Recent advances in var compensators

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Abstract. Static var compensators have been, for many years, an essential component in the operation of power transmission systems. They are part of a family of devices known as Flexible AC Transmission System (FACTS) devices. The advent of large capacity force-commutated semiconductor switches allows many developments in power electronic converters to be applied to the implementation of high power compensators. This paper describes the principles of controlled reactive power compensation, particularly in the context of power systems. It focuses on active static power converter-based compensators and discusses issues related to the power circuit topology and control techniques, including the impact of Pulse Width Modulation (PWM) techniques. Compensators based on current and voltage source converters and on *ac* controllers, both in the shunt and series configurations, are covered. Methods to enhance power capacity using multi-level and multi-pulse arrangements are discussed.

Keywords. Reactive compensation; power electronic converters; power systems.

1. Introduction

Reactive power (var) compensation has long been recognized as an essential function in the operation of power systems. At the distribution level, it is used to improve the power factor and support the voltage of large industrial loads, such as line commutated-thyristor drives and electric arc furnaces. Reactive power compensation also plays a crucial role at the transmission level in supporting the line voltage and stabilizing the system. Rotating synchronous condensers and mechanically-switched capacitor and inductor banks have been replaced in the 1970s by thyristor-based technologies: in typical installations, a thyristor-controlled reactor (TCR) provides variable lagging vars, and fixed or thyristor-switched capacitors (TSC) provide the leading vars. The combination of both devices in parallel allows continuous control of vars over a wide range of values, from leading to lagging vars (Gyugyi 1979). A large number of units have been successfully installed and operated for many years. At the same time, the potential of var compensators based on

static power converters have also been recognized and a number of configurations proposed and investigated (Gyugyi 1979).

However, thyristor technology only allows the implementation of lagging var generators, unless complex force-commutation circuits are used. This drawback has been eliminated with the introduction of Gate Turn-Off (GTO) thyristors (Larsen *et al* 1992). This has allowed the development of a number of configurations based on the use of synchronous voltage sources (Gyugyi 1993). Prototype GTO-based var compensation units, known as STATCOMs have been installed and tested by utilities (Schauder *et al* 1995). The STATCOM and other static var compensators have recently been grouped, together with other types of transmission system control devices, under the heading of Flexible AC Transmission System (FACTS) devices.

Reactive power compensators are typically connected in shunt across transmission and distribution systems. An alternative connection, the series connection, has recently received much attention from utilities (Gyugyi *et al* 1996). Technological solutions have been developed to solve problems associated with insulating the equipment from ground and the full potential of series connections can now be exploited. The latest development in var compensation technology has been the combination of series and shunt static compensators into one unit, known in the area of power systems under the name of Unified Power Flow Controller, or UPFC (Gyugyi 1992).

Static power converters have been successfully applied to a large number of power conversion problems at low and medium power levels. However adapting these solutions to high power transmission and distribution levels raises special issues. Although the capacity of power semiconductor switching devices has gradually increased, large ratings still require combining devices in series and parallel. In addition to the large power handling capacity, static compensators must have very high efficiency, since losses have a negative impact on both the initial and operating costs of the power system. Switching losses are therefore a primary concern and switching frequencies must therefore be kept low. This may result in large harmonic waveform distortion, unless special power circuit configurations are used.

This paper reviews the various methods available for generating reactive power (var) by means of force-commutated static power converters, taking into account the above constraints. It discusses topologies suitable for use with devices such as GTOs and the more recently available high power IGBTs and addresses switch gating issues, including the use of Pulse Width Modulation (PWM) techniques. Methods for designing high power converters suitable for transmission level compensation are presented, particularly multi-level and multi-module topologies.

2. Principles of var compensation

Var compensation can be viewed as the injection of reactive power, leading or lagging, into the *ac* system. In its simplest form, reactive power injection is achieved by inserting fixed capacitors or inductors in either series or shunt into the *ac* system. Assuming a compensation reactance X_c is inserted in a transmission system, the generated var Q_c is derived as follows.

Figure 1. Principles of var compensation in transmission systems. (a) Shunt compensation. (b) Series compensation.

- (a) For the shunt connection, figure 1a, a reactive current I_{cq} is generated, allowing in particular line voltage support at the point of connection, V_c :

$$I_{cq} = V_c / X_c,$$

$$Q_c = V_c^2 / X_c.$$

- (b) For the series connection, figure 1b the reactive impedance X_c partially compensates the line reactance, and a reactive voltage V_{cq} is inserted in series, the current I_c being the line current:

$$V_{cq} = I_c X_c,$$

$$Q_c = I_c^2 X_c.$$

In addition to the lack of controllability of the reactive power injection, fixed capacitive compensation can lead to *ac* system instability, such as in the phenomenon known as subsynchronous resonance, or SSR, associated with series compensation (Ooi & Dai 1993; Gyugyi *et al* 1996). In order to control the amount of reactive power injected, the reactive

impedance must be varied. Equivalently, a variable current or variable voltage is injected into the system, emulating a variable reactance, figure 1b.

The apparent reactive impedance of a fixed element can be varied using *ac* switches, or *ac* controllers. On the other hand, the current or voltage required to emulate a variable reactance can be injected into the *ac* system by means of synthetic sources, which can be realized using static power converters (Agaki *et al* 1984; Campos *et al* 1994). In addition to providing reactive power, these active compensators can also supply real power, either transiently or for a number of periods of the *ac* supply. This real power can be used to dampen power system oscillations or temporarily support the power system voltage under fault conditions. Furthermore, since the compensator is fully controllable, resonant frequencies associated with the use of capacitors are eliminated and the potential for instability suppressed.

Figure 2. Thyristor-controlled variable reactance compensators. (a) Thyristor-controlled reactor (TCR) and thyristor-switched capacitor (TSC) