CHAPTER TWO

REVIEW OF DEVELOPMENT

2.1 INTRODUCTION

AC to DC converters have been extensively used in various applications [47-51]. There have been many applications which demand bi-directional power flow. Earlier, this conversion was done primarily through line commutated thyristor converters. Twelve and higher pulse constructions have been introduced and even used at present, to eliminate lower order harmonics. Forced commutated thyristor converters have also been used in specific application. The usage has been restricted due to requirement of bulky commutation circuit. Availability of self-commutated devices and improvement in their power handling capability in the last two decades, has given rise to usage of two basic topologies for ac to dc converters. The topologies are namely, Current Source topology and Voltage Source topology. The Current Source Converters (CSCs) have been discussed in [52-61] while the performance of Voltage Source Converters (VSCs) is discussed in [58, 62-76]. The discussion here however, is confined to VSCs and their use in reactive power compensation in low voltage applications. Considerable efforts have been put in the last decade by researchers to further improve the performance capabilities of VSCs so that power conversion can be achieved economically and to identify the optimal design for various applications. Configurations, techniques, semiconductors ratings and applications hence have to be critically assessed to obtain a comprehensive idea about the present scenario. These are hence considered separately to appreciate the developments.

2.2 CONVERTER CONFIGURATIONS

Fig 2.1 and 2.2a shows CSC and VSC topologies. These topologies, deliver near sinusoidal input currents at unity power factor or even leading power factor.

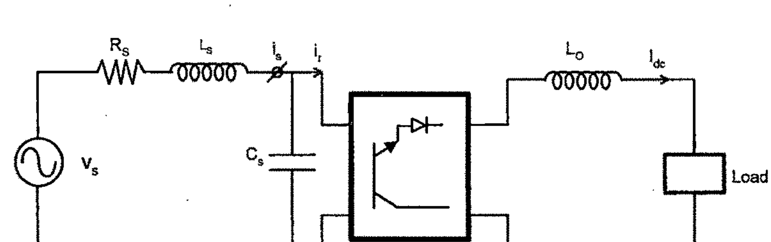
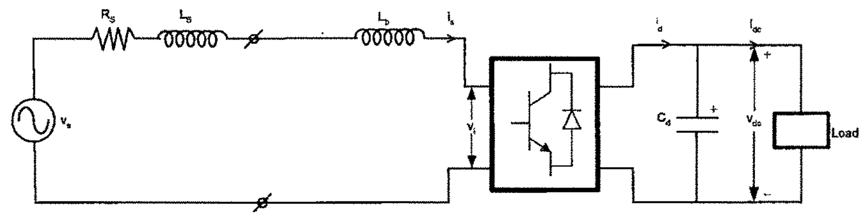
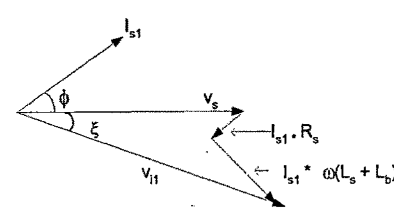


Fig 2.1 Current Source Topology



(a)



(b)

Fig 2.2 (a) Voltage Source Topology
(b) Vector relationship

Further description here, however is confined to VSCs.

2.2.1 VOLTAGE SOURCE CONVERTERS (VSCs)

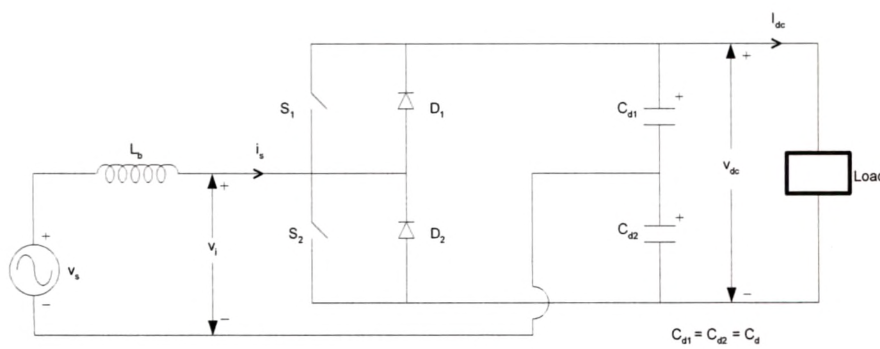
Fig 2.2(b) shows the vector relationship among the input voltage V_s, the fundamental component I_{S1} of supply current i_S and the fundamental component V_{i1} of converter input voltage v_i for the Voltage Source Converter (VSC) shown in fig 2.2(a). By controlling the voltage V_{i1} (its magnitude and phase) the input current I_{S1} and the power factor angle $\varnothing$ can be controlled. The converter switching input voltage v_i consists of the fundamental component and harmonics and is produced by some kind of Pulse Width Modulation (PWM). Figures 2.2 (a) and (b) show that for the fundamental component, system resembles a synchronous machine supplying or regenerating power from an active load. The load could be a dc motor with an ac to dc converter or an induction motor with an ac to dc converter and dc to ac inverter arrangement. The inductors L_S and L_b together separate the machine emf and the reflected ac voltage at the input terminals of ac to dc converter and thus work as synchronous link between the two ends. These converters are hence called as Synchronous Link Converters (SLCs).

VSCs work in boost mode. Output dc link voltage is fixed and is higher than the supply voltage. As such, the fixed input ac voltage is converted to fixed output dc voltage. Output power is controlled by controlling dc link current. In case of unidirectional power transfer, dc link current is maintained in one direction only. This finds applications mostly in power supplies used in computers, telecommunication and space equipment. Typically for such applications power requirement is low and hence power transistors or MOSFETs are used in these power supplies to derive maximum benefit from their higher switching frequency ratings [77].

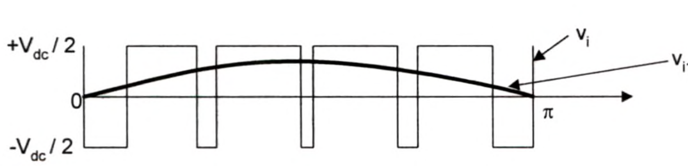
In case of bi-directional power transfer, dc link current can flow in either direction allowing the converters to work in two quadrants, as seen from output side. The converters deliver near sinusoidal currents and are capable of working in 360 degrees power angle range. The 360 degrees power angle range provides them potential in static var compensation applications [78-91]. For sake of completeness it should be noted that this converters are also widely deployed for induction motor drives [71, 92-94], synchronous machine drives [95], HVDC transmission [96-98], active filters for harmonic compensation [99-103] and traction applications. Similarly, a separate class of Pulse Width Modulated (PWM) converters also exists for dc drive applications [104-106]. These applications clearly reflect suitability of VSCs as well as their capability to handle low to large power requirements.

2.2.2 VSCs CONFIGURATIONS

The two commonly used single-phase VSC configurations are shown in figs. 2.3 (a) and 2.4 (a). Figure 2.3 (a) shows a half bridge configuration [107, 108] while fig 2.4 (a) gives full bridge configurations [109]. The converter input switching voltage v_i has a two level waveform for a half bridge configuration, while it has a three level waveform for a full bridge configuration. This is shown in figs. 2.3 (b) and 2.4 (b) respectively. Operating modes of two configurations are given in fig. 2.3 (c) and 2.4 (c).



(a)



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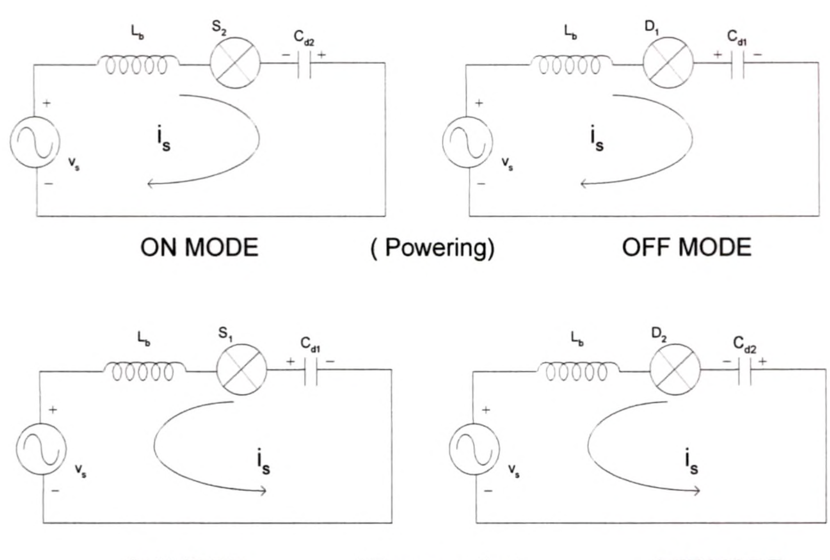
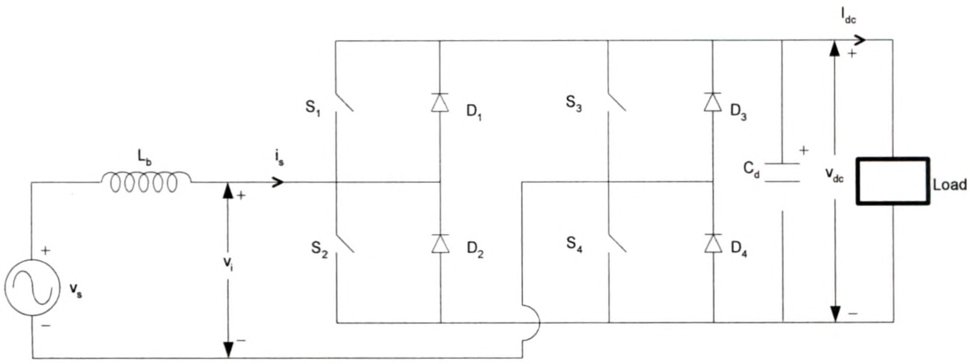
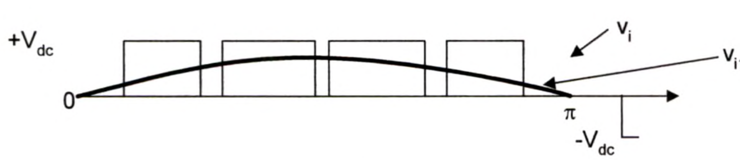


(c)

Fig 2.3 (a) Half bridge single phase VSC
(b) Typical two level input voltage waveform
(c) Operating modes



(a)



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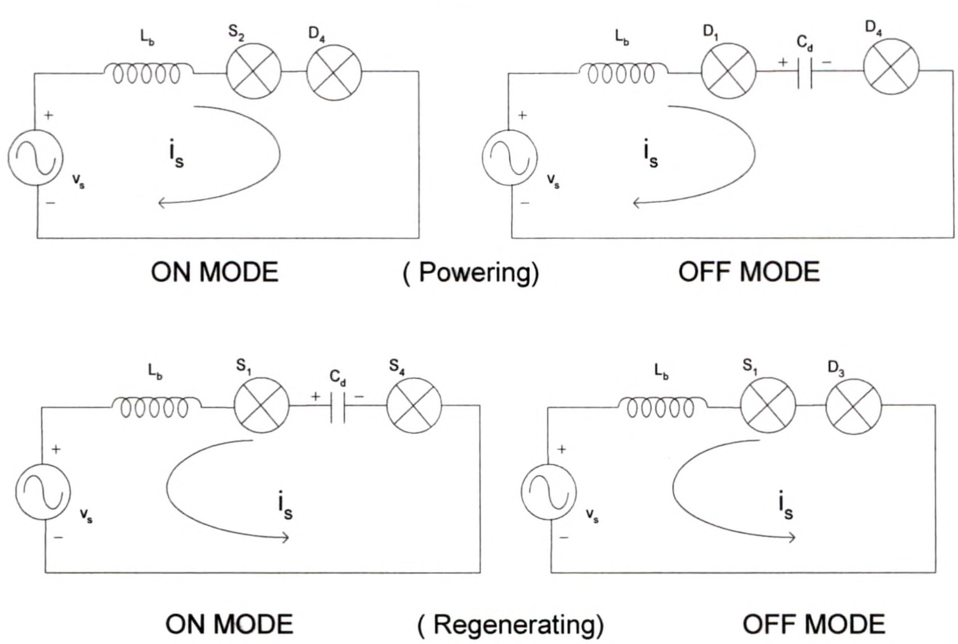


(c)

Fig 2.4 : **(a) Full bridge single phase VSC**
(b) Typical three level input voltage waveform
(c) Operating modes

The half bridge configurations of fig. 2.3 (a) having simple construction has three disadvantages as compared to full bridge configuration of fig. 2.4 (a).

- Higher harmonic content in the supply current (assuming same switching frequencies of power devices) due to two level converter input voltage waveform [110]
- More output dc voltage ripple owing to charging and discharging of two halves of the capacitor bank per half cycle of the supply voltage.
- Higher semiconductor stress (voltage and current) on the switching devices [108].

However, its major advantage is its direct extension to three phases which is shown in fig. 2.5 [68, 111,112]. It should be noted that to realize a three phase configuration from fig. 2.4 (a), three individual single phase configurations of fig. 2.2 (a), need to be operated in parallel as shown in fig. 2.6. This does not allow proper transformer core utilization and can generate triplen harmonics due to component tolerances.

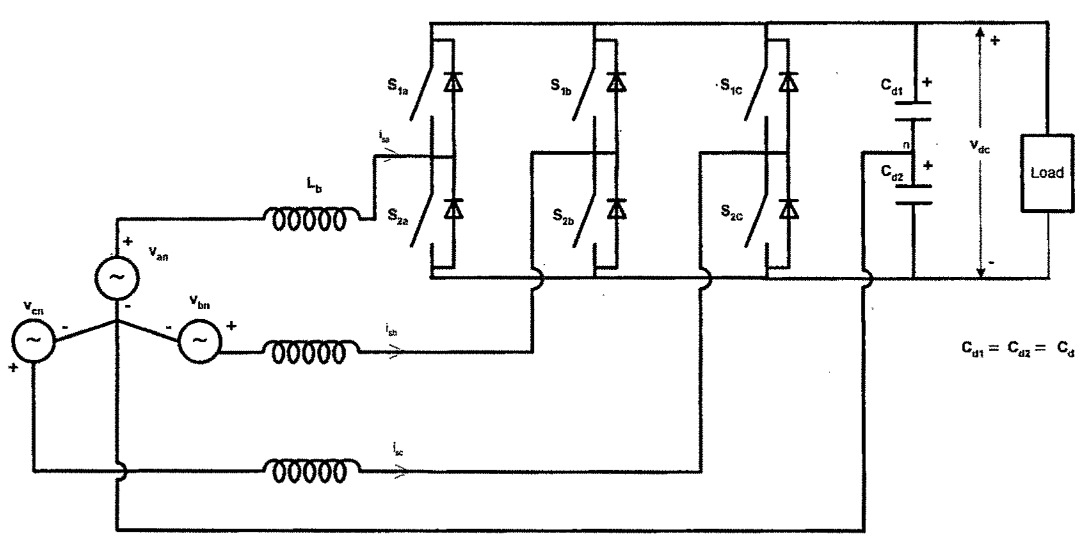


Fig 2.5 Half bridge type three phase VSC

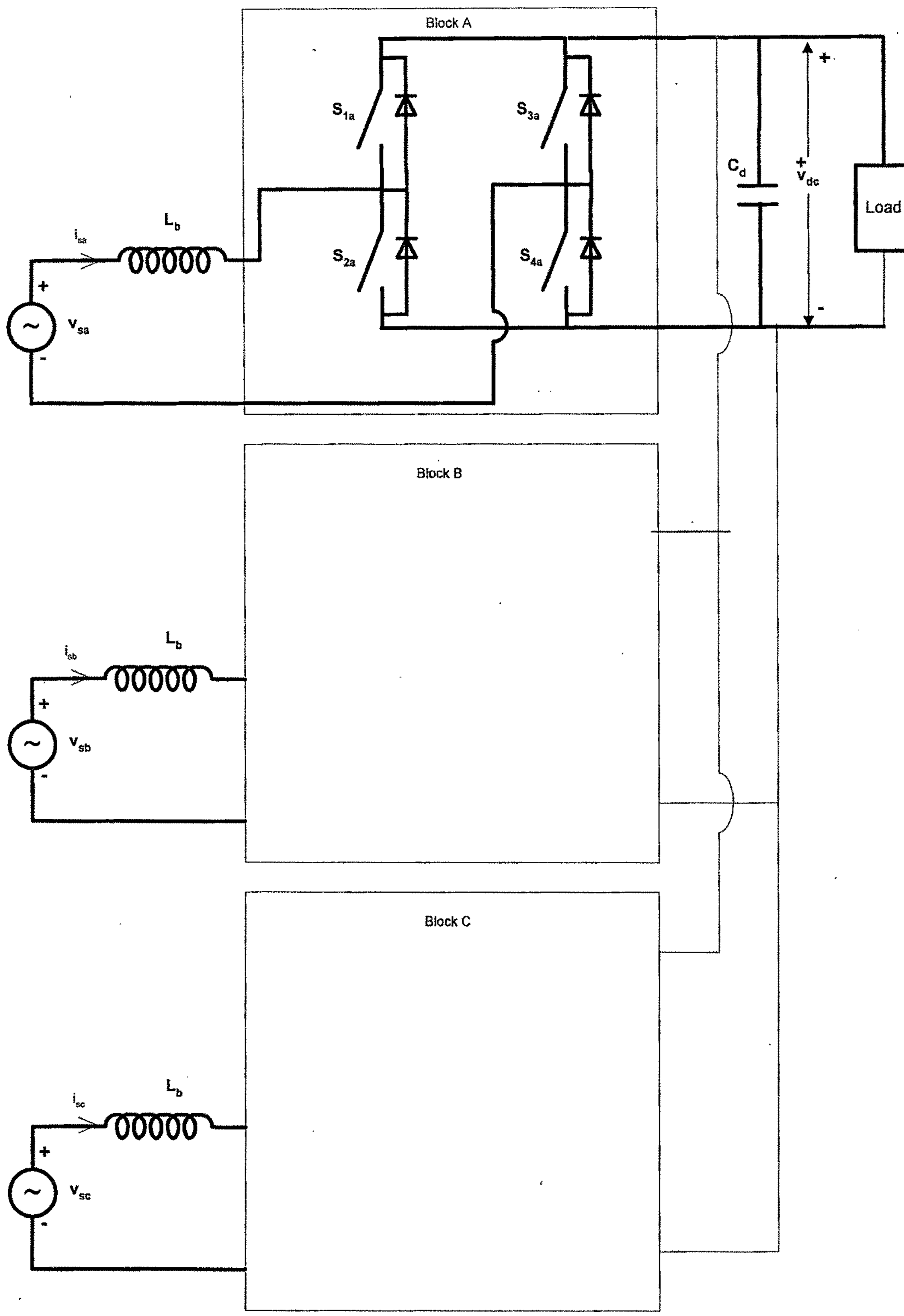
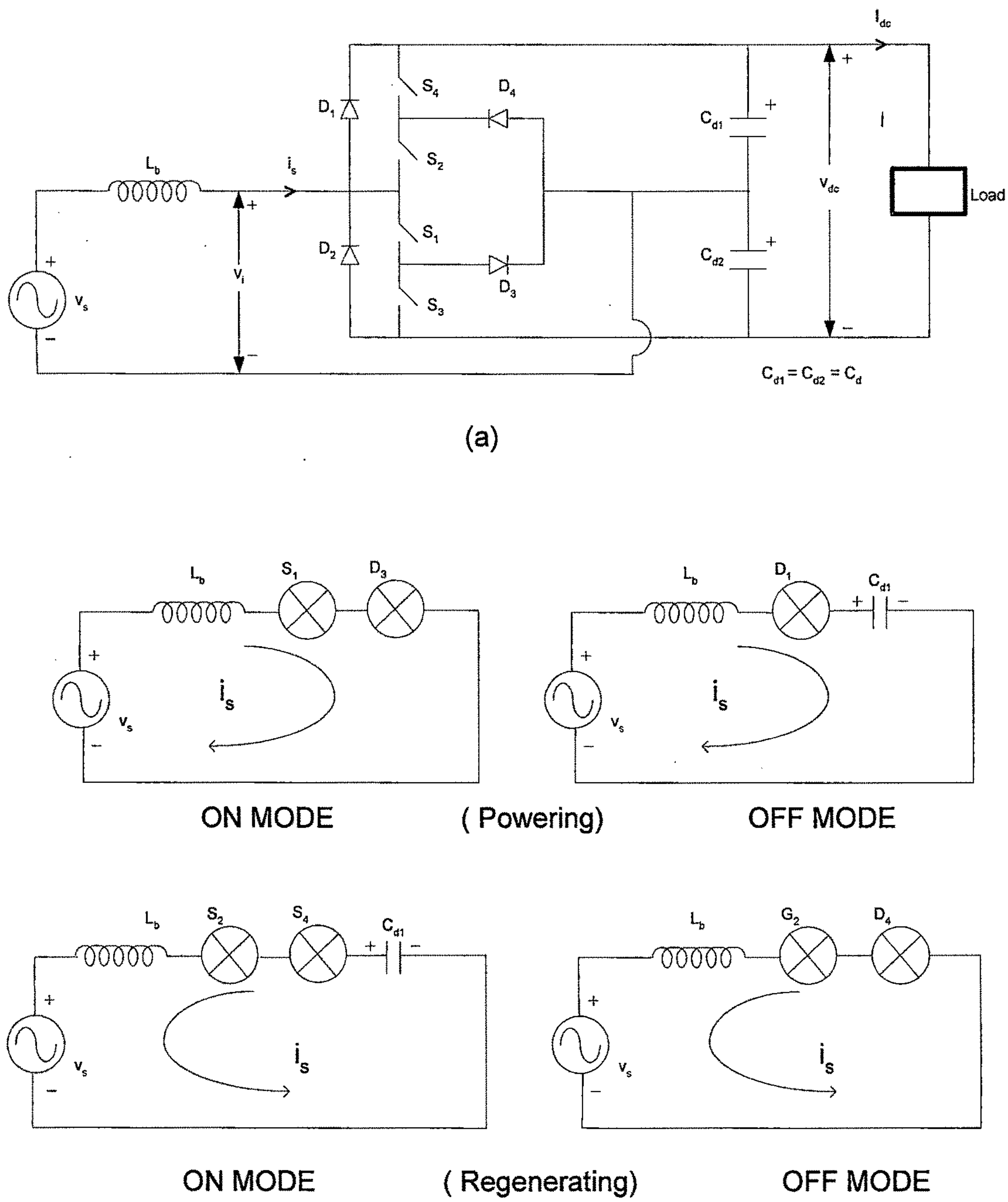


Fig 2.6 Full bridge type three phase VSC



(b)

Fig 2.7 : **(a) Three level VSC with centre tapped output capactior bank**
(b) Operating modes

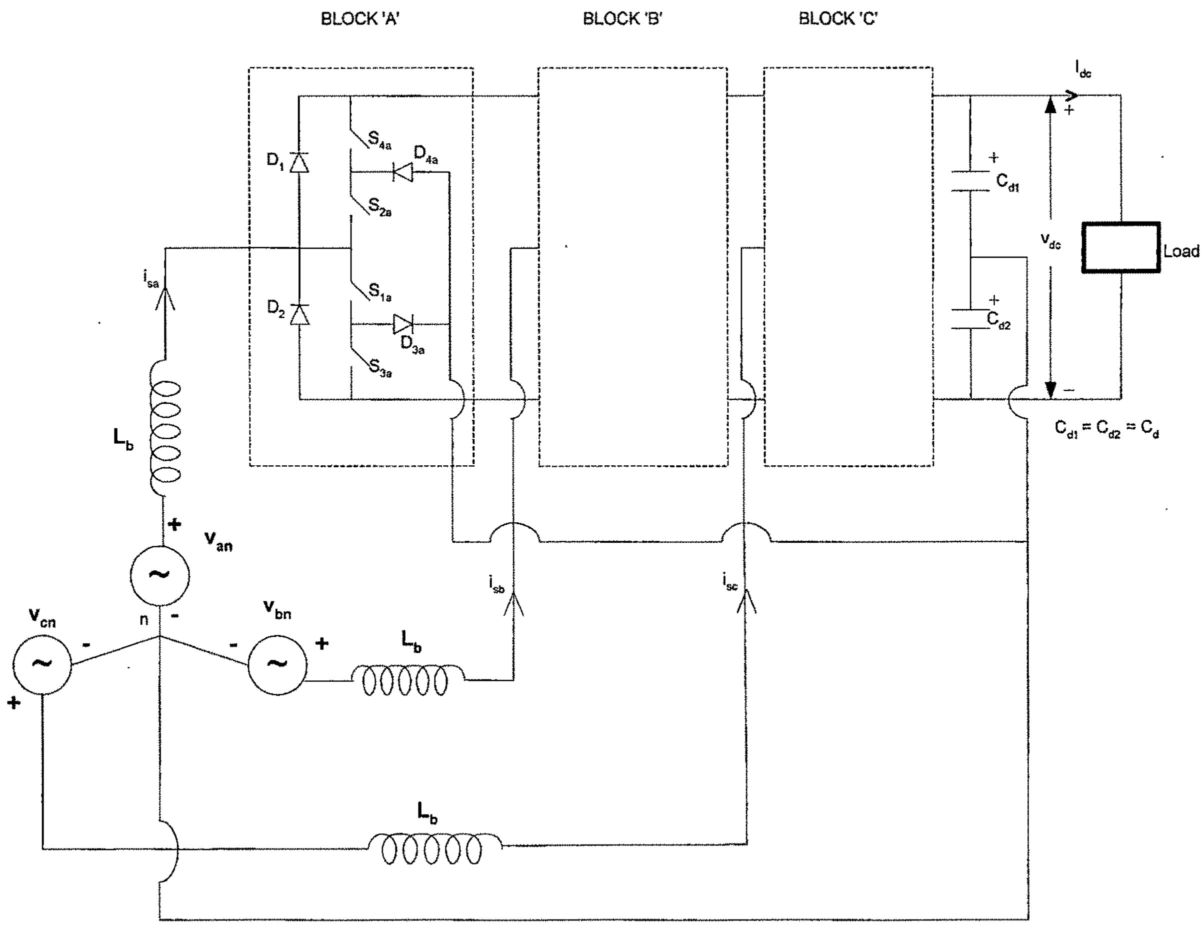


Fig 2.8 : Three level three-phase VSC with centre tapped output capactior bank

Another interesting single-phase Voltage Source Converter (VSC) configuration [113] which is also extendable to three-phase directly is shown in fig. 2.7 (a). It gives a three level waveform of the converter input voltage as shown in fig. 2.4(b). The operating modes are given in the fig. 2.7 (b). The three-phase configuration is shown in fig. 2.8. Considering low switching frequency working of converters, harmonic reduction from a PWM waveform can be improved by increasing number of voltage levels on dc side [113, 114]. These configurations hence show potential to serve as a base for multilevel waveforms.

