NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

REACTIVE POWER COMPENSATION TECHNOLOGIES

Graduation Project
EE- 400

Student:Cenk Keçecioğlu (20041565)

Supervisor: : Asst.Professor
Dr.Özgür C. Özerdem

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ABSTRACT

This paper presents an overview of the state of the art in reactive power compensation technologies. The principles of operation, design characteristics and application examples of VAR compensators implemented with thyristors and selfcommutated converters are presented. Static VAR Generators are used to improve voltage regulation, stability, and power factor in ac transmission and distribution systems. Examples obtained from relevant applications describing the use of reactive power compensators implemented with new static VAR technologies are also described.Reactive power compensation in electric systems is usually studied as a constrained single-objective optimization problem where an objective function is a linear combination of several factors, such as, investment and transmission losses. At the same time, constrains limit other parameters as reliability and voltage profile. This paper presents a new approach using multi-objective optimization evolutionary algorithms. It proposes a variant of the strength Pareto evolutionary algorithm (SPEA) that independently optimizes several parameters, turning most traditional constraints into new objective functions. That way, a wide set of optimal solutions, known as Pareto set, is found before deciding which solution best combines different features. Several sets of solutions calculated by different methods are compared to a Pareto set found with the proposed approach using appropriate test suite metrics. Comparison results emphasize outstanding advantages of the proposed computational approach, such as: ease of calculation, better defined Pareto front and a larger number of Pareto solutions.

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INTRODUCTION

VAR compensation is defined as the management of reactive power to improve the performance of ac power systems. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most of power quality problems can be attenuated or solved with an adequate control of reactive power [1]. In general, the problem of reactive power compensation is viewed from two aspects: load compensation and voltage support. In load compensation the objectives are to increase the value of the system power factor, to balance the real power drawn from the ac supply, compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads [2], [3]. Voltage support is generally required to reduce voltage fluctuation at a given terminal of a transmission line. Reactive power compensation in transmission systems also improves the stability of the ac system by increasing the maximum active power that can be transmitted. It also helps to maintain a substantially flat voltage profile at all levels of power transmission, it improves HVDC (High Voltage Direct Current) conversion terminal performance, increases transmission efficiency, controls steady-state and temporary overvoltages [4], and can avoid disastrous blackouts [5],[6]. Series and shunt VAR compensation are used to modify the natural electrical characteristics of ac power systems. Series compensation modifies the transmission or distribution system parameters, while shunt compensation changes the equivalent impedance of the load [1], [7]. In both cases, the reactive power that flows through the system can be effectively controlled improving the performance of the overall ac power system. Traditionally, rotating synchronous condensers and fixed or mechanically switched capacitors or inductors have been used for reactive power compensation. However, in recent years, static VAR compensators employing thyristor switched capacitors and thyristor controlled reactors to provide or absorb the required reactive power have been developed [7], [8], [9]. Also, the use of self-commutated PWM converters with an appropriate control scheme permits the implementation of static compensators capable of generating or absorbing reactive current components with a time response faster than the fundamental power network cycle [10], [11], [12]. Based on the use of reliable high-speed power electronics, powerful analytical tools, advanced control and microcomputer technologies, Flexible AC Transmission Systems, also known as FACTS, have been developed and represent a new concept for the operation of power transmission systems [13], [14]. In these systems, the use of static VAR compensators with fast response times play an important role, allowing to increase the amount of apparent power transfer through an existing line, close to its thermal capacity, without compromising its stability limits. These opportunities arise through the ability of special static VAR compensators to adjust the interrelated parameters that govern the operation of transmission systems, including shunt impedance, current,voltage, phase angle and the damping of oscillations [15]. This paper presents an overview of the state of the art

of static VAR technologies. Static compensators implemented with thyristors and self-commutated converters are described. Their principles of operation, compensation characteristics and performance are presented and analyzed. A comparison of different VAR generator compensation characteristics is also presented. New static compensators such as Unified Power Flow Controllers (UPFC), Dynamic Voltage Restorers (DVR), required to compensate modern power distribution systems are also presented and described [28].

1- REACTIVE POWER COMPENSATION PRINCIPLES

In a linear circuit, the reactive power is defined as the ac component of the instantaneous power, with a frequency equal to 100 / 120 Hz in a 50 or 60 Hz system. The reactive power generated by the ac power source is stored in a capacitor or a reactor during a quarter of a cycle, and in the next quarter cycle is sent back to the power source. In other words, the reactive power oscillates between the ac source and the capacitor or reactor, and also between them, at a frequency equals to two times the rated value (50 or 60 Hz). For this reason it can be compensated using VAR generators, avoiding its circulation between the load (inductive or capacitive) and the source, and therefore improving voltage stability of the power system. Reactive power compensation can be implemented with VAR generators connected in parallel or in series. The principles of both, shunt and series reactive power compensation alternatives, are described below.

1.1.- Shunt Compensation.

Figure 1 shows the principles and theoretical effects of shunt reactive power compensation in a basic ac system, which comprises a source V1, a power line and a typical inductive load. Figure 1-a) shows the system without compensation, and its associated phasor diagram. In the phasor diagram, the phase angle of the current has been related to the load side, which means that the active current IP is in phase with the load voltage V2. Since the load is assumed inductive, it requires reactive power for proper operation and hence, the source must supply it, increasing the current from the generator and through power lines. If reactive power is supplied near the load, the line current can be reduced or minimized, reducing power losses and improving voltage regulation at the load terminals. This can be done in three ways: a) with a capacitor, b) with a voltage source, or c) with a current source. In Fig. 1-b), a current source device is being used to compensate the reactive component of the load current (IQ). As a result, the system voltage regulation is improved and the reactive current component from the source is reduced or almost eliminated. If the load needs leading compensation, then an inductor would be required. Also a current source or a voltage source can be used for inductive shunt compensation. The main advantages of using voltage or current source VAR generators (instead of inductors or capacitors) is that the reactive power generated is independent of the voltage at the point of connection.

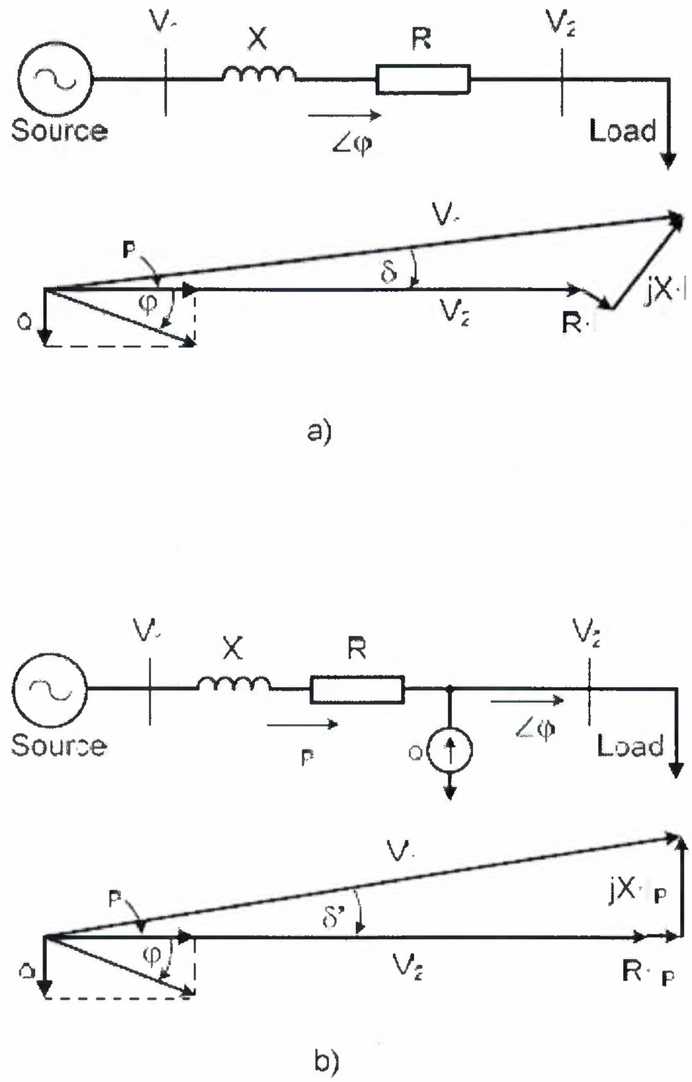


Fig. 1.- Principles of shunt compensation in a radial ac system.

a) Without reactive compensation

b) Shunt compensation with a current source.

1.2.- Series Compensation

VAR compensation can also be of the series type. Typical series compensation systems use capacitors to decrease the equivalent reactance of a power line at rated frequency. The connection of a series capacitor generates reactive power that, in a self-regulated manner, balances a fraction of the line's transfer reactance. The result is improved functionality of the power transmission system through:

i) increased angular stability of the power corridor,

ii) improved voltage stability of the corridor,

iii) optimized power sharing between parallel circuits.

Like shunt compensation, series compensation may also be implemented with current or voltage source devices, as shown in Fig. 2. Figure 2-a) shows the same power system of figure 1-a), also with the reference angle in V2, and Fig. 2-b) the results obtained with the series compensation through a voltage source, which has been adjusted again to have unity power factor operation at V2. However, the compensation strategy is different when compared with shunt compensation. In this case, voltage VCOMP has been added between the line and the load to change the angle of V2', which is now the voltage at the load side. With the appropriate magnitude adjustment of VCOMP, unity power factor can again be reached at V2. As can be seen from the phasor diagram of Fig. 2-b), VCOMP generates a voltage with opposite direction to the voltage drop in the line inductance because it lags the current IP.

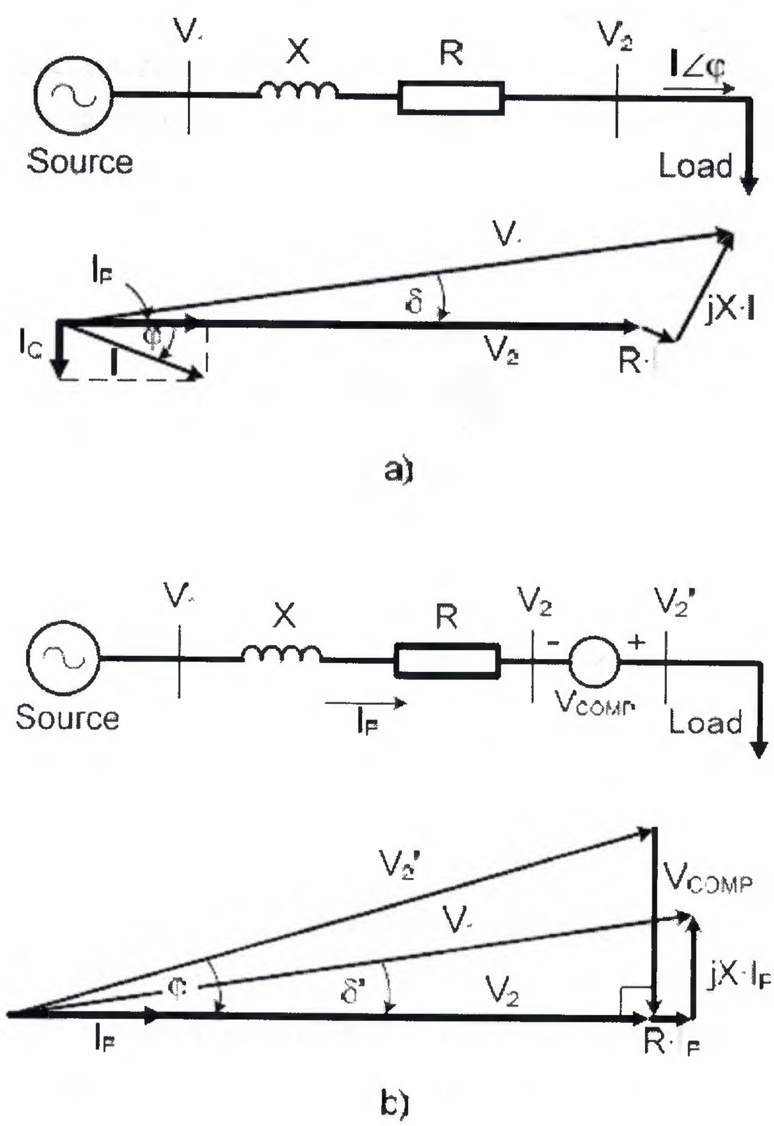


Fig. 2.- Principles of series compensation.

a) The same system of figure 1-a) without compensation.

b) Series compensation with a voltage source.

As was already mentioned, series compensation with capacitors is the most common strategy. Series Capacitor are installed in series with a transmission line as shown in Fig.3, which means that all the equipment must be installed on a platform that is fully insulated for the system voltage (both the terminals are at the line voltage). On this platform, the main capacitor is located together with overvoltage protection circuits. The overvoltage protection is a key design factor as the capacitor bank has to withstand the throughput fault current, even at a severe nearby fault. The primary overvoltage protection typically involves non-linear metal-oxide varistors, a spark gap and a fast bypass switch. Secondary protection is achieved with ground mounted electronics acting on signals from optical current transducers in the high voltage circuit.

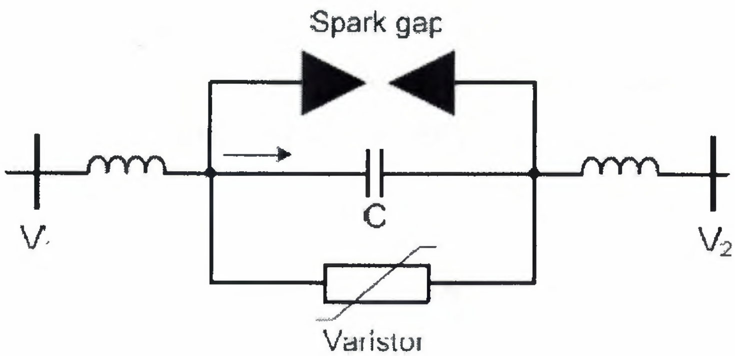


Fig. 3.- Series Capacitor Compensator and associated protection system.

Independent of the source type or system configuration, different requirements have to be taken into consideration for a successful operation of VAR generators. Some of these requirements are simplicity, controllability, dynamics, cost, reliability and harmonic distortion. The following sections describe different solutions used for VAR generation with their associated principles of operation and compensation characteristics.

2- POWER FACTOR

Power factor (pf) is defined as the ratio of the real power (P) to apparent power (S), or the cosine (for pure sine wave for both current and voltage) that represents the phase angle between the current and voltage waveforms (see Figure 4). The power factor can vary between 0 and 1, and can be either inductive (lagging, pointing up) or capacitive (leading, pointing down). In order to reduce an inductive lag, capacitors are added until pf equals 1. hen the current and voltage waveforms are in phase, the power factor is 1 (cos (0°) = 1). The whole purpose of making the power factor equal to one is to make the circuit look purely resistive (apparent power equal to real power). Real power (watts) produces real work; this is the energy transfer component (example electricity-to-motor rpm). Reactive power is the power required to produce the magnetic fields (lost power) to enable the real work to be done, where apparent power is considered the total power that the power company supplies, as shown in Figure 1. This total power is the power supplied through the power mains to produce the required amount of real power.

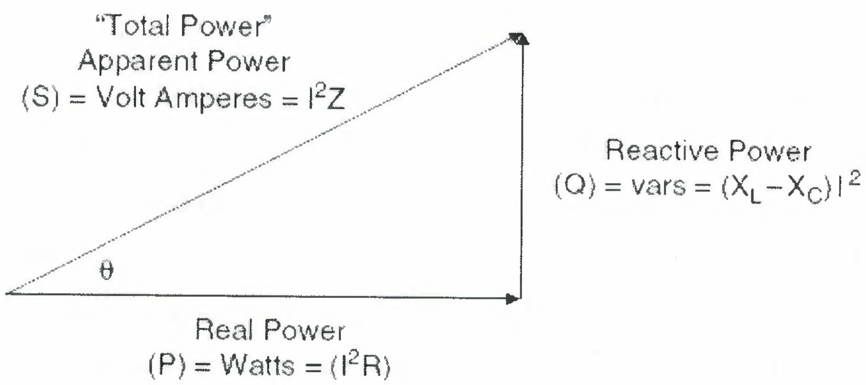


Fig. 4.- Power Factor Triangle (Lagging)

The previously-stated definition of power factor related to phase angle is valid when considering ideal sinusoidal waveforms for both current and voltage; however, most power supplies draw a non-sinusoidal current. When the current is not sinusoidal and the voltage is sinusoidal, the power factor consists of two factors: 1) the displacement factor related to phase angle and 2) the distortion factor related to wave shape. Equation 1 represents the relationship of the displacement and distortion factor as it pertains to power factor.

$$PF = \frac{Irms(1)}{Irms}\cos\theta = Kd \cdot K\theta \qquad (1)$$

Irms (1) is the current's fundamental component and *Irms* is the current's RMS value. Therefore, the purpose of the power factor correction circuit is to minimize the input current distortion and make the current in phase with the voltage. When the power factor is not equal to 1, the current waveform does not follow the voltage waveform. This results not only in power losses, but may also cause harmonics that travel down the neutral line and disrupt other devices connected to the line. The closer the power factor is to 1, the closer the current harmonics will be to zero since all the power is contained in the fundamental frequency.

2.1.- Causes of Inefficiencies

One problem with switch mode power supplies (SMPS) is that they do not use any form of power factor correction and that the input capacitor (shown in Figure 5) will only charge when V IN is close to V PEAK or when V IN is greater than the capacitor voltage V CIN. If C IN is designed using the input voltage frequency, the current will look much closer to the input waveform (load dependent); however, any little interruption on the mainline will cause the entire system to react negatively. In saying that, in designing a SMPS, the hold-up time for C IN is designed to be greater than the frequency of V IN, so that if there is a glitch in V IN and a few cycles are missed, C IN will have enough energy stored to continue to power its load.

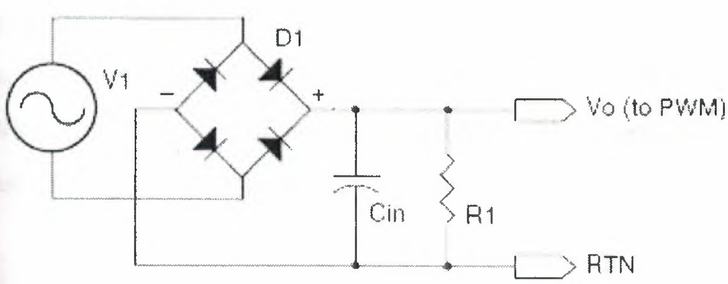


Fig. 5. SMPS Input Without PFC

Figure 6 represents a theoretical result of Vcin (t) (shown in the circuit in Figure 4) with a very light load, and hence, very little discharge of Cin . As the load impedance increases, there will be more droop from Vcin (t) between subsequent peaks, but only a small percentage with respect to the overall Vin (e.g. with the input being 120V, maybe a 3-5 volt droop. As previously stated, Cin will only charge when Vin is greater than its stored voltage, meaning that a non-PFC circuit will only charge Cin a small percentage of the overall cycle time.

