TSC exhibits perfect performance. It has the advantage of lower voltage rating thyristors in comparison with delta connected topology.

- In order to eliminate notches in the line current waveform, forward and backwards thyristors in each line should receive their firing pulses simultaneously.

- The major drawback of thyristors as a switching element in TSC applications in comparison with TCR applications is that the thyristors are subjected to a voltage higher than two times the supply voltage in the blocking state.

- In shunt capacitor applications with inrush current limiting or detuning or tuning reactors, it is recommended to use either three individual iron-core reactors or air-core reactors instead of an iron core reactor bank having a common magnetic circuits.

- Experimental data collected from laboratory and application prototypes are found to be quite consistent with the theoretical findings.

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APPENDIX A

DERIVATION OF ORDINARY DIFFERENTIAL EQUATION

$$\frac{d^2i(t)}{dt^2} + \frac{1}{LC}i(t) = \frac{w\hat{V}}{L}\cos(wt+\alpha),$$
$$i(0) = 0.$$

Since the above ordinary differential equation (ODE) is non homogenous of the form

$$y'' + p(x)y' + q(x)y = g(x) \ ,$$

the solution to this equation can be expressed as:

$$y = y_p(x) + y_h(x) \ ,$$

where $y_p(x)$ represents the particular solution and $y_h(x)$ is the homogeneous part of the solution. To find the homogeneous solution, the auxiliary equation should be written as:

$$r^2 + \frac{1}{LC} = 0,$$
$$\Rightarrow r^2 = -\frac{1}{LC},$$
$$\Rightarrow r_{1,2} = \pm j\sqrt{\frac{1}{LC}} = \pm j\frac{1}{\sqrt{LC}}. \quad \text{(A.1)}$$

Since the roots of this equation are complex conjugates, the resultant solution is of the form

$$i_h = c_1 \sin(\frac{1}{\sqrt{LC}}t) + c_2 \cos(\frac{1}{\sqrt{LC}}t). \tag{A.2}$$

The particular solution can be found by trial-error method. For example,

$$i_p = \frac{\hat{V}wC}{1 - w^2LC} \cos(wt + \alpha), \tag{A.3}$$

is a candidate for the particular solution. Differentiation of this equation which respect to t gives,

$$\begin{aligned}\frac{di_p}{dt} &= -\frac{\hat{V}w^2C}{1 - w^2LC} \sin(wt + \alpha), \\ \frac{d^2i_p}{dt^2} &= -\frac{\hat{V}w^3C}{1 - w^2LC} \cos(wt + \alpha).\end{aligned}$$

To verify this claim, this solution should be simply put into the original equation. The procedure is shown below:

$$\begin{aligned}&\frac{d^2i(t)}{dt^2} + \frac{1}{LC}i(t) = \frac{w\hat{V}}{L}\cos(wt + \alpha), \\ &\Rightarrow -\frac{\hat{V}w^3C}{1 - w^2LC}\cos(wt + \alpha) + \frac{\hat{V}w}{L(1 - w^2LC)}\cos(wt + \alpha) = \frac{\hat{V}w}{L}\cos(wt + \alpha), \\ &\Rightarrow \frac{\hat{V}w}{1 - w^2LC}\left(\frac{1}{L} - w^2C\right) = \frac{\hat{V}w}{(1 - w^2LC)}\frac{(1 - w^2LC)}{L} \Longleftrightarrow \frac{\hat{V}w}{L} \checkmark \end{aligned} \tag{A.4}$$

A.4 proves that the particular solution satisfies the ODE. Since the complete solution is the sum of homogenous and particular solutions, it can be written as:

$$i(t) = c_1 \sin(\frac{1}{\sqrt{LC}}t) + c_2 \cos(\frac{1}{\sqrt{LC}}t) + \frac{\hat{V}wC}{1 - w^2LC} \cos(wt + \alpha). \tag{A.5}$$

To find c_1 and c_2, initial condition will be used. c_2 can be easily found by inserting the initial condition to the complete solution as in A.6. Differentiation of the complete solution will yield to c_1 as in A.7.

$$\begin{aligned} i(0) &= c_2 + \frac{\hat{V}wC}{1-w^2LC}\cos(\alpha), \\ \Rightarrow c_2 &= -\frac{\hat{V}wC}{1-w^2LC}\cos(\alpha). \end{aligned} \tag{A.6}$$

$$\begin{aligned} \frac{di(t)}{dt} &= \frac{c_1}{\sqrt{LC}}\cos(\frac{1}{\sqrt{LC}}t) - \frac{c_2}{\sqrt{LC}}\sin(\frac{1}{\sqrt{LC}}t) - \frac{\hat{V}w^2C}{1-w^2LC}\sin(wt+\alpha), \\ \frac{di(t)}{dt}|_{t=0} &= \frac{c_1}{\sqrt{LC}} - \frac{\hat{V}w^2C}{1-w^2LC}\sin\alpha = \frac{\hat{V}}{L}\sin\alpha - \frac{V_{co}}{L}, \\ \Rightarrow c_1 &= \sqrt{LC}\left(\frac{\hat{V}}{L} + \frac{\hat{V}w^2C}{1-w^2LC}\right)\sin\alpha - \frac{\sqrt{LC}}{L}V_{co}. \end{aligned} \tag{A.7}$$

Therefore, the complete solution becomes

$$\begin{aligned} i(t) = & \frac{wC\hat{V}}{1-w^2LC}\cos(wt+\alpha) - \sqrt{LC}\left[\frac{V_{co}}{L} - \hat{V}\left(\frac{1}{L} + \frac{w^2C}{1-w^2LC}\right)\sin\alpha\right] \\ & .\sin(\frac{1}{\sqrt{LC}}t) - \frac{wC\hat{V}}{1-w^2LC}\cos\alpha\cos(\frac{1}{\sqrt{LC}}t). \end{aligned} \tag{A.8}$$

APPENDIX B

DISTINCTIVE CURVES OF THE THYRISTOR

The graphs mainly helped to design the thyristor's auxiliary equipment and the firing signals in this thesis are given in this appendix. These curves are taken from the datasheet of the thyristor manufactured by Dynex Semiconductor with a product number of DCR1950C52. The rest of the figures not mentioned in this appendix should also be examined in order to fully understand the behavior of the thyristor. In Figure B.1, the power dissipation curve is given. Power dissipation increases exponentially with the increase in on-state current as expected. The curve is given for sine waves and when the application requires the thyristor to stay in conduction for one full cycle as in the case of TSC, the rate of power dissipation rises abruptly. The curve is drawn independently for different commutation angles which is shown on the figure. By the help of this curve, the type and the size of the heatsink can be determined.

Reverse recovery characteristics of the thyristor is shown in Figure B.2. The stored charge and reverse recovery current versus rate of decay of on-state current are shown respectively. This information is used to determine the snubber values connected across the thyristors. Since the stored charge causes an overshoot in the reverse voltage and the thyristors are sensitive to sudden voltage increases, an appropriate snubber should be designed out of these curves. Fortunately, the thyristors are not exposed to a forced commutation and the current vanishes naturally in TSC design. This keeps the effects of the reverse recovery charge in minimum.

The last figure (Figure B.3) denotes the gate characteristics of the thyristor. The voltage and current values and their applied frequencies should be chosen in accordance by the help of this figure. Otherwise, the gate of thyristor can get burned with the applied pulse power. Another importance of staying within the upper and lower limits shown in this figure is to spread the current evenly to the anode surface. This enables the current to use the whole area of the anode while passing through. A firing signal whose values are chosen to be outside these limits can either burn the gate by excessive power dissipation or burn the thyristor as the current tries to penetrate the anode through one point.

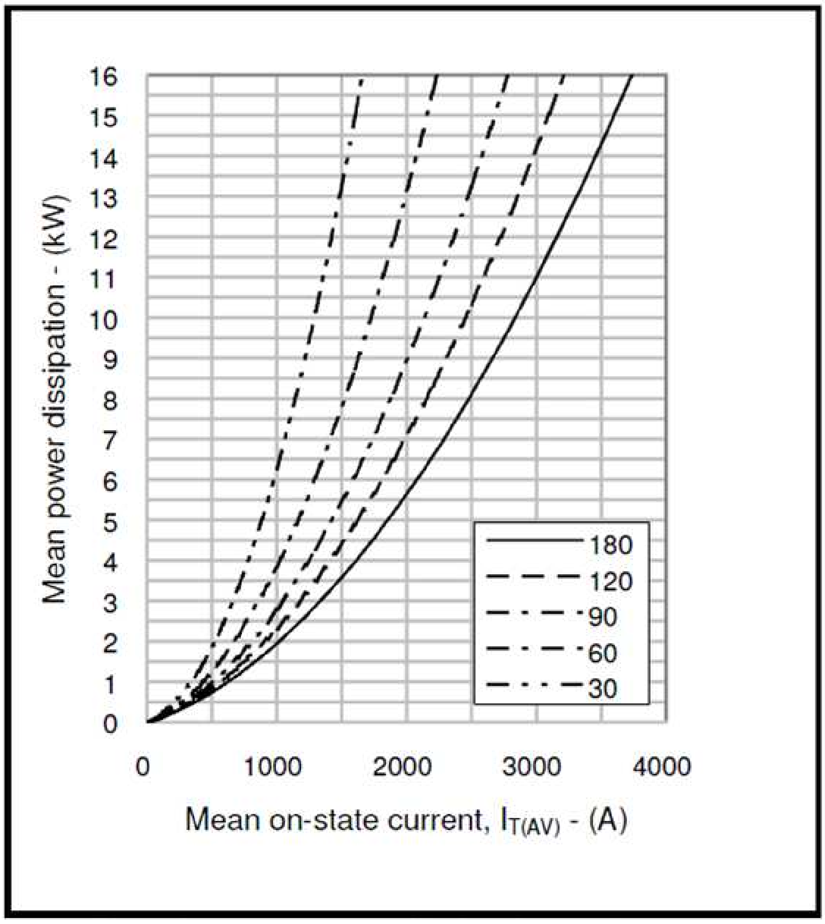

Figure B.1: On-state power dissipation curve of the thyristor.

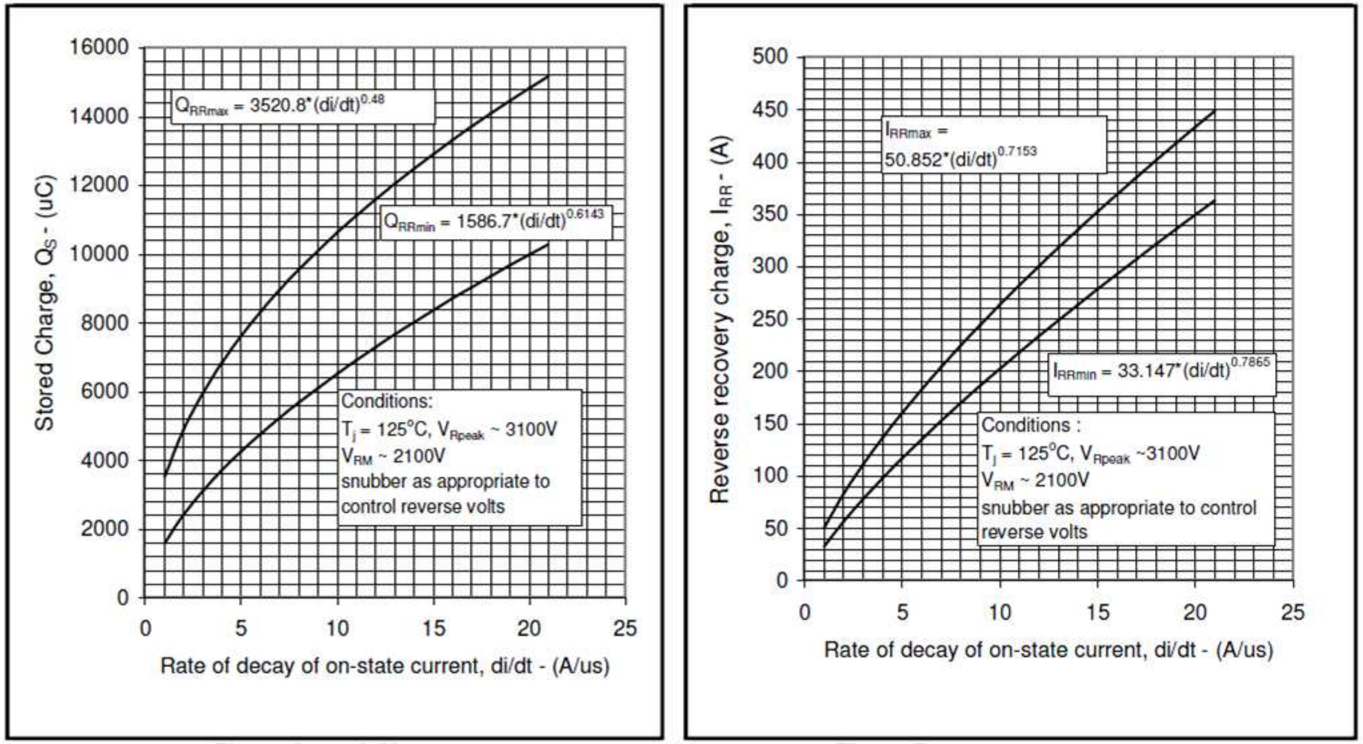

Figure B.2: Stored charge and reverse recovery current curves of the thyristor.

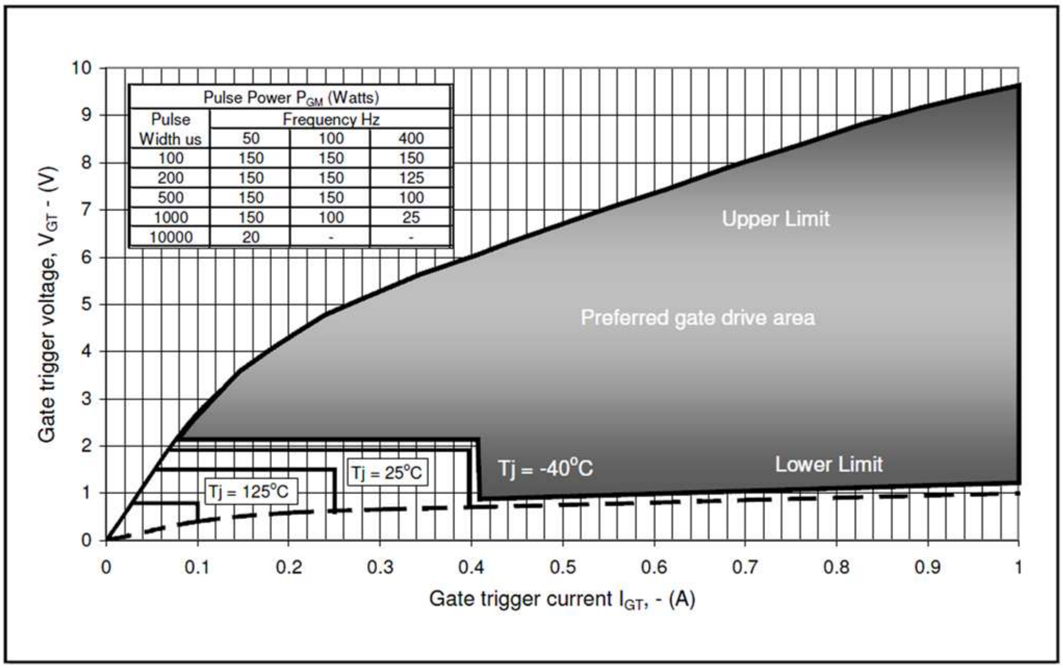

Figure B.3: Gate characteristics curve of the thyristor.

APPENDIX C

DETAILS OF THE CONTROL CARD

The TSC Enabling Unit is a control card of TSC system which initiates the operation of TSC, produces firing signals and checks the possible faults at the same time. It takes the information of the phase current and the voltage across the thyristor, and produces firing signals to the related thyristor. Since each phase is switched on independently, there are 3 firing signal for each back-to-back connected thyristor pair. It also receives an enabling signal from the main control unit of TSC and TCR systems to initiate the computation. There are 3 kinds of error signal created inside this unit. These are the overvoltage across the thyristor, overcurrent through the phase and failure of the supply which converts $48V$ to $\pm 15V$ for EU. Below, the details of this control card can be seen. Each page is responsible for one task.

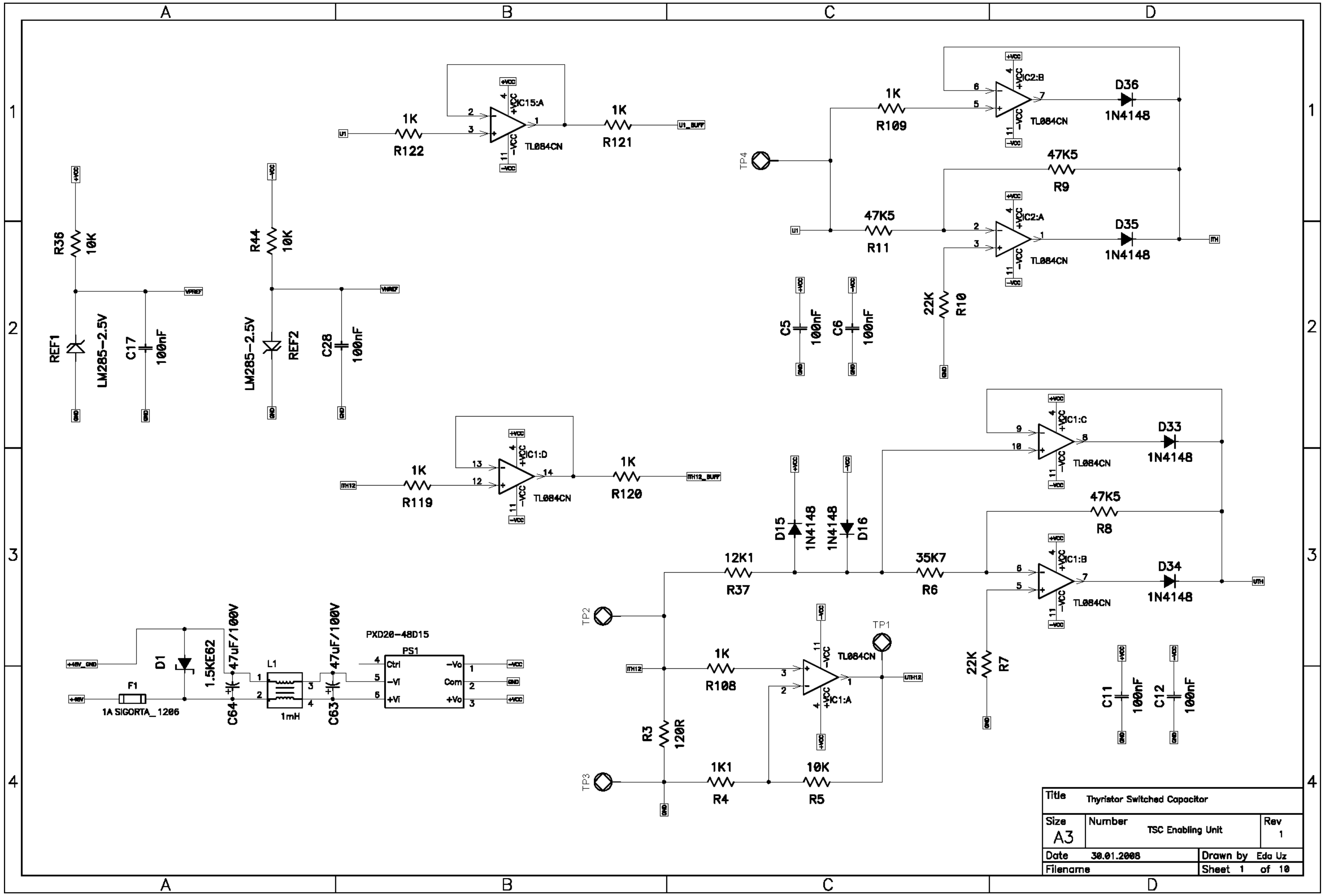

Figure C.1: P-CAD 2002 Schematic File of TSC Enabling Unit, part 1.

