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Design and Implementation for PV Inverter Based on Novel Soft Switching Current –Fed Half-Bridge Front End Converter

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ABSTRACT: Multi-port dc-dc isolated converter has emerged recently as very important in the case of PV based storage and distribution application. A new front end converter is introduced for efficient PV generation and Common solid state transformer to improve the converter operating speed. Half bridge non-isolated dc-dc converter introduced for battery storage and Controller is implemented based on BESS (battery energy storage system) for high power grid distribution proposed in secondary of transformer. Front end converter (FEC) plays a major role and its switching operation is per-formed by MPPT based pulse generations. The overall converter performance is verified through MATLAB (Simulink).
Recent days the growth in peak demand for the increasing of distributed and deregulated energy systems require an optimized grid control unit. The advances in computing and communication technologies forming the traditional power network into a smart grid, capable of real-time remote monitoring and control. Mart is particularly well- suited for renewable energy sources; power is utilized, depending upon the availability of natural resources. Three port converters for interfacing multi power sources and storage devices are widely used in years. Instead of using individual power electronic converters for each of the energy sources, multiport converters have the ad- vantages including less components, lower cost, more com-pact size, and better dynamic performance. In the electric vehicle application, the regenerative energy occurs during acceleration or startup for the port connected to the energy storage to allow frictional power flow.

1. INTRODUCTION

Power systems are complicated networks with hundreds of generating stations and load centers being interconnected through power transmission lines. An electric power system can be separated into four stages: i) generation, ii) transmission iii) distribution and iv) utilization. The basic structure of a power system is as shown in Fig.1.1. It is composed of generating plants, a transmission system and distribution system. These subsystems are interconnected through transformers T1, T2 and T3.

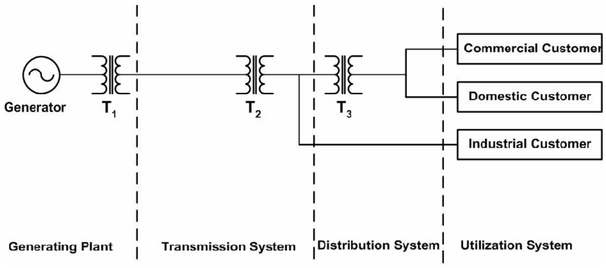

Figure 1.1 Typical power system

1.1 Power Quality Concept

Even a few years back, the main concern of consumers in power system was the reliability of supply which is defined as the continuity of electricity. It is however not only the reliability that consumers want these days, quality of electricity supply is also very important for consumers. The term, electric power quality, broadly refers to maintaining a nearly sinusoidal bus voltage at rated magnitude and frequency in an uninterrupted manner from the reliability point of view. For a well-designed generating plant which generates voltages almost perfectly sinusoidal at rated magnitude and

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frequency, power quality problems start with transmission system and stay valid until end users in distribution system. In [1,2], the terms, characterizing the power quality in the power system have been defined and are summarized as follows:

− **Transients:** are defined as the change in a system variable that disappears during transition from one steady-state operating condition to another and can be classified as impulsive transients and oscillatory transients. Impulse transients are mainly caused by the impact of lightning strikes to the power system. The typical causes of oscillatory transients are capacitor or transformer energization and converter switching. While impulsive transient is a sudden and has non-power frequency change in voltage and current with a fast rise and decaying time, oscillatory transient has one or more sinusoidal components with frequencies in the range from power frequency to 500 kHz and decays in time.

− **Short Duration Voltage Variations:** are defined as the variations in the supply voltage for durations not exceeding one minute and caused by faults, energization of large loads that having large inrush currents or rapidly varying large reactive power demands of the loads. These are further classified as voltage sags, voltage swells and interruption.

− **Long Duration Voltage Variations:** are defined as the rms variations in the supply voltage at fundamental frequency for exceeding one minute, such as overvoltage, under voltage and sustained interruption. The causes of overvoltage (or under voltage) may be the switching off (or on) of a large load having poor power factor, or the energization of a large capacitor bank or reactors.

− **Voltage Unbalance:** is the condition in which three phase voltages of the supply are not equal in magnitude and may not be equally displaced in time. The primary cause is the single phase loads.

− **Waveform Distortion:** is defined as steady-state deviation in the voltage or current waveform from an ideal sine wave. These distortions are classified as dc-offset, harmonics and notching. The causes of dc offsets in power systems are geomagnetic disturbances, especially at higher altitudes and half-wave rectifications. These may increase the peak value of the flux in the transformer, pushing it into saturation and resulting in heating in the transformer. Power electronics like UPS, adjustable speed drives cause harmonics in the power systems.

Notching is a periodic voltage distortion due to the operation of power converters when current commutates from one phase to another.