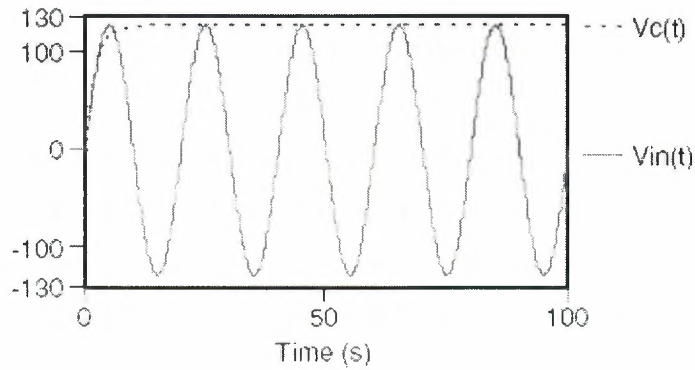


Fig. 6. Vin with charging Cin

After 90 degrees (Figure 6), the half cycle from the bridge drops below the capacitor voltage ; which back biases the bridge, inhibiting current flow into the capacitor.Notice how big the input current spike of the inductor is. All the circuitry in the supply chain (the wall wiring, the diodes in the bridge, circuit breakers, etc) must be capable of carrying this huge peak current. During these short periods the Cin must be fully charged, therefore large pulses of current for a short duration are drawn from Vin . There is a way to average this spike out so it can use the rest of the cycle to accumulate energy, in essence smoothing out the huge peak current, by using power factor correction.

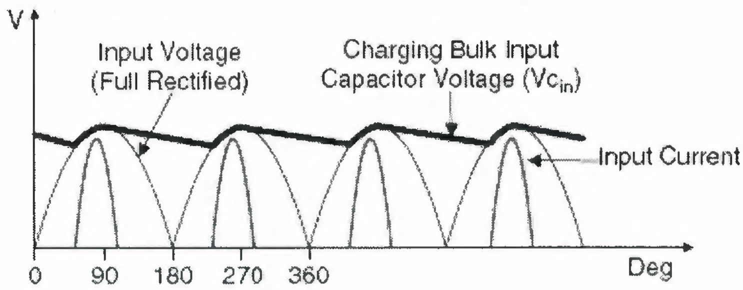


Fig. 7. Voltage and Current Waveforms in a Simple Rectifier Circuit

In order to follow Vin have these high amplitude current pulses, C IN must charge over the entire cycle rather than just a small portion of it. Today's non-linear loads make it impossible to know when a large surge of current will be required, so keeping the inrush to the capacitor constant over the entire cycle is beneficial and allows a much smaller C IN to be used. This method is called power factor correction.

2.2.- Modes of Operation

There are two modes of PFC operation; discontinuous and continuous mode. Discontinuous mode is when the boost converter's MOSFET is turned on when the inductor current reaches zero, and turned off when the inductor current meets the desired input reference voltage as shown in Figure 8. In this way, the input current waveform follows that of the input voltage, therefore attaining a power factor of close to 1.

Discontinuous mode can be used for SMPS that have power levels of 300W or less. In comparison with continuous mode devices, discontinuous ones use larger cores and have higher I 2 R and skin effect losses due to the larger inductor current swings.

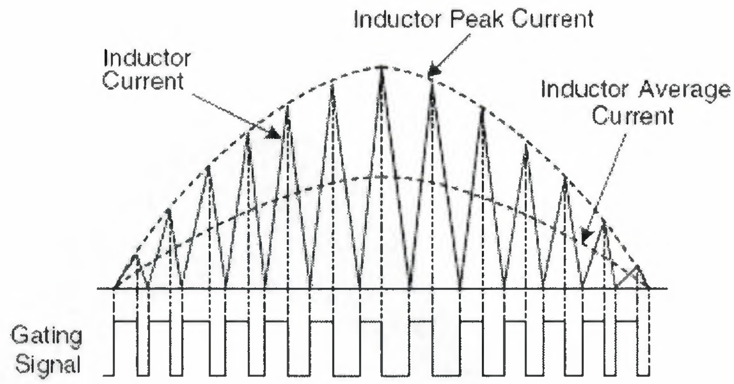


Fig.8. Discontinuous mode of operation

With the increased swing a larger input filter is also required. On the positive side, since discontinuous mode devices switch the boost MOSFET on when the inductor current is at zero, there is no reverse recovery current specification required on the boost diode. This means that less expensive diodes can be used. Continuous mode typically suits SMPS power levels greater than 300W. This is where the boost converter's MOSFET does not switch on when the boost inductor is at zero current, instead the current in the energy transfer inductor never reaches zero during the switching cycle (Figure 9). With this in mind, the voltage swing is less than in discontinuous mode—resulting in lower I 2 R losses—and the lower ripple current results in lower inductor core losses. Less voltage swing also reduces EMI and allows for a smaller input filter to be used. Since the MOSFET is not being turned on when the boost inductor's current is at zero, a very fast reverse recovery diode is required to keep losses to a minimum.

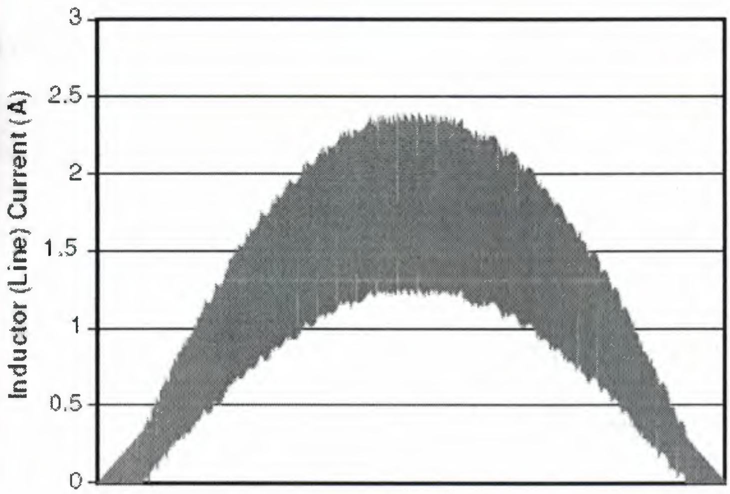


Fig.9. Continuous Mode of Operation

Fairchild offers products for all discontinuous and continuous modes of PFC operation, including critical conduction mode (FAN7527B), average current mode (FAN4810), and input current shaping mode (FAN4803).

2.2.1. Discontinuous Mode:

A Critical Conduction mode device is a voltage mode device that works in the area between continuous and discontinuous mode. To better explain critical conduction mode lets look at the difference between discontinuous and continuous mode in a SMPS design such as a flyback converter. In discontinuous mode, the primary winding of the transformer has a dead time once the switch is turned off (including is a minimum winding reset time) and before it is energized again (Figure 10).

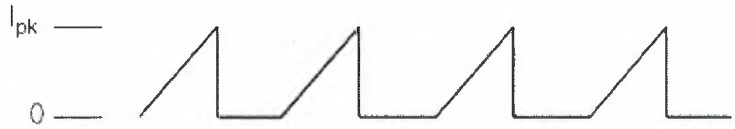


Fig. 10. Discontinuous Mode, Flyback Power Supply Ip (Primary Current)

In continuous mode, the primary winding has not fully depleted all of its energy. Figure 11 shows that the primary winding does not start energizing at zero, rather residual current still resides in the winding.

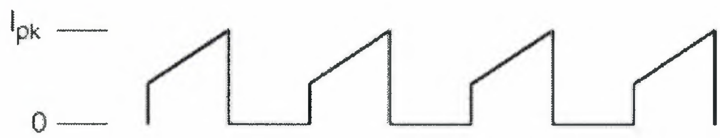


Fig. 11. Continuous Mode, Flyback Power Supply (Primary Current)

In critical conduction mode there are no dead-time gaps between cycles and the inductor current is always at zero before the switch is turned on. In Figure 9, the ac line current is shown as a continuous waveform where the peak switch current is twice the average input current. In this mode, the operation frequency varies with constant on time.

2.2.2. Continuous Mode:

The heart of the PFC controller is the gain modulator. The gain modulator has two inputs and one output. As shown in Figure 12, the left input to the gain modulator block is called the reference current.The reference current is the input current that is proportional to the input full-wave-rectified voltage. The other input, located at the bottom of the gain modulator, is from the voltage error amplifier. The error amplifier takes in the output voltage (using a voltage divider) after the boost diode and compares it to a reference voltage of 5 volts. The error amplifier will have a small bandwidth so as not to let any abrupt changes in the output or ripple erratically affect the output of the error amplifier. The gain modulator multiplies or is the product of the reference current and the error voltage from the error amplifier (defined by the output voltage). Figure 12 shows the critical blocks within the ML4821 (a stand alone PFC controller) to produce a power factor of greater than 95 percent. These critical blocks include the current control loop, voltage control loop, PWM control, and the gain modulator.

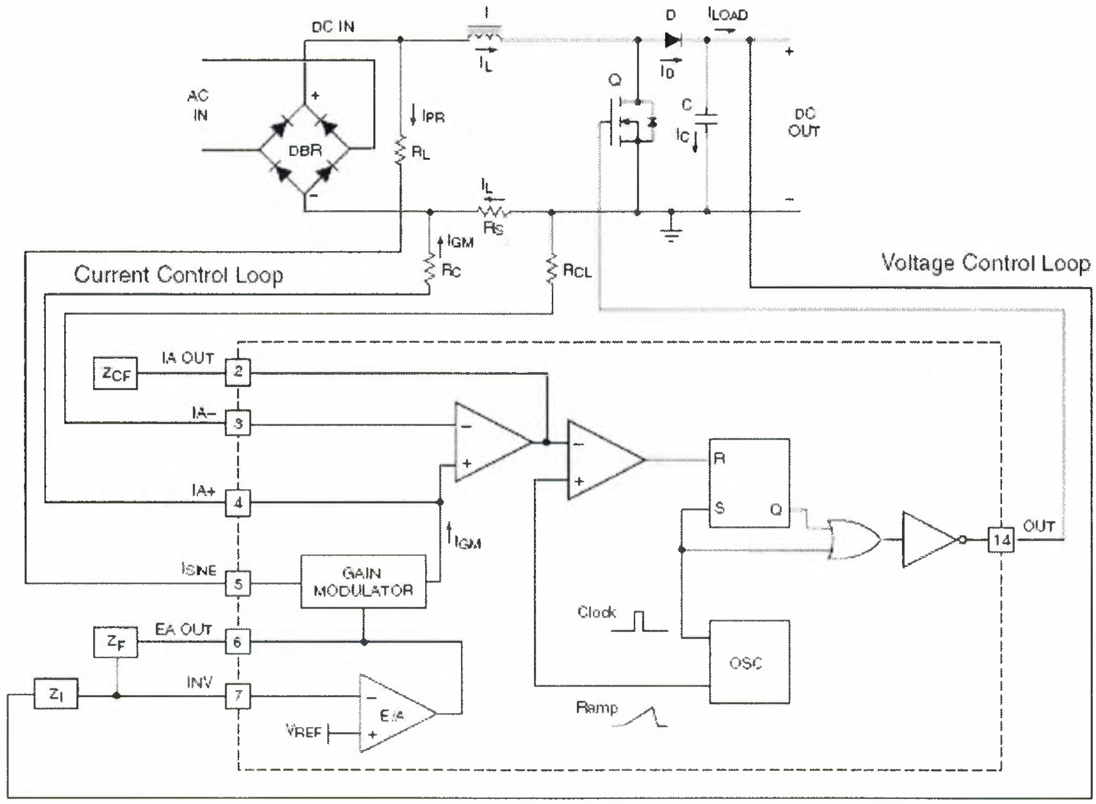


Figure 12. Example of an Average Current Mode PFC Control (ML4821)

3- CONTROL CIRCUIT FOR ACTİVE POWER-HARMONIC-COMPENSATİON FILTER IN POWER SYSTEMS

Recent wide spread of power electronic equipment has caused an increase of the harmonic disturbances in the power distribution systems. The control of AC power thyristors and other semiconductor switches is widely employed to feed electric power to electrical loads, such as: furnaces, computer power supplies, adjusable speed drives etc. The nonlinear loads draw harmonic and reactive power componets of current from AC mains. In three-phase systems, they could also cause unbalance and draw excessive neutral currents. Reactive power burden, injected harmonics, unbalance, and draw excessive neutral currents cause a poor power factor and a low power system efficiency. Conventionally, passive *LC* filters and capacitors have been used to eliminate line current harmonics and to increase the power factor. However, in some practical applications, in which the amplitude and the harmonic content of the distortion power can vary randomly, this conventional solution becomes ineffective.

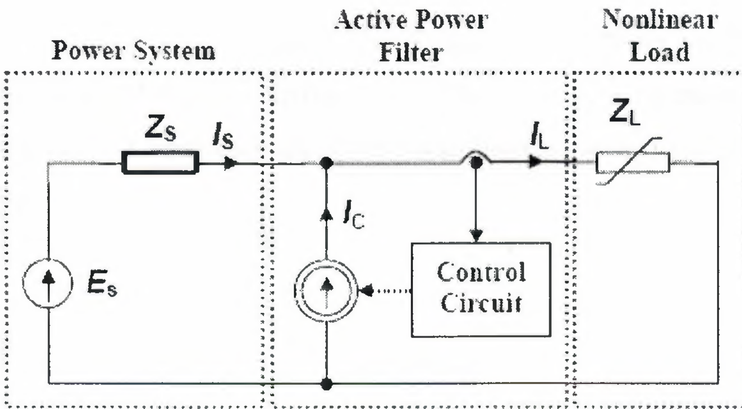


Fig. 13. Harmonic compensation circuit with current-fed active power filter

To suppress these harmonics, an active power-harmonic-compensation filter (APF) should be used. The active power filter can be connected in series or in parallel with the supply network. The series APF is applicable to the harmonic compensation of a large capacity diode rectifier with a DC link capacitor. The parallel APF (shunt active power filter) permits to compensate the harmonics and asymmetries of the mains currents caused by nonlinear loads. Harmonic compensation circuit with current-fed active power filter is depicted in Fig. 13. Shunt active power filter injects AC power current *i*C to cancel the main AC harmonic content. The line current *i*S is the result of summing the load current *i*L and the compensating current *i*C

$$i_S = i_L + i_C \; . \qquad (2)$$

3.1. Proposed Active Power Filter

Simplified block diagram of the proposed active power compensation circuit with the parallel APF for power of 75 kVA is depicted in Fig.14. The circuit consists of the power part with a three-phase IGBT power transistor bridge IPM (intelligent power module) connected to the AC mains through an inductive filtering system composed of inductors *L*1, *L*2, *L*3. The APF circuit contains a DC energy storage, ensured by two capacitors *C*1 and *C*2. The control circuit is realized using the digital signal processor TMS320C50 (the TMS320C50 DSP Starter Kit). The active power filter injects the harmonic currents *I*C1, *I*C2, *I*C3 into the power network and offers a notable compensation for harmonics, reactive power and unbalance.

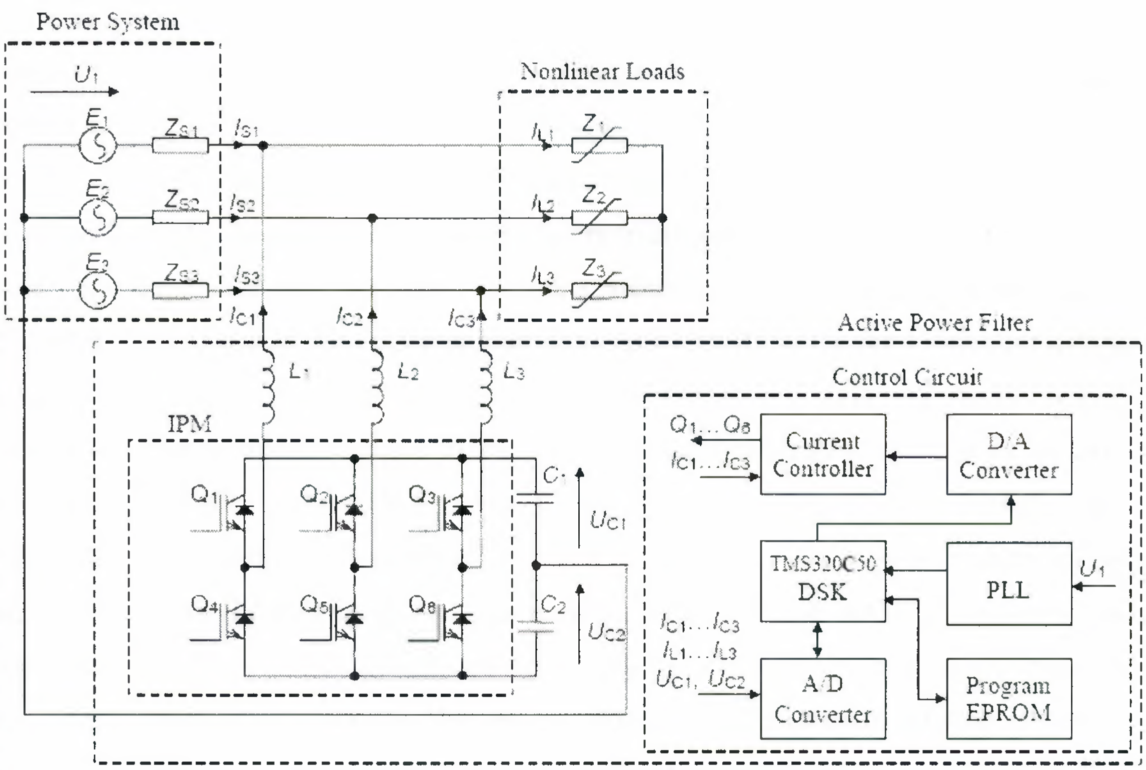


Fig. 14. Simplified block diagram of the proposed active power compensation circuit

4- POWER COMPENSATION EFFECT OF AN ADJUSTABLE-SPEED ROTARY CONDENSER

Direct connection of the synchrotron magnet power supply to the utilities causes the effect of pulsed reactive and active power in the ac line. Conventionally, Static Var Control system compensates the reactive power generated by the thyristor converter to reduce the flicker in the power line. However, it is necessary to control not only a reactive power but also an active power for the future large scale synchrotron magnet power supply in order to reduce the dissipation power and to realize the stabilization in the ac line. An adjustable-speed rotary condenser is capable of not only reactive power control but also active power control since it utilize a flywheel effect of the rotor. Research and development on these problems are now under going using a model system of 7.5kW rotary condenser with flywheel (GD2=3kg-m2). Control and characteristic of an adjustable-speed rotary condenser and the experiment result will be presented.