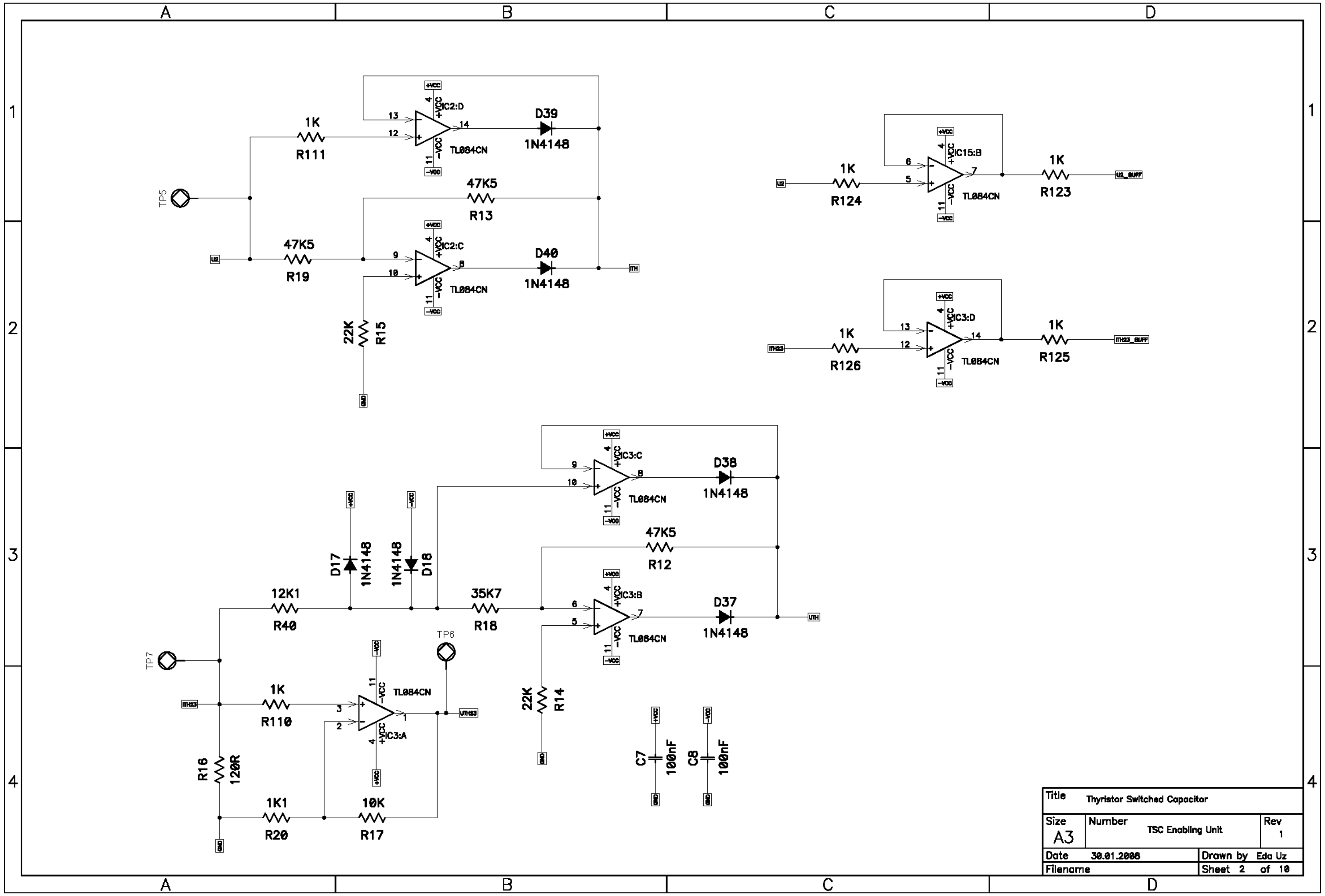

Figure C.2: P-CAD 2002 Schematic File of TSC Enabling Unit, part 2.

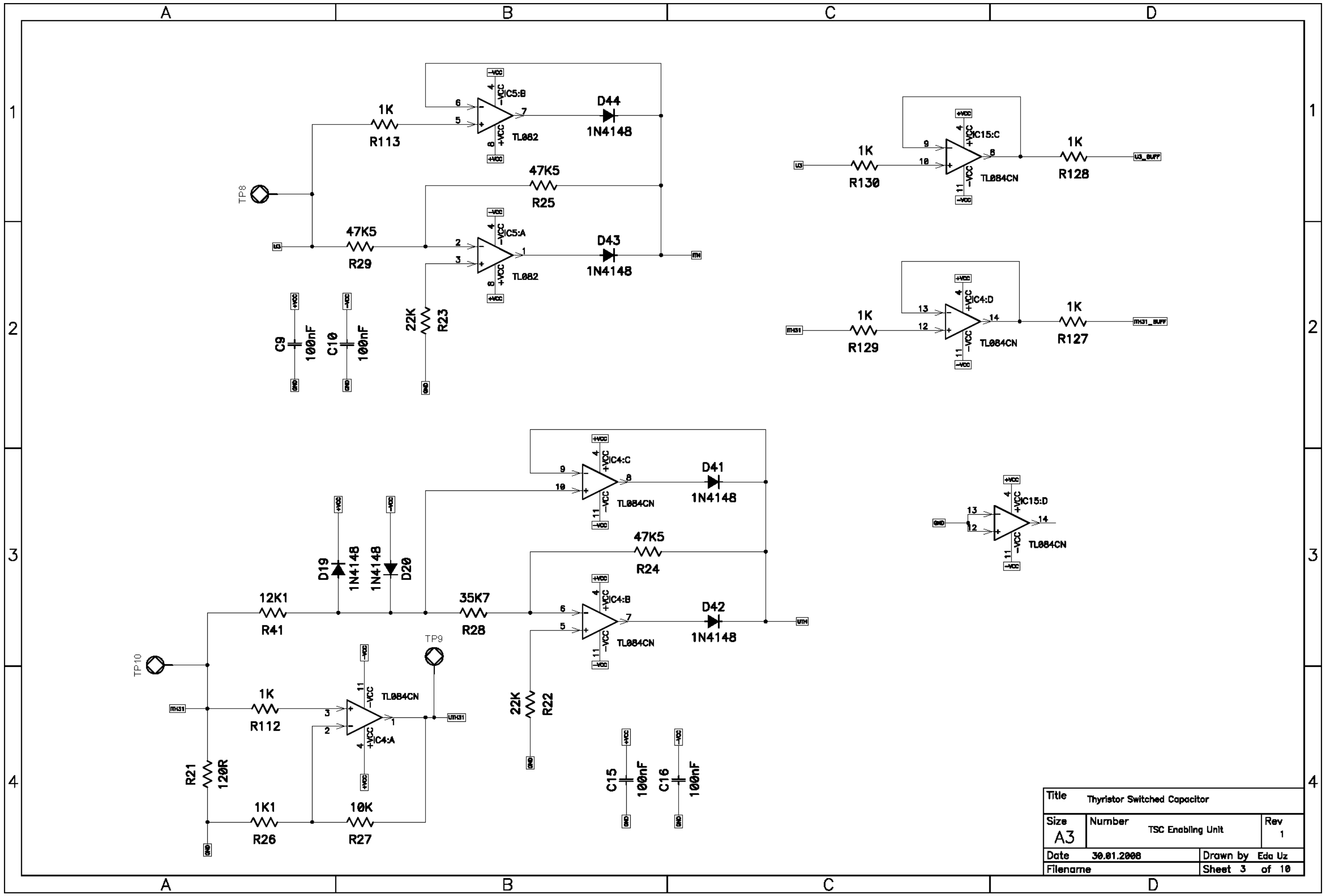

Figure C.3: P-CAD 2002 Schematic File of TSC Enabling Unit, part 3.

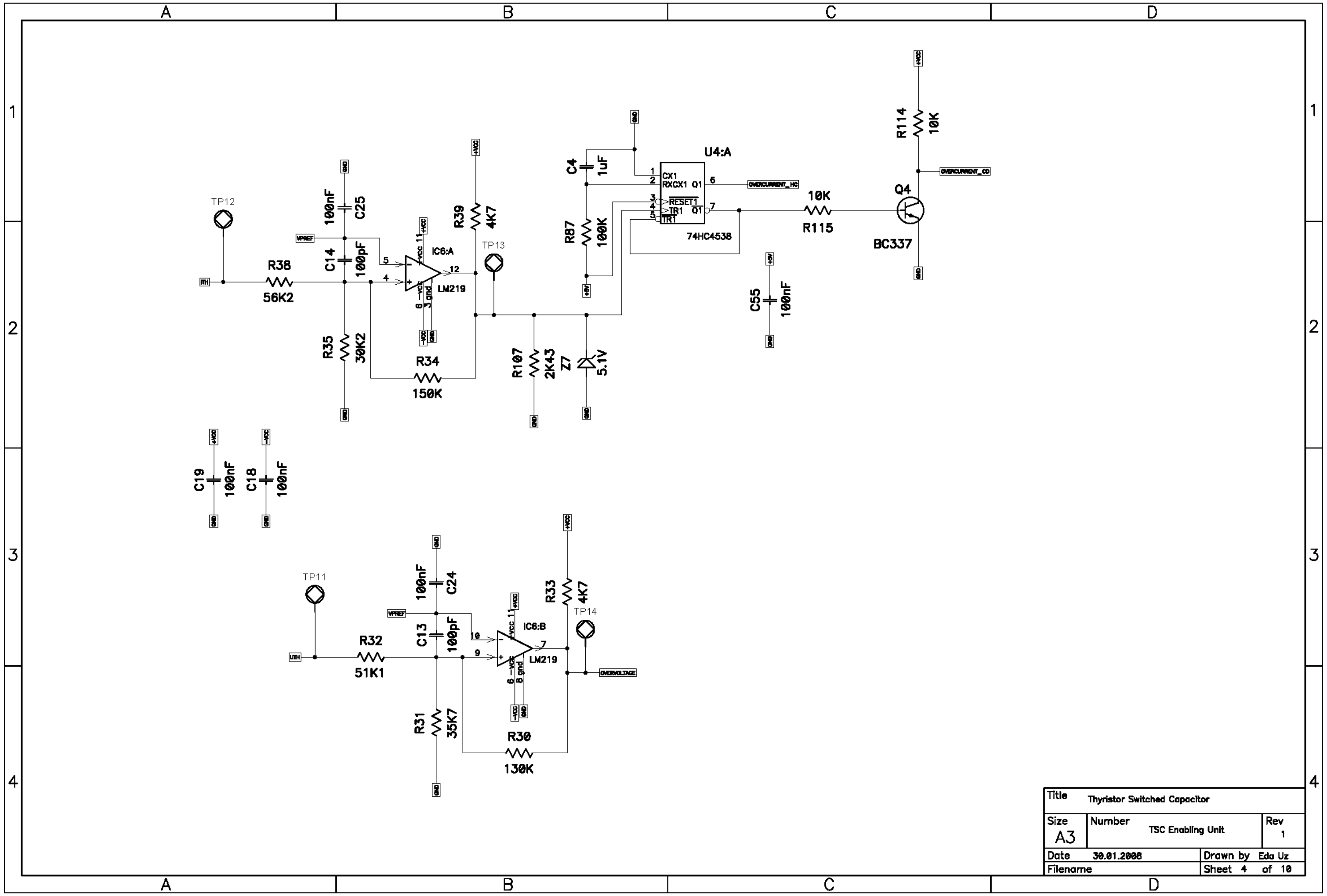

Figure C.4: P-CAD 2002 Schematic File of TSC Enabling Unit, part 4.

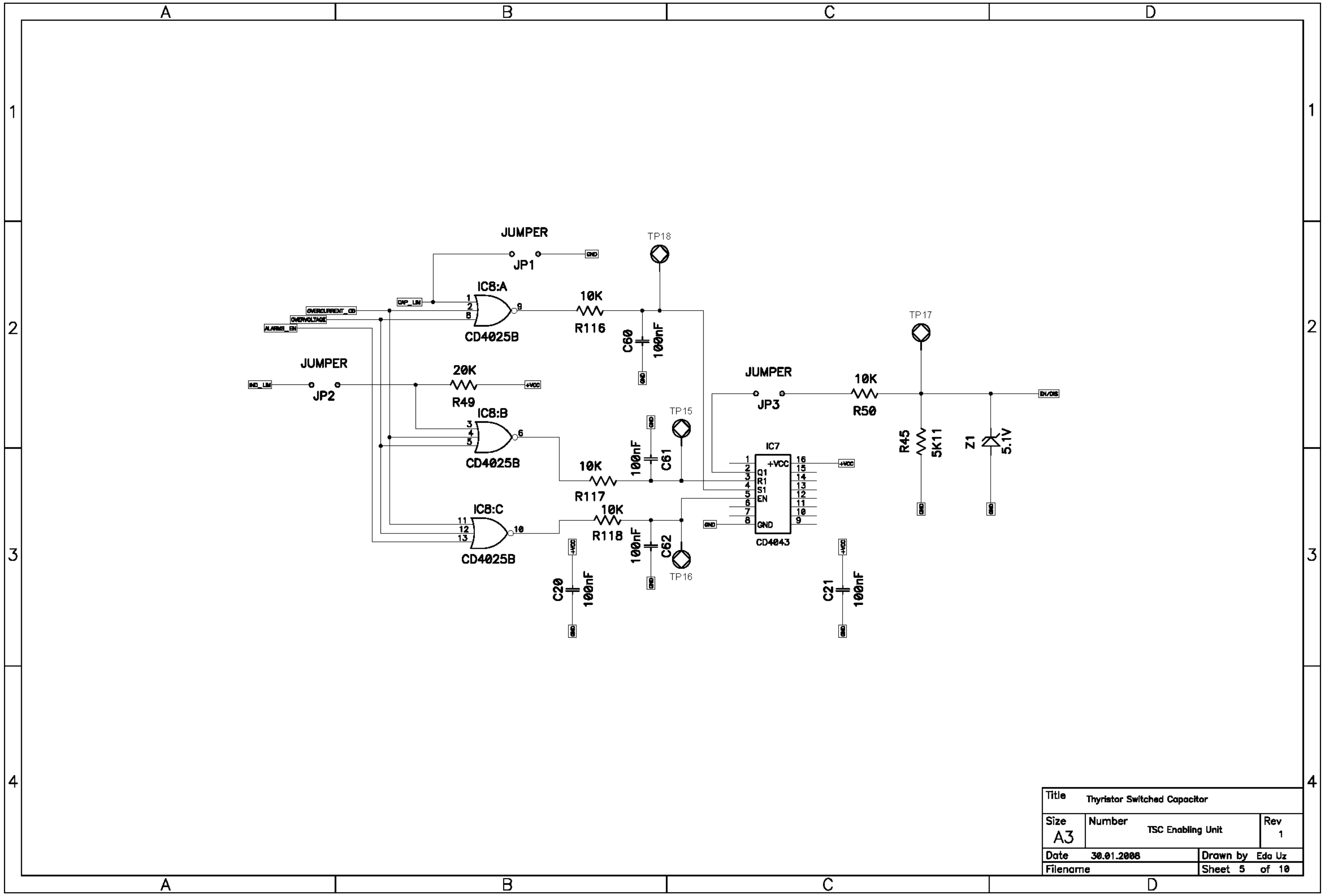

Figure C.5: P-CAD 2002 Schematic File of TSC Enabling Unit, part 5.

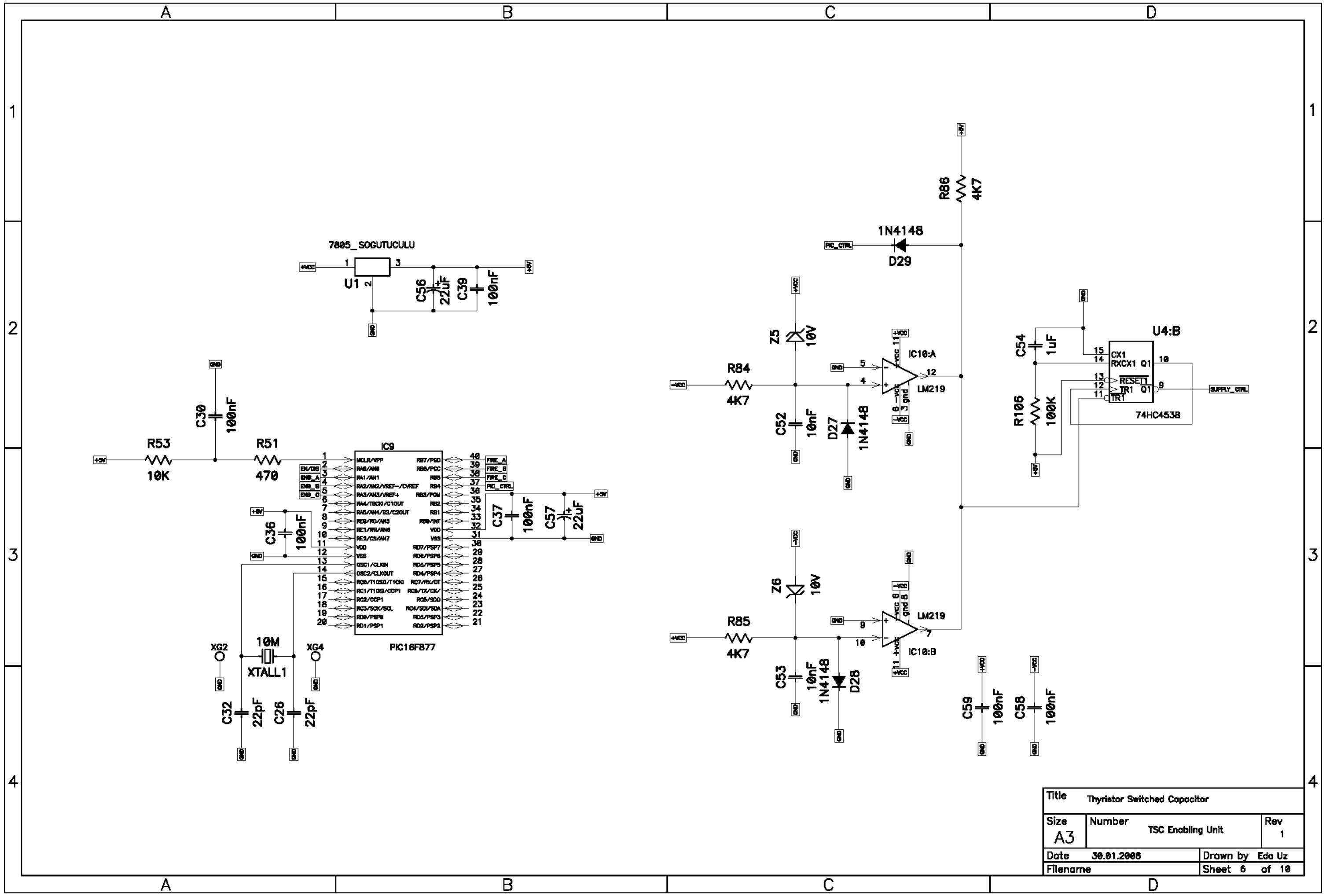

Figure C.6: P-CAD 2002 Schematic File of TSC Enabling Unit, part 6.

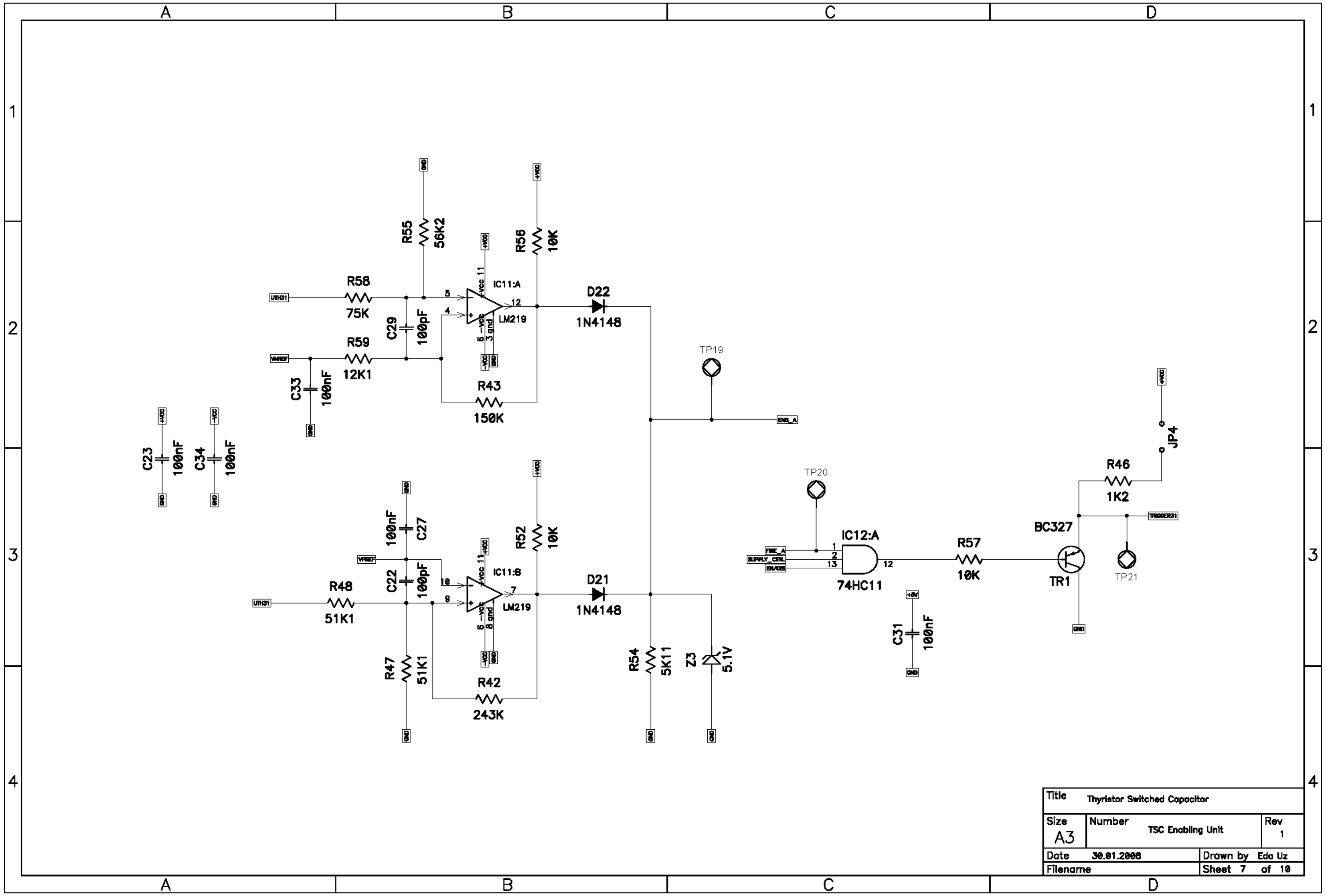

Figure C.7: P-CAD 2002 Schematic File of TSC Enabling Unit, part 7.

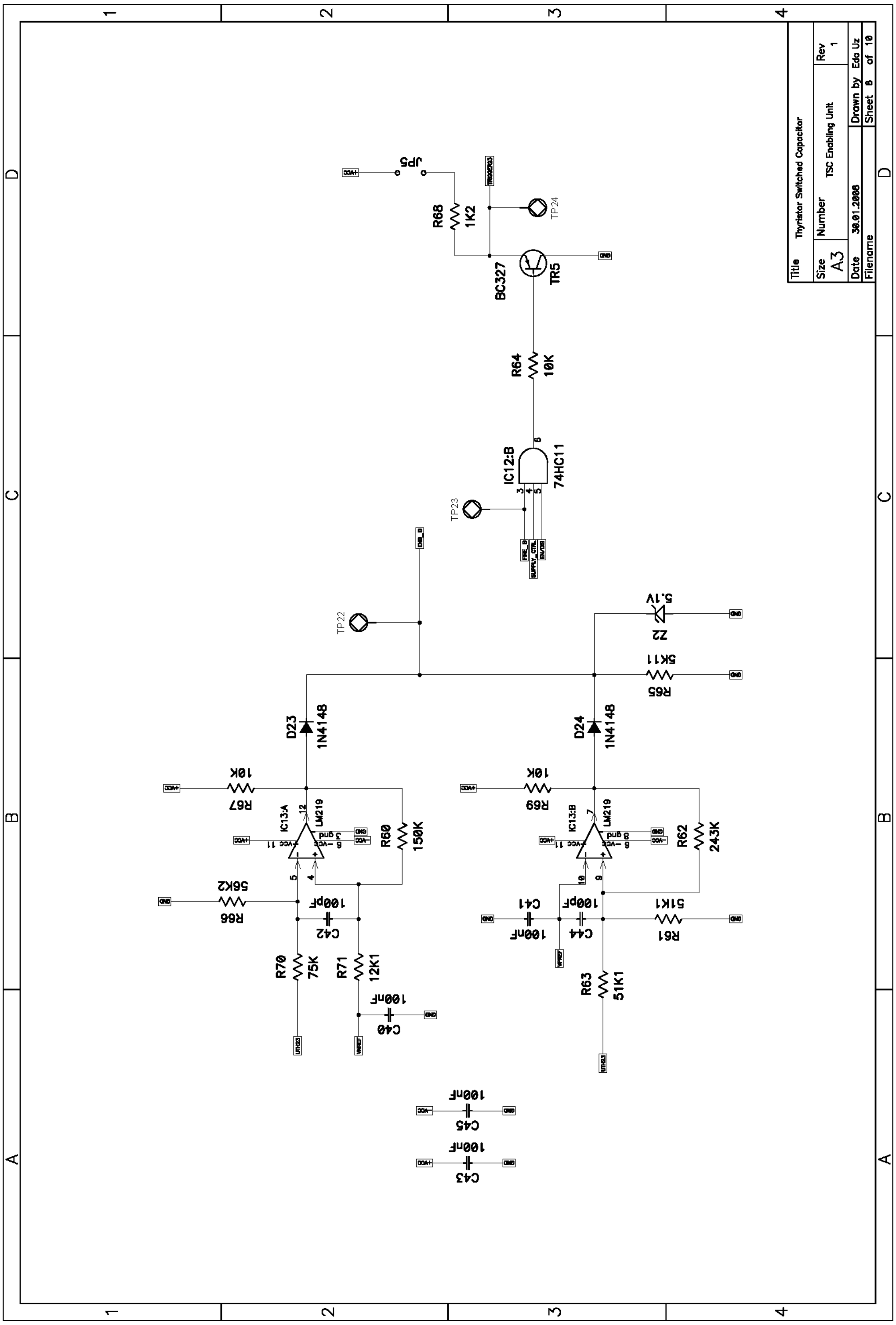

Figure C.8: P-CAD 2002 Schematic File of TSC Enabling Unit, part 8.

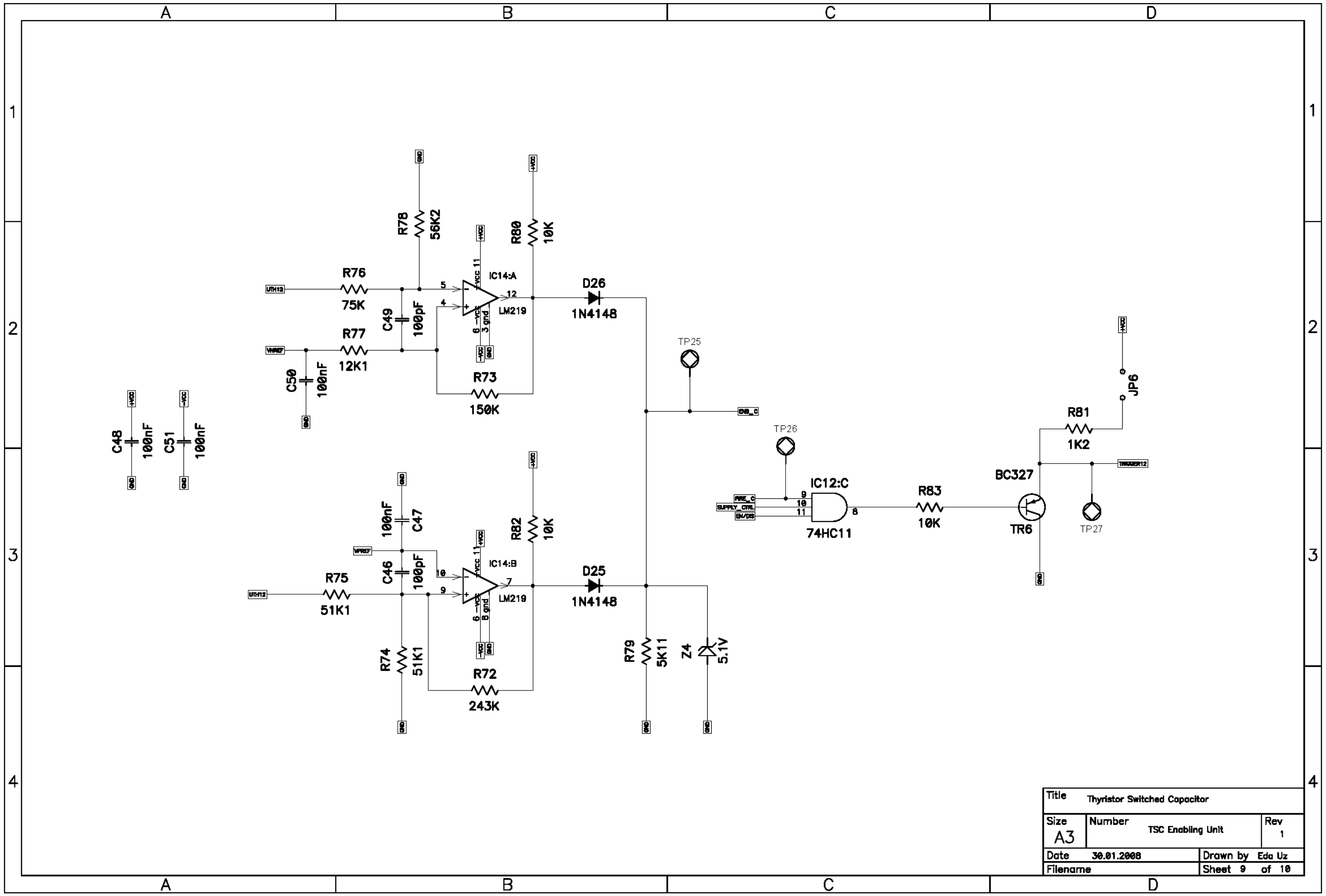

Figure C.9: P-CAD 2002 Schematic File of TSC Enabling Unit, part 9.

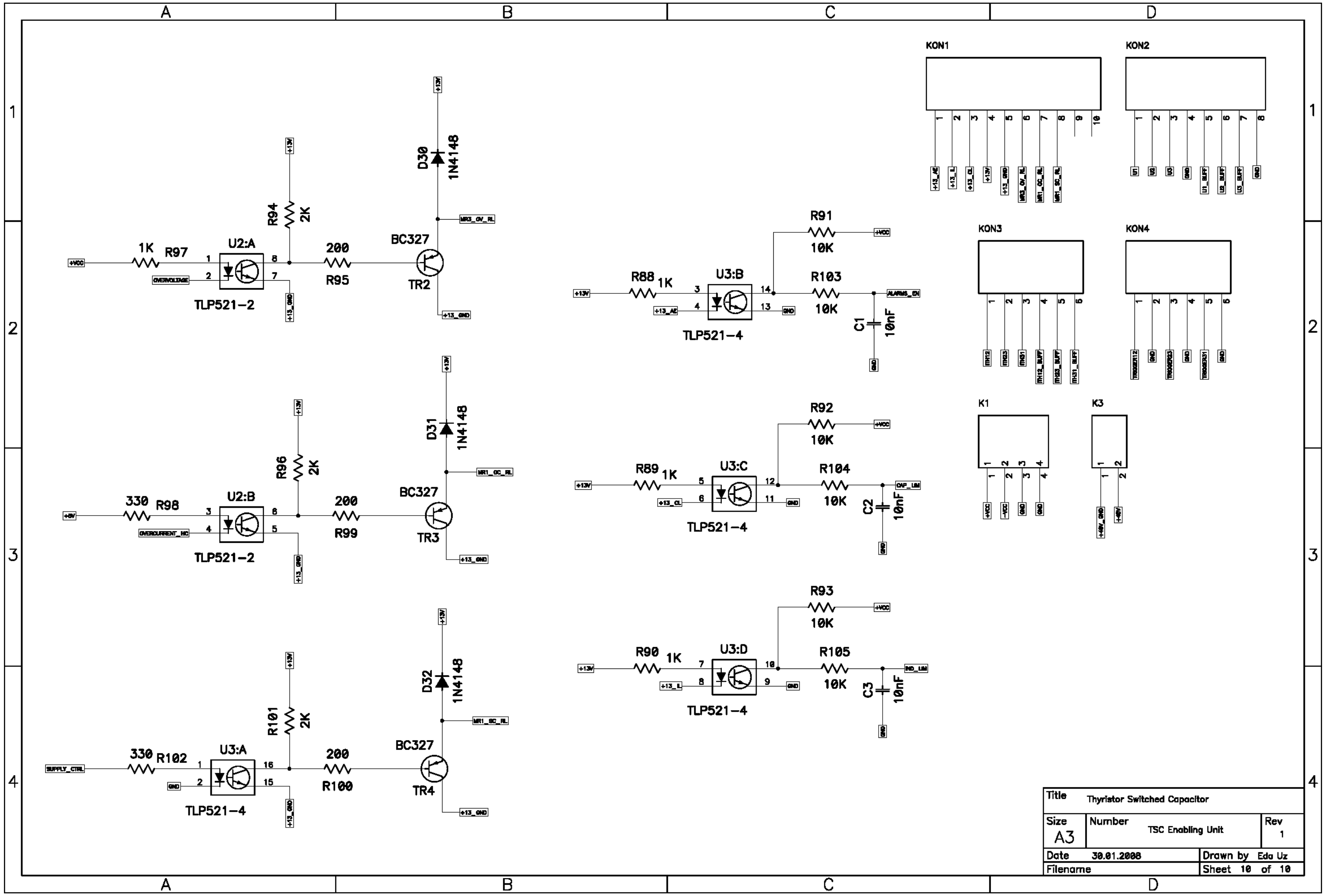

Figure C.10: P-CAD 2002 Schematic File of TSC Enabling Unit, part 10.

APPENDIX D

SIMULATION MODEL OF THE TSC ENABLING UNIT

PSCAD model of TSC is shown in the figures below. All the simulation results mentioned in Chapter 4 are created by this model. The passive filters for 5^{th} and 7^{th} harmonics are included in the system model. The discharge resistors of the capacitors are modeled with their actual values as well. The source voltage is adjusted to supply three different voltage levels at three different frequencies which are 31.5 kV, 34.5 kV and 36 kV; 49, 50 and 51 Hz respectively to simulate the practical fluctuations. A damping resistor across the reactor is shown in Figure D.1 to observe its effects to the transients. Lastly, the fft blocks are placed to examine the harmonics on the phase current and line voltage created during the transient.

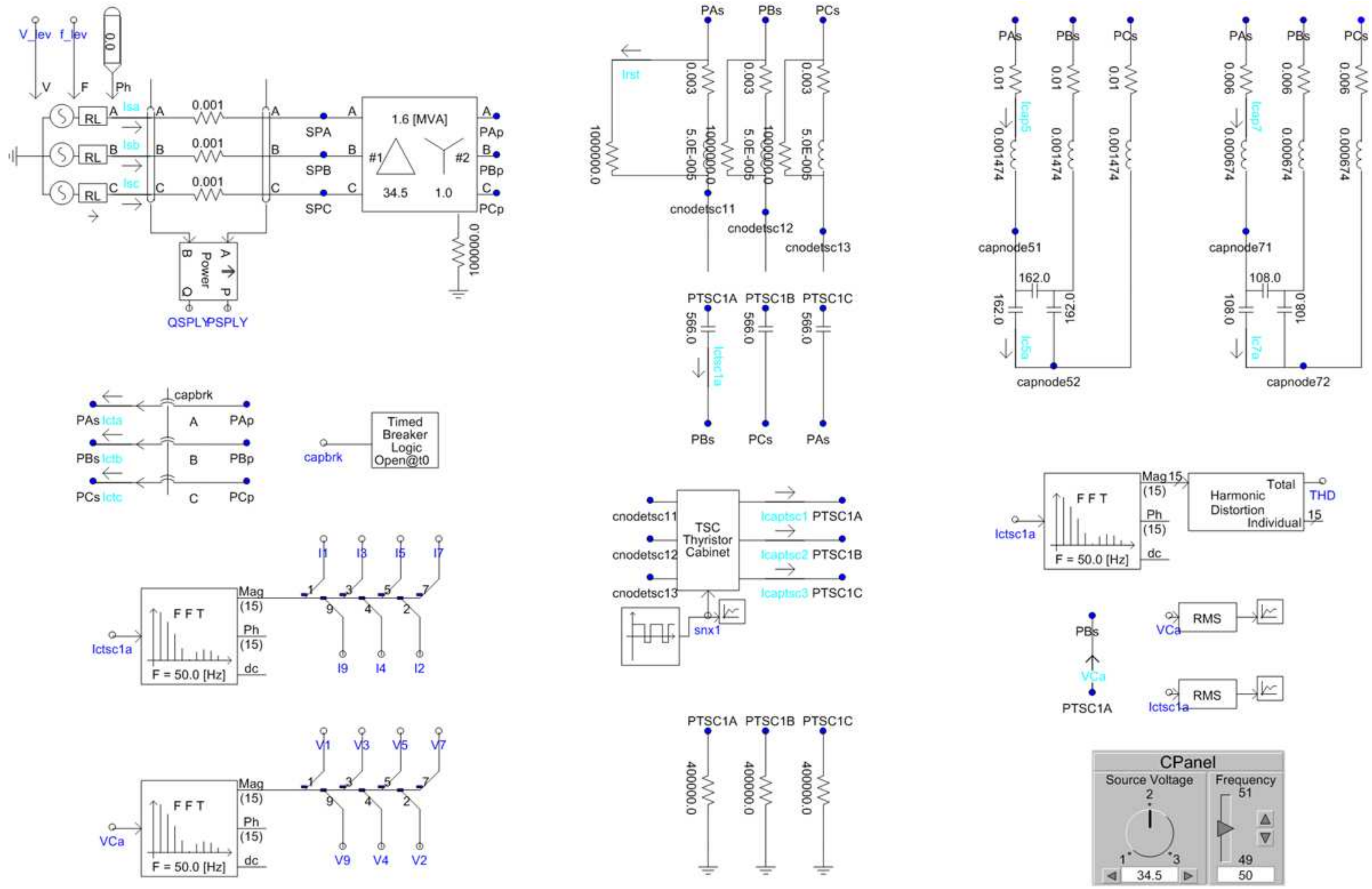

Figure D.1: General view of the simulation model of TSC in PSCAD/EMTDC V3.0.6.