− **Voltage Fluctuations:** are defined as the rapid, systematic and random variations in the supply voltage. These are known as “Voltage Flicker”. These are caused by rapid and large variations in current magnitude of loads having poor power factor such as arc furnaces. This large variation in load current causes severe dips in the supply voltage unless the supply bus is very stiff.

− **Power Frequency Variations:** are the variations that are caused by rapid changes in the load connected to the system, such as the operation of draglines connected to a comparatively low inertia system. Since the frequency is directly related to rotational speeds of the generators, large variations in power frequency may reduce the life span of turbine blades on the shaft connected to the generator. Although these terms, above, are not new, customer awareness on power quality has increased. In recent times, power quality issues and custom solutions have generated tremendous amount of interest among power system authorities and engineers. International Electro technical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE) have proposed various standards on power quality [65, 93, 94]. This led to more stringent regulations and limits imposed by electricity authorities although they differ from one country to another in a limited extend. As an example, the progress in both reactive energy limits and distortion limits for the near future is recently imposed by the Energy Market Regulatory.

Although terms of power quality are valid for transmission and distribution systems, their approach to power quality has different concerns. An engineer of transmission system deals with the control of active and reactive power flow in order to maximize both the loading capability and stability limits of the transmission system. On the other hand, an engineer of distribution system deals with load compensation (by means of individual or group compensation) in order to maintain power quality for each load in the distribution system, for example achieving nearly sinusoidal bus voltage at rated magnitude for every load. These interests on power quality have also brought the solution by utilizing power electronic based power conditioning devices.

Current Source Converter

Although the possible use of CSCs for reactive power compensation has been known over a quarter of a century [3, 56], it has not been realized for many years due to reasons given in previous section. In fact, the basic topology of current source converter has been known since the first application of line commutated rectifiers. Line commutated rectifiers have similar the topology as in except the ac capacitors since they do not need capacitors at their ac terminal due to their line commutated thyristors. In fundamental topology of CSC given the converter is build up of forced commutated power semiconductors and hence the capacitors at ac terminal provide not only commutation path for the currents of power semiconductors but also low impedance for the high order harmonics injected by the converter.

The advents in power semiconductor and capacitor technology have made PWM voltage source converters popular in power electronics, leaving application of CSC as line commutated thyristorized front end rectifiers in DC drives, or load commutated thyristorized inverters in MV synchronous motor drives. With the introduction of GTOs and GCTs, PWM CSC has found wide application in MV AC drives due to their simple converter topology, motor friendly waveforms and reliable inherent short circuit protection [4, 22]. PWM CSC has also been used in MV drives as an active front end rectifier [14, 27, 31, 51] and dc motor drive [53] instead of line commutated thyristor rectifiers, thus eliminating their inherent properties such as poor power factor, distorted line currents. The application of single phase CSC as a resonant inverter in induction heating has also been reported in [78]. The research works on CSC are generally based on its use as a rectifier or inverter. Its control strategies and modulation techniques have been proposed accordingly [11-55]. However, there are limited research on CSC based STATCOM as compared to VSC based STATCOM [56-64]. Among these research work, only [64], which has been the part of this study presents the first application of CSC based STATCOM for load compensation.

A reactive power compensation system which employs a three-phase PWM current source converter which is modulated by optimized PWM patterns stored in an EPROM is presented in [56]. This work also includes the methods of reactive power current control for optimizing the system response, input filter and dc-link reactor design, specification of power semiconductor ratings, and a method of closing reactive power demand loop by using phase angle control. The proposed methods were verified on a 117V, 1.1kVA power circuit. However, filter components and dc-link reactor are not so realistic that the results cannot prove viability of CSC based STATCOM.

The research work in [57] is an experimental verification of CSC based STATCOM on a 120V, 500VA laboratory set-up by employing a different control approach: reactive power control by varying modulation index while maintaining constant dc-link current by phase shift angle control. However, the proposed control technique with Space Vector PWM (SVPWM) is not suitable for medium and high power applications.

In order to minimize the switching losses in CSC, [58] proposed a soft switching scheme by integrating H-type soft switching module to three phase current source converter for static power compensation. By using trapezoidal PWM with a carrier frequency of 5kHz and only phase shift angle control for reactive power control, the proposed topology has been tested on a scaled prototype at 120V/2kVA. The results shows that proposed topology improves higher efficiency
at the expense of higher circuit and control complexity.

The simultaneous control of modulation index and phase shift angle is proposed in [59] in order to eliminate oscillations due to poorly damped input filter while improving dynamic response of CSC based STATCOM. For this purpose, full state- feedback and integral controllers are employed by using the state space representation of CSC based STATCOM in dq frame. The proposed control method is compared with phase angle control employing conventional PI controller and the results are verified by 1kVA laboratory set-up.

FACTS Controllers

The IEEE Power Engineering Society (PES) Task Force of the FACTS Working Group has defined FACTS and FACTS Controller as given below [3].

Flexible AC Transmission System (FACTS): Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability

FACTS Controller A power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters the general symbol for FACTS Controller is shown in Fig.1.2a. FACTS Controllers are divided into four categories [3]: i) Series FACTS Controllers, ii) Shunt FACTS Controllers, iii) Combined Series-Series FACTS Controllers, iv) Combined Series-Shunt FACTS Controllers.

i) Series FACTS Controllers: These FACTS Controllers could be variable impedance such as capacitor, reactor or a power electronic based variable source, which in principle injects voltage in series with the line as illustrated in Fig.1.2b.

ii) Shunt FACTS Controllers: may be variable impedance such as capacitor, reactor or power electronic based variable source, which are shunt connected to the line in order to inject variable current, as shown in Fig.1.2c.

iii) Combined Series-Series FACTS Controllers: are the combinations of separate Series FACTS Controllers, which are controlled in a coordinated manner in a multiline transmission system, as illustrated in Fig.1.2d. This configuration provides independent series reactive power compensation for each line but also transfers real power among the lines via

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power link. The presence of power link between series controllers names this configuration as "Unified Series-Series Controller".

iv) Combined Series-Shunt FACTS Controllers: are combination of separate shunt and series controller, which are controlled in a coordinated manner (Fig.1.2e) or a Unified Power Flow Controller with series and shunt elements (Fig.1.2f). When the Shunt and Series FACTS Controllers are unified, there can be a real power exchange between the series and shunt controllers via power link. Although Series FACTS Controllers for a given MVA size is several times more powerful than Shunt FACTS Controllers, they have to be designed to ride through contingency and dynamic overloads, and ride through or by-pass short circuit currents [3]. Therefore, Shunt FACTS Controllers are more popular in order to control voltage at and around the point of connection through injection of reactive current (lagging or leading) or a combination of active and reactive current for a more effective voltage control and damping of voltage oscillations.

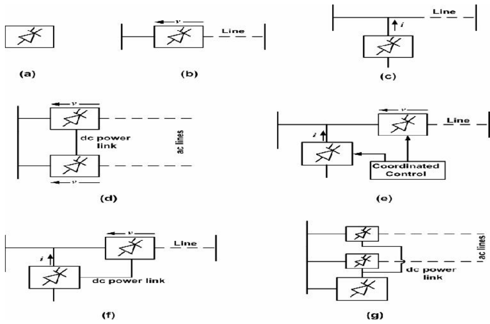

Figure 1.2 Basic types of FACTS Controllers [3]: (a) general symbol for FACTS Controller, (b) series FACTS Controller, (c) shunt FACTS Controller, (d) unified series-series FACTS Controller, (e) coordinated series and shunt Controller, (f) unified series-shunt Controller, (g) unified Controller for multiple lines Due to the same reasons, Shunt connected FACTS Controllers have also found wide applications in the distribution systems for many years since they present simple, cost effective solutions in load compensation. The common Shunt connected
FACTS Controllers are static shunt compensators: SVC and STATCOM.

1.3 Static Shunt Compensators: SVC AND STATCOM

Although static shunt compensators in both transmission systems and distribution systems have the same structure, their objectives are different due to their concerns on the power quality issues. The primary objectives of a shunt compensator in a distribution system are as
Follows

− Compensation of poor load power factor so that the current drawn from the source will have a nearly unity power factor
− Suppression of harmonics in loads so that the current drawn from source is nearly sinusoidal
− Voltage regulation for the loads that cause fluctuations in the supply voltage
− Cancelation of the effect of unbalance loads so that the current drawn from the source is balanced (load balancing)

All of these objectives are not necessarily met for a typical shunt compensator.
The required shunt compensator should be designed in view of the needs of load to be compensated since each of these functions has a certain cost to the compensator. On the other hand, the objectives of these shunt compensator in a transmission system are as given below in order to increase the transmitted power in the transmission lines.

− Midpoint voltage regulation for Line Segmentation in order to increase transmittable power in the transmission system
− End of line voltage support to prevent voltage instability requires the compensation of load having poor factor. This increases the maximum power transmission capability of the transmission line while improving the voltage instability limits.
− Improvement of transient stability margin by increasing the maximum transmittable power in the transmission line.
− Power oscillation damping by exchanging active (real) power with power system so that oscillations in the machine angle due to any minor disturbance can be damped out rapidly.

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1.3.1 Static VAr Compensators

According to definition of IEEE PES Task Force of FACTS Working Group:

Static VAr Compensator (SVC): A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage)

This is a general term for a Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TCR) and/or Thyristor Switched Capacitor (TSC) (Fig.1.3). The term, "SVC" has been used for shunt connected compensators, which are based on thyristors without gate turn-off capability.

In a TSC, a capacitor is connected in series with two back-to-back connected thyristors. The control of TSC is obtained by cycle selection principle such that capacitor is totally connected to line by firing thyristors or disconnected by blocking thyristors. An important issue in TSC is to achieve transient free switching. This can only be achieved firing thyristors if the voltage across the capacitor is in either positive peak or negative peak of the supply voltage.

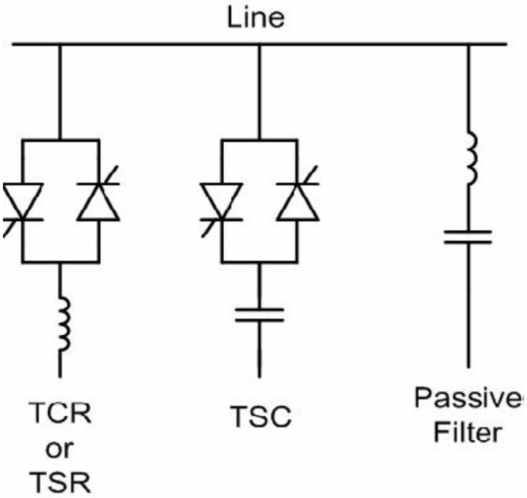

Figure 1.3 Static VAr Compensators: Thyristor Controlled Reactor (TCR) or Thyristor Switched

Reactor (TSR), Thyristor Switched Capacitor (TSC), Passive Filter

In a TCR, a reactor is connected in series with back-to-back connected thyristors. By controlling the delay angle, which is defined as the angle between the zero-crossing of line voltage and firing signal of thyristors, it absorbs variable reactive (inductive) power. For shunt compensation in both transmission and distribution systems, the SVC system can be realized by one of the following combinations:

i) Fixed Capacitor and TCR (FC-TCR): In order to achieve variable capacitance and variable inductance, FC-TCR is generally used. The typical operating V-I area of FC-TCR is as given in Fig.1.4a. The fixed capacitor in proactive is usually substituted fully or partially by a filter network that has the necessary capacitive impedance at the fundamental frequency to generate the reactive power. Not only this filter network filters out the characteristic low order harmonics of TCR but also the selected low order harmonics injected by the load [5].

ii) A combination of TCR and TSC: Typical loss versus VAr output characteristics of FC-TCR is given in Fig.1.4b. In order to decrease the losses in inductive operating region of FC-TCR and achieve increased operating flexibility, a combination of TCR-TSC with multiple TSC units can be used at the expense of decrease in dynamic response in capacitive region. Then typical operating V-I area and loss versus VAr output characteristics can be improved as shown in Fig.1.5.

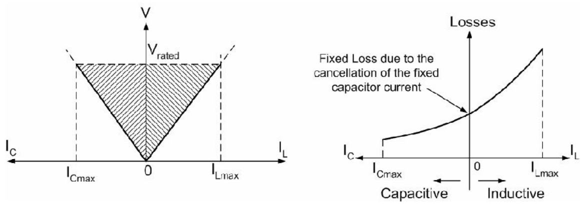

Figure 1.4 For FC-TCR: (a) operating V-I area (b) loss vs. output VAr characteristic

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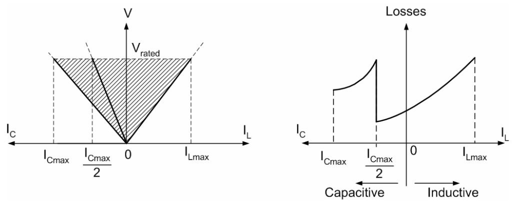

Figure 1.5 For TSC-TCR: (a) operating V-I area (b) loss vs. output VAr characteristic

1.3.2 STATCOM

According to definition of IEEE PES Task Force of FACTS Working Group:

Static Synchronous Compensator (STATCOM): A Static synchronous generator operates as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors by various switching power converters was disclosed by Gyugi in 1976 [3]. Functionality, from the standpoint of reactive power generation, their operation is similar to that of an ideal synchronous machine whose reactive power output is varied by excitation control (Fig.1.6a). Like the mechanically powered machine these converters can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source (Fig.1.6b). Because of these similarities with a rotating synchronous generator, they are termed Static Synchronous Generator (SSG). When SSG is operated without an energy source and with appropriate controls to function as shunt-connected reactive compensator, it is termed, analogously to the rotating synchronous compensator (condenser) a Static Synchronous Compensator (STATCOM) or Static Synchronous Condenser (STATCON).

Rotating synchronous condensers (Fig.1.6a) have been used in both distribution and transmission systems for 50 years. However, they are rarely used today because of their following drawbacks: i) require substantial foundations and a significant amount of starting and protective equipment, ii) contribute to the short circuit current, iii) cannot be controlled fast enough to compensate for rapid load changes due to the large time constant of their field circuit, iv) have much higher losses as compared with STATCOM [90].