The KEK-PS main ring magnet power system works at repetition rate 0.25 - 0.4 Hz for the power to be fed in and fed out from the utility to the magnets by converter and inverter mode operations. The magnet power system, consists of the ring magnet power supply (23.6MVA), the reactive power compensator systems (20 MVar lag for fundamental) and the harmonic filter banks (20 MVar lead) As a case of the 50 GeV main ring magnet power system of the Japan Hadron Project (JHF), peak power and dissipation power are estimated to be about 120MW and 34.5MW, respectively. For such a large scale magnet power system, the fluctuation of active power produce serious effects on power systems of the installation site of the magnet power supply, even if the reactive power is compensated. Hence, installation of a large-capacity energy storage system to the magnet power supply is now under consideration. For the JHF design, doubly-fed flywheel generating system is under consideration. Attention has been paid to a flywheel energy storage system based on a doubly-fed induction generator-motor for the purpose of power conditioning with aiming at load-leveling over a repetitive period. Figure 1, for example, shows the typical pattern of which active power changes drastically in a range from +55MW to -55MW within 4 sec. It is also referred to as an "adjustable-speed rotary condenser" capable of both active power control and reactive power control, in contrast with a conventional "synchronous-speed rotary condenser" capable of only reactive power control.

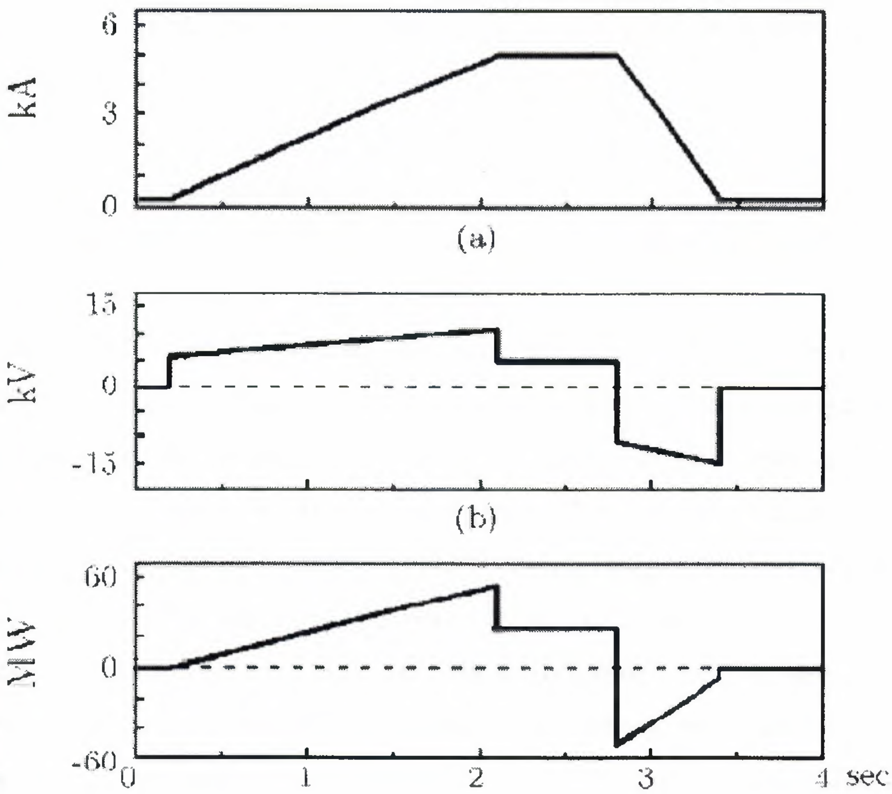


Fig. 15.- Typical operating pattern of a magnetic power supply for a proton synchrotron.

(a) Magnet current.

(b) Magnet voltage.

(c) Active power.

4.1. The 200-MJ flywheel energy Storage System

For example, the 200 MJ ROTES (Rotary Energy Storage System) was successfully commissioned at the Chujowan substation on Okinawa island of Japan [3]. The ROTES is an application of adjustable speed pumped and is an excellent system designed to suppress frequency fluctuations caused by sudden and frequent load changes in the power system. With the 200 MJ ROTES, frequency fluctuations have been greatly improved from ± 0.6 Hz to ± 0.3 Hz.

4.2. System Configuration

A doubly-fed flywheel generator-motor of a wound-rotor induction machine and a cycloconverter or a voltagesource PWM rectifier-inverter which is used as an ac excitor. Adjusting the rotor speed makes the generatormotor either release the kinetic energy to the power system or absorb it from the power system. Thus, the generator-motor has the capability of achieving, not only reactive power control, but also active power control based on a flywheel effect of the rotor. The control strategy enables the flywheel generatormotor to perform active power control independent of reactive power control even in transient states. The flywheel generator-motor based on leading edge power electronics and electric machine technologies shows promise as a versatile power conditioner, in particular, being capable of repetitively absorbing or releasing electric energy for a periodical operation such as a synchrotron magnet power supply. The ac excitation on the basis of a rotor-position feedback loop makes it possible to achieve stable variablespeed operation. Adjusting the rotor speed makes the generator-motor either release the electric power to the utility grid or absorb it from the utility grid. Therefore, the flywheel energy storage system is more suitable for repetitively absorbing and releasing electric energy for a short period of time. The required capacity of power electronic equipment for ac excitation is in a range from one-fifth to one-seventh as small as the capacity of the wound-rotor induction machine. A 40-MJ flywheel energy storage system based on a 70-MVA doubly-fed induction machine should be installed on the ac side of the magnet power supply shown in Fig. 14, in order to achieve perfect load-leveling. Comparison with the 200-MJ system installed for line-frequency regulation leads to the possibility that the 40-MJ system does *not need to couple any flywheel with the rotor, because the induction machine rating* required to the 40- MJ system is 2.6 times as large as that required to the 200-MJ system. On the contrary, the 40-MJ system needs to achieve much faster charge/discharge of active power than the 200-MJ system.

4.3. Experiment System and Simulation

4.3.1- Experiment System

Despite of the 200-MJ successful example, it is necessary to confirm that a new control strategy for a doubly-fed flywheel generator-motor would be effective by an experiment.

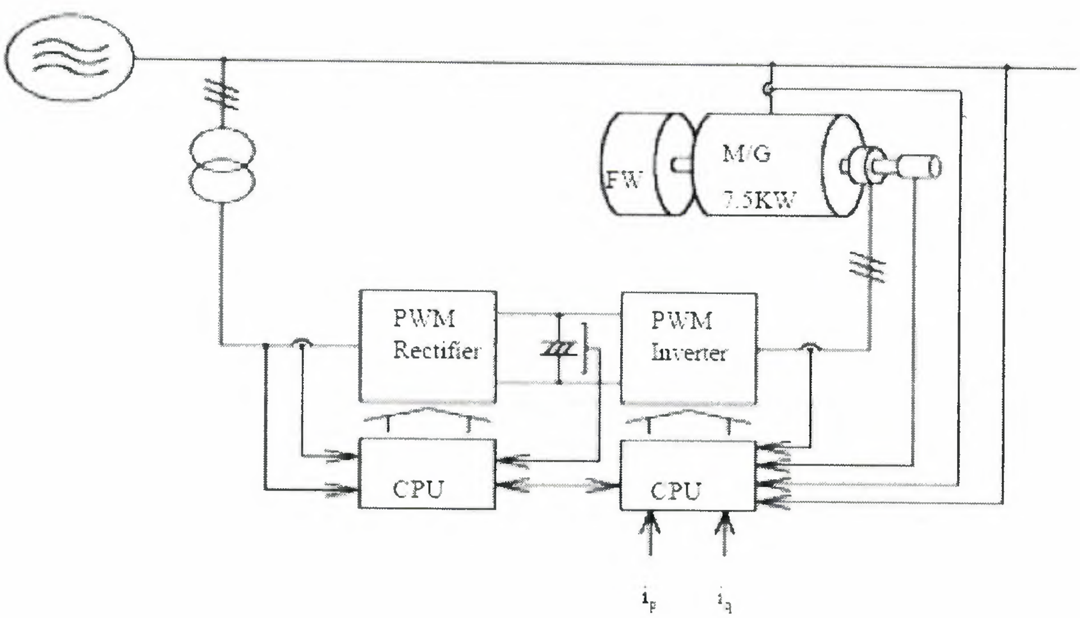


Fig. 16 - Experiment system of the 7.5 kW doubly-fed flywheel with

The experiment system consists of a 7.5-kW doublyfed induction machine equipped with a flywheel of 3 kgm2, a 2-kVA voltage-source PWM rectifier, a 2-kVA voltage-source PWM inverter, and dual CPUs (Hitachi SH-1). Fig. 2 shows a block diagram of the experiment system. The rectifier and inverter using insulated gate bipolar transistors (IGBTs) rated at 600 V and 30 A, are controlled by the CPUs. Three-phase currents and voltages are detected by CTs or PTs, while the rotor position is detected by a rotary encoder (RE).

These signals are sent to the CPUs in order to calculate threephase inverter output voltages. The inverter excites the secondary winding of the induction machine through slip rings, forcing the active and/or reactive power released to, or absorbed from, the utility to follow its references *ip* and *iq*. The experiment is now under processing.

4.3.2. Simulation

Here, the control system for *ip* and *iq* has a proportional-plus-integral (PI) controller, the time constant of which is set at 100 ms. The proportional gain is designed to be K = 0.5 [V/A], so that the time constant of *ip* and *iq* for a step change in *ip* and *iq* is T = 2.5 ms.

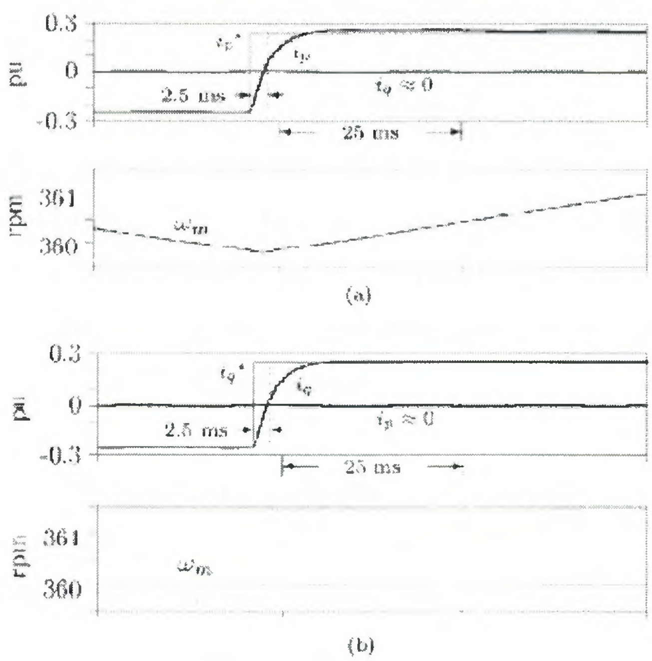


Fig. 17 Shows simulated waveforms in which the switching operation of the voltage-fed PWM inverter is taken into account [4].

The triangle-carrier frequency of the voltage-fed PWM inverter is 1 kHz, and the dc link voltage is 0.2 pu. The magnitude of the step change in *ip* and *iq* is set to be ± 0.25 pu, so that the maximum output voltage of the inverter does not reach the saturation voltage, that is, the dc link voltage of 0.2 pu. If the magnitude of the step change is large enough for the control system to reach saturation, it would be impossible to evaluate the response inherent in the control system from the resulting response to the step change, because the saturation voltage would dominate the resulting response to the step change. Fig. 17 exhibits that the time constant of *ip* and *iq* is 2.5 ms (wc= 400 rad/s) which is equal to its design value, and that no cross-coupling occurs between *ip* and *iq*. The rotor speed of the induction machine, wm varies in Fig. 17 (a), whereas it is held constant at 360 rpm in Fig. 17 (b) because *ip* = 0. Detailed results of the simulation will be presented in another place.

5- TRADITIONAL VAR GENERATORS

In general, VAR generators are classified depending on the technology used in their implementation and the way they are connected to the power system (shunt or series). Rotating and static generators were commonly used to compensate reactive power. In the last decade, a large number of different static VAR generators, using power electronic technologies have been proposed and developed [7]. There are two approaches to the realization of power electronics based VAR compensators, the one that employs thyristor-swicthed capacitors and reactors with tapchanging transformers, and the other group that uses selfcommutated static converters. A brief description of the most commonly used shunt and series compensators is presented below.

5.1. Fixed or mechanically switched capacitors

Shunt capacitors were first employed for power factor correction in the year 1914 [16]. The leading current drawn by the shunt capacitors compensates the lagging current drawn by the load. The selection of shunt capacitors depends on many factors, the most important of which is the amount of lagging reactive power taken by the load. In the case of widely fluctuating loads, the reactive power also varies over a wide range. Thus, a fixed capacitor bank may often lead to either over-compensation or under-compensation. Variable VAR compensation is achieved using switched capacitors [17]. Depending on the total VAR requirement, capacitor banks are switched into or switched out of the system. The smoothness of control is solely dependent on the number of capacitors switching units used. The switching is usually accomplished using relays and circuit breakers. However, hese methods based on mechanical switches and relays have the disadvantage of being sluggish and unreliable. Also they generate high inrush currents, and require frequent maintenance [16].

5.2. Synchronous Condensers

Synchronous condensers have played a major role in voltage and reactive power control for more than 50 years. Functionally, a synchronous condenser is simply a synchronous machine connected to the power system. After the unit is synchronized, the field current is adjusted to either generate or absorb reactive power as required by the ac system. The machine can provide continuous reactive power control when used with the proper automatic exciter circuit. Synchronous condensers have been used at both distribution and transmission voltage levels to improve stability and to maintain voltages within desired limits under varying load conditions and contingency situations. However, synchronous condensers are rarely used today because they require substantial foundations and a significant amount of starting and protective equipment. They also contribute to the short circuit current and they cannot be controlled fast enough to compensate for rapid load changes. Moreover, their losses are much higher than those associated with static compensators, and the cost is much higher compared with static compensators. Their advantage lies in their high temporary overload capability [1].

5.3.- Thyristorized VAR Compensators

As in the case of the synchronous condenser, the aim of achieving fine control over the entire VAR range, has been fulfilled with the development of static compensators (SVC) but with the advantage of faster response times [6], [7]. Static VAR compensators (SVC) consist of standard reactive power shunt elements (reactors and capacitors) which are controlled to provide rapid and variable reactive power. They can be grouped into two basic categories, the thyristor-switched capacitor and the thyristor-controlled reactor.

i) Thyristor-Switched Capacitors

Figure 18 shows the basic scheme of a static compensator of the thyristor-switched capacitor (TSC) type. First introduced by ASEA in 1971 [16], the shunt capacitor bank is split up into appropriately small steps, which are individually switched in and out using bidirectional thyristor switches. Each single-phase branch consists of two major parts, the capacitor C and the thyristor switches Sw1 and Sw2. In addition, there is a minor component, the inductor L, whose purpose is to limit the rate of rise of the current through the thyristors and to prevent resonance with the network (normally 6% with respect to Xc). The capacitor may be switched with a minimum of transients if the thyristor is turned on at the instant when the capacitor voltage and the network voltage have the same value. Static compensators of the TSC type have the following properties: stepwise control, average delay of one half a cycle (maximum one cycle), and no generation of harmonics since current transient component can be attenuated effectively [16], [17].

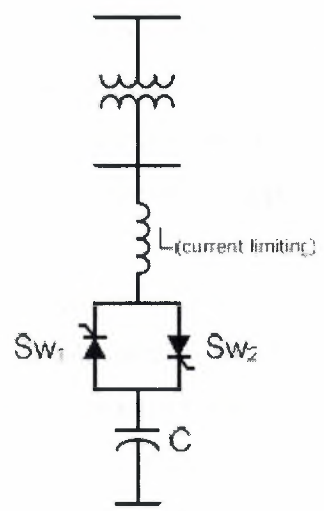


Fig. 18.- The thyristor-switched capacitor configuration.

The current that flows through the capacitor at a given time t, is defined by the following expression:

$$i(t)=\frac{V_m}{X_C-X_L}\cos(\omega t+\alpha)-\frac{V_m}{X_C-X_L}\cos(\alpha)\cos(\omega_r t)+\left[\frac{X_C V_m \sin(\alpha)}{\omega_r L(X_C-X_L)}-\frac{V_{CO}}{\omega_r L}\right]\sin(\omega_r t) \quad (3)$$

where *Xc* and *XL* are the compensator capacitive and inductive reactance, *Vm* the source maximum instantaneous voltage, α the voltage phase-shift angle at which the capacitor is connected, and ω *r* the system resonant frequency

$$(\omega_r = 1/\sqrt{LC})$$

, *Vco* capacitor voltage at t = 0.

This expression has been obtained assuming that the system equivalent resistance is negligible as compared with the system reactance. This assumption is valid in high voltage transmission lines. If the capacitor is connected at the moment that the source voltage is maximum and Vco is equal to the source voltage peak value, *Vm*, (α = ± 90°) the current transient component is zero. Despite the attractive theoretical simplicity of the switched capacitor scheme, its popularity has been hindered by a number of practical disadvantages: the VAR compensation is not continuous, each capacitor bank requires a separate thyristor switch and therefore the construction is not economical, the steady state voltage across the non-conducting thyristor switch is twice the peak supply voltage, and the thyristor must be rated for or protected by external means against line voltage transients and fault currents. An attractive solution to the disadvantages of using TSC is to replace one of the thyristor switches by a diode. In this case, inrush currents are eliminated when thyristors are fired at the right time, and a more continuous reactive power control can be achieved if the rated power of each capacitor bank is selected following a binary combination, as described in [13] and [18]. This configuration is shown in Fig. 19. In this figure, the inductor Lmin is used to prevent any inrush current produced by a firing pulse out of time.

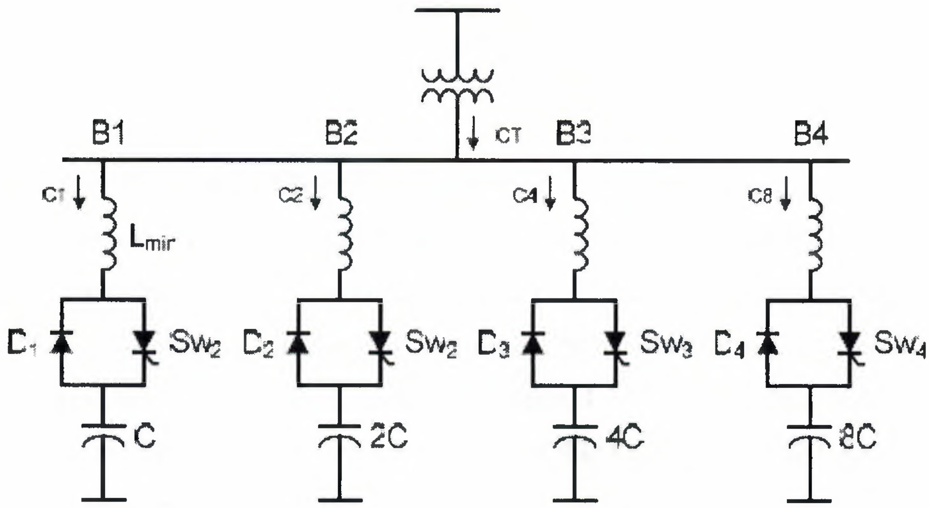


Fig. 19.- Binary thyristor-diode-switched capacitor configuration.

To connect each branch, a firing pulse is applied at the thyristor gate, but only when the voltage supply reaches its maximum negative value. In this way, a soft connection is obtained (3). The current will increase starting from zero without distortion, following a sinusoidal waveform, and after the cycle is completed, the capacitor voltage will have the voltage ***-Vm***, and the thyristor automatically will block. In this form of operation, both connection and disconnection of the branch will be soft, and without distortion. If the firing pulses, and the voltage ***-Vm*** are properly adjusted, neither harmonics nor inrush currents are generated, since two important conditions are achieved: a) dv/dt at $v=-Vm$ is zero, and b) anode-to-cathode thyristor voltage is equal to zero. Assuming that $v(t) = \mathbf{Vm} \sin \omega t$, is the source voltage, Vco the initial capacitor voltage, and $vTh(t)$ the thyristor anode-to-cathode voltage, the right connection of the branch will be when $vTh(t) = 0$,

that is:

$$vTh(t) = v(t) - Vco = \mathbf{Vm} \sin \omega t - Vco \qquad (4)$$

since $Vco = -Vm$:

$$vTh(t) = Vm \sin \omega t + Vm = Vm(1 + \sin \omega t) \qquad (5)$$

The compensating capacitor current starting at to will be:

$$i_c = C\frac{dv_c}{dt} = C \cdot V_m \frac{d}{dt}(-\cos\omega \cdot t_o) = C \cdot V_m \sin\omega \cdot t_o \qquad (6)$$

Equation (6) shows that the current starts from zero as a sinusoidal waveform without distortion and/or inrush component. If the above switching conditions are satisfied, the inductor L may be minimized or even eliminated. The experimental oscillograms of Fig. 20 shows how the binary connection of many branches allows an almost continuous compensating current variation. These experimental current waveforms were obtained in a 5 kVAr laboratory prototype. The advantages of this topology are that many compensation levels can be implemented with few branches allowing continuous variations without distortion. Moreover, the topology is simpler and more economical as compared with thyristor switched capacitors. The main drawback is that it has a time delay of one complete cycle compared with the half cycle of TSC.

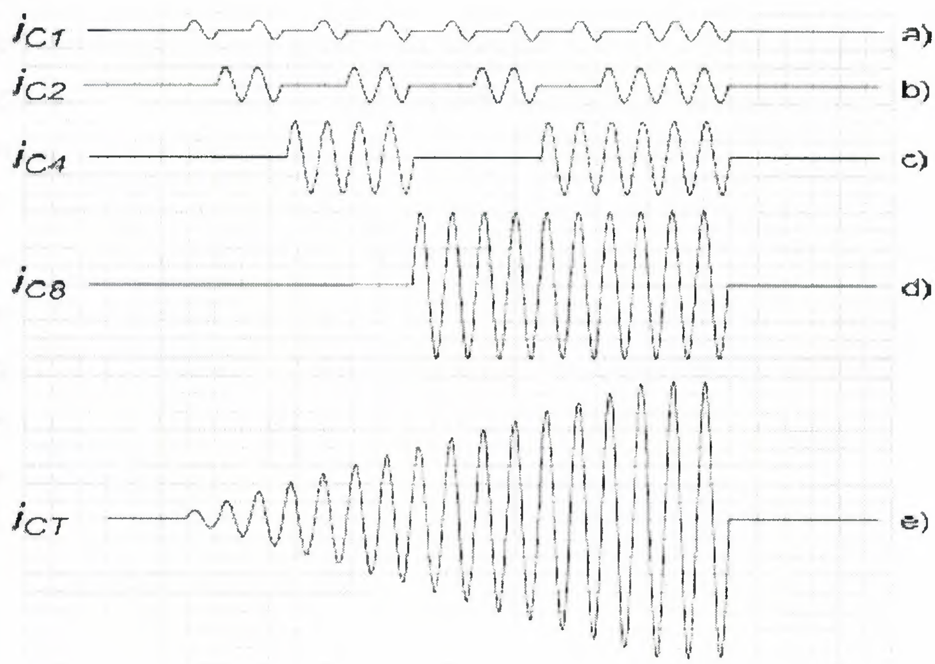


Fig. 20.- Experimental compensating phase current of the thyristor-diode switched capacitor.

a) Current through B1.

b) Current through B2.

c) Current through B3.

d) Current through B4.

e) Total system compensating current.

ii) Thyristor-Controlled Reactor

Figure 20 shows the scheme of a static compensator of the thyristor controlled reactor (TCR) type. In most cases, the compensator also includes a fixed capacitor and a filter for low order harmonics, which is not show in this figure. Each of the three phase branches includes an inductor L, and the thyristor switches Sw1 and Sw2. Reactors may be both switched and phase-angle controlled [20], [21], [22]. When phase-angle control is used, a continuous range of reactive power consumption is obtained. It results, however, in the generation of odd harmonic current components during the control process. Full conduction is achieved with a gating angle of 90°. Partial conduction is obtained with gating angles between 90° and 180°, as shown in Fig. 21. By increasing the thyristor gating angle, the fundamental component of the current reactor is reduced. This is equivalent to increase the inductance, reducing the reactive power absorbed by the reactor. However, it should be pointed out that the change in the reactor current may only take place at discrete points of time, which means that adjustments cannot be made more frequently than once per half-cycle. Static compensators of the TCR type are characterized by the ability to perform continuous control, maximum delay of one half cycle and practically no transients. The principal disadvantages of this configuration are the generation of low frequency harmonic current components, and higher losses when working in the inductive region (i.e. absorbing reactive power) [20].

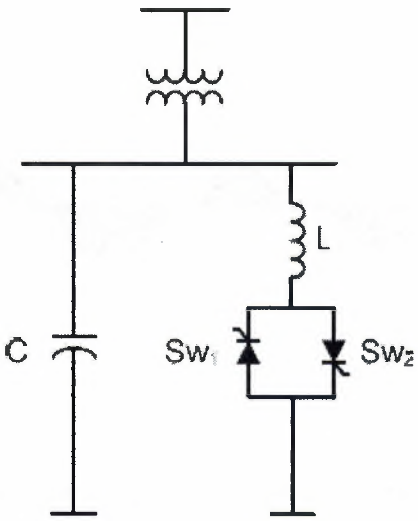


Fig. 20.- The thyristor-controlled reactor configuration.

The relation between the fundamental component of the reactor current, and the phase-shift ngle α is given by (6):

$$I_1 = \frac{V_{rms}}{\pi\omega L}\left(2\pi - 2\alpha + \sin(2\alpha)\right) \tag{7}$$

In a single-phase unit, with balanced phase-shift angles, only odd harmonic components are presented in the current of the reactor. The amplitude of each harmonic component is defined by (7).

$$I_k = \frac{4V_{rms}}{\pi X_L}\left[\frac{\sin(k+1)\alpha}{2(k+1)} + \frac{\sin(k-1)\alpha}{2(k-1)} - \cos(\alpha)\frac{\sin(k\alpha)}{k}\right] \tag{8}$$

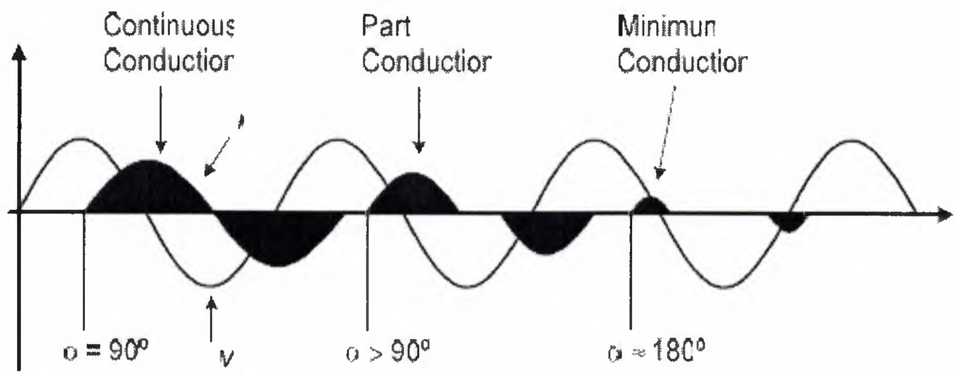


Fig. 21-. Simulated voltage and current waveforms in a TCR for different thyristor phase-shift angles, α.

In order to eliminate low frequency current harmonics (3rd, 5th, 7th), delta configurations (for zero zequence harmonics) and passive filters may be used, as shown in Fig. 22-a). Twelve pulse configurations are also used as shown in Fig. 22-b). In this case passive filters are not required, since the 5th and 7th current harmonics are eliminated by the phase-shift introduced by the transformer.

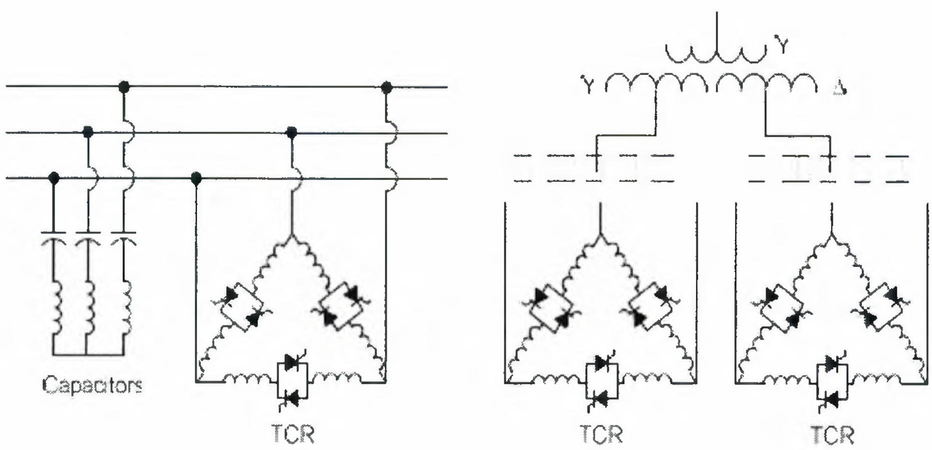


Fig. 22.- Fixed capacitor – thyristor controlled reactor configuration.

(a) Six pulse topology.

(b) Twelve pulse topology.

iii) VAR compensation characteristics

One of the main characteristics of static VAR compensators is that the amount of reactive power interchanged with the system depends on the applied voltage, as shown in Fig. 23. This Figure displays the steady state Q-V characteristics of a combination of fixed capacitor - thyristor controlled reactor (FC-TCR) compensator. This characteristic shows the amount of reactive power generated or absorbed by the FC-TCR, as a function of the applied voltage. At rated voltage, the FCTCR presents a linear characteristic, which is limited by the rated power of the capacitor and reactor respectively. Beyond these limits, the VT – Q characteristic is not linear [1], [7], which is one of the principal disadvantages of this type of VAR compensator.

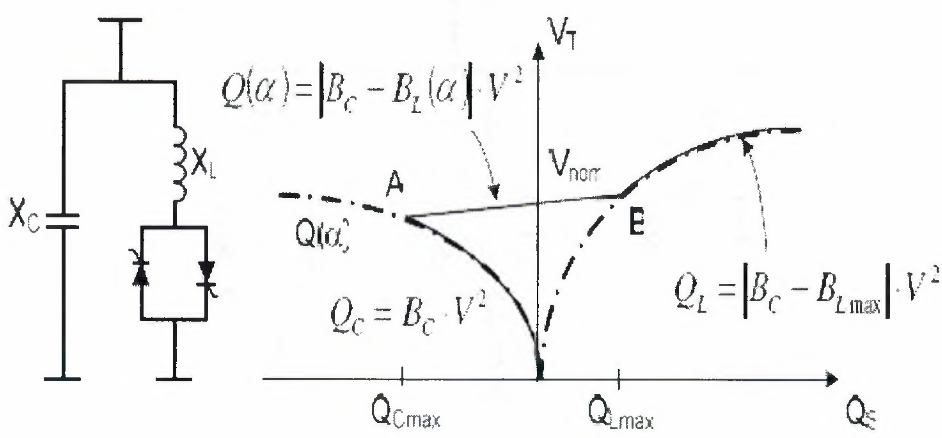


Fig. 23.- Voltage – reactive power characteristic of a FC-TCR.

iv) Combined TSC and TCR

Irrespective of the reactive power control range required, any static compensator can be built up from one or both of the above mentioned schemes (i.e. TSC and TCR), as shown in

Fig. 24. In those cases where the system with switched capacitors is used, the reactive power is divided into a suitable number of steps and the variation will therefore take place stepwise. Continuous control may be obtained with the addition of a thyristor-controlled reactor. If it is required to absorb reactive power, the entire capacitor bank is disconnected and the equalizing reactor becomes responsible for the absorption. By coordinating the control between the reactor and the capacitor steps, it is possible to obtain fully stepless control. Static compensators of the combined TSC and TCR type are characterized by a continuous control, practically no transients, low generation of harmonics (because the controlled reactor rating is small compared to the total reactive power), and flexibility in control and operation. An obvious disadvantage of the TSC-TCR as compared with TCR and TSC type compensators is the higher cost. A smaller TCR rating results in some savings, but these savings are more than absorbed by the cost of the capacitor switches and the more complex control system [16].

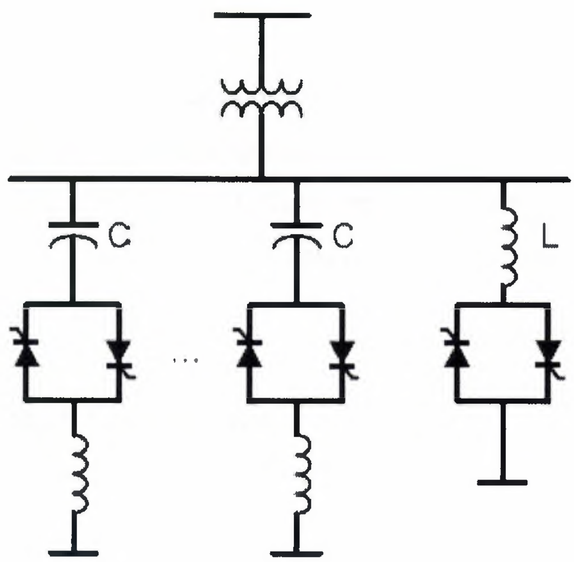


Fig. 24.- Combined TSC and TCR configuration.

The V-Q characteristic of this compensator is shown in Fig. 25.

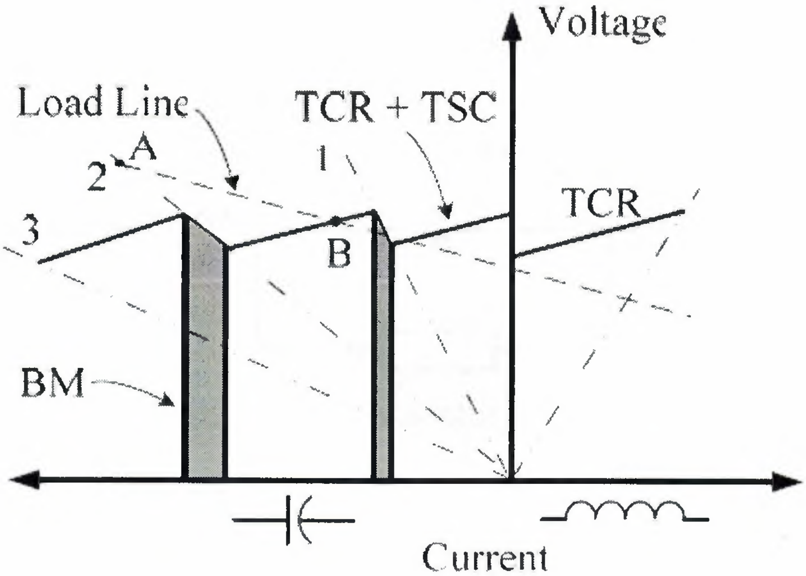


Fig. 25. Steady-state voltage – reactive power characteristic of a combined TSC – TCR compensator.

To reduce transient phenomena and harmonics distortion, and to improve the dynamics of the compensator, some researchers have applied selfcommutation to TSC and TCR. Some examples of this can be found in [21], [22]. However, best results have been obtained using self-commutated compensators based on conventional two-level and three-level inverters. They are analyzed in section IV.

v) Thyristor Controlled Series Compensation

Figure 26 shows a single line diagram of a Thyristor Controlled Series Compensator (TCSC). TCSC. provides a proven technology that addresses specific dynamic problems in transmission systems. TCSC's are an excellent tool to introduce if increased damping is required when interconnecting large electrical systems. Additionally, they can overcome the problem of Subsynchronous Resonance (SSR), a phenomenon that involves an interaction between large thermal generating units and series compensated transmission systems.

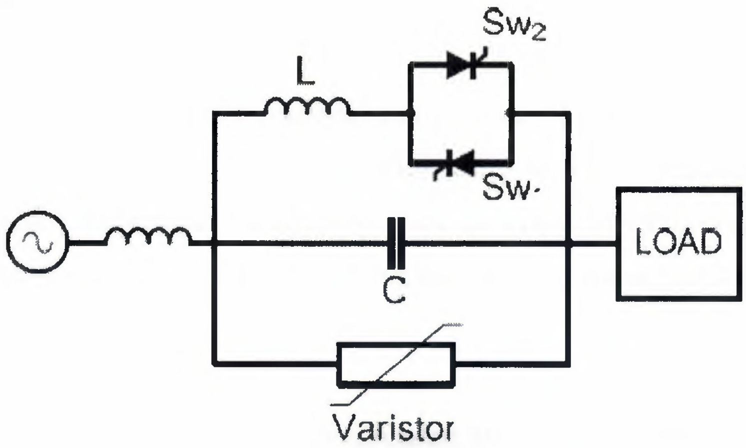


Fig. 26.- Power circuit topology of a Thyristor Controlled Series Compensator.

There are two bearing principles of the TCSC concept. First, the TCSC provides electromechanical damping between large electrical systems by changing the reactance of a specific interconnecting power line, i.e. the TCSC will provide a variable capacitive reactance. Second, the TCSC shall change its apparent impedance (as seen by the line current) for subsynchronous frequencies such that a prospective subsynchronous resonance is avoided. Both these objectives are achieved with the TCSC using control algorithms that operate concurrently. The controls will function on the thyristor circuit (in parallel to the main capacitor bank) such that controlled charges are added to the main capacitor, making it a variable capacitor at fundamental frequency but a "virtual inductor" at subsynchronous frequencies. For power oscillation damping, the TCSC scheme introduces a component of modulation of the effective reactance of the power transmission corridor. By suitable system control, this modulation of the reactance is made to counteract the oscillations of the active power transfer, in order to damp these out.