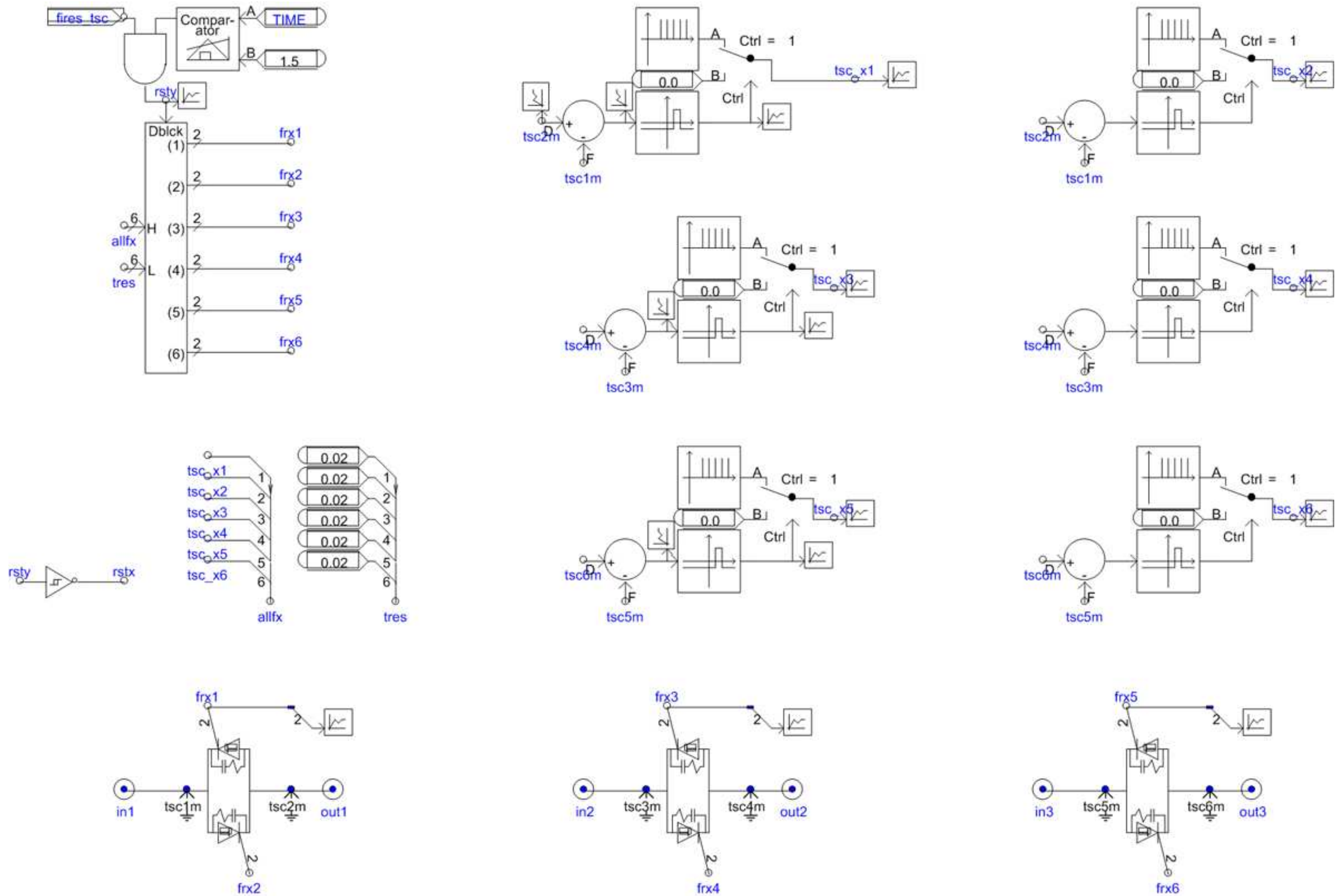

Figure D.2: The details of TSC thyristor cabinet in Figure D.1.

APPENDIX E

APPLICATION MODEL OF THE TSC CABINET

The practical cabling and settlement of TSC cabinet can be seen in Figure E.1 and Figure E.2 respectively. The connection diagram of electric terminals which is used to terminate the local cables and transfer them to another cabinet is clearly shown. The used connectors of each electronic unit and their connection diagram can also be found in the former figure. Since EU card is located outside the TSC cabinet (it is in Control Cabinet), it is circled by dashed lines. However, the details of this its connectors, the cable numbers and the respective electric terminals are still indicated.

The latter figure is drawn to have an idea about the placement of each equipment. The length of the busbars (the width and the height of these bars have been chosen to be 30x5 mm calculated according to the current passing thorugh) connecting the main parts to each other has been determined by the help of this plot.

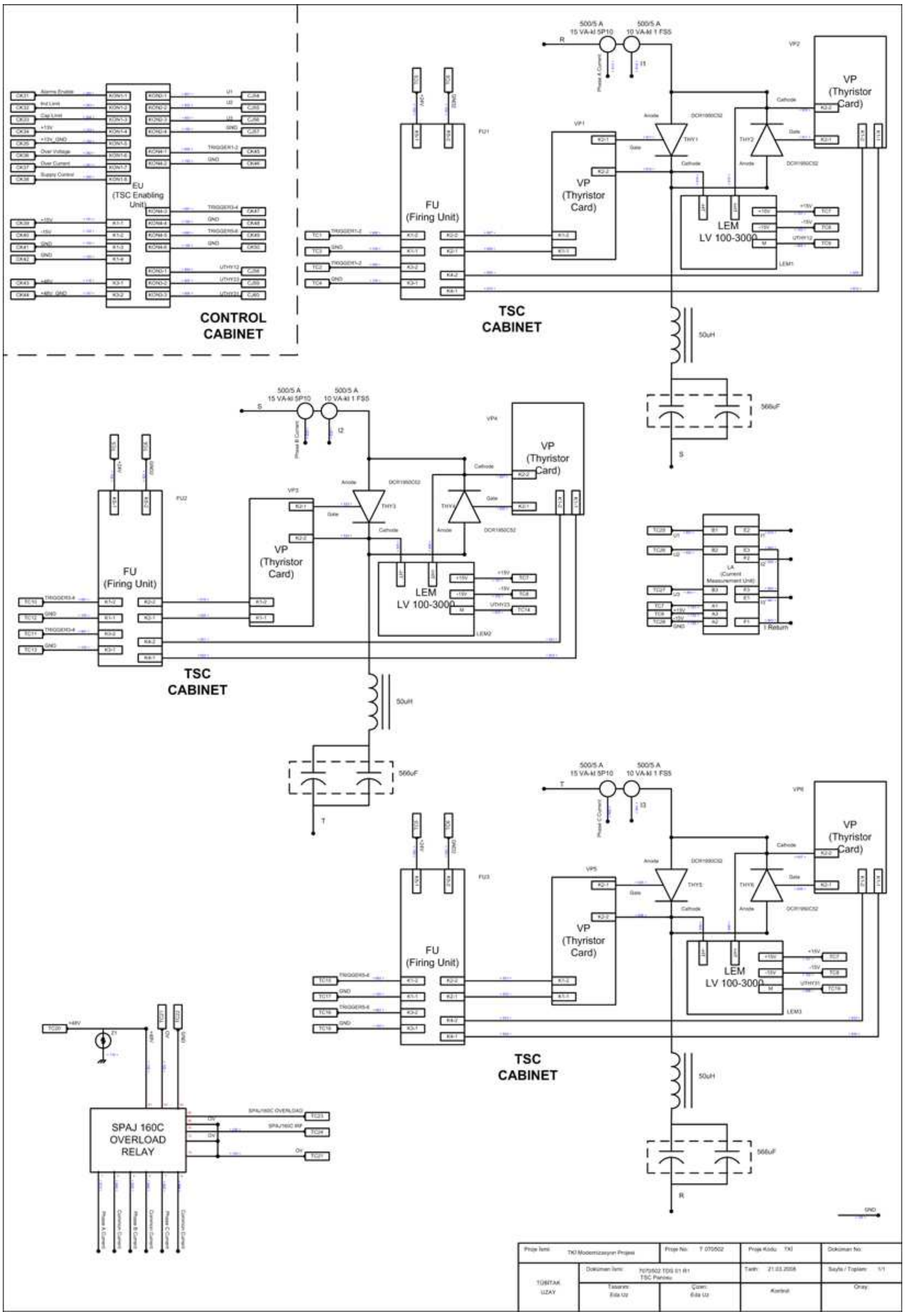

Figure E.1: The details of TSC cabinet created by Microsoft Office Visio 2003.

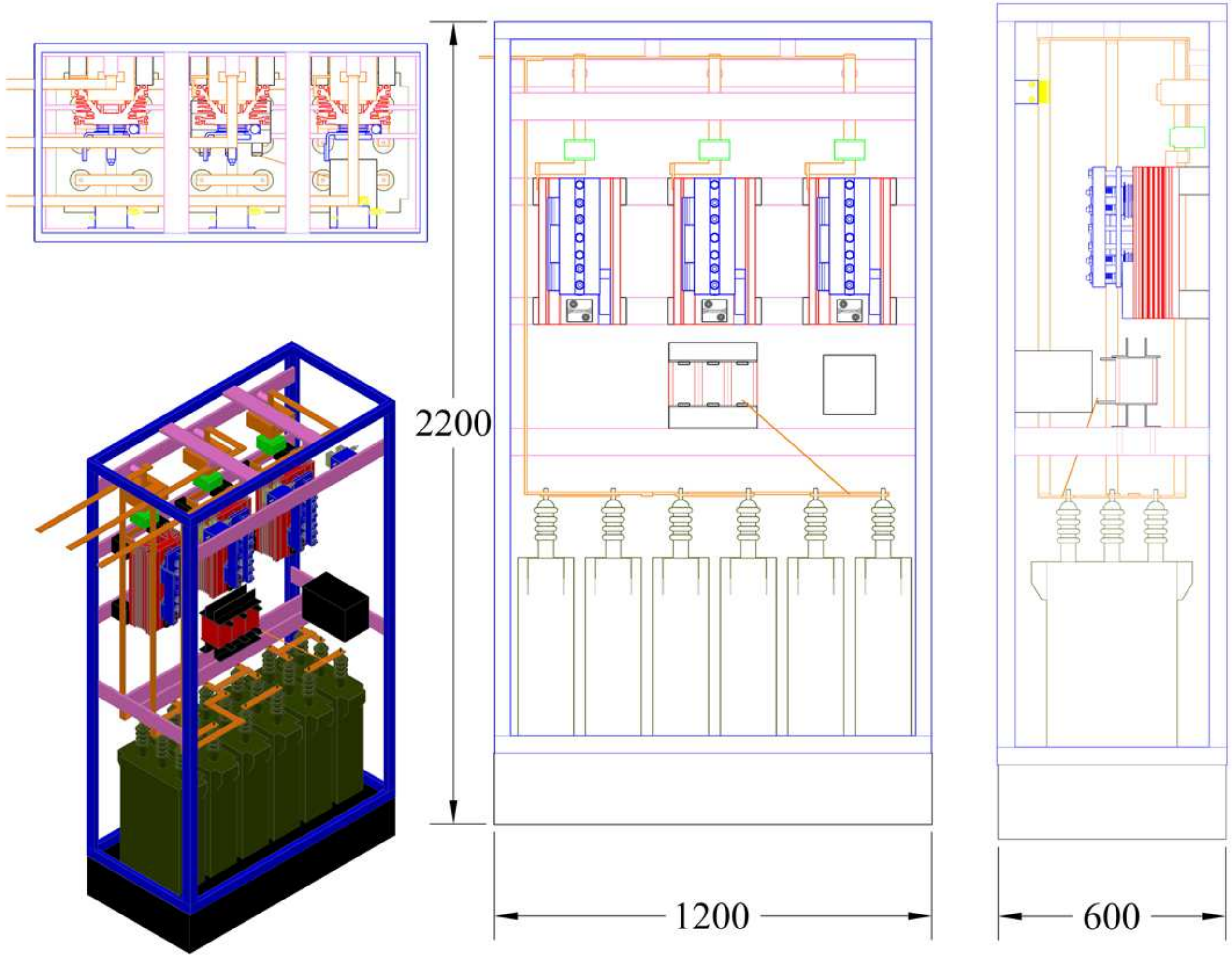

Figure E.2: 3 dimensional plot of TSC cabinet drawn by AutoCAD 2007.