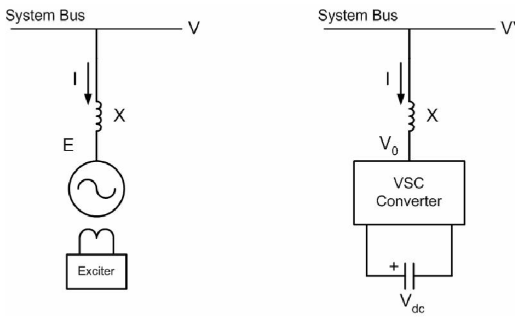

Figure 1.6 Reactive power generation by (a) a rotating synchronous compensator,
(b) Voltage source converter based Static Synchronous Compensator (STATCOM)

For the generation of controllable reactive power by the converter can be a voltage soure type (VSC) (Fig.1.7a) or a current source type (CSC) (1.7b). However, converters presently employed in FACTS Controllers are based on voltage source converter [3]. The major reasons for this preference are as follows: i) Current source converters require power semiconductors with bidirectional voltage blocking capability. The available high power semiconductors with gate turn-off capability (GTOs, IGBTs) either can not block reverse voltage at all or can only do it with detrimental effort on other parameters (e.g., increased conduction losses)

ii) Dc-link reactor of CSC is practically more lossy than complementary dc-link capacitor of VSC.

iii) The CSC requires capacitors at its ac terminals while VSC requires reactors, which may be naturally provided by the leakage inductance of the coupling transformer.

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II. SYSTEM DESCRIPTION AND OPERATING PRINCIPLES

2.1 Introduction

In the most general case, a shunt connected compensator in a distribution system can also filter out load harmonics and balance the unbalanced load currents in addition to the correction of load power factor. Each additional capability obviously increases initial cost of the implemented system. However, for the balanced clean loads although their reactive power demand varies rapidly the shunt connected compensator is required only for power factor correction.
The three phase CSC based STATCOM is a shunt connected compensator, which injects nearly sinusoidal three phase balanced currents with adjustable magnitudes and leading or lagging the corresponding line voltages by nearly 90°. Therefore, the three phase CSC based STATCOM can compensate for the balanced loads having rapidly fluctuating reactive power demands of harmonic less loads, such as synchronous or asynchronous motors in Ward-Leonard drives.
In this chapter, the system description and operating principles of three phase Current Source Converter (CSC) based STATCOM will be presented in order to meet following objectives:
• Harmonic content of the nearly sinusoidal current produced by STATCOM should comply with IEEE 512 Std 1992 and limits imposed by the Energy Market Regulatory Authority of Turkey,
• The magnitude of the reactive current component produced by STATCOM should be controllable between zero and pre-specified value,
• The STATCOM current can be made either lagging or leading corresponding supply voltage by 90° according to the reactive power demand of the load.
After defining basic circuit topology chosen for the CSC based STATCOM, its operating principles during reactive power control will be explained. Different modulation techniques which are commonly applied to CSC to create nearly sinusoidal currents in the supply lines will be compared and among these modulation techniques Selective Harmonic Elimination Method is going to be explained. Then, the control methods applicable to CSC based STATCOM for reactive power control will be presented. The equivalent circuit model in dq stationary frame will be given in the same section. The current commutations in CSC will also be defined. At the end of the chapter, brief conclusions will be posted.

2.2 Basic Circuit Configuration

The general circuit topology of the three phase Current Source Converter (CSC) based STATCOM is shown in Fig 2.1 [56, 57, 61-64]. It consists of six fully controllable power semiconductor switches (S1, S2, S3, S4, S5, S6) which have unidirectional current carrying and bipolar voltage blocking capabilities.

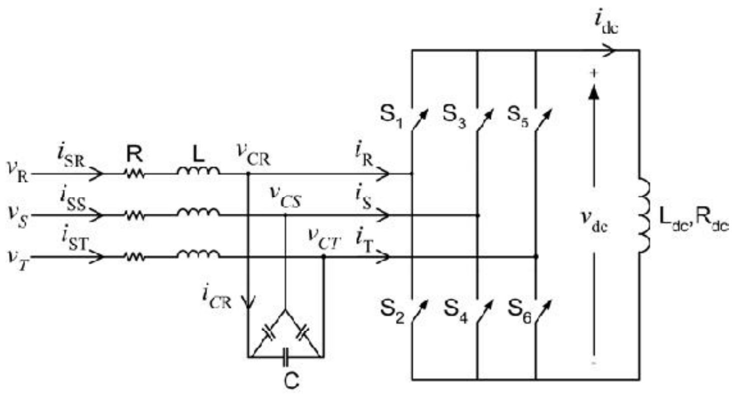

Figure 2.1 General circuit topology of Three Phase Current Source Converter

A dc-link reactor has been placed in dc-link as the energy storage element. The dc-link reactor has an electrical equivalent circuit which is composed of series connection of dc-link inductance Ldc and its internal resistance Rdc. Due to relatively high time constant of dc-link circuit, dc-link current, *idc* becomes nearly constant over a switching period.
Because of the switching's of the power semiconductors in accordance with a pre-specified pattern, the nearly constant dc-link current in the steady state is reflected to the ac lines of the CSC in the form of bidirectional current pulses. The