6- SELF-COMMUTATED VAR COMPENSATORS

The application of self-commutated converters as a means of compensating reactive power has demonstrated to be an effective solution. This technology has been used to implement more sophisticated compensator equipment such as static synchronous compensators, unified power flow controllers (UPFCs), and dynamic voltage restorers (DVRs) [15], [19].

6.1. Principles of Operation

With the remarkable progress of gate commutated semiconductor devices, attention has been focused on selfcommutated VAR compensators capable of generating or absorbing reactive power without requiring large banks of capacitors or reactors. Several approaches are possible including current-source and voltage-source converters. The current-source approach shown in Fig. 27 uses a reactor supplied with a regulated dc current, while the voltage-source inverter, displayed in Fig. 28, uses a capacitor with a regulated dc voltage.

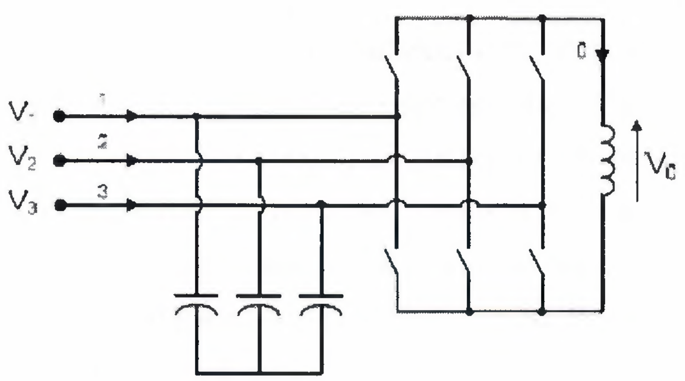


Fig. 27.- A VAR compensator topology implemented with a current source converter.

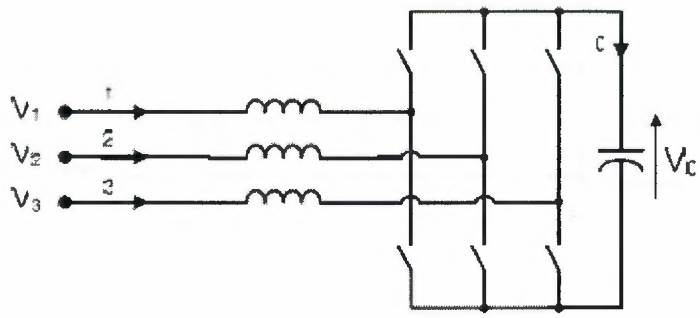


Fig. 28.- A VAR compensator topology implemented with a
voltage source converter.

The principal advantages of self-commutated VAR compensators are the significant reduction of size, and the potential reduction in cost achieved from the elimination of a large number of passive components and lower relative capacity requirement for the semiconductor switches [19], [23]. Because of its smaller size, self-commutated VAR compensators are well suited for applications where space is a premium. Self-commutated compensators are used to stabilize transmission systems, improve voltage regulation, correct power factor and also correct load unbalances [19], [23]. Moreover, they can be used for the implementation of shunt and series compensators. Figure 29 shows a shunt VAR compensator, implemented with a boost type voltage source converter. Neglecting the internal power losses of the overall converter, the control of the reactive power is done by adjusting the amplitude of the fundamental component of the output voltage *VMOD*, which can be modified with the PWM pattern as shown in figure 30. When *VMOD* is larger than the voltage *VCOMP*, the VAR compensator generates reactive power (Fig. 29-b) and when *VMOD* is smaller than *VCOMP*, the compensator absorbs reactive power (Fig. 29-c). Its principle of operation is similar to the synchronous machine. The compensation current can be leading or lagging, depending of the relative amplitudes of *VCOMP* and *VMOD*. The capacitor voltage *VD*, connected to the dc link of the converter, is kept constant and equal to a reference value VREF with a special feedback control loop, which controls the phase-shift angle between *VCOMP* and *VMOD*.

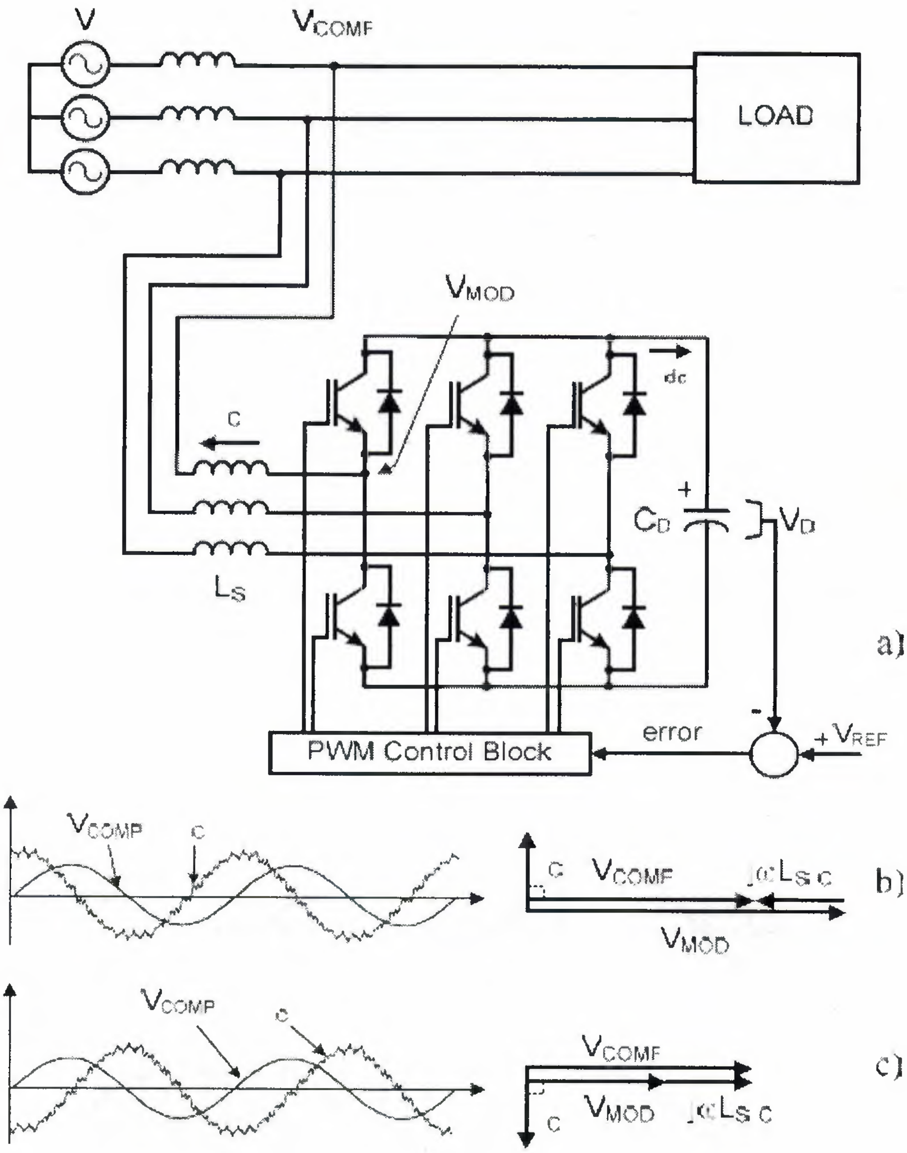


Fig. 29.- Simulated current and voltage waveforms of a voltagesource self-commutated shunt VAR compensator.

a) Compensator topology.

b) Simulated current and voltage waveforms for leading compensation (VMOD > VCOMP).

c) Simulated current and voltage waveforms for lagging compensation (VMOD < VCOMP).

The amplitude of the compensator output voltage (*VMOD*) can be controlled by changing the switching pattern modulation index (Fig. 30), or by changing the amplitude of the converter dc voltage *VD*. Faster time response is achieved by changing the switching pattern modulation index instead of *VD*. The converter dc voltage *VD*, is changed by adjusting the small amount of active power absorbed by the converter and defined by (9)

$$P = \frac{V_{COMP} \cdot V_{MOD}}{X_S} \sin(\delta) \quad (9)$$

where *Xs* is the converter linked reactor, and δ is the phaseshift angle between voltages *VCOMP* and *VMOD*.

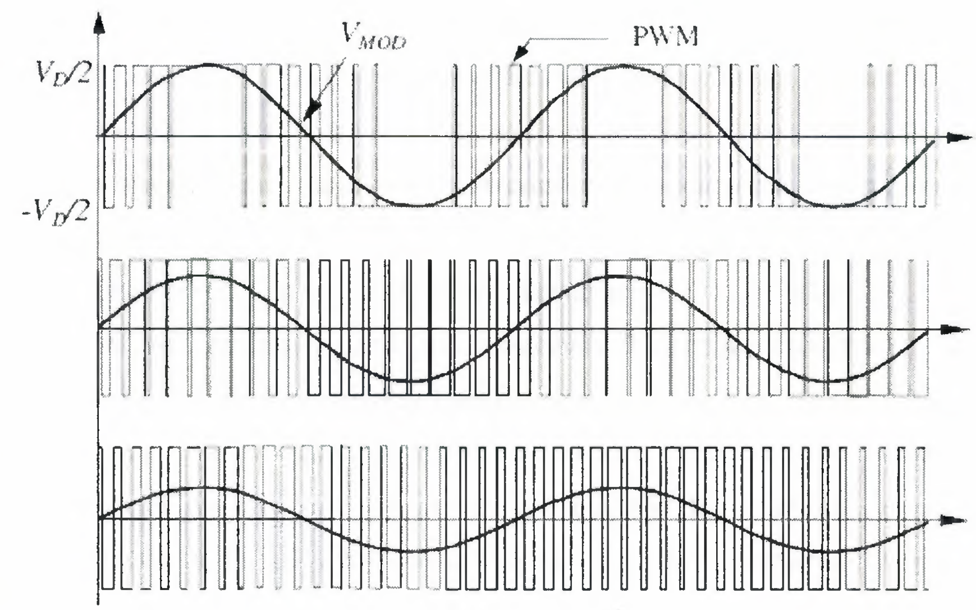


Fig. 30. Simulated compensator output voltage waveform for different modulation index (amplitude of the voltage fundamental component).

One of the major problems that must be solved to use self-commutated converters in high voltage systems is the limited capacity of the controlled semiconductors (IGBTs and IGCTs) available in the market. Actual semiconductors can handle a few thousands of amperes and 6 to 10 kV reverse voltage blocking capabilities, which is clearly not enough for high voltage applications. This problem can be overcome by using more sophisticated converters topologies, as described below.

6.2. Multi-Level Compensators

Multilevel converters are being investigated and some topologies are used today as static VAR compensators. The main advantages of multilevel converters are less harmonic generation and higher voltage capability because of serial connection of bridges or semiconductors. The most popular arrangement today is the three-level neutralpoint clamped topology.

6.2.1.Three-Level Compensators

Figure 18 shows a shunt VAR compensator implemented with a three-level neutral-point clamped (NPC) converter. Three-level converters [24] are becoming the standard topology for medium voltage converter applications, such as machine drives and active front-end rectifiers. The advantage of three-level converters is that they can reduce the generated harmonic content, since they produce a voltage waveform with more levels than the conventional two-level topology. Another advantage is that they can reduce the semiconductors voltage rating and the associated switching frequency. Three-level converters consist of 12 self-commutated semiconductors such as IGBTs or IGCTs, each of them shunted by a reverse parallel connected power diode, and six diode branches connected between the midpoint of the dc link bus and the midpoint of each pair of switches as shown in Fig. 31. By connecting the dc source sequentially to the output terminals, the converter can produce a set of PWM signals in which the frequency, amplitude and phase of the ac voltage can be modified with adequate control signals.

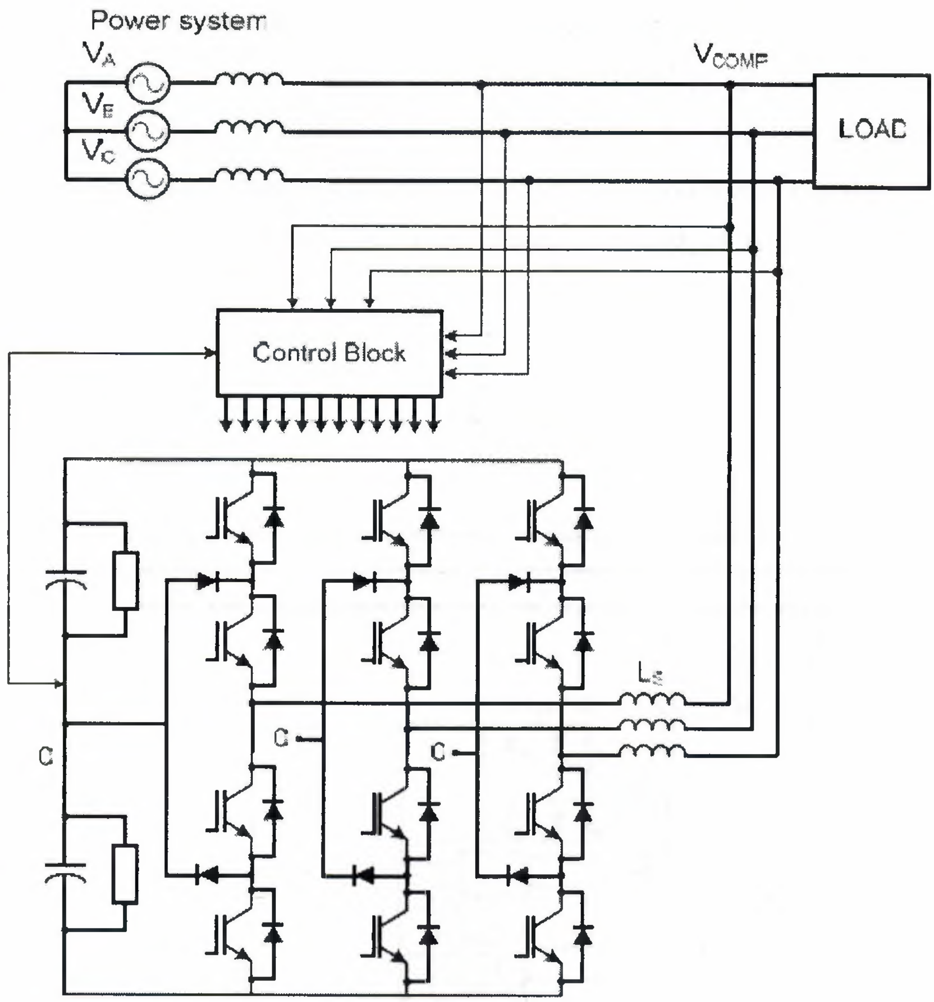
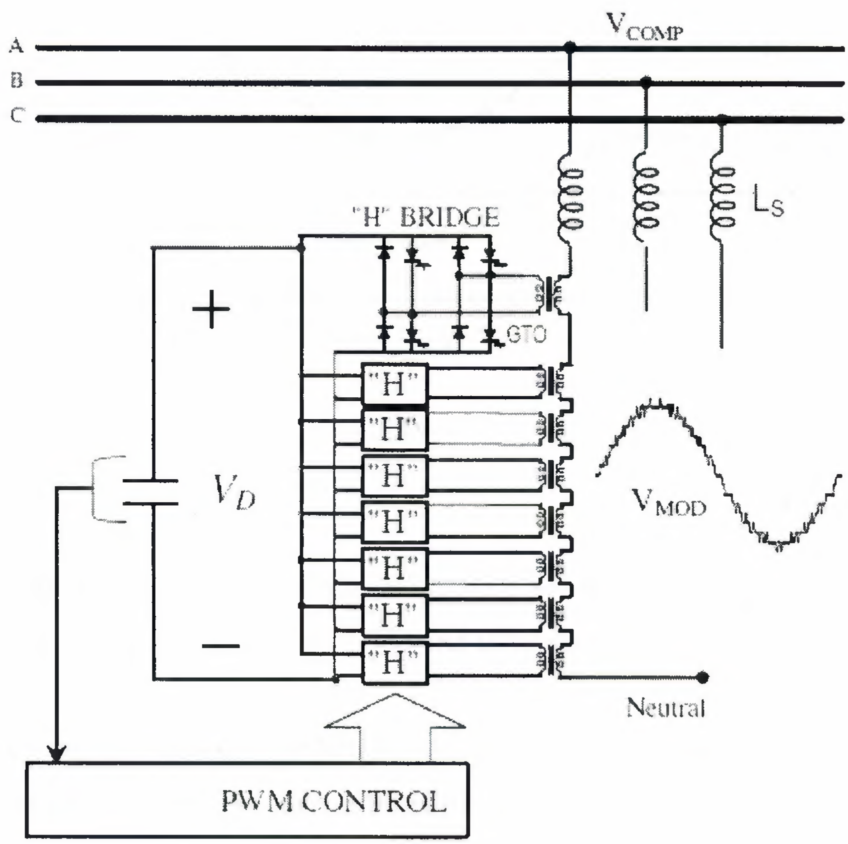


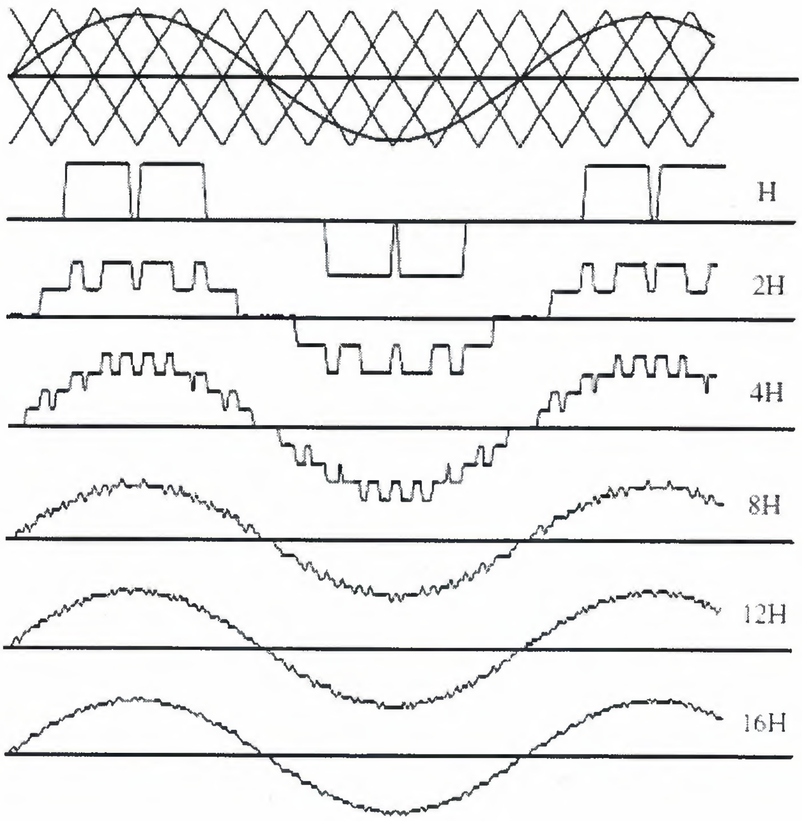
Fig. 31.- A shunt VAR compensator implemented with a threelevel NPC inverter.

6.2.2.Multi-Level Converters with Carriers Shifted

Another exciting technology that has been succesfully proven uses basic "H" bridges as shown in Fig. 32, connected to line through power transformers. These transformers are connected in parallel at the converter side, and in series at the line side [25]. The system uses SPWM (Sinusoidal Pulse Width Modulation) with triangular carriers shifted and depending on the number of converters connected in the chain of bridges, the voltage waveform becomes more and more sinusoidal. Figure 19 a)shows one phase of this topology implemented with eight "H" bridges and Fig. 19 b) shows the voltgae waveforms obtained as a function of number of "H" bridges. An interesting result with this converter is that the *ac* voltages become modulated by pulse width and by amplitude (PWM and AM). This is because when the pulse modulation changes, the steps of the amplitude also changes. The maximum number of steps of the resultant voltage is equal to two times the number of converters plus the zero level. Then, four bridges will result in a nine-level converter per phase.



a)



b)

Fig. 32 (a) Multilevel converter with eight "H" bridges and triangular carriers shifted; (b) voltage quality as a function of number of bridges.

Figure 33 shows the AM operation. When the voltage decreases, some steps disappear, and then the amplitude modulation becomes a discrete function.

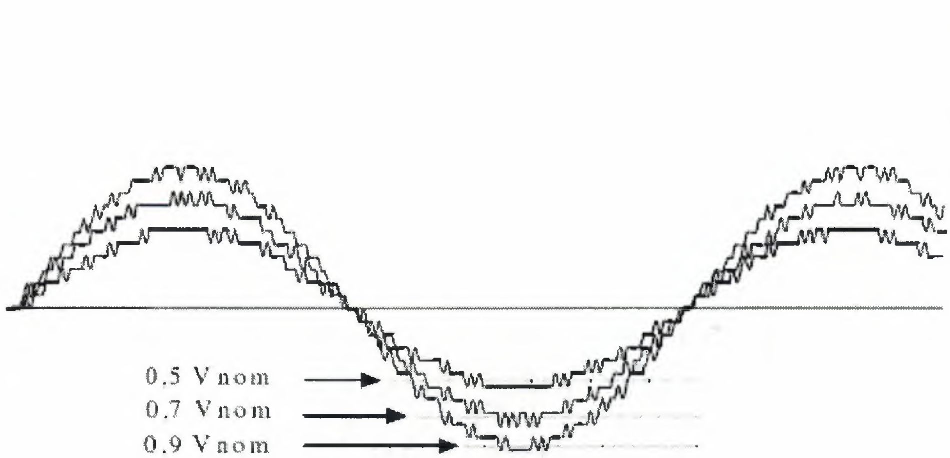
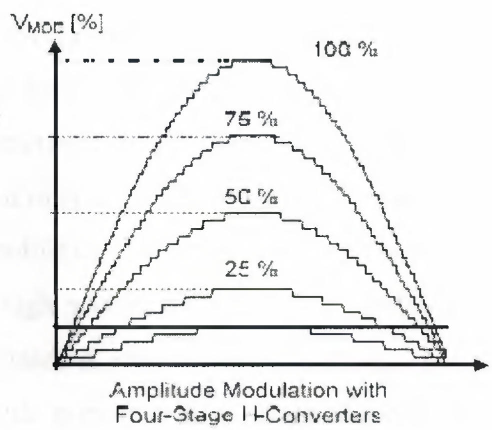


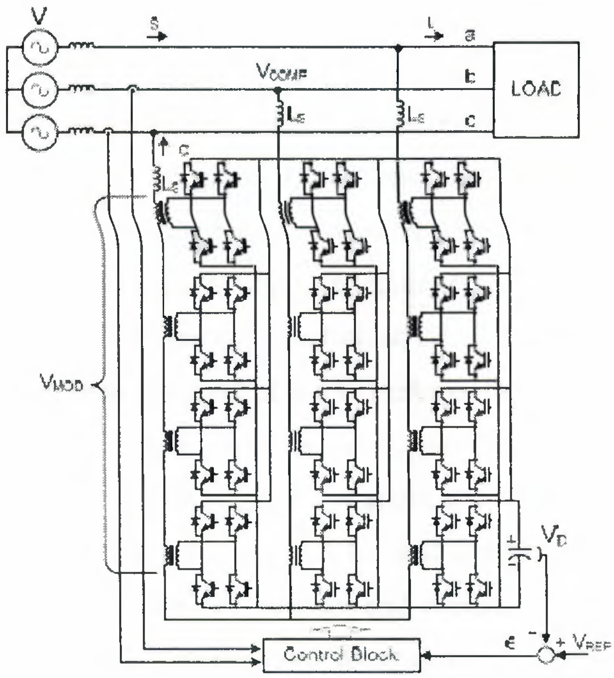
Fig. 33 Amplitude modulation in topology of Fig. 32a.

6.2.3.Optimized Multi-Level Converter

The number of levels can increase rapidly with few converters when voltage scalation is applied. In a similar way of converter in Fig. 19-a), the topology of Fig. 21-a) has a common dc link with voltage isolation through output transformers, connected in series at the line side. However, the voltages at the line side are scaled in power of three. By using this strategy, the number of voltage steps is maximized and few converters are required to obtain almost sinusoidal voltage waveforms. In the example of Fig. 21, Amplitude Modulation with 81 levels of voltage is obtained using only four "H" converters per phase (fourstage inverter). In this way, VAR compensators with "harmonic-free" characteristics can be implemented.



(a)



(b)

Fig. 34. (a) Converter output using amplitude modulation.

(b) Four-stage, 81-level VAR compensator, using "H" bridges scaled in power of three;

It is important to remark that the bridge with the higher voltage is being commutated at the line frequency, which is a major advantage of this topology for high power applications. Another interesting characteristic of this converter, compared with the multilevel strategy with carriers shifted, is that only four "H" bridges per phase are required to get 81 levels of voltage. In the previous multilevel converter with carriers shifted, forty "H" bridges instead of four are required. For high power applications, probably a less complicated three-stage (three "H" bridges per phase) is enough. In this case, 27-levels or steps of voltage are obtained, which will provide good enough voltage and current waveforms for high quality operation [26].

6.3. Semiconductor Devices used for Self-Commutated VAR Compensators

Three are the most relevant devices for applications in SVC: thyristors, Insulated Gate Bipolar Transistor (IGBTs) and Integrated Gate Controlled Thyristors (IGCTs). This field of application requires that the semiconductor must be able to block high voltages in the kV range. High voltage IGBTs required to apply selfcommutated converters in SVC reach now the level of 6.5 kV, allowing for the construction of circuits with a power of several MW. Also IGCTs are reaching now the level of 6 kV. Perhaps, the most important development in semiconductors for SVC applications is the Light Triggered Thyristor (LTT). This device is the most important for ultrahigh power applications. Recently, LTTs devices have been developed with a capability of up to 13.5 kV and a current of up to 6 kA. These new devices reduce the number of elements in series and in parallel, reducing consequently the number of gate and protection circuits. With these elements, it is possible to reduce cost and increase reactive power in SVC installations of up to several hundreds of MVARs [27].

6.4. Comparison Between Thyristorized and Selfcommutated Compensators

As compared with thyristor-controlled capacitor and reactor banks, self-commutated VAR compensators have the following advantages:

i) They can provide both leading and lagging reactive power, thus enabling a considerable saving in capacitors and reactors. This in turn reduces the possibility of resonances at some critical operating conditions.

ii) Since the time response of self-commutated converter can be faster than the fundamental power network cycle, reactive power can be controlled continuously and precisely.

iii) High frequency modulation of self-commutated converter results in a low harmonic content of the supply current, thus reducing the size of filter components.

iv) They don't generate inrush current.

v) The dynamic performance under voltage variations and transients is improved.

vi) Self-commutated VAR compensators are capable of generating 1 p.u. reactive current even when the line voltages are very low. This ability to support the power system is better than that obtained with thyristor controlled VAR compensators because the current in shunt capacitors and reactors is proportional to the voltage.

vii) Self-commutated compensators with appropriate control can also act as active line harmonic filters, dynamic voltage restorers, or unified power flow controllers.

Table 1 summarizes the comparative merits of the main types of VAR compensators. The significant advantages of self-commutated compensators make them an interesting alternative to improve compensation characteristics and also to increase the performance of ac power systems.

Table 1. Comparison of Basic Types of Compensators

	Synchronous Condenser	Static Compensator		Self-commutated Compensator
		TCR (with shunt capacitors if necessary)	TSC (with TCR if necessary)	
Accuracy of Compensation	Good	Very Good	Good, very good with TCR	Excellent
Control Flexibility	Good	Very Good	Good, very good with TCR	Excellent
Reactive Power Capability	Leading/Lagging	Lagging/Leading indirect	Leading/Lagging indirect	Leading/Lagging
Control	Continuous	Continuous	Discontinuous (cont. with TCR)	Continuous
Response Time	Slow	Fast, 0.5 to 2 cycles	Fast, 0.5 to 2 cycles	Very fast but depends on the control system and switching frequency
Harmonics	Very Good	Very high (large size filters are needed)	Good, filters are necessary with TCR	Good, but depends on switching pattern
Losses	Moderate	Good, but increase in lagging mode	Good, but increase in leading mode	Very good, but increase with switching frequency
Phase Balancing Ability	Limited	Good	Limited	Very good with 1-φ units, limited with 3-φ units
Cost	High	Moderate	Moderate	Low to moderate

Figure 35 shows the voltage / current characteristic of a self-commutated VAR compensator compared with that of thyristor controlled SVC. This figure illustrates that the self-commutated compensator offers better voltage support and improved transient stability margin by providing more reactive power at lower voltages. Because no large capacitors and reactors are used to generate reactive power, the self-commutated compensator provides faster time response and better stability to variations in system impedances.

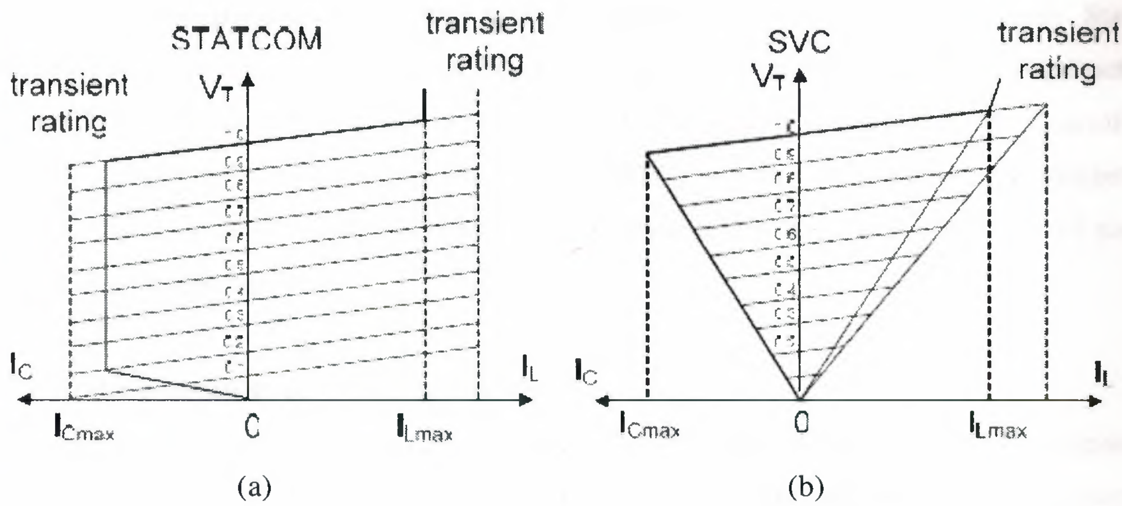


Fig. 35. Voltage – Current characteristics of shunt VAR compensators.

(a) Compensator implemented with selfcommutated converter (STATCOM).

(b) Compensator implemented with back to back thyristors.

7- NEW VAR COMPENSATOR´S TECHNOLOGY

Based on power electronics converters and digital control schemes, reactive power compensators implemented with self-commutated converters have been developed to compensate not only reactive power, but also voltage regulation, flicker, harmonics, real and reactive power, transmission line impedance and phase-shift angle. It is important to note, that even though the final effect is to improve power system performance, the control variable in all cases is basically the reactive power. Using selfcommutated converters the following high performance power system controllers have been implemented: Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the Dynamic Voltage Restorer (DVR), the Unified Power Flow Controller (UPFC), the Interline Power Flow Controller (IPFC) and the Superconducting Magnetic Energy Storage (SMES). The principles of operation and power circuit topology of each one are described below.

7.1. Static Synchronous Compensator (STATCOM).

The static synchronous compensator is based on a solid-state voltage source, implemented with an inverter and connected in parallel to the power system through a coupling reactor, in analogy with a synchronous machine, generating balanced set of three sinusoidal voltages at the fundamental frequency, with controllable amplitude and phase-shift angle. This equipment, however, has no inertia and no overload capability. Examples of these topologies are the figures 31, 32 and 34 [19], [28].

7.2. Static Synchronous Series Compensator (SSSC).

A voltage source converter can also be used as a series compensator as shown in Fig. 36. The SSSC injects a voltage in series to the line, 90° phase-shifted with the load current, operating as a controllable series capacitor. The basic difference, as compared with series capacitor, is that the voltage injected by an SSSC is not related to the line current and can be independently controlled. [28].

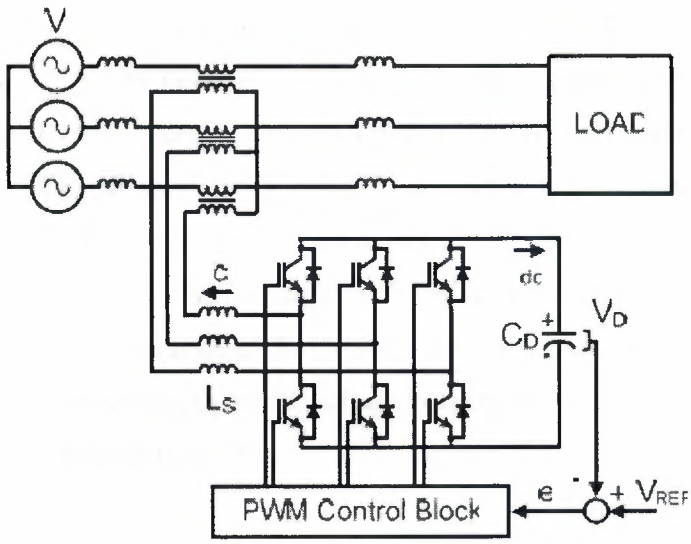


Fig. 36. Static Synchronous Series Compensator (SSSC).

7.3. Dynamic Voltage Restorer (DVR)

A DVR, shown in Fig. 37, is a device connected in series with the power system and is used to keep the load voltage constant, independently of the source voltage fluctuations [29]. When voltage sags or swells are present at the load terminals, the DVR responds by injecting three ac voltages in series with the incoming three-phase network voltages, compensating for the difference between faulted and prefault voltages. Each phase of the injected voltages can be controlled separately (ie, their magnitude and angle). Active and reactive power required for generating these voltages are supplied by the voltage source converter, fed from a DC link as shown in Figure 37 [28], [29], [30]. In order to be able to mitigate voltage sag, the DVR must present a fast control response. The key components of the DVR are:

- Switchgear
- Booster transformer
- Harmonic filter
- IGCT voltage source converter
- DC charging unit
- Control and protection system

• Energy source, that is, a storage capacitor bank When power supply conditions remain normal the DVR can operate in low-loss standby mode, with the converter side of the booster transformer shorted. Since no voltage source converter (VSC) modulation takes place, the DVR produces only conduction losses. Use of Integrated Gate Commutated Thyristor (IGCT) technology minimizes these losses. Static Synchronous Series Compensators (SSSC) and Dynamic Voltage Restorers (DVR) can be integrated to get a system capable of controlling the power flow of a transmission line during steady state conditions and providing dynamic voltage compensation and short circuit current limitation during system disturbances [30].

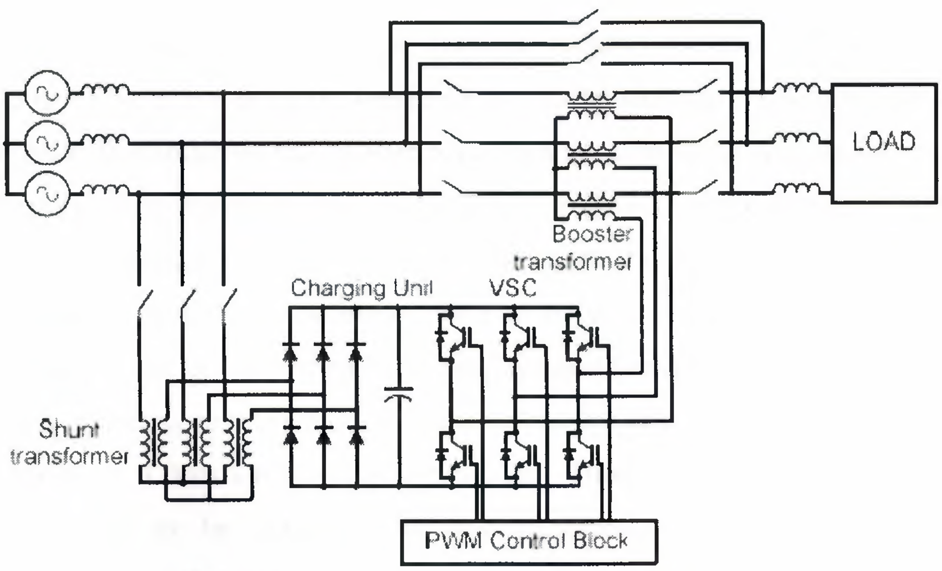


Fig. 37.- Dynamic Voltage Restorer (DVR)

7.4. Unified Power Flow Controller (UPFC).

The unified power flow controller (UPFC), shown in Fig. 38, consists of two switching converters operated from a common dc link provided by a dc storage capacitor. One connected in series with the line, and the other in parallel [28], [32]. This arrangement functions as an ideal ac to ac power converter in which the real power can freely flow in either direction between the ac terminals of the two inverters and each inverter can independently generate (or absorb) reactive power at its own ac output terminal. The series converter of the UPFC injects via series transformer, an ac voltage with controllable magnitude and phase angle in series with the transmission line. The shunt converter supplies or absorbs the real power demanded by the series converter through the common dc link. The inverter connected in series provides the main function of the UPFC by injecting an ac voltage *Vpq* with controllable magnitude ($0 \leq Vpq \leq Vpqmax$) and phase angle $\rho(0 \leq \rho \leq 360)$, at the power frequency, in series with the line via a transformer. The transmission line current flows through the series voltage source resulting in real and reactive power exchange between it and the ac system. The real power exchanged at the ac terminal, that is the terminal of the coupling transformer, is converted by the inverter into dc power which appears at the dc link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the inverter. The basic function of the inverter connected in parallel (inverter 1) is to supply or absorb the real power demanded by the inverter connected in series to the ac system (inverter 2), at the common dc link. Inverter 1 can also generate or absorb controllable reactive power, if it is desired, and thereby it can provide independent shunt reactive compensation for the line. It is important to note that whereas there is a closed "direct" path for the real power negotiated by the action of series voltage injection through inverter 1 and back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by inverter 2 and therefore it does not flow through the line. Thus, inverter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independently of the reactive power exchanged by inverter 2. This means that there is no continuous reactive power flow through the UPFC.

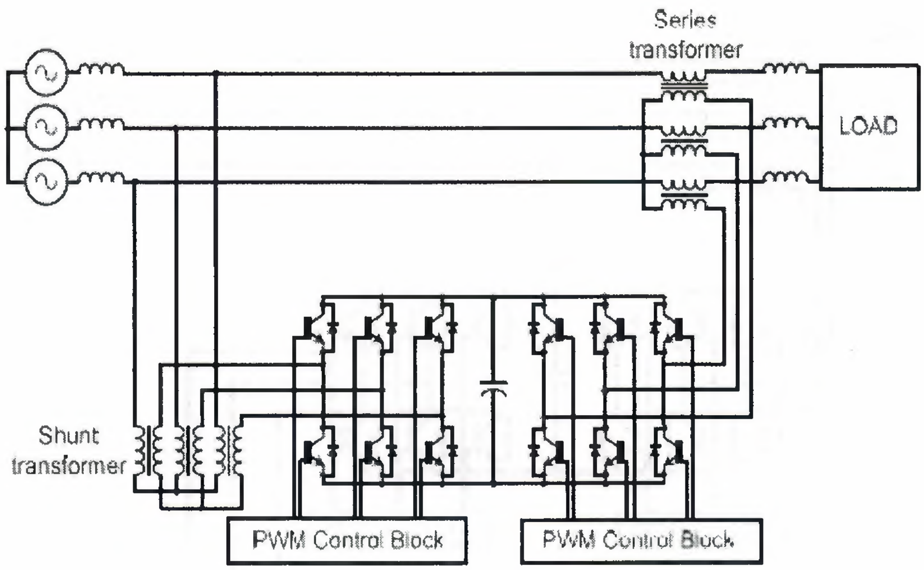


Fig. 38.- UPFC power circuit topology.

7.5. Interline Power Flow Controller (IPFC)

An Interline Power Flow Controller (IPFC), shown in Fig. 39, consists of two series VSCs whose DC capacitors are coupled, allowing active power to circulate between different power lines [33]. When operating below its rated capacity, the IPFC is in regulation mode, allowing the regulation of the P and Q flows on one line, and the P flow on the other line. In addition, the net active power generation by the two coupled VSCs is zero, neglecting power losses.

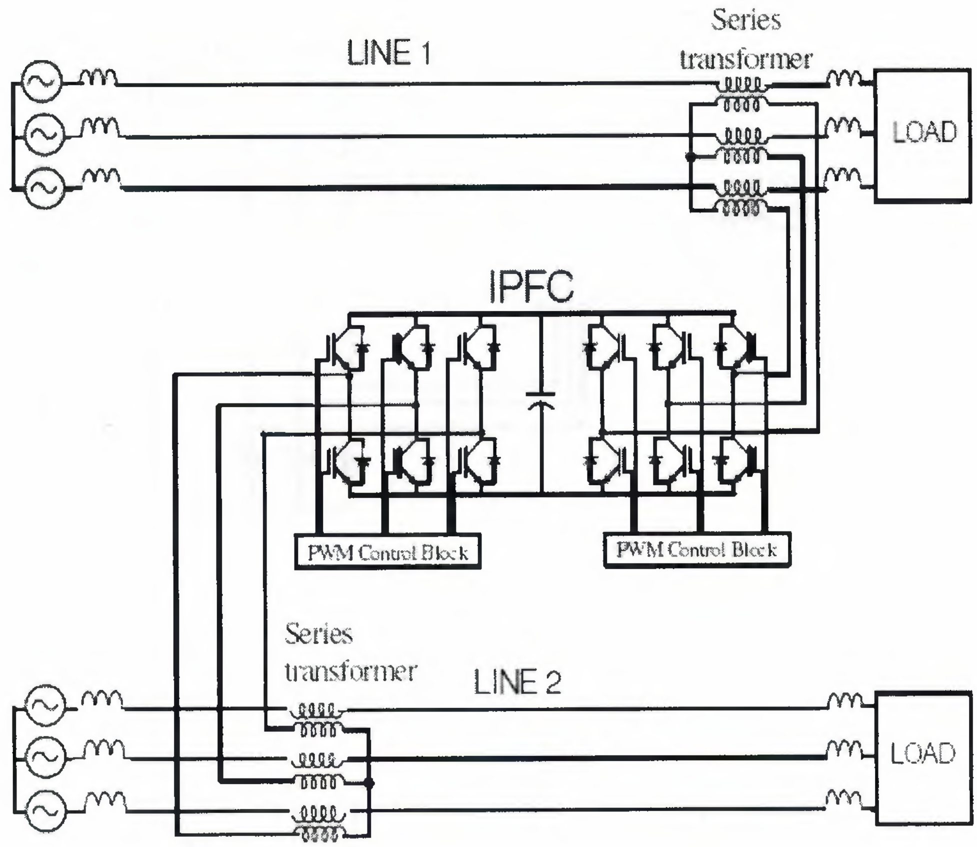


Fig. 39.- IPFC power circuit topology.

7.6. Superconducting Magnetic Energy Storage (SMES)

A superconducting magnetic energy storage (SMES) system, shown in Fig. 40, is a device for storing and instantaneously discharging large quantities of power [34], [35]. It stores energy in the magnetic field created by the flow of DC current in a coil of superconducting material that has been cryogenically cooled. These systems have been in use for several years to improve industrial power quality and to provide a premium-quality service for individual customers vulnerable to voltage fluctuations. The SMES recharges within minutes and can repeat the charge/discharge sequence thousands of times without any degradation of the magnet. Recharge time can be accelerated to meet specific requirements, depending on system capacity. It is claimed that SMES is 97-98% efficient and it is much better at providing reactive power on demand. Figure 28 shows another SMES topology using three-level converters:

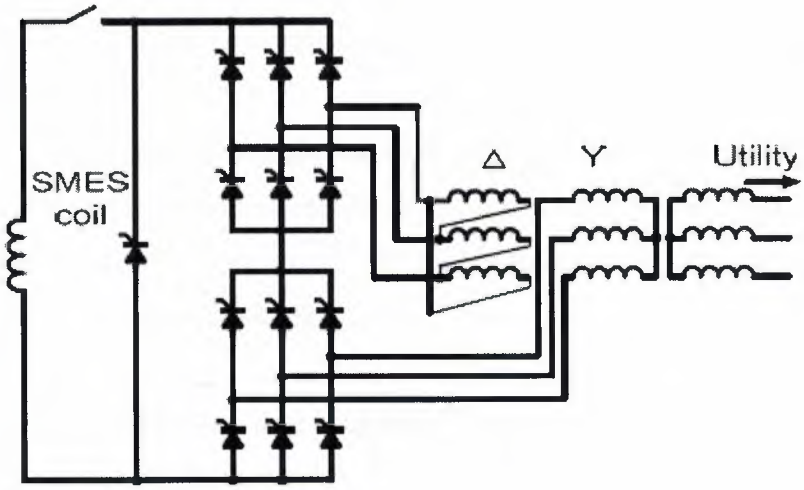


Fig. 40.- SMES implemented with a thyristor converter.

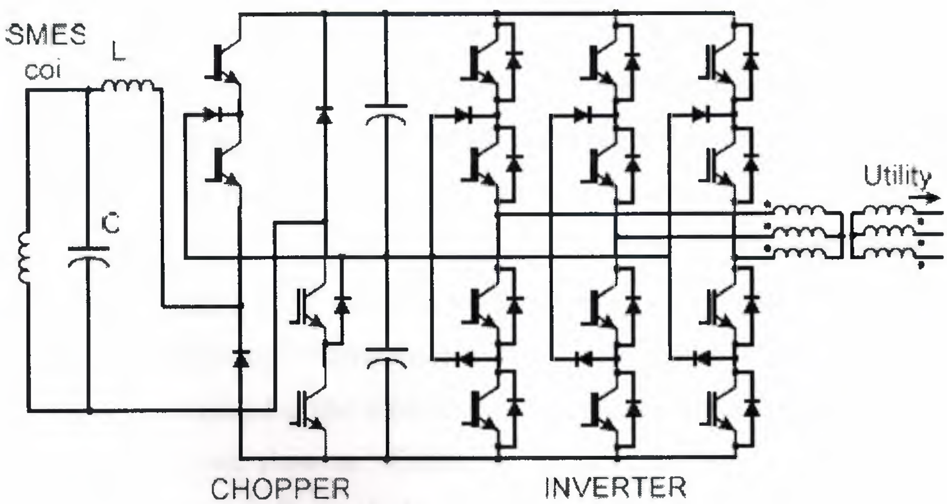


Fig. 41.- SMES implemented with a three-level converter.

The first commercial application of SMES was in 1981 [36] along the 500-kV Pacific Intertie, which interconnects California and the Northwest. The device's purpose was to demonstrate the feasibility of SMES to improve transmission capacity by damping interarea modal oscillations. Since that time, many studies have been performed and prototypes developed for installing SMES to enhance transmission line capacity and performance. A major cost driver for SMES is the amount of stored energy. Previous studies have shown that SMES can substantially increase transmission line capacity when utilities apply relatively small amounts of stored energy and a large power rating (greater than 50 MW). Another interesting application of SMES for frequency stabilization is in combination with static synchronous series compensator [37].

7.7. VAR Generation Using Coupling Transformers.

The power industry is in constant search for the most economic way to transfer bulk power along a desired path. This can only be achieved through the independent control of active and reactive power flow in a transmission line. Traditional solutions, such as shunt or series inductor/capacitor and phase angle regulator affect both the active and the reactive power flow in the transmission line simultaneously. With the use of Unified Power Flow Controller (UPFC), which is based on Voltage-Sourced Converter (VSC), the active and the reactive power flow in the line can also independently be regulated. However, a new concept using proven transformer topologies is being investigated: The SEN Transformer [38]. The SEN Transformer (ST), which is shown in Fig.42, is a new family of controlled power flow transformers that meets the new requirements of independent active and reactive power flow control in a transmission line. Using state-of-the-art power flow control techniques, the ST redirects the active and reactive power from an overloaded line and offers effective power flow management. . The main advantage of ST, compared with UPFC is its low cost, but the drawback of this alternative is its low dynamic response. The series compensation, show as VCOMP in Fig. 42, is a series connection of the three phases of the secondary windings of the transformer. This connection allows for independent control of voltage magnitude and phase-shift in each one of the three phases.

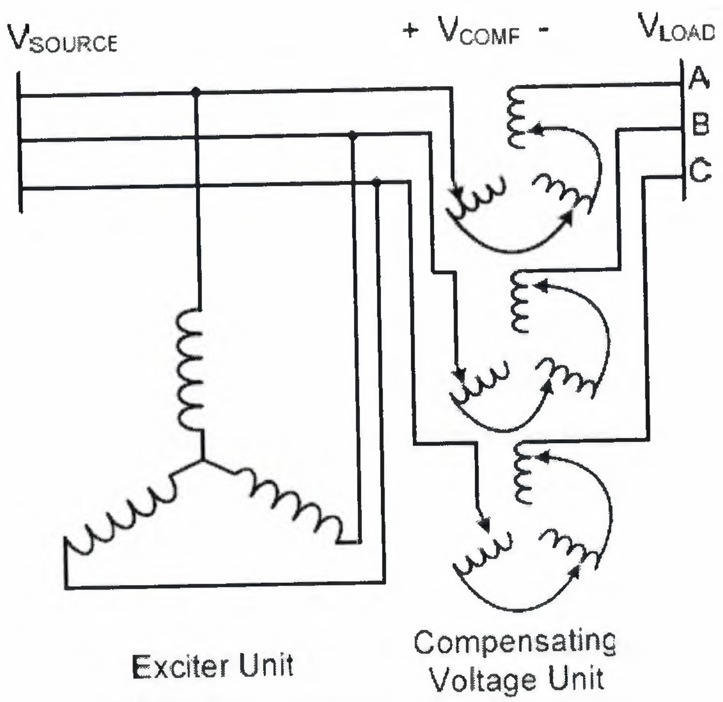


Fig. 42.- SEN Transformer (ST)

8- VAR COMPENSATOR´S APPLICATIONS

The implementation of high performance reactive power compensators enable power grid owners to increase existing transmission network capacity while maintaining or improving the operating margins necessary for grid stability. As a result, more power can reach consumers with a minimum impact on the environment, after substantially shorter project implementation times, and at lower investment costs - all compared to the alternative of building new transmission lines or power generation facilities. Some of the examples of high performance reactive power controllers that have been installed and are operating in power systems are described below. Some of these projects have been sponsored by the Electric Power Research Institute (EPRI), based on a research program implemented to develop and promote FACTS.

i) Series compensation in a 400 kV transmission system in Sweden [24].

The 420 kV transmission system between Northern and Middle Sweden comprises 8 lines with 8 Series Capacitors, having a total rating of 4800 MVAr. The degree of compensation for the individual Series Capacitor Banks, has been selected in such a way, that the sharing of active load (real power) between the individual 420 kV lines, which are of different designs, and the parallel connected 245 kV network, became most favorable. In the optimum point, minimum losses for the total network are obtained. The reduction in losses, compared to the uncompensated case, has alone paid for the Series Capacitor investment in a few years. Another benefit of the Series Capacitors in the Swedish 420 kV network is the ability to supply reactive power and support the voltage during and after a large disturbance. Figure 3 showed a typical compensated line with series capacitors.

The selected degree of compensation is between 30 – 70 % for the individual banks. With this compensation, stable transmission of more than 7000 MW on 8 parallel lines is achieved. Without Series Compensation five additional lines would have been needed to transmit the same amount of power. This, of course, would have been impermissible, not only from an investment point of view, but also with respect to the environmental impact, right of way problems, etc. The operating experience has been very good. The overall failure rate of capacitor units has been less than 0.1 per cent per year. Other faults have also been insignificant and caused no interruption of service. A simple and reliable design of the protective and supervising system has contributed to this.

ii) 500 kV Winnipeg – Minnesota Interconnection

(Canada – USA) [24].

Northern States Power Co. (NSP) of Minnesota, USA is operating an SVC in its 500 kV power transmission network between Winnipeg and Minnesota. This device is located at Forbes substation, in the state of Minnesota, and is shown in Fig.43. The purpose is to increase the power interchange capability on existing transmission lines. This solution was chosen instead of building a new line as it was found superior with respect to increased advantage utilization as well as reduced environmental impact. With the SVC in operation, the power transmission capability was increased in about 200 MW.

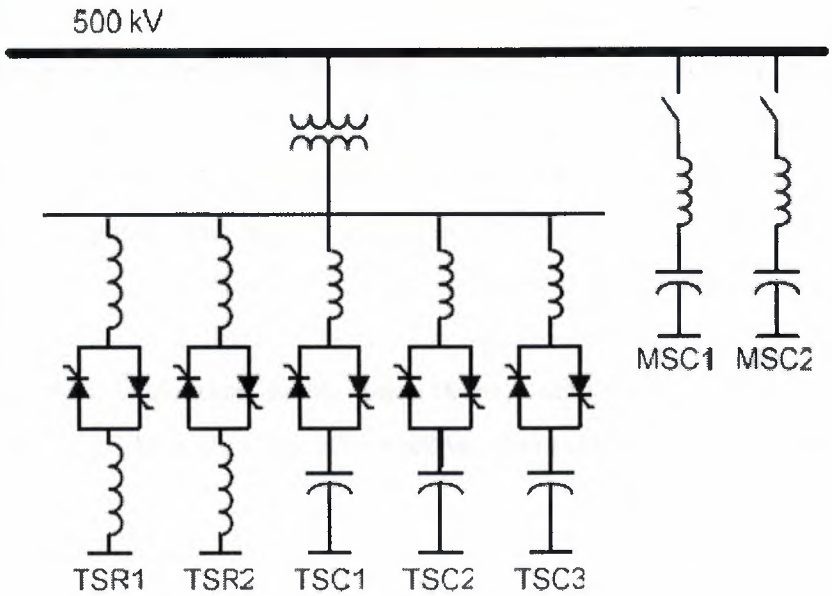


Fig. 43.- SVC at the Forbes Substation

The system has a dynamic range of 450 MVAr inductive to 1000 MVAr capacitive at 500 kV, making it one of the largest of its kind in the world. It consists of a Static VAR Compensator (SVC) and two 500 kV, 300 MVAr Mechanically switched Capacitor Banks (MSC). The large inductive capability of the SVC is required to control the overvoltage during loss of power from the incoming HVDC at the northern end of the 500 kV line.
The SVC consists of two Thyristor-switched Reactors (TSR) and three Thyristor-switched Capacitors (TSC). Additionally, the SVC has been designed to withstand brief (< 200 ms) overvoltages up to 150 % of rated voltage. Without the SVC, power transmission capacity of the NSP network would be severely limited, either due to excessive voltage fluctuations following certain fault situations in the underlying 345 kV system, or to severe overvoltages at loss of feeding power from HVDC lines coming from Manitoba.

iii) Namibia's long transmission lines give rise to unusual resonance. A new SVC has solved the problem [40].

Namibia is located at the South-West of Africa, between Angola, Botswana, South Africa and the Atlantic Ocean. While construction of the new 400 kV line has brought reliable power to Namibia, it was not without troubles. The line's length of 890 km, for instance, aggravated certain problems, mainly voltage instability and near 50-Hz resonance, which already existed in the NamPower system. To solve the problem, several solutions were considered as an answer to the resonance problem, including fixed and switched reactors, before deciding to install a FACTS device in the Auas substation. Finally, preference was given to conventional, proven SVC technology, which is shown in Fig.44, provided by three thyristor controlled reactors (TCRs), a fourth, continuously energized TCR, and two identical double-tuned filters, each rated at 40 MVAr. The filters take care of harmonics and supply capacitive reactive power during steadystate operation.

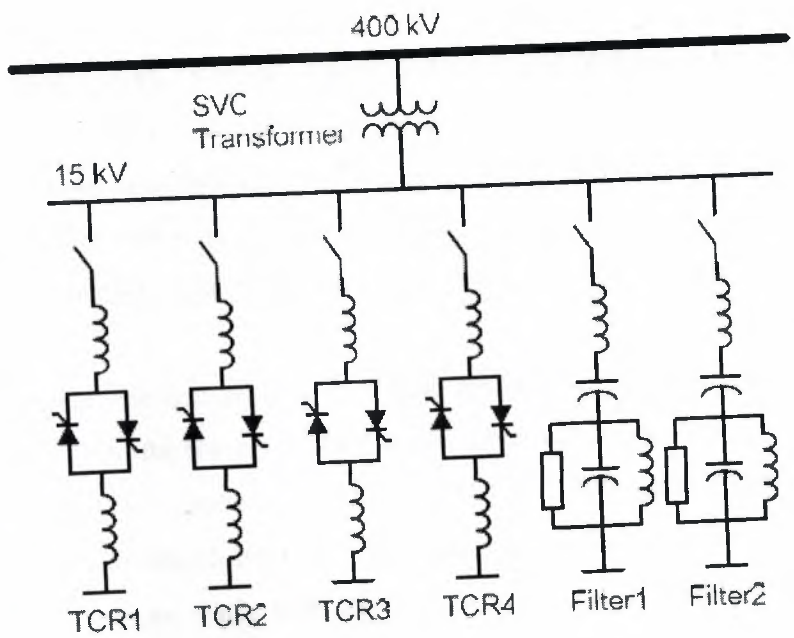


Fig. 44.- SVC at the Auas Substation

The SVC has a dynamic range of 330 MVAr (250 MVAr inductive to 80 MVAr capacitive) and is installed primarily to control the system voltage. High availability is essential for the SVC system. If, for any reason, it should have to be taken out of service, the 400-kV transmission system could not be operated without risking dangerous overvoltages. As a result, an availability figure of 99.7 % was specified, and this strongly influenced the design, quality, functionality and layout of its components and subsystems as well as of the SVC scheme as a whole. The required capacitive MVAr are provided by two 40-MVAr filter banks. Each filter is double-tuned to the 3rd/5th harmonics and connected in an ungrounded configuration. The double-tuned design was chosen to ensure sufficient filtering even in the case of one filter becoming defective.

iv) Channel Tunnel rail link [41].

Today, it is possible to travel between London and Paris in just over two hours, at a maximum speed of 300 km/h. The railway power system is designed for power loads in the range of 10 MW. The traction feeding system is a modern 50-Hz, 2-25-kV supply incorporating an autotransformer scheme to keep the voltage drop along the traction lines low. Power step-down from the grid is direct, via transformers connected between two phases. A major feature of this power system, shown in Fig. 45, is the static VAR compensator (SVC) support. The primary purpose of VAR is to balance the unsymmetrical load and to support the railway voltage in the case of a feeder station trip – when two sections have to be fed from one station. The second purpose of the SVCs is to ensure a low tariff for the active power by maintaining unity power factor during normal operation. Thirdly, the SVCs alleviate harmonic pollution by filtering the harmonics from the traction load.

Harmonic compensation is important because strict limits apply to the traction system's contribution to the harmonic level at the supergrid connection points. The SVCs for voltage support only are connected on the traction side of the interconnecting power transformers. The supergrid transformers for the traction supply have two series-connected medium-voltage windings, each with its midpoint grounded. This results in two voltages, 180 degrees apart, between the winding terminals and ground.

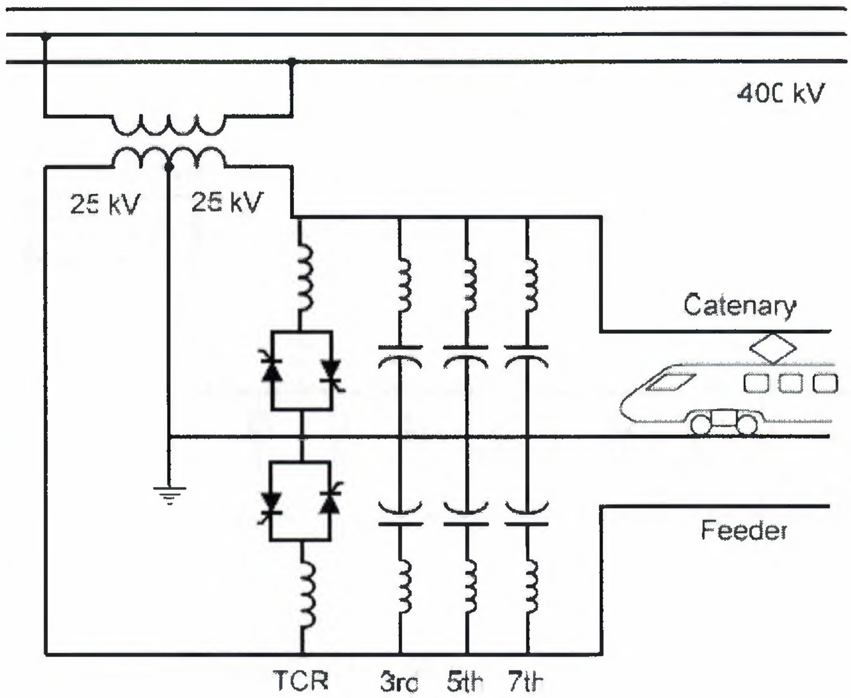


Fig. 45 .- VAR compensation system for the Channel Tunnel.

The SVCs are connected across these windings; consequently, there are identical single-phase SVCs connected feeder to ground and catenary to ground. The traction load of up to 120 MW is connected between two phases. Without compensation, this would result in an approximately 2 % negative phase sequence voltage. To counteract the unbalanced load, a load balancer (an asymmetrically controlled SVC) has been installed in the Sellindge substation. This has a three-phase connection to the grid. The load balancer transfers active power between the phases in order to create a balanced load (as seen by the supergrid).

v) Static Compensator (STATCOM) "voltage controller" ± 100 MVAr STATCOM at Sullivan Substation (TVA) in northeastern Tennessee, USA [42].

The Sullivan substation is supplied by a 500 kV bulk power network and by four 161 kV lines that are interconnected through a 1200 MVA transformer bank. Seven distributors and one large industrial customer are served from this substation. The STATCOM, shown in

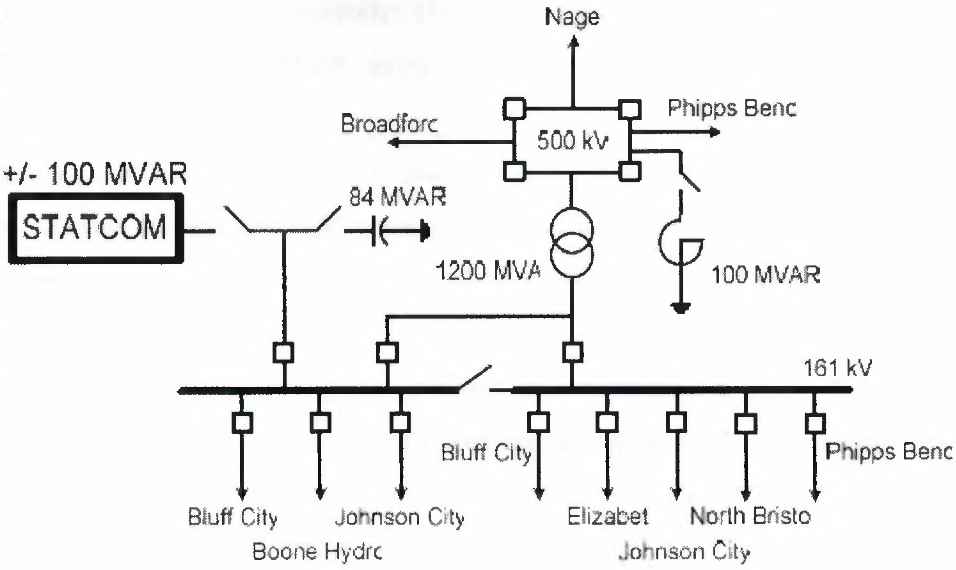


Fig. 46 is implemented with a 48 pulse, two-level voltagesource inverter that combines eight, six pulse three-phase inverter bridges, each with a nominal rating of 12.5 MVA.

The system also comprises a single step-down transformer having a wye and delta secondary to couple the inverter to the 161 kV transmission line, and a central control system with operator interface. The statcom system is housed in one building that is a standard commercial design with metal walls and roof and measured 27.4 x 15.2 m. Fig. 46.- The 100 MVAr STATCOM at Sullivan Substation The statcom regulates the 161 kV bus voltage during daily load increases to minimize the activation of the tap changing mechanism on the transformer bank, which interconnects the two power systems. The use of this VAR compensator to regulate the bus voltage has resulted in the reduction of the use tap changer from about 250 times per month to 2 to 5 times per month. Tap changing mechanisms are prone to failure, and the estimated cost of each failure is about $ 1 million. Without the STATCOM, the transmission company would be compelled either to install a second transformer bank or to construct a fifth 161 kV line into the area; both are costly alternatives.

vi) Unified power flow controller (UPFC) "all transmission parameters controller": ± 160 MVA shunt and ± 160 MVA series at Inez Substation *(AEP), northeastern Virginia, USA [42].*

The Inez load area has a power demand of approximately 2000 MW and is served by a long and heavily loaded 138 kV transmission lines. This means that, during normal power delivery, there is a very small voltage stability margin for system contingencies. Single contingency outages in the area will adversely affect the underlying 138 kV system, and in certain cases, a second contingency would be intolerable, resulting in a wide-area blackout. A reliable power supply to the Inez area requires effective voltage support and added real power supply facilities. System studies have identified a reinforcement plan that includes, among other things, the following system upgrades:

a) Construction of a new double-circuit high-capacity 138 kV transmission line from Big Sandy to Inez substation.

b) Installation of FACTS controller to provide dynamic voltage support at the Inez substation and to ensure full utilization of the new high capacity transmission line.

The UPFC satisfies all these needs, providing independent dynamic control of transmission voltage as well as real and reactive power flow. The UPFC installation (see Fig. 47 comprises two identical threephase 48-pulse, 160 MVA voltage-source inverters couple to two sets of dc capacitor banks. The two inverters are interfaced with the ac system via two transformers, a set of magnetically coupled windings configured to construct a 48-pulse sinusoidal waveshape. With this arrangement, the following operation modes are possible: Inverter 1 (connected in parallel) can operate as a STATCOM, with either one of the two main shunt transformers, while inverter 2 (connected in series) operates as a series static synchronous compensator (SSSC). Alternatively, inverter 2 can be connected to the spare shunt transformer and operates as an additional STATCOM. With the later configuration, a formidable shunt reactive capability of ± 320 MVA would be available, necessary for voltage support at some transmission contingencies in the Inez area. The expected benefits of the installed UPFC are the following:

a) Dynamic voltage support at the Inez substation to prevent voltage collapse under double transmission contingency conditions.

b) Flexible and independent control of real and reactive power flow on the new high capacity (950 MVA thermal rating) of the 138 kV transmission line.

c) Reduction of real power losses by more than 24 MW, which is equivalent to a reduction of CO_2 emissions by about 85000 tons per year.

d) More than 100 MW increase in the power transfer and excellent voltage support at the Inez bus.

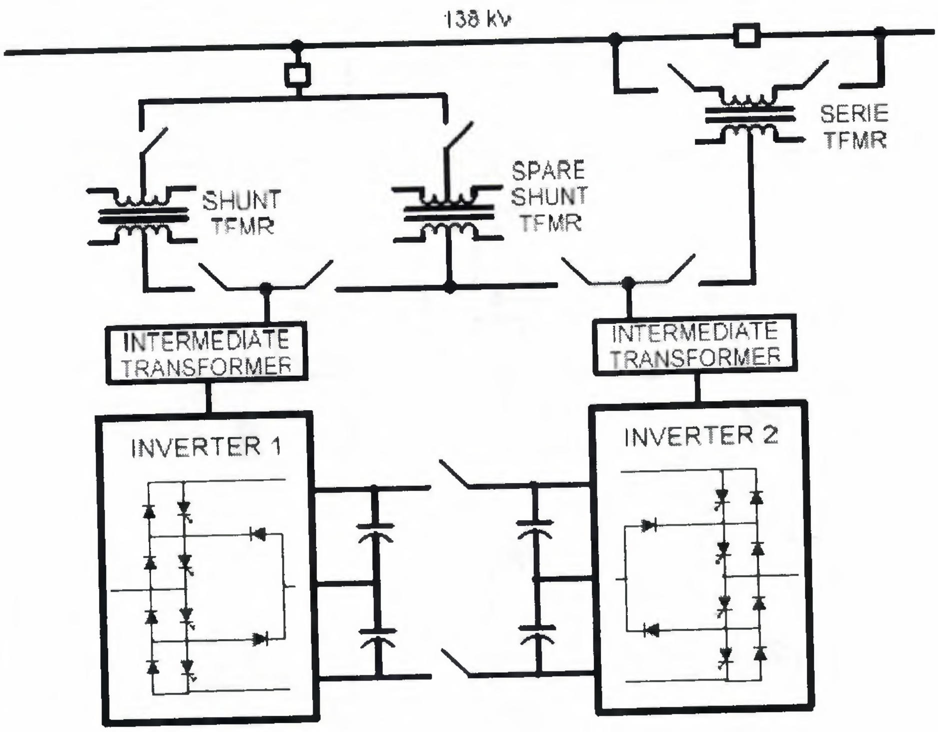


Fig. 47.- Inverter Pole Assembly of UPFC at Inez Substation.

vii) Convertible Static Compensator in the New York 345 kV Transmission System [43]. Convertible Static Compensator (CSC), a versatile and reconfigurable device based on FACTS technology was designed, developed, tested and commissioned in the New York 345 kV transmission system. The CSC, shown in Fig. 48, consists of two 100 MVA voltage source converters which can be reconfigured and operated as either Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC). The CSC installation at the New York Power Authority's (NYPA) Marcy 345 kV substation consists of a 200 MVA shunt transformer with two identical secondary windings, and two 100

MVA series coupling transformers for series devices in two 345 kV lines. The CSC provides voltage control on the 345 kV Marcy bus, improved power flow transfers and superior power flow control on the two 345 kV lines leaving the Marcy substation: Marcy–New Scotland line and Marcy– Coopers Corner line.

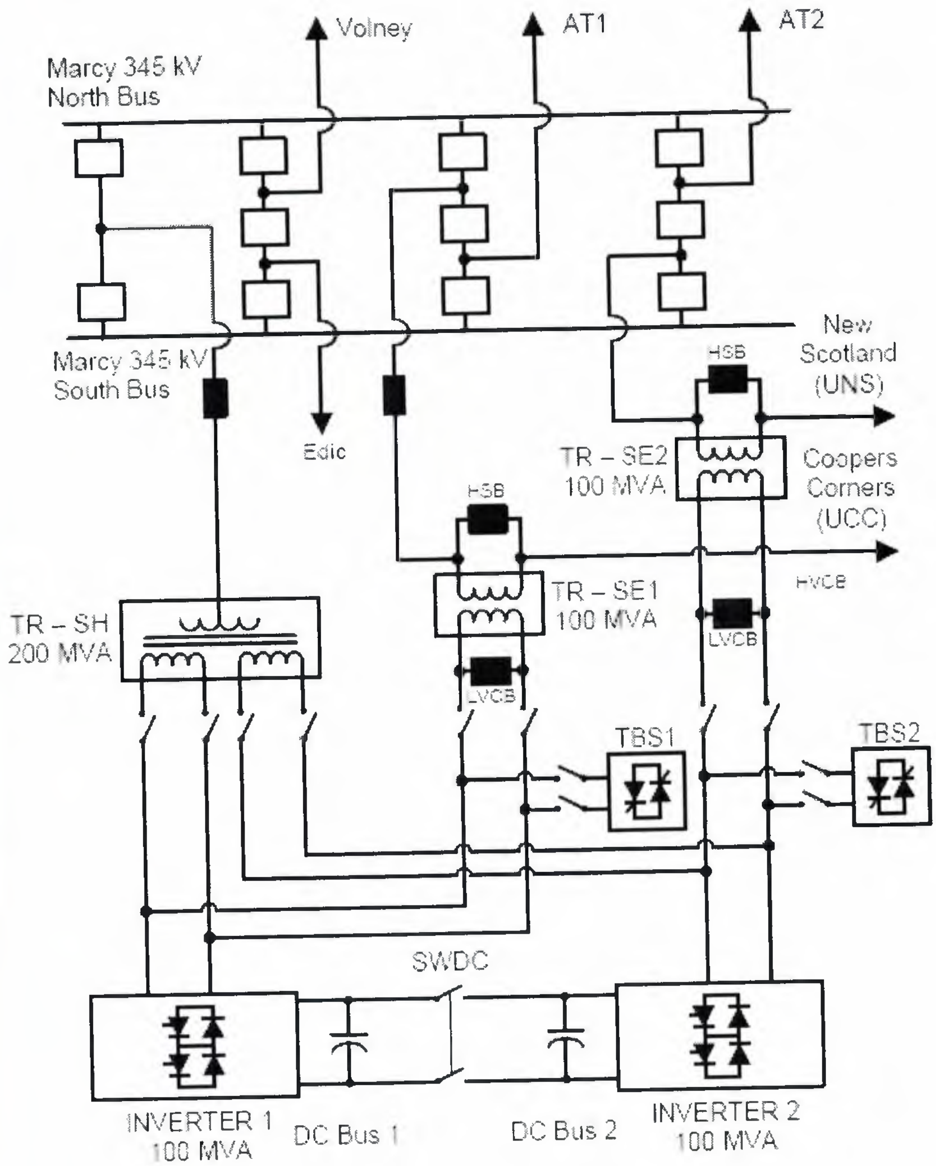


Fig. 48.- One-line diagram of 2x100 MVA CSC.

Each voltage source inverter of Fig. 33 has 12 threelevel Neutral-Point Clamped (NPC) poles connected to a common DC bus. Inverter pole outputs are connected to an intermediate transformer, which synthesize the three-phase near-sinusoidal 48-pulse voltage waveform that is coupled into the transmission system.

CONCLUSIONS

An overview of the technological development of VAR generators and compensators has been presented. Starting from the principles of VAR compensation, classical solutions using phase controlled semiconductors have been reviewed. The introduction of self-commutated topologies based on IGBTs and IGCTs semiconductors produced a dramatic improvement in the performance of VAR compensators: they have a faster dynamic behaviour and they can control more variables. The introduction of new self-commutated topologies at even higher voltage levels will increase the inpact of VAR compensation in future applications. Some relevant examples of projects have been described, where it can be observed that modern VAR compensators improve power systems performance, helping to increase reliability and the quality of power delivered to the customers. These examples show that VAR compensators will be used on a much wider scale in the future as grid performance and reliability becomes an even more important factor. Having better grid controllability will allow utilities to reduce investment in the transmission lines themselves. The combination of modern control with real-time information and information technologies will move them very close to their physical limits. Besides, the development of faster and more powerful semiconductor valves will increase the applicability of VAR generators to higher limits.

LIST OF ABBREVIATIONS

AC	Alternative Current
DC	Direct Current
RCD	Residual-current Devices
RCBO	Residual-current Breakers with Overcurrent Protection
CU	Consumer Unit
MCCB	Moulded Case Circuit Breakers
BMC	Bold Moulded Compound
AUX	Auxiliary
UVT	Undervoltage Release
ST	Shunt Trip
AS	Alarm Switch
PIK	Plug in Kit
RH	Rotary Handle
MOD	Motor Operating Mechanism
PFC	Power Factor Correction

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