APPENDIX F

REACTIVE POWER COMPENSATION REFERENCE LIST OF SIEMENS

The TSC systems that have been installed to various places by Siemens for reactive power compensation are shown in Figures F.1, F.2, F.3, F.4.

The list of some companies that design TSC systems in low voltage are shown below:

- ABB, www.abb.com
- Nokian Capacitors, www.nokiancapacitors.com/lowvoltage.htm
- Toshiba, www.tic.toshiba.com.au
- Mantle Power Quality Design, www.mantlepqd.com
- Powercap Capacitors Pvt. Ltd., www.powercap.in
- AB Power System Solution, www.abpowerindia.com
- Ergun Elektrik, www.ergunelektrik.com
- Artronik Elektronik, www.artronic.com.tr/default.aspx
- RPS Mühendislik, www.rps.com.tr/index.html

SIEMENS

Energy Sector Power Transmission Division

Reactive Power Compensation Projects
Reference List

Year	Customer	Type / Station /Scope	Voltage	Configuration	Use / Remarks
2009	EDM Mozambique	1 x SVC PLUS Mocuba	33 kV	Rating: +/- 35 MVAr	Turn key Project
2009	RTE France	4 x MSCDNs 1 x MSCDN	225 kV 63 kV	Rating: 80 MVAr Rating: 8 MVAr	Turn key Project
2008	Adani Power Limited India	2 x FSC 400 kV S/S Sami	400 kV	Rating: 2 x 212 MVAr	Turnkey Project
2008	Power Grid Corporation of India Limited	2 x FSC 765 kV S/S Meerut	765 kV	Rating: 2 x 412 MVAr	Turnkey Project
2008	ComEd USA	2 x SVC Elmhurst	230 kV	Rating: 2 x 0/300 MVAr 3 x TSC	Turn key Project
2008	China Southern Power Grid	2 x FSC 500 kV S/S Yulin	500 kV	Rating: 2 x 286 MVAr	Turnkey Project
2008	Transpower New Zealand	2 x SVC PLUS Kikiwa	11 kV	Rating: 2 x 40 MVAr	Turnkey Project w/o transformer
2008	Transpower New Zealand	1 x SVC Islington	220 kV	Rating: -75 / 150 MVAr 1 x TCR 1 x TSC 1 x STF	Turnkey Project
2008	Hydro One Networks Inc. Canada	1 x SVC Lakehead	230 kV	Rating: -40 / 45 (60) MVAr 1 x TCR 1 x STF	Turnkey Project
2007	Powerlink – Brisbane Australia	1 x SVC Alligator Creek	132 kV	Rating: -80 / 150 (230) MVAr 1 x TCR 1 x TSC 2 x DTF	Turnkey Project

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Figure F.1: Installed SVC systems by Siemens Energy Sector Power Transmission Division, part 1.

SIEMENS

Energy Sector Power Transmission Division

Reactive Power Compensation Projects
Reference List

Year	Customer	Type / Station /Scope	Voltage	Configuration	Use / Remarks
2007	Tanesco - Tanzania Electric Supply Company Limited, Tanzania	1 x FSC 220kV S/S Dodoma	220 KV	Rating: 1 x FSC 91 MVAr	Turnkey Project
2007	Power Grid Corporation of India Limited	2 x FSC 400kV S/S Unnao	400 KV	Rating: 2 x FSC 288 MVAr	Turnkey Project
2007	Power Grid Corporation of India Limited	2 x FSC 400kV S/S Barielly	400 KV	Rating: 2 x FSC 180 MVAr	Turnkey Project
2007	Power Grid Corporation of India Limited	2 x FSC 400kV S/S Lucknow	400 KV	Rating: 2 x FSC 210 MVAr	Turnkey Project
2007	Powerlink – Brisbane Australia	1 x SVC Greenbank	275 kV	Rating: -100 / 250 (350) MVAr 1 x TCR 2 x TSC 3 x STF	Turnkey project
2007	Powerlink – Brisbane Australia	1 x SVC Southpine	275 kV	Rating: -100 / 250 (350) MVAr 1 x TCR 2 x TSC 3 x STF	Turnkey project
2006	Center Point Energy USA	1 x SVC Bellaire	138 kV	Control range: 0 / 140 MVAr 1 x TSC	Turnkey Project
2006	Center Point Energy USA	1 x SVC Crosby	138 kV	Control range: 0 / 140 MVAr 1 x TSC	Turnkey Project
2006	Intesa – Integração Transmisora de Energia S.A., Brazil	1 x FSC 500kV S/S Colinas North-South III project (Lot B)	500 KV	Rating: FSC 200 MVAr	Turnkey Project
2006	Intesa – Integração Transmisora de Energia S.A., Brazil	1 x FSC 500kV S/S Miracema North-South III project (Lot B)	500kV	Rating: FSC 194 MVAr	Turnkey Project

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Figure F.2: Installed SVC systems by Siemens Energy Sector Power Transmission Division, part 2.

SIEMENS

Energy Sector Power Transmission Division

Reactive Power Compensation Projects
Reference List

Year	Customer	Type / Station /Scope	Voltage	Configuration	Use / Remarks
2006	Intesa – Integração Transmisora de Energia S.A., Brazil	1 x FSC 500kV S/S Peixe 2 North-South III project (Lot B)	500kV	Rating: FSC 343 MVAr	Turnkey Project
2006	Intesa – Integração Transmisora de Energia S.A., Brazil	2 x FSC 500kV S/S Gurupí North-South III project (Lot B)	500kV	Rating: 1 x FSC 194 MVAr 1 x FSC 130 MVAr	Turnkey Project
2006	Powerlink – Brisbane Australia	1 x SVC Strathmore	275 kV	Control range: -80/180(260)MVAr 1 x TCR 1 x TSC 3 x STF	Turnkey project Negative phase control TSC single phase switching
2006	ELETRONORTE Centrais Elétricas do Norte do Brasil S.A. Brazil	3 x FSC S/S Barra do Peixe	230 kV	Rating: FSC 120 MVAr FSC 37 MVAr FSC 35 MVAr	Turnkey Project
2005	FURNAS Centrais Elétricas S.A., Brazil	1 x FSC S/S Rio Verde	230 kV	Rating 216 MVAr	Turnkey Project
2005	ELETRONORTE Centrais Elétricas do Norte do Brasil S.A., Brazil	1 x SVC S/S Sinop	230 kV	Control range: -20/55 MVAr 1 x TCR 1 x STF	Turnkey Project, VC
2005	ELETRONORTE Centrais Elétricas do Norte do Brasil S.A. Brazil	1 x SVC S/S São Luis II	230 kV	Control range: -100/150 MVAr 1 x TCR 1 x TSC 1 x STF	Turnkey Project, VC
2005	CFE – Comisión Federal de Electricidad / Mexico	1 x SVC S/S Nopala	400 kV	Control range: -90/300 MVAr 1 x TCR	Turnkey Project, VC

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Figure F.3: Installed SVC systems by Siemens Energy Sector Power Transmission Division, part 3.

SIEMENS

Energy Sector Power Transmission Division

Reactive Power Compensation Projects
Reference List

Year	Customer	Type / Station /Scope	Voltage	Configuration	Use / Remarks
				3 x TSC 2 x STF	
2005	National Grid Company, U.K.	1 x MSCDN Grendon	400 kV	Rating 225 Mvar	Turnkey Project,
2005	RED Eléctrica de España, Spain	2 x MSCDN Benejama / Saladas	220 kV	Rating 100 Mvar	Turnkey Project,
2005	Southern California Edison Los Angeles, USA	1 x SVC Devers	12.5 kV / 500kV	Control range: -110/605 MVAr 2 x TCR 110 MVAr 3 x TSC 110 MVAr 2 x STF 2x55 MVAr 1 x MSC at HV 165 MVAr	Turnkey Project,
2005	State Grid Corporation Beijing - China	2 x FSC Fengjie FSC Station Wanxian	500 kV	Rating 2 x 610Mvar	35MJ MOV per Phase
2005	SEAS – NVE, Haslev – Danmark	1 x SVC Radsted	7.5 kV / 132 kV	Control range: -65/80 MVAr 2 x TCR 135 MVAr 2 x STF 80 MVAr	Turnkey Project, 12-pulse configuration, VC
2005	SESB, Kota Kinabalu - Malayisa	SVC Segaliud	275 kV	Control range: -60/60 MVAr	DS, VC, PSDC
2005	SESB, Kota Kinabalu - Malayisa	SVC Dam Road	132 kV	Control range: -60/60 MVAr	DS, VC, PSDC

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Figure F.4: Installed SVC systems by Siemens Energy Sector Power Transmission Division, part 4.