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converter line currents (i.e., *iR*, *iS*, and *iT* in Fig.2.1) will therefore have harmonic spectra in addition to the fundamental component at supply frequency. In order to filter out these harmonic components, a three phase low pass input filter is to be used at the AC side of the converter. By this way, nearly sinusoidal supply line currents, (i.e., *iSR*, *iSS*, *iST*) which comply with the harmonic standards [65] can be obtained. Capacitors in the input filter are inherent to the Current Source Converters in order to provide a low impedance return path to the converter current pulses. Although the use of series reactor in the input filter is optional their use is beneficial for adjusting the corner frequency of the filter and thus lowering effectively the harmonic content of the injected currents to the supply by the STATCOM. Since the filter inductance is composed of leakage inductance of the coupling transformer, cable and bulbar inductances and the inductance of external reactor for medium voltage applications, fine tuning of the corner frequency can only be achieved by the use of an external reactor in each line as shown in Fig.2.1. The series resistance, R in Fig.2.1 takes account of internal resistances of coupling transformer, cables and bus bars and the external filter reactor. In the input filter electrical damping is provided only by R

III. DESIGN OF CURRENT SOURCE CONVERTER

3.1 Introduction

The system description and operating principles of three phase Current Source Converter (CSC) based STATCOM have been presented in previous chapter. It has been illustrated that three phase CSC based STATCOM should meet following objectives

- Nearly sinusoidal currents should be produced,
- Magnitude of these currents should be fully controlled,
- The phases of the produced current should be fully controlled with respect to supply voltages in order to permit the flow of desired amount of active and reactive powers in the desired direction.

In this chapter, the design and implementation of a high power prototype for three phase CSC based STATCOM satisfying the above objectives will be presented. Design of the prototype system will be accomplished in view of reactive power compensation requirements of an actual sample application that is load compensation of coal mining excavators.

The design methodology used in this work is based on analysis, simulation and experimental work. The simulation of CSC based STATCOM has been carried out by using PSCAD/EMDTC simulation tool. The modulation techniques and control methods of the prototype system has been exercised with this model. The ratings of power semiconductors, input filter components, dc-link reactor, snubber components have all been determined by using this simulation model. The details of this simulation model can be found in Appendix C. Analysis such as the effects of snubber components in snubber design has been carried out by MATLAB/Simulink.

The optimization algorithms for calculating independent chopping angles for Selective Harmonic Elimination have been applied by using MATLAB/Optimization Toolbox. In some cases, where the use of simulation is not adequate or impractical, experimental work has been carried out in the laboratory, such as in determination of switching characteristics for power semiconductors or

Verification of snubber effects.

In this chapter, defining the load characteristics of sample application (load compensation of coal mining excavators) technical specifications of the prototype CSC based STATCOM will be determined first. Then, criteria on the selection of power semiconductors will be given by comparing different combinations of candidate power semiconductors and then the application of proper modulation technique will be discussed on the basis of selected power semiconductor. Next, a qualitative design criterion for input filter and dc-link reactor will be posted. The design of power stage for CSC based STATCOM will be presented in two different parts: design of CSC power stage layout and design of overall power stage for STATCOM system. The design criteria on selection of snubber type and its components will be given on the basis of power semiconductor switching waveforms and then verified by experimental results. The design of protection circuit used in prototype system will be discussed. The implementation of the control system including reactive power controller and switching signal generator will be presented. In the final section, discussion on maximum utilization of designed CSC based STATCOM will be posted.

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3.2 Design Specifications of Prototype System

Within the scope of this thesis, the prototype of CSC based STATCOM has been designed and developed in order to compensate the reactive power demands of coal mining electric excavators in Tınaz Transformer Substation of South Eagen Open Cast Lignite Mining Enterprise (GELI) connected to Turkish Coal Enterprises (TKI).

Electrical excavators, shown in Fig.3.1 are the key equipments in open cast coal mining applications. In addition to their intermittent character as a load on the network, they may be the sources of harmonics, and consumers of reactive power. The severity of power quality problems arising from electric motor drive technology: i)Ward Leonard drives, ii) dc motor drives based on phase-controlled thyristor rectifiers and, iii) variable frequency ac motor drives based on dc link converters [64]. Within the scope of this work, electric excavators are powered by Ward Leonard drives. As shown in Fig.3.1, there are two types of electric excavators in Tınaz Transformer Substation: i) dragline and ii) power shovel.

Figure 3.1 General view of open-cast lignite mining site (top: power shovels, bottom: dragline)

Dragline is the largest electric excavator, which is rated at 2000kW and 6.3kV.

Its Ward-Leonard drive is powered by synchronous motors, which are operated in over-excited mode to maximize the electromechnical torque. Therefore, dragline behaves as a capacitive load. The typical active and reactive power variation of the dragline for a few operating cycle.

Power shovel, the other type of electric excavators, is rated at 600kW, 6.3kV. Its Ward-Leonard drive is powered by an asynchronous motor, which always behaves as an inductive load. The typical active and reactive power variations of a power shovel for a few operating cycle.

One dragline and one power shovel are connected to a common 6.3kV medium voltage bus as shown in Fig.3.4. Instead of solving reactive power compensation problem on each electric excavators individually, group compensation approach [5,64] is found to be more feasible and economical. For group compensation, CSC based STATCOM system is connected to 31.5kV medium voltage level. Then, STATCOM compensates the reactive power demand of the

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transformer substation, where electric excavators are the main loads. Considering the reactive power demands of the electric excavators and reactive energy penalty limits, reactive power rating of CSC STATCOM has been specified to be in the range from 500kVAr capacitive (-500kVAr) to 500kVAr inductive (+500kVAr). CSC based STATCOM system is intended to meet the harmonic limits (TDD-Total Demand Distortion) specified to be 15% for PCC.

The voltage level at which CSC is designed has been specified as 1kV, because it is a standard low voltage level [66], thus permitting the use of standard components and switchgear devices. Moreover, this choice makes the CSC STATCOM specifications compatible with other TCR based SVCs in TKI [5,64].This also provides the unification of SVC systems.

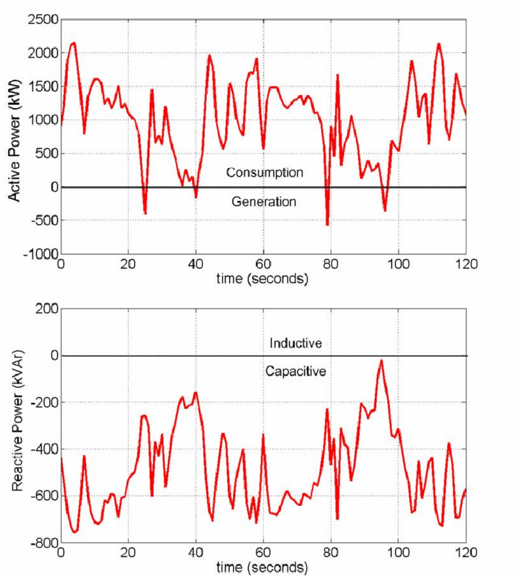

Figure 3.2 (a) Active (b) reactive power variation of dragline in Tınaz open cast mine of TKI

IV. FIELD TEST RESULTS

Introduction

Using the design principles given in Chapter 3, +/- 500kVAr CSC based STATCOM has been developed at 1kV. In order to verify theoretical results, implemented system has been applied to two different sites of Turkish Coal Enterprises in order to provide group compensation of coal mining excavators, which have the similar load characteristics as explained in Chapter 3.2.

The complete circuit diagram of the developed STATCOM system has already been given in Fig.3.25. The modulation technique of the developed system is SHEM with elimination of 5th, 7th, 11th and 13th harmonic at a fixed modulation index of 0.8. The reactive power control of the developed system has been achieved by the control of phase shift angle φ as explained in Chapter 3.9. During the field tests, performance of the developed system has been tested at different operating conditions and various characteristics of CSC based STATCOM have been obtained. In this Chapter, these characteristics obtained from these field tests will be presented. Field test results include the records taken from the developed system for the worst operating cases and illustrations derived from the results of several records.

The records have been obtained by the measuring apparatus, which are listed. Two different oscilloscopes have been used. These are 500MHz oscilloscope (TDS5054) from Tektronix and 300MHz oscilloscope (Wave Jet 324) from Lecroy. The later one has the data acquisition capability of 500K samples whereas the former has 100K samples. High voltage measurements have been made by using differential high voltage probes such as DP100 from Pintek and P5210 from Tektronix. Since P5210 is an active probe which is supplied by TDS5054 it has been used together with TDS5054. On the other hand, DP100 which is supplied by its isolated power supply from 220VAC has been used with WaveJet 324. Voltage signals smaller than 100V were recorded by signal probe (P5050) from Tektronix so that the signal can be measure accurately. Not only ac currents in the system but also the currents through power semiconductors were measured by Rogowski coils. Rogowski coil is an electrical device for measuring AC currents or

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high current pulses. Since a Rogowski coil has an air core unlike other types of current transformers, it does not saturate and can respond to fast-changing currents.

Bandwidth of the Rogowski coils is approximately 16MHz. It is supplied either from a battery or a 220V ac power supply. Variations in active and reactive power have been measured with the use of data acquisition system. The current waveforms are acquired via current probe (80i-110S) from Fluke through associated current transformer and voltage waveforms are taken with the use of divider in terms of resistors. The data acquisition system samples voltage and current waveforms at a sampling rate of 3200kS/sec. Ferrite beads in different sizes have been used for the measuring devices supplied from power supply in order to suppress common mode noise in the measurements.

In this Chapter, first current and voltage waveforms of power semiconductors in steady –and transient-state will be given in order to verify the design criteria and demonstrate operating characteristics of CSC based STATCOM. Then, the compliance of the developed system with the corresponding standards will be shown both by the records obtained for the maximum operating conditions and the results obtained at various operating conditions. The efficacy figure of the developed system will then be defined on the basis of the variations in power loss against reactive power produced by the system. Typical records of state variables of CSC based STATCOM on both AC and DC sides will be presented at maximum operating conditions in order to verify the design work and show the operating principles of CSC based STATCOM. After that the performance of CSC based STATCOM in reactive power control will be evaluated by the records obtained from the transient –and steady-state responses to the different types of reactive power demands

Table 4.1 List of measuring apparatus

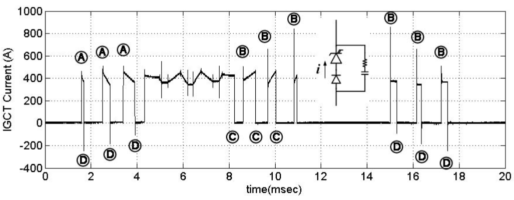
− Tektronix TDS5054 Digital Phosphor Oscilloscope
− LeCroy WaveJet 324 Oscilloscope
− Pintek DP100 High Voltage Differential Probe (100MHz)
− Tektronix P5210 High Voltage Differential Probe (50MHz)
− Tektronix P5050 Passive Voltage Probe (500MHz)
− LEM LT 1005 S Hall-Effect Closed Loop Current Transducer
− Powertek, Rogowski Current Waveform Transducers:
CWT 15B, 2mV/A, and CWT 6B, 5mV/A
− Data Acquisition System:
National Instruments DAQ 6062 E Data Acquisition System
National Instruments SC2040 Sample and Hold Card
Fluke 80i-110S AC/DC Current Probe

4.2 Field Test Results

4.2.1 Current and Voltage Waveforms of Power Semiconductors

Current and voltage waveforms of IGCT and DIODE have been recorded by the use of Rogowski coils and DP100 high voltage differential probes in the field. Two sample records, one for 650kVAr capacitive and the other for 500kVAr inductive reactive power generation of overall STATCOM are given in Fig.4.1 and 4.2 respectively for one supply cycle (20msec).

Since the power semiconductors employed in CSC are self-commutated devices, switching patterns and semiconductor current waveforms are to be the same. A comparison between waveforms in Fig.2.17, Fig.3.7 and Fig.4.1-4.2 shows that the implemented CSC operates successfully. Different than Fig.2.
17 and Fig.3.7 there are negative currents in IGCT current waveforms due to reverse recovery of its series diode.



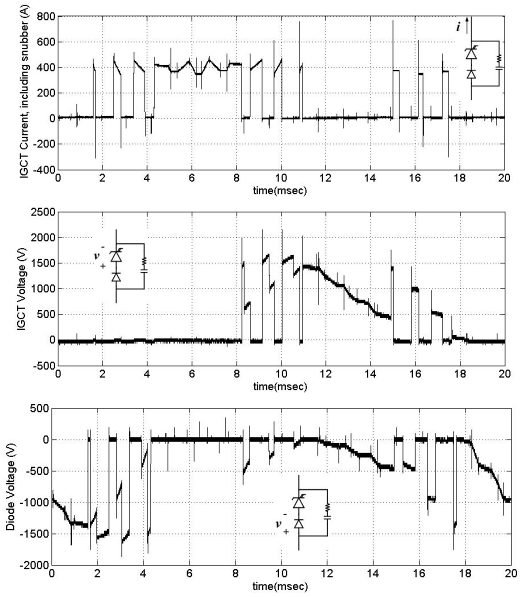


Figure 4.1 Typical voltage and current waveforms of IGCT and Diode, recorded for 650kVAr capacitive reactive power generation of STATCOM (sampling rate= 25MS/sec)

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