Interest in multilevel converter topology also is observed during last decade. By the use of multilevel converter concepts (three levels and more) it is possible to realize an amplitude modulation of the converter voltage by smaller voltage steps, i.e. a good approximation of sine waves can be achieved. The number of devices in series connection, which switch at the same time, is reduced, resulting in lower dv/dts of the power device. Furthermore, the pulse frequency of a single device can be reduced.

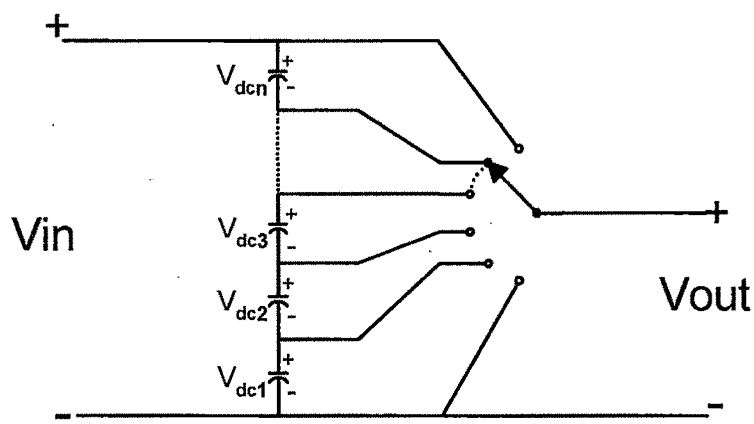


Fig 2.9 Equivalent circuit of multi level voltage source converter

Based on the same switching frequency and equal dv/dt per switching device, harmonics and EMC emission for multilevel converter can be effectively controlled. Thus filter circuits can be much smaller. However, these advantages have to be paid by more complex converter designs and higher control efforts. The three main concepts involving multi level topologies are

i) Diode clamped multi-level converter

ii) Flying capacitor converter, and

iii) Series connected H- Bridge cells.

Research and efforts for laboratory prototypes for VSC using multilevel configurations are reported in [115-119].

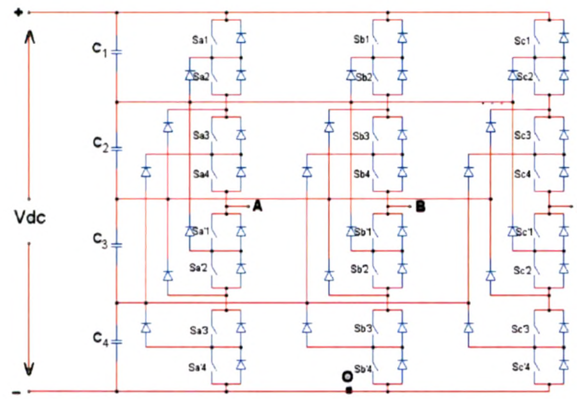


Fig. 2.10 A three phase, five level diode clamped converter

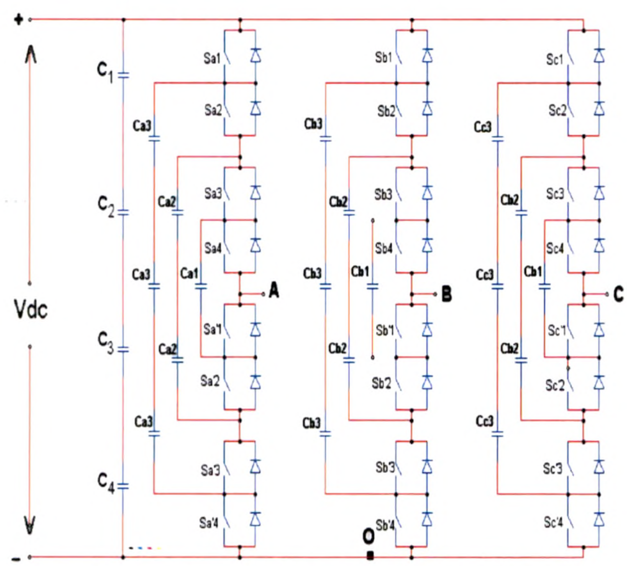


Fig. 2.11 A three phase, five level flying capacitor converter

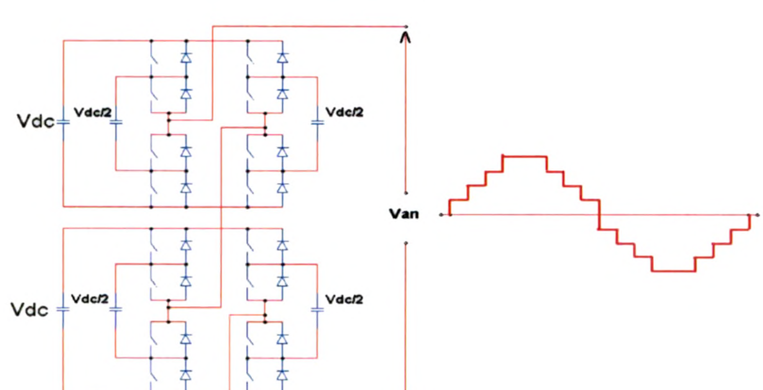


Fig. 2.12 A Hybrid multivel converter

2.3 HARMONIC ELIMINATION TECHNIQUES

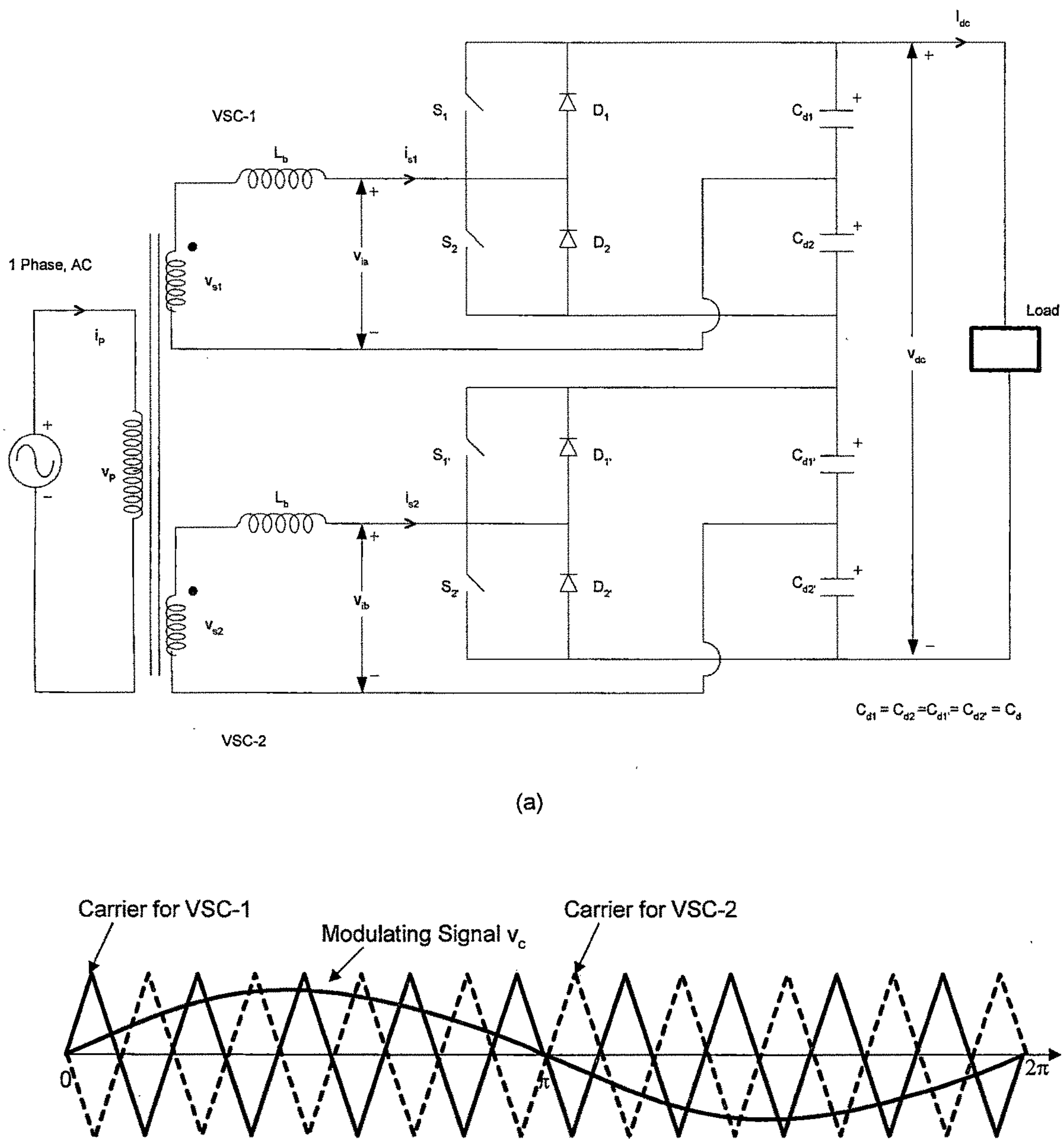
In the simplest form, VSCs use two level or three level converter input voltage waveforms. Three level waveforms have additional zero level switching state which reduces device switching frequency by about 25% for the same harmonic content of the load current. Alternatively, for the same switching frequency, harmonic content is much reduced as compared to a two level switching waveform [120-122].

Sinusoidal Pulse Width Modulation (SPWM) or programmed PWM technique [123] based on generalized harmonic elimination method suggested by Patel and Hoft [124] have been used with these VSCs.

Programmed PWM techniques exhibit several distinct advantages when compared to the SPWM technique. Further, Improvement in the SPWM technique with injection of harmonic signals (3rd and 9^{th}) on the modulating signal has been explained in [125] and harmonic reduction approaches are also consolidated in [126,127].

Technique, of operating two converters in series for reducing supply current harmonics considerably has been suggested in [73,128]. The principle is explained in fig 2.13(a). This principle of harmonic reduction can also be employed to converters operating in parallel with the same common output dc voltage bus. The transformer required with this technique can be avoided with the use of interphase reactors [94]. This is shown in fig. 2.14, where the converters operate in parallel. However, this arrangement has constraints use of more than two converters and hence limits output power transfer if it has to be deployed in large power applications. Another modified harmonic reduction approach is also discussed in paper [114].

Harmonic reduction by using multi-level converter configurations is also being investigated as one of the potential approach [117,119].



(a)

(b)

Fig 2.13 : **(a) Series operating converters**
(b) Carrier signals and common modulating signal

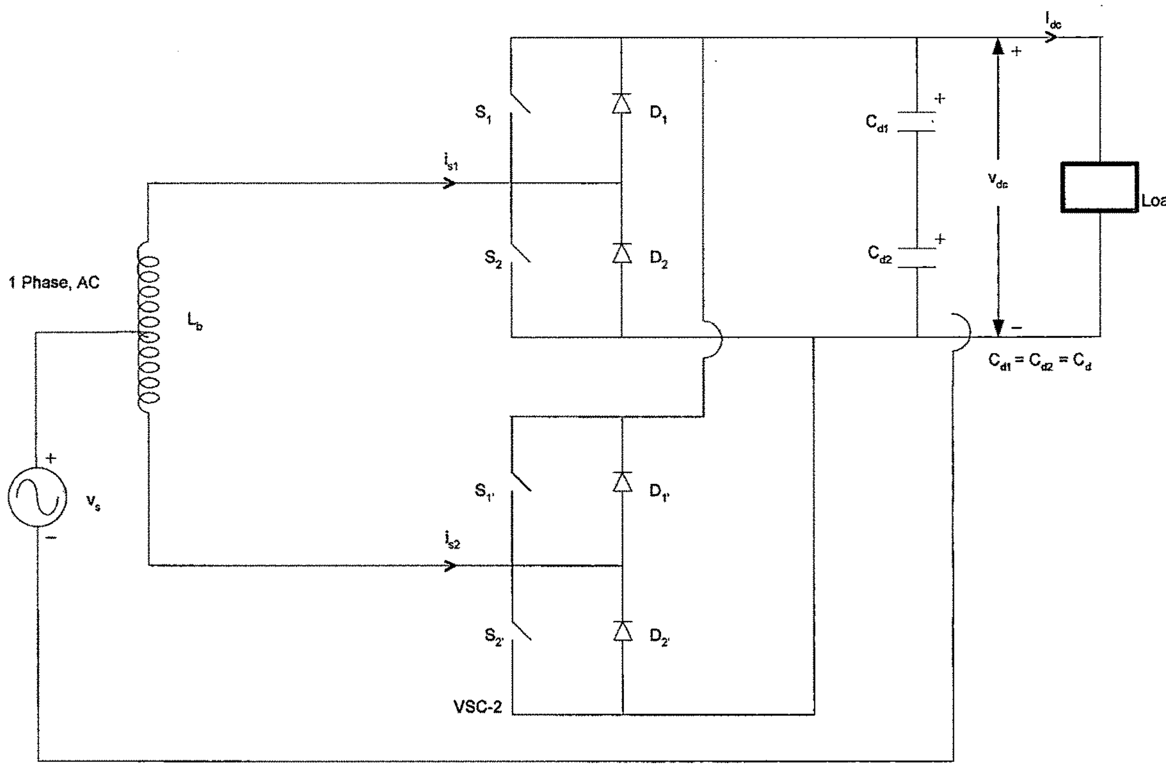


Fig 2.14 : **Parallel operating VSCs with interphase reactor**

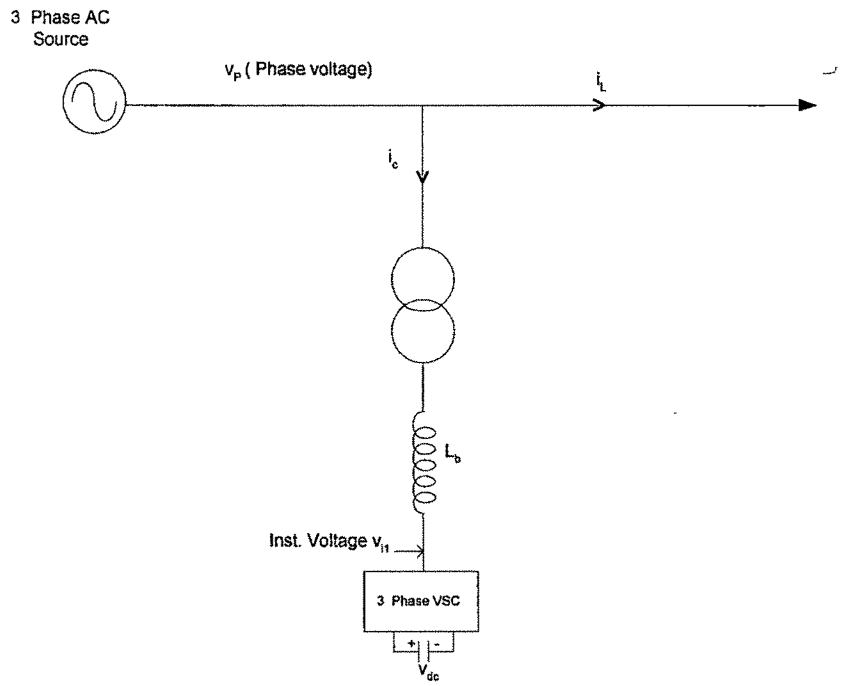


Fig 2.15 Line diagram for typical reactive power compensation scheme

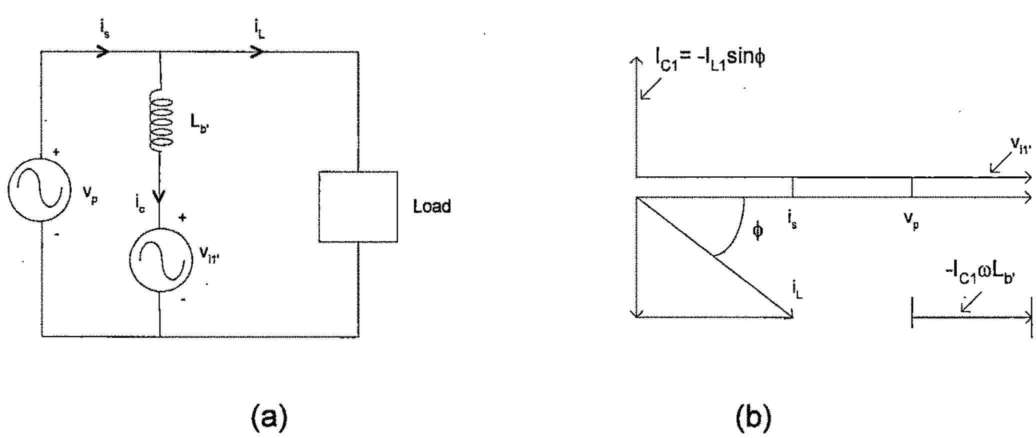


Fig 2.16 For typical reactive power compensation scheme
(a) Circuit diagram
(b) Vector relationship

2.4 VSCs FOR REACTIVE POWER COMPENSATION)

The principle of reactive power compensation using Voltage Source Converter (VSC) is shown in fig. 2.15 and 2.16. Figure 2.15 shows the line diagram of typical reactive power compensation scheme. circuit diagram and equivalent circuit diagram of the system considering only fundamental voltages and currents is also shown in 2.16 . The load current I_L lags the input system voltage V_p by an angle ϕ. The converter produces a compensating current equal to the $I_L \sin\phi$ component of the load current so that the input power factor is maintained at unity. This is shown in fig. 2.16 (b). The fundamental component V_{i1}, of the reflected converter input voltage V_i, on to the primary side of the transformer injects current I_c which compensates the $I_L \sin\phi$ component of the load current at the ac bus.

The idea here is to generate the reflected voltage v_i, (hence V_{i1}), as close to a sinusoidal voltage as possible. Since the current levels are quite high, power devices-switches Insulated Gate Bipolar Transistors (IGBTs), then need to be switched at low frequencies. Thus to realize sinusoidal voltage v_i, number of transformer secondaries connected to the individual converters are used and the converters are coupled on dc side to a single capacitor bank. In this connection, two basic schemes which appeared in 1990s in literature are given here. Some more schemes of recent installations are covered later in the chapter.

2.4.1 SCHEME -1

This scheme is shown in fig. 2.17 [89]. The scheme while eliminating the triplen harmonics by use of star / delta construction with appropriate winding ratios helps in reducing harmonics at the concerned substation to 1%.

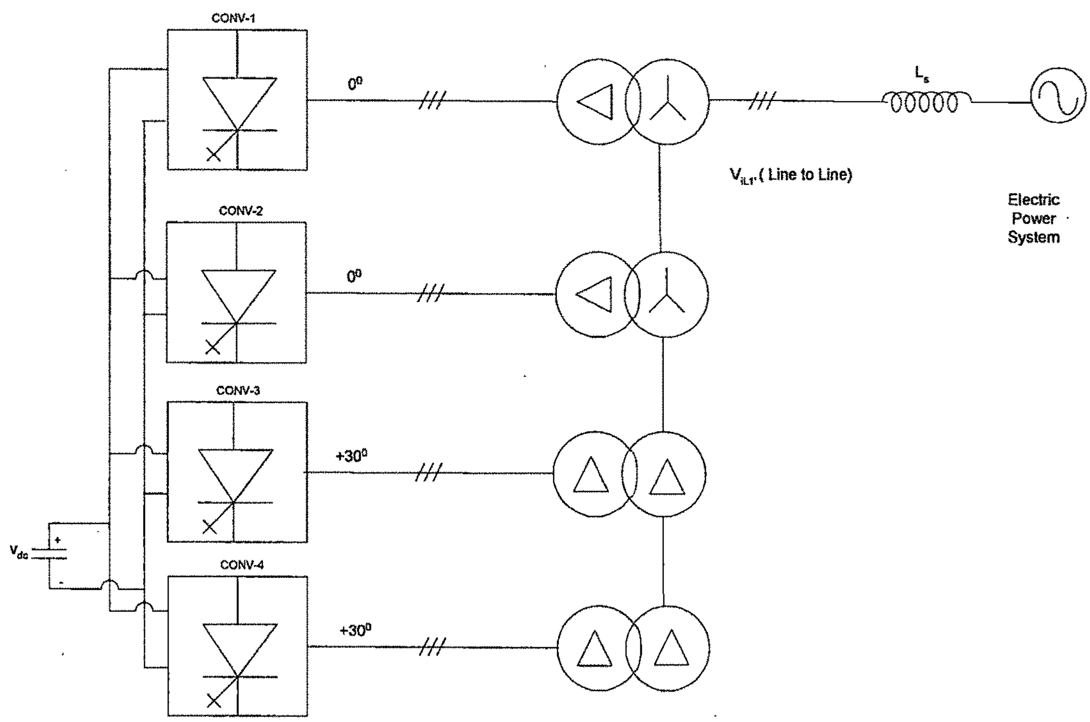


Fig 2.17 Static VAR compensator Scheme-1

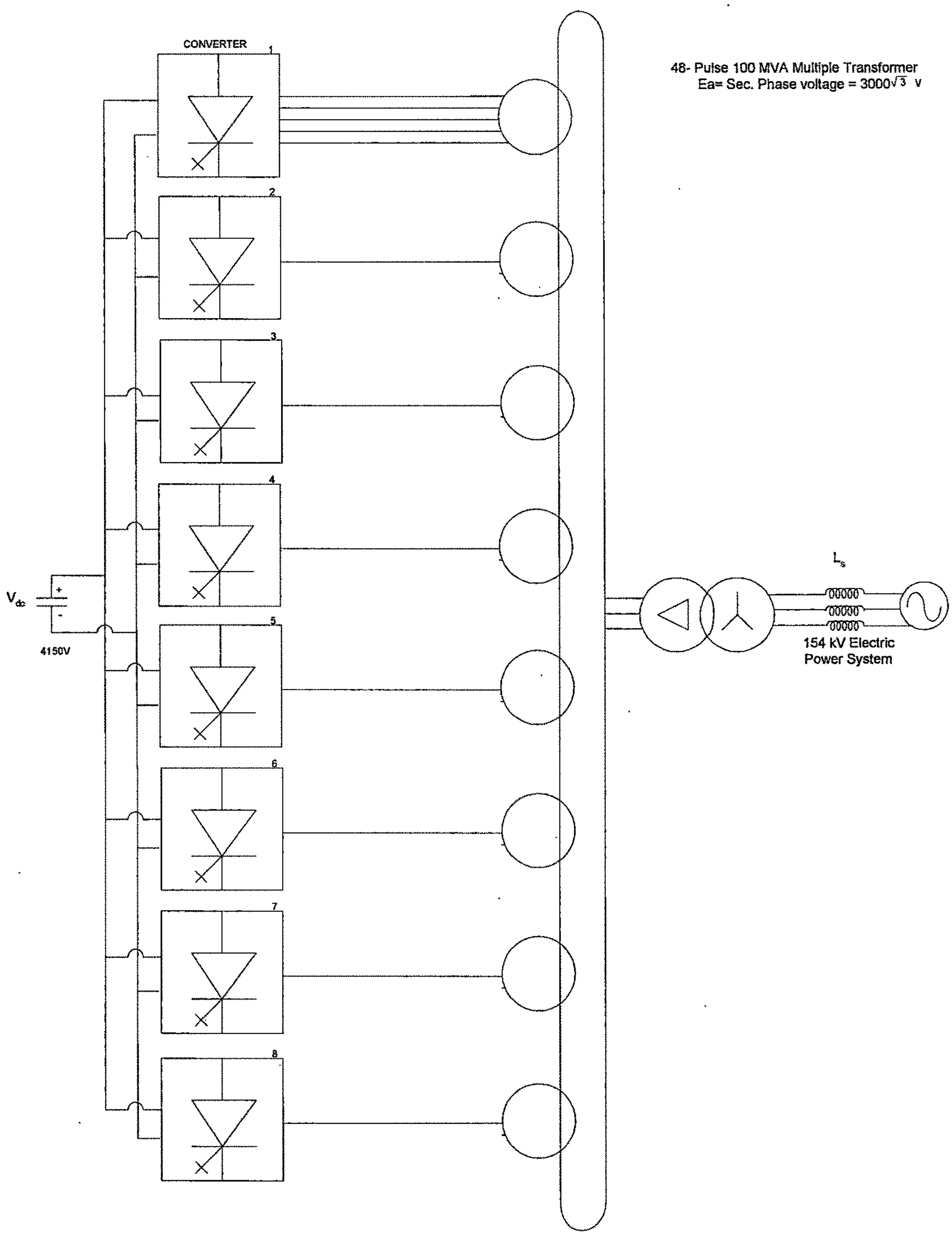


Fig 2.18 Static VAR compensator Scheme-2

2.4.2 SCHEME-2

This scheme is shown in fig. 2.18 [51]. It has been proposed for 100MVA static VAR Compensator. The given configuration helps in developing 48 pulse phase voltage waveforms as a reflected voltage from the VSCs. This is quite close to sinusoidal voltage and develops only $48k\pm1$ current harmonics with power system network.

Further, reactive power compensator using multilevel Voltage Source Converter (VSC), with n chain links per phase can also help to produce converter waveform with n voltage steps (transitions) per quarter cycle. It is therefore possible theoretically to eliminate n harmonic voltages from the output waveform by choice of power device switching angles. For installations of higher rating, the number of links and therefore voltage steps increases, giving further improvements in the harmonic performance [117,118]. However, till mid 1990s limitations for conversion into field product solutions were felt due to complex converter designs and higher control efforts.

2.5 CURRENT CONTROL TECHNIQUES

VSC use following current control techniques

- Hysterisis current control (HCC)
- Predictive current control with fixed switching frequency (PCFF)
- Indirect current control (ICC)
- Load current control (LCC)

From the point of view of low switching frequency operation of VSCs, only ICC and LCC techniques are given here.

2.5.1 INDIRECT CURRENT CONTROL (ICC)

This technique [72] is well suited for low switching frequency operation. The current control principle for a given power angle ϕ is same as defined in fig. 2.2 (b). The operation is shown in fig. 2.19

From fig. 2.2 (b) two equations governing the current control could be written as follows.

$$V_{i1}\cos\xi = V_s - I_{S1} R_s \cos\phi + I_{S1}\,\omega\,(L_s + L_b)\sin\phi \qquad (2.1)$$

$$V_{i1}\sin\xi = I_{s1} R_s \sin\phi + I_{S1}\,\omega\,(L_s + L_b)\cos\phi \qquad (2.2)$$

The ICC regulator solves these two simultaneous equations. The error in V_{dc} from a set reference defines the input current required. Assuming a simple SPWM process, the in phase and quadrature components of the modulating signal are obtained separately and added to get the modulating signal displaced at ξ degrees. This modulating signal develops the necessary fundamental converter input voltage V_{i1} at ξ degrees to obtain the demanded input current I_{s1} at a pre-selected power factor angleϕ. The triangular carrier is synchronized with the modulating signal at ξ degrees. For low switching frequency operation triangular carrier frequency is ess than nine times the fundamental frequency.

It must be noted that the regulator is sensitive to R_s and $(L_s + L_b)$ input parameters which have to be defined accurately. The above steady state equations solved do not contain Ldi/dt term which makes the regulator inferior to an HCC regulator. As such, a dynamically stabilized ICC regulator has been proposed in [73]. With the incorporation of Ldi/dt effect, the regulator performance is brought on par with HCC regulator.

The ICC regulator can accept any other PWM process provided the relation with fundamental converter input voltage is established (Voltage amplitude and displacement both should be known). The ICC technique also eliminates the need for the current sensing and hence eliminates the need for costly current transducers. This is an advantage of the technique over the HCC technique.

2.5.2 LOAD CURRENT CONTROL (LCC)

This technique is suggested in 1990s [129]. VSC operation in this case is controlled by load side direct current. The control scheme is given in fig. 2.20.

Referring the fig 2.2 (b) and equation as given earlier it is clear that there exists a definite relation between converter input voltage Vi1 and its power angle ξ so that the output dc voltage Vdc of the converter can be maintained constant while the converter delivers or regenerates the power. In fig. 2.20 input voltage Vi1 is maintained constant by fixed pattern PWM and power angle ξ is only varied. This results in leading or lagging power factor angle ϕ. The power angle ξ gets decided depending upon load current Idc.

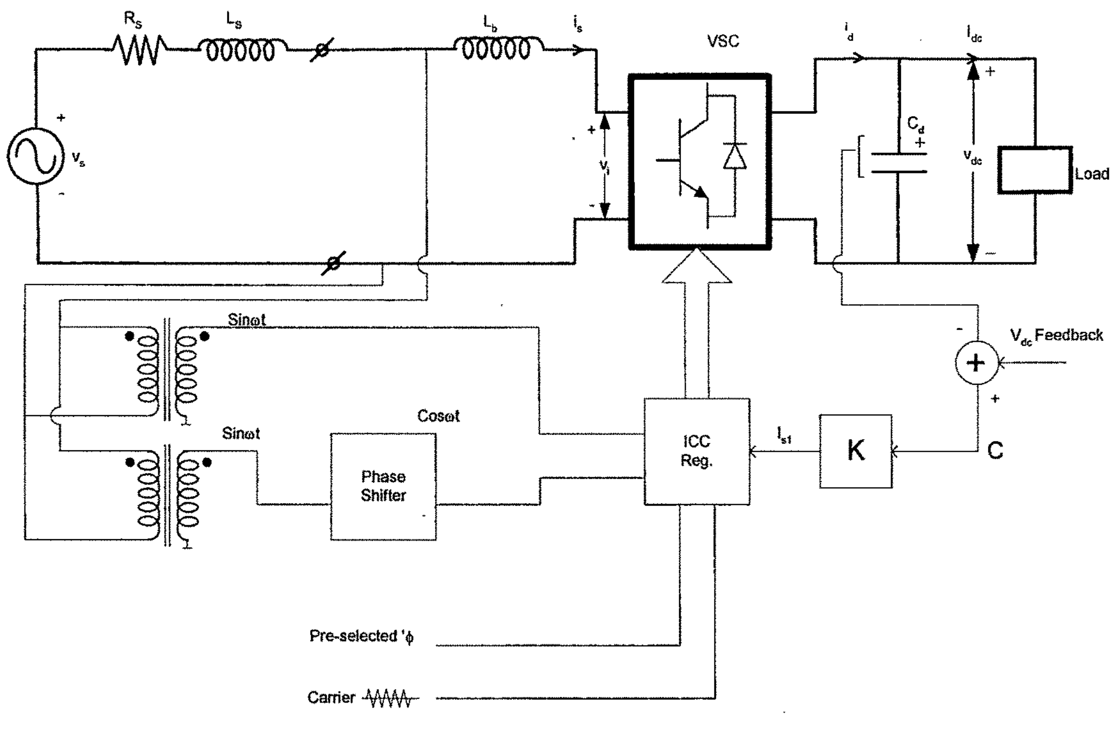


Fig 2.19 : Indirect Current Control Scheme

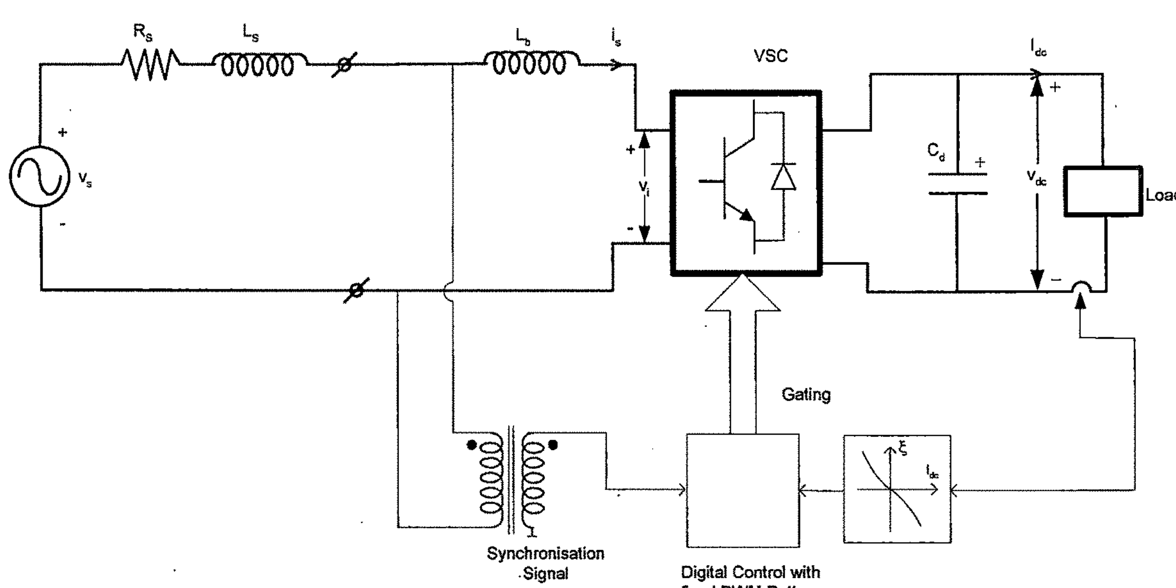


Fig 2.20 : Load Current Control Scheme

The advantages of this control technique are as below [129].

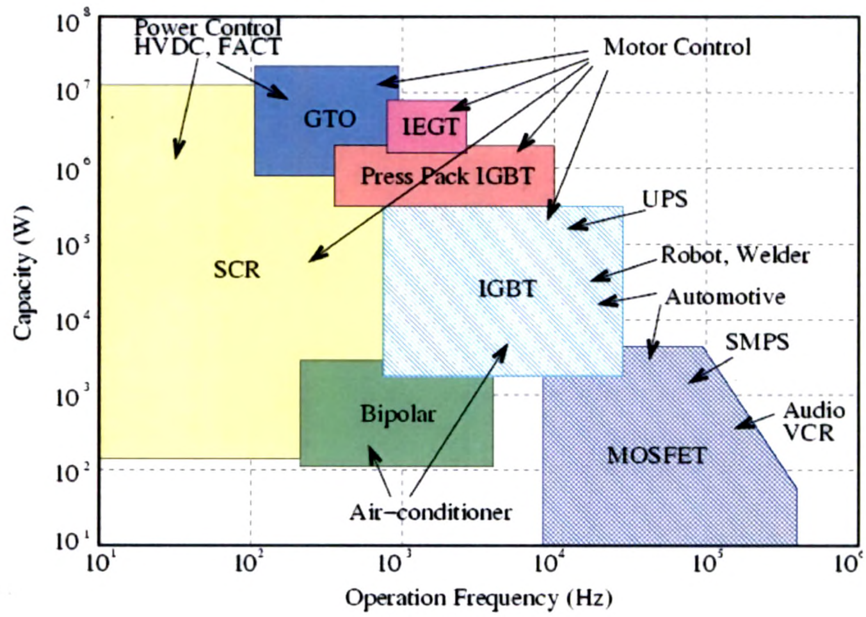
- Input current or dc voltage sensing is not required
- It uses fixed PWM pattern for voltage control. The pattern being fixed, it can be optimized.
- It can work with leading and lagging power factors with zero output dc voltage regulation for all load conditions.
- It presents a stable operation independent of the size of dc side capacitor.
- The technique works with open loop system.

It should, however, be noted that operating at unity power factor (powering as well as regenerating) is not possible with this control technique. The technique could be useful for correcting power factor of loads connected on the same ac bus while delivering power to a given load, thus correcting power factor for overall system.

2.6 POWER SEMICONDUCTORS- GENERAL TRENDS

Power semiconductor devices are used to control the energy transfer of electronic systems. Over the last two decades the technology of power semiconductors has made impressive progress [130]. The power function (switching or protection) is achieved through the combined use of low-voltage data and signal processing circuits with power devices. The application of Integrated Circuits (ICs) along-with power semiconductor devices has offered efficient protection components, simple drive characteristics, and good control dynamics together with a direct interface to the monolithic integration with the signal processing circuitry on the same chip. As a result, power electronic systems have greatly benefited from advances in power semiconductor technology. The technological trends have been in direction of lowering the system costs and simplified system design by reducing the number of components [38].

Generally, high power semiconductors can be classified in diodes, and controllable devices/ switches (with and without turn-off capability). The general trends in last years are described as below.



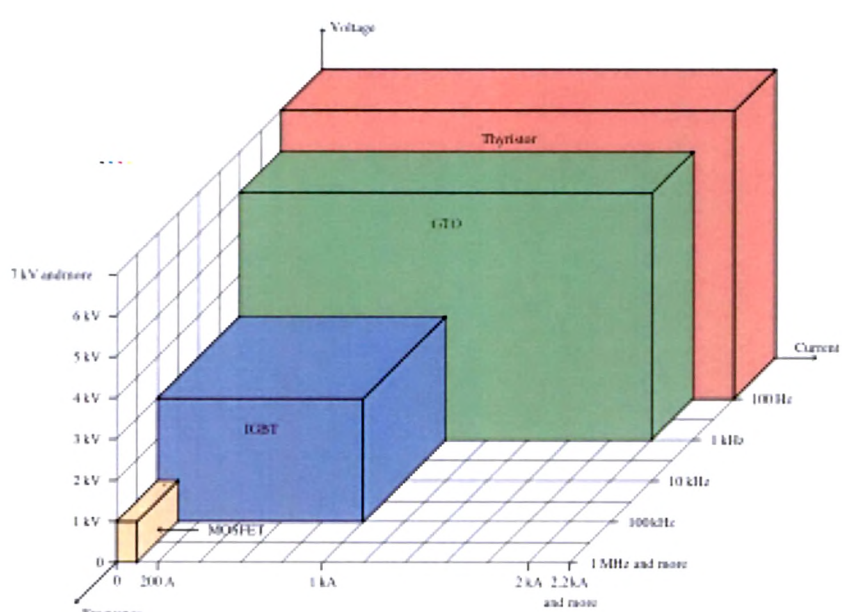


Fig. 2.21 Power Semiconductors Spectrum

2.6.1 DIODES

Rectifier diodes are mostly used as uncontrolled rectifiers for converters. Press pack diodes are available on the market up to four inch pellet diameter, 9kV blocking capability and more than 4kA average current. Trend in these devices is a development towards higher blocking voltages and towards bigger diameters to reduce the number of parallel connected devices in galvanic applications. Freewheeling diodes with improved designs have also been in use with the introduction of fast power switches such as IGBTs or hard-driven Gate Turn off Thyristors (GTOs) results, which have switching transitions at high di/dt and dv/dt values so as to provide soft recovery behavior and low recovery losses. Snubber diodes for usage in applications with GTOs, or with IGBTs in series connected stacks have also been supported with continued usage of GTO based converters.

2.6.2 THYRISTORS (DEVICES WITHOUT TURNOFF CAPABILITY)

Silicon Controlled Rectifiers (SCRs) developments have continued with the desire of increasing the blocking voltage and the current capability of the devices. Electrical Triggered Thyristors (ETTs) have been reported to get produced in small quantities for experimental or demonstrator applications with blocking voltages of up to 12kV and diameters of up to 6 inches; however, for a few years, the maximum repetitive blocking voltage commercially available has been about 8kV, with a wafer diameter of 5 inches. With the biggest markets for ETTs being HVDC and FACTS with application demanding high blocking capabilities for usage in the rectifier and the inverter to reduce the number of series connected devices. Light Triggered Thyristors (LTTs) which were developed for HVDC applications since 1970, have very limited commercial availability. Bi-directional thyristor (two thyristor in parallel) for AC applications, are available on the market up to 5 inch pellet diameter and blocking voltages of 6.5kV.

2.6.3 GTO AND IGCTS (DEVICES WITH TURN OFF CAPABILITY)

Asymmetric GTOs find good use in traction application. There are no reported significant developments based on GTO technology, with few suppliers in recent years. Insulated Gate Bipolar Transistors (IGBTs) and Integrated Gate Commutated Thyristor (IGCTs) are slowly replacing GTOs in many applications.

Development, of IGCT, has been quite successful. Intermediate device GCT used separate gate drive connected via a lead. While in the IGCT, a modified housing is used, allowing the gate drive circuit to be integrated very closely with the semiconductor device, and thereby achieving exceptionally low values of gate inductance. IGCTs with blocking voltages up to 6.5kV are now available on the market, while IGCTs with 10kV development has been reported [131].

2.6.4 TRANSISTORS

Bipolar transistors popularly in use during past decades have been largely replaced by the IGBT for low and high power applications. IGBTs, after introduction in the market in late 1980s have over the years seen the development towards new generations so as to reduce the losses and increase the efficiency. In contrast to high-power inverters using Thyristors or GTOs as power switches, IGBT inverters have been popular for use at higher PWM frequencies. The development over the last years has made the IGBT a power switch with rugged switching characteristics, low losses, simple gate drive and the possibility to control the device at any time (turn off of short circuits). Commercially available IGBTs with "module" construction have facilitated small thermal impedance between chips and base plate to guide the heat from the power chips which is of high significance [132-133].

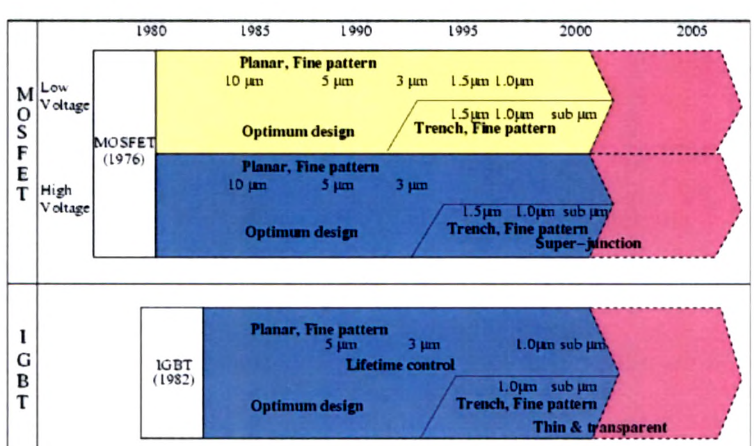


Fig. 2.22 Growth of IGBT technology

For high power inverters, IGBT modules are available on the market up to 6.5kV 600A and 1200//1700V 3600A. The current rating is realized by parallel switching of IGBT chips in the module. The trend for IGBT modules is to reduce the overall losses and hence reduce the size of IGBT modules. Few IGBTs, with press packs construction are used in applications like voltage sourced HVDC and Pulsed Power applications. The max voltage for a standard Press Pack IGBTs (PPI) is 4.5kV. IGBTs with contact to the chips getting realized by springs, guarantee a uniform contact pressure and the ability to short in case of a failure [133]

Overview of available semi-conductors is given in Table 2.1 [134-140]

Table 2.1 Overview of available Power Semiconductors

	Thyristor	BJT	FET	GTO	IGBT	IGCT
Availa-bility	Early 60s	Late70s	Early 80s	Mid 80s	Late 80s	Late 90s
State of technology	Mature	Mature	Mature / Improve	Mature	Rapid improve	Rapid improve
Voltage Ratings	8.5KV	1KV	0.5KV	6KV	2.5KV/3.3KV*	6KV
Current Ratings	5.5KA	0.4KA	0.2KA	4KA	1.3KA/2.8KA*	4KA
Switching Frequencies	N/A	5KHz	1MHz	2kHz	100kHz (15kHz med power)	3 kHz
On state Voltage	2V	1-2V	I * R ds (on)	2-3V	2-3V	Less than GTO
Drive circuits	Simple	Difficult	Very simple	Very simple	Very simple	Integrated
Comments	Cannot turn off using gate signal	Phasing out in new products	Good performance in high frequency	Very good in very high power	Best overall performance	Best in very high power

*Recent trends

2.6.5 CONTROL ELECTRONICS

On the basic control electronics side, the rapid growth of Microprocessors since early seventies and subsequent availability of Micro-controllers and Digital Signal Processors (DSPs), in combination with new generation of Analog interfaces (on chip/ off chip) have led to "Embedded Control Hardware" designs [40, 141]. Even varied control approaches using simulation tools and adaptive, fuzzy, neural networks based controls with variety of hardware-software integrated features are equally deployed to achieve the optimal performance [142-146].

Considering Power Electronics (PE) application requirements, the power to be converted in a controlled manner ranges from a few watts to several hundred megawatts. The basic operation in power conversion is the switching of the power devices in a controlled manner, which demands real time performance with complex online signal acquisition and processing based on system parameters (voltage, current, line frequency). Other than this, many non-critical signal processing work like operating interlocks including reporting status of the application system, some online parameters value display, communication with other control system etc. also becomes a integral part of control electronics and associated logic deployment.

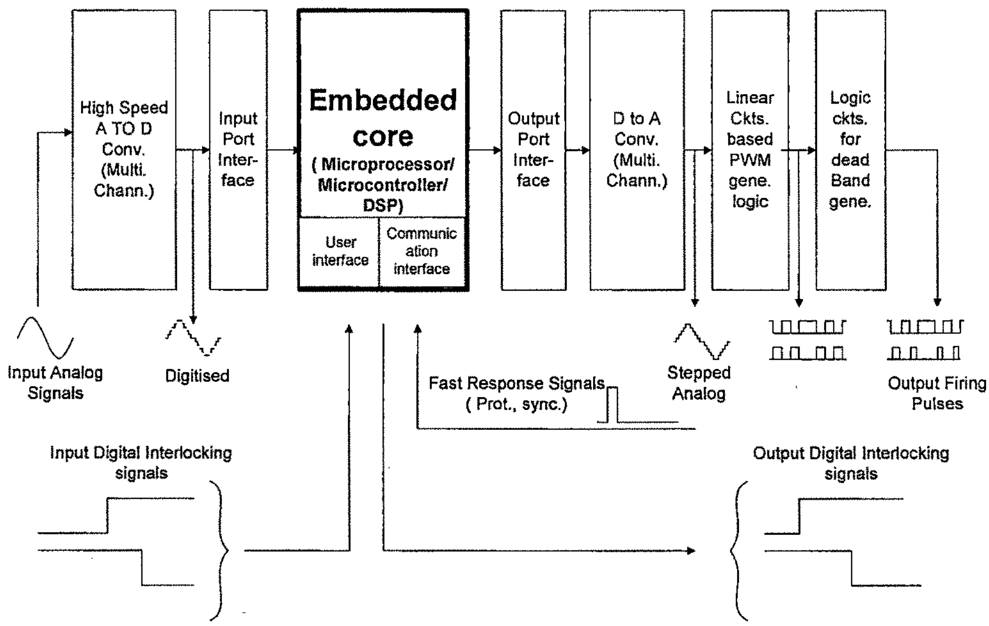


Fig. 2.23 Control Electronics

Presently, there are varieties of Microcontrollers and Microprocessors from various manufacturers. These available processors are categorized in conventional processors and DSPs based on their architecture, speed, power consumption and real time performance etc. Other than the conventional processors, the current trend is to use DSP because of its application specific architecture fulfilling the needs [40,147-149]. Details of presently available DSPs are in the Table 2.2.

Some of the recent developments also indicate progressive integration of Power devices, Gate drivers, and other components into basic building block with clear defined functionality. This provides interface capabilities to serve multiple applications and thereby reducing cost, losses, weight, size and engineering effort for the application and maintenance of power electronics systems. Power Electronic Building Block (PEBB) is one such concept promoted by many manufacturers in order to develop standardized and universally applicable intelligent power modules [38,150].

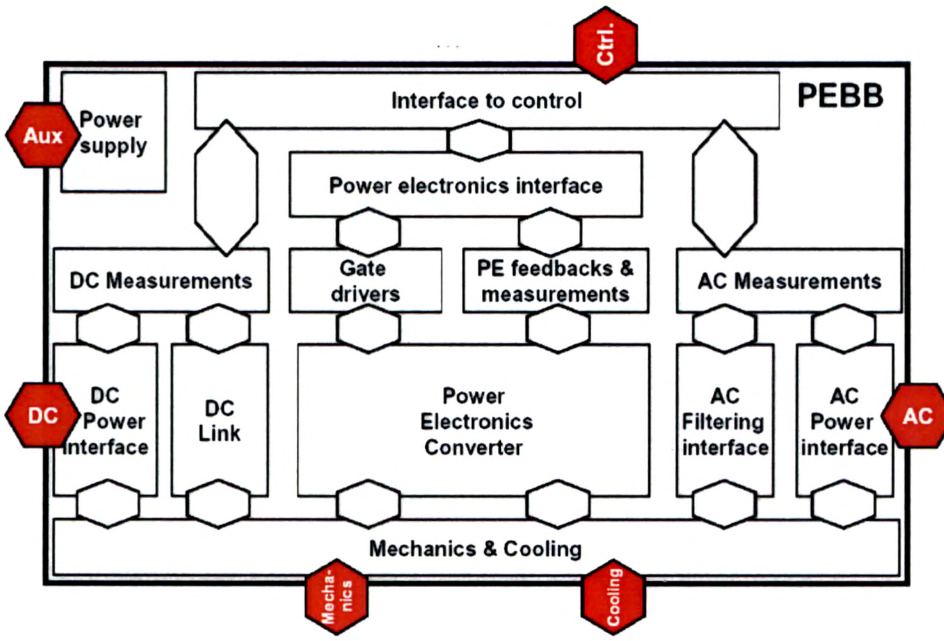


Fig. 2.24 PEBB Functionality and interfaces

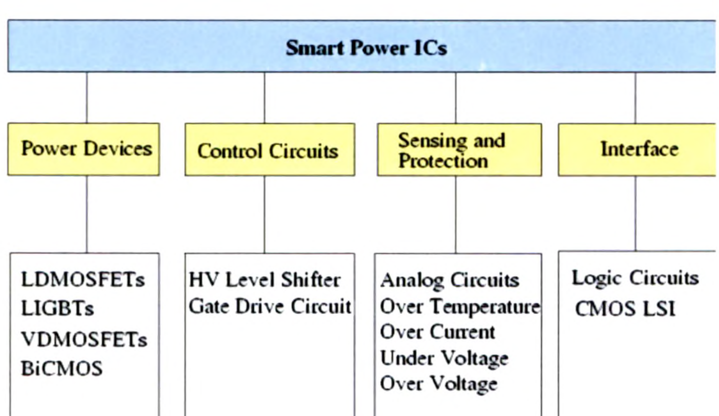


Fig. 2.25 Smart Power ICs

Different vendors have also been offering intelligent power modules, or the devices with gate driver circuits, and even sometime readily built standard power stacks for facilitating rapid engineering solutions development [130, 38].

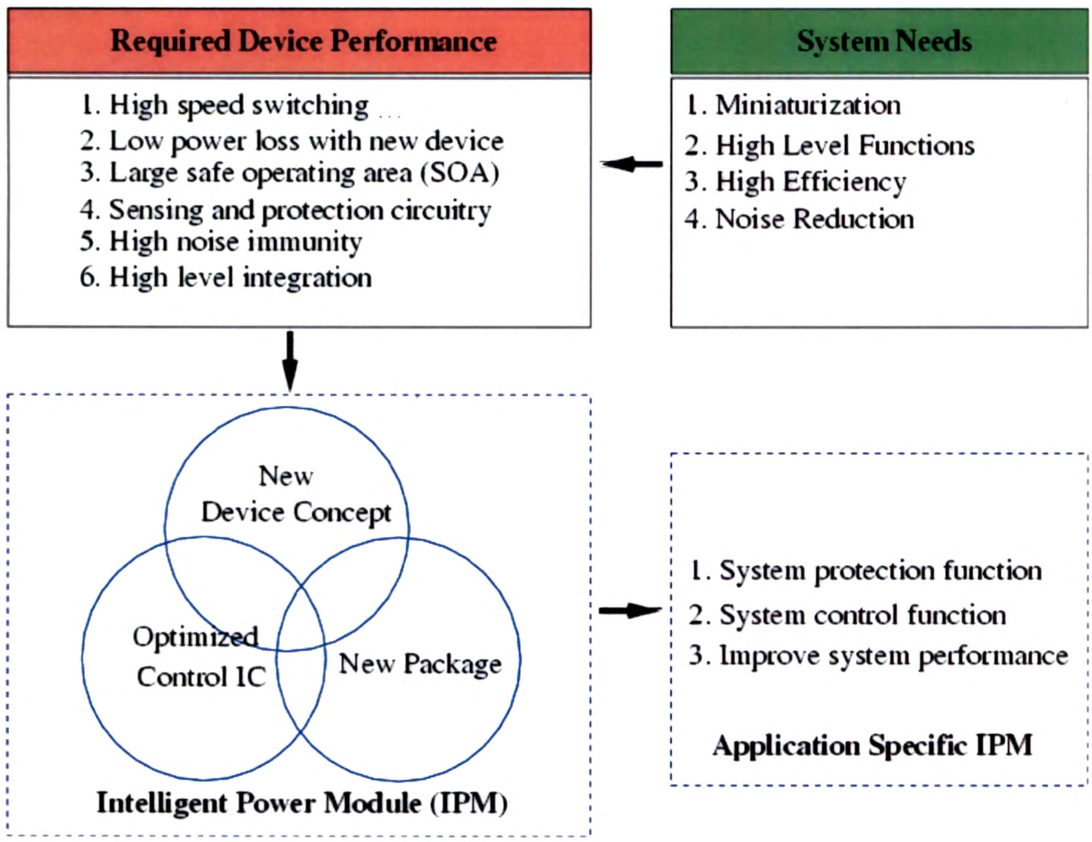


Fig. 2.26 New Concept in Power Devices Integration

Due to increase global demand of high power semiconductors, developments based on new semiconductor materials (Silicon Carbide instead of presently used silicon) with devices having small area are reported with lower losses to improve the overall performance. Research also has been reported for device with high temperature packages, in order to utilize the high temperature capability of some of these new devices [38,39].

Table 2.2 Recent commercially available DSP details

Sr.No.	3DSP	AMSI	ANALOG DEVICES	ARM	BOPS	HITACHI	MICROCHIP	RABBIT SEMICONDUCTOR	ATMEL	INFINEON
DSP family	MCU-based		MCU-based	MPU-based	MCU-based	MCU/MPU-based	MCU-based	MPU-based	MCU, MPU-based	MCU/MPU-based
CISC/ RISC	RISC	RISC	RISC/CISC	RISC	RISC	RISC	RISC	CISC		RISC/ CISC
Program Memory	ROM,RAM, FLASH, CACHE	ROM	ROM,RAM	ROM,RAM, EPROM, EEPROM	RAM	ROM,FLAS, SDRAM, CACHE	RAM, FLASH	SRAM, FLASH	RAM, FLASH	ROM,RAM, EPROM, EEPROM
Data Memory	ROM,RAM, FLASH	RAM	RAM	ROM,RAM, EPROM, EEPROM		RAM, CACHE	RAM,FLASH	SRAM, FLASH	RAM, FLASH	ROM,RAM, EPROM
Peripheral Available	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO
C Compiler Available	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES
Assembly optimization tools available	YES	NO	NO	NO	YES	YES		YES	YES	YES
JTAG Support for Emulation	YES	NO	YES	YES	YES	YES	YES		YES	YES
Full JTAG test support	YES	NO	YES	YES	YES	YES	YES		YES	YES
Part family	SP-5,SP-3	GEPxx	ADSP-21xx, Blackfins, Tigersharc, sharc	ARM9xx, ARM7xx	2010xx, 2020xx, 2040xx	HD6417xx, HD6437xx, HD64F2623x	dsPIC33, PIC32	Rabbit2000, Rabbit3000, Rabbit4000, Rabbit5000	AT91, SAM7, SAM11	CARMEL, TC10GP
URL link for datasheet	www.3dsp.com		www.analog.com/dsp	http://www.arm.com/products/CPUs/embedded.html	www.bops.com	http://www.hitachi.com/New/cnews/E/1998/980910B.html	http://ww1.microchip.com/downloads/en/DeviceDoc/61143E.pdf	http://www.rabbit.com/products/rab4000/	http://www.atmel.com/products/at91/	http://www.infineon.com/cms/en/product
URL link for Application Note	www.3dsp.com		www.analog.com/dsp	www.arm.com/Documentation/AppNotes/	www.bops.com	www.hitachi.com	http://www.microchip.com	http://www.rabbit.com/products/rab4000/	http://www.atmel.com	www.infineon.com

Table 2.2 Recent commercially available DSP details (contd…)

Sr.No.	LSI Logic	LUCENT	PHILIPS	Star* Core	Texas Instruments	VLSI	ZiLOG	RENESAS SEMICONDUCTOR	FREESCALE SEMICONDUCTOR
DSP family	DSP-based	DSP-based	MCU/MPU-based	MPU-based	DSP-based	MPU-based	MCU-based	MCU-based	MCU-based
CISC/ RISC	RISC	RISC	CISC/RISC	RISC	CISC/RISC	RISC	RISC	RISC/CISC	RISC,
Program Memory	ROM,RAM	ROM,RAM, EPROM,EEPROM	ROM, SDRAM, FLASH		RAM,ROM, OTPROM,FLASH	ROM, RAM	SDRAM, ROM, FLASH	RAM,FLASH	SRAM,EEROM, FLASH
Data Memory	ROM,RAM	RAM	ROM,SDRAM, FLASH		RAM,ROM, OTPROM,FLASH	ROM, RAM	SDRAM, ROM, FLASH	RAM,FLASH	SRAM,EEROM, FLASH
Peripheral Available	YES	YES	YES	YES	YES	YES	YES	YES	YES
C Compiler Available	YES	YES	YES	YES	YES	YES	YES	YES	YES
Assembly optimization tools available	NO	NO	YES	YES	YES	YES	NO		
JTAG Support for emulation	YES	YES	YES	YES	YES	NO	NO	YES	
Full JTAG test support	YES	YES	YES	YES	YES	YES	NO	YES	
Part family	LSI401Z, ZSP 400, ZSP 800	DSP 16xx	LPC 21xx, TM-11xx	SC 140	TMS320F2xx, TMS320F3xx, MSP430	VS 10xx, VS 11xx	ZA9Lxxxx	M32Cxx,M16Cxx, M32Rxx,SH7xxx	MMC2114, MAC 7200
URL link for datasheet	www.zsp.com	www.lucent.com/micro/dsp16000/dsp16000_doc.html	http://www.nxp.com/	www.starcore-dsp.com	www.ti.com/sc/dmc	www.vlsi.fi/en/product	www.zilog.com/products	http://www.renesas.com/products (Hitachi/Mitsubishi)	www.freescale.com (Motorola)
URL link for Application Note	www.zsp.com	www.lucent.com/micro/dsp16000/dsp16000_doc.html	http://www.nxp.com/	www.starcore-dsp.com	www.ti.com/sc/dmc	www.vlsi.fi/en/product	www.zilog.com/products	http://www.renesas.com/products	www.freescale.com

2.7 APPLICATIONS

With advancement in control techniques, power devices and converter topologies, state of the art power electronic systems are applied in electric power distribution as well as transmission systems. Power quality remains the prime objective in distribution systems. While in transmission system power electronic systems are used for voltage and transient stability enhancements and power flow control. It is to be noted for AC transmission systems the devices are called FACTs while for dc transmission systems these devices are termed as HVDC components [150-154].

Further however, focus here is maintained on the distribution systems where application requirements are mainly based on following parameters,

- Reduction of voltage sags and swells
- Elimination of harmful harmonics [155-156]
- Voltage Flicker or ride-through of short outages [157-164].

Typical applications include spot welding applications, windmill [165-172], hydro power plants [173], electric traction [174-176] etc.

Use of technologies utilizing large pulsed type load characteristics such as arc furnace, resistance and/or spot welding equipment, rolling mills, wood chip mills, rock crushing equipment have become widespread. Similarly, in application like railways, traction substation sees highly dynamic loading conditions, while in power generation through windmill or hydro turbine, the time varying nature of the basic source (wind flow / water flow) also results in fluctuating source itself. With emphasis on infrastructure build up in developing countries and increase demands in developed countries, the number and size of such fluctuating source/loads getting installed do end up in power quality problems. For example, typical arc furnaces in 1980's were rated 30-40MVA with 40-50 tons of scrap metal processing capacity. Currently typical arc furnaces are rated at 160-200MVA and have a scrap metal processing capacity of 150-200 tons. Similarly, rural and railway electrification have seen a big thrust in India during the last decade [5]. Installations for Wind based power generation have also grown considerably during the previous years [6]. Equally well, automotive manufacturing units are on rise with improving standard of living of people in India. Thirst for the economical solution for addressing Power Quality issues for such sector therefore has been on rise.

Earlier, in absence of other technologies offering better solutions, Static VAR Compensators (SVCs) have been widely utilized for such needs. In fact out of 900 SVC applications around the world to date, around 600 have been utilized for improving power quality, (mainly flicker reduction applications) [157].

Further, in last three decades problems related to power supply quality however, has also significantly grown [177]. This is, partially due to the higher sensitivity of power electronic equipment to reductions in supply quality. Also, on the other side there is also increase in consumer awareness of widespread consequences of power quality problems. In addition, the lack of sufficiently low system impedance (transmission system strength) for connecting such loads and the performance limits of the SVC has created an urgent need for a new technology based solution [178].

From the conventional technology point of view, SVCs, based on Thyristor-Controlled Reactor (TCR), have been used for arc furnace and flicker compensation for over three decades. These solutions have limitation related to the,

- Inherent time delay of the thyristor controlled reactor (TCR),
- Dynamic interactions between the highly resonant LC filter network of the SVC, the fluctuating load and the TCR, and
- SVCs inherent inability to compensate active (real) power fluctuation.

Because of these limitations, the SVC is, in general, only able to reduce the flicker by a factor close to two. However, in many applications a flicker reduction factor greater than two is usually required to meet the power quality requirements of the power system to which the arc furnace or fluctuating load is connected. The limitations of the SVCs due their inherent characteristics also meant that no further flicker reduction could be obtained by applying SVCs with increased ratings.

The Dynamic reactive power compensator(STATCOM/ STATCON), based on the operating experience in technology demonstration projects at Sweden, Japan and the USA, demonstrated that a reduction in flicker by a factor of four to six was achievable when compared with an SVC of comparable size and cost. Furthermore, due to the inherent characteristics of such compensator application of additional units, would result in further significant reduction in flicker i.e., unlike in the case of SVC, increasing the STATCOM rating would result in a larger reduction in flicker.

Specific cases for Railways, Automotive and windmill applications have been highlighted in the references [165-176]. Some more developmental efforts are also reported [179-195]. However, no specific technological solution for Low Voltage (LV) application which also provides economical installation for such requirements were made available till 2005 [196].

Some of important installations of Reactive Power Compensator (SVC/ STATCOM) reported in literature are given below [197].

2.7.1 SEQUIN, TEXAS, USA

Siemens (formerly Westinghouse) announced the application of STATCOM for arc furnace compensation in 1995 and has subsequently installed a large STATCOM based compensator for Structural Metals Inc. (SMI) of Seguin, Texas in 1998. It comprises a ±80 MVA STATCOM with a shunt coupling transformer connecting it to the 15 kV furnace bus. The STATCOM operates in conjunction with a fixed 60 MVA ac capacitor bank,

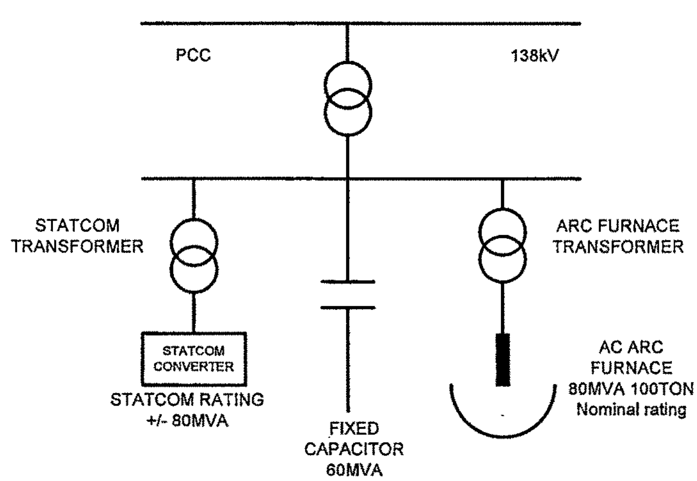


Fig 2.27 Single line diagram of the Statcon installation at Seguin, USA

2.7.2 HAGFORS, SWEDEN

This is a ±22MVAR STATCOM (trade marked SVC Light. by the manufacturer ABB) installation in operation since 1999 which together with the existing harmonic filters at the site yields an overall reactive compensation range of 0-44MVAR (capacitive). The voltage sourced converter (VSC) of a three-level design utilizes Integrated Gate Bipolar Transistors (IGBTs) as switching devices. The converter also uses Pulse-Width Modulation (PWM), with a switching frequency of 1.65 kHz to generate a smooth balanced sinusoidal voltage.

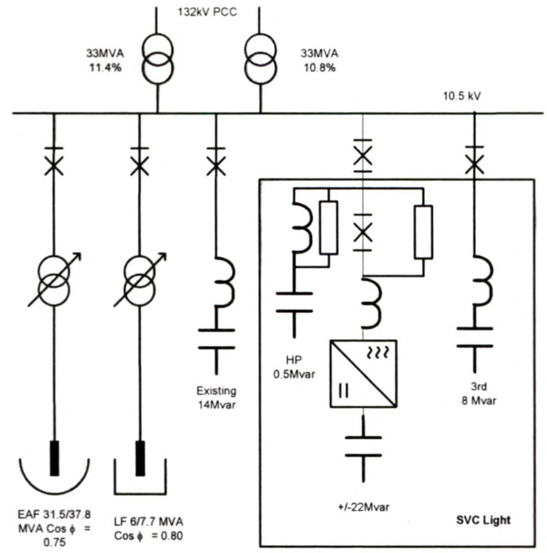


Fig 2.28 Single line diagram of the Statcon installation at Hagfors, Sweden

2.7.3 TRIER, GERMANY

This is a ±19MVAR STATCOM (trade marked SVC Light. by the manufacturer ABB) installation in operation since 2000 which together with the existing harmonic filters at the site yields an overall reactive compensation range of 0- 38MVAR (capacitive). The installation owned by the steel producer Moselstahlwerk, at Trier, Germany, consists of an a.c. Electric Arc Furnace (EAF) for scrap metal melting rated at 25/30 MVA.

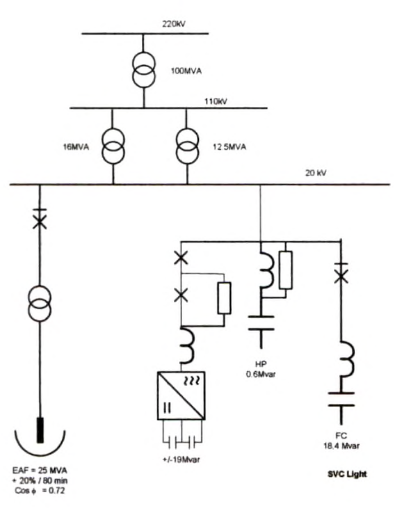


Fig 2.29 Single line diagram of the Statcon installation at Trier, Germany

2.7.4 TORNIO, FINLAND

This is a ±82MVAR STATCOM (trade marked SVC Light. by the manufacturer ABB) installation which will become operational in 2002 which together with the existing harmonic filters at the site yields an overall reactive compensation range of 0- 164MVAR. The installation owned by the steel producer Avesta Polarit, at Tornio, Finland, consists of an a.c. Electric Arc Furnace (EAF) for scrap metal melting rated at 140/160 MVA.

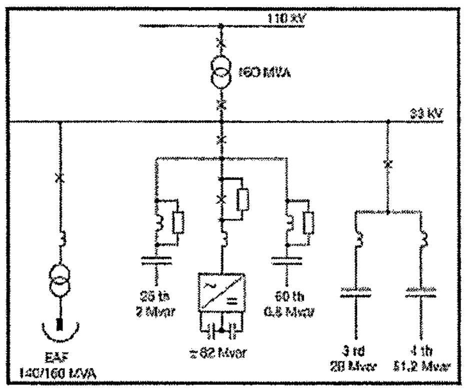


Fig 2.30 : Single line diagram of the Statcon installation at Tornio, Finland

2.7.5 REJSBY HEDE WINDFARM, DENMARK

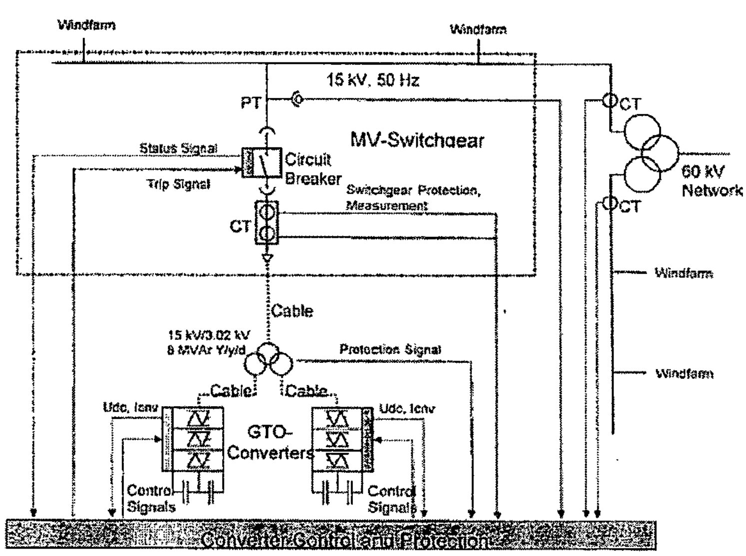


Fig 2.31 : Single line diagram of the Statcon installation at Rejsby Hede windfarm, Denmark

In 1997, trial operation of ±8 MVAR STATCOM was installed to provide reactive power to Rejsby Hede Windfarm of the Danish utility ELSAM. These wind-farm one of the largest in Denmark, consists of wind generator of 600kW (max) and 150kW (max) ratings. Use of induction generators results in significant loading of local grid, hence reactive power must be generated close to the wind-farm. This design is based on two number three level voltage source GTO based converter connected to 15kV/3.02kV system through transformer.

2.7.6 EAST CLAYDON, UK

This installation done in 1996 is for National Grid Company by Alsthom, and design includes +/-75MVAR STATCOM in conjunction with 127MVAR TSC and 23MVAR fixed capacitor to provide a full controlled range of output +225 to -52MVAR.

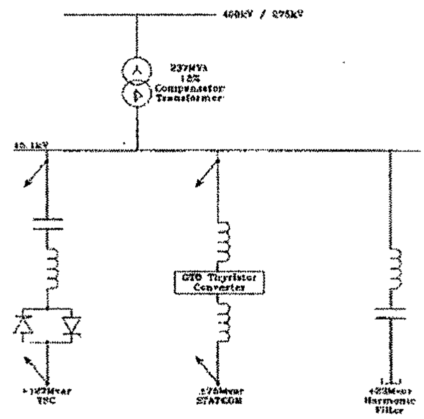


Figure 10.7 : East Claydon SVC Installation

Fig 2.32 : Single line diagram of the Statcon installation at East Claydon, UK

2.7.7 SHIN SHINANO, JAPAN

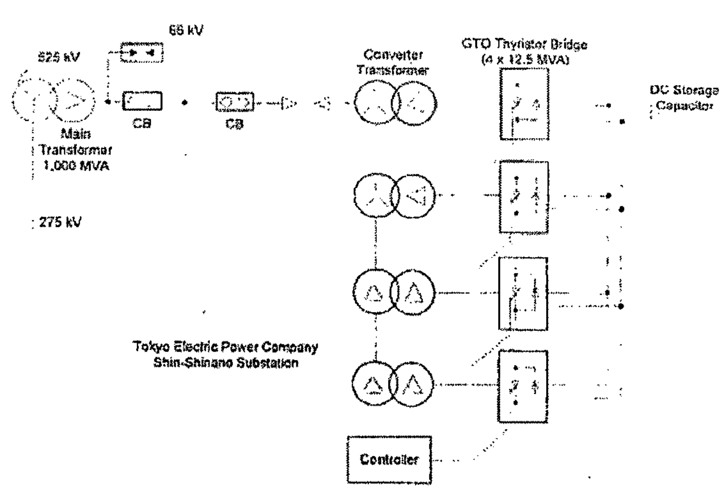


Fig 2.33 : Single line diagram of the Statcon installation at Shin Shinano, Japan

The installation, done during 1992-96, is +/-50MVAR which is developed by joint efforts of Tokyo Electric Power Company with Toshiba Corporation and similar rating unit is also deployed at the substation which is supported by Hitachi Corporation. Basic unit are of 12.5MVA VSC based converters

2.7.8 CHANNEL TUNNEL RAIL LINK, BETWEEN ENGLAND AND FRANCE

In recent years, STATCOM installation for railway substation installations also has been reported. Channel Tunnel rail link between England and France. Singlewell substation with two single-phase static var compensators, each rated 25 kV, –5/+40 MVAR

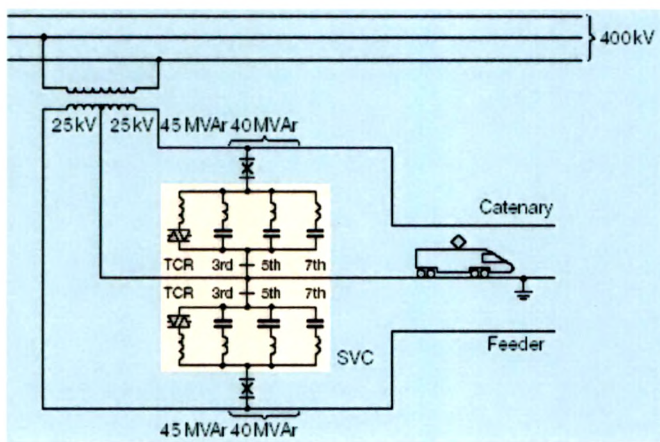


Fig 2.34 : Single line diagram of the SVC installation at Channel Tunnel rail link between England and France

More Details of different installations of SVC/ STATCON are covered in the reference [198,199]

2.8 CONCLUSION

As seen from this review, Voltage Source Converters remain the backbone for the dynamic reactive power compensation applications. Major changes in the basic converter topologies are not explored due to well engineered and well proven design experiences now available for tens of years on these topologies. IGBTs based Voltage Sourced Converters with two or three level technologies seem to be emerging as popular solutions for various power electronic applications including energy distribution.

On the other side, as covered in chapter, for reactive power compensation the SVC/STATCOM installations, across globe which have emerged and reported during till 2003, have been mainly for medium voltage and MVAR as the ratings. There have not been any major reported installations for the low voltage applications. Deployment of reported solutions for low voltage applications, have also been prohibitive in terms of economics, since the system cost of available solutions have not been comparable with the cost of traditional solutions in use. Few manufacturers in US, Belgium have been working on dynamic reactive power compensator solutions [200-205]. Similarly, there have not been any reported commercial installations for low voltage distributions systems using Statcom in India. Different manufacturers in India however, in the recent past have tried to develop economical solutions as reported from reference [206-214], but from the field installation point of view there have been none for dynamic reactive power compensation, especially for application like spot welding applications in automobile industry, for single-phase traction substations etc [215].This also has led the Indian Government to push through TIFAC the development of the power factor correction products. [216].

As also reflected from the details of available power quality solution [8, 10, and 14], need for economical solutions to address power quality issues, especially for weak networks is on rise. Thus, continuation of research on mitigation of reactive power (more so dynamically varying) and current harmonics / distortion caused by them has been need of hour. This further, has fuelled demand for new methods / techniques for power quality and especially reactive power control based on Voltage Source Converters (VSCs) for low voltage applications. Further, availability of high quality of power for process critical industries have so far remained unaddressed, fuelling the strong need for economical methods and product solutions which can fill the gaps.

In line with this scenario, work presented in this thesis thus deals with new methods / techniques for reactive power control using Pulse Width Modulation (PWM) based Voltage Source Converters (VSCs) including design approaches for overcoming the challenges which can be faced for reliable field installations. This is then followed, by details on economical technique for controlling sudden voltage dips/rises in the industry networks and unity power factor based Electronic Transformer, facilitating availability of quality power for the critical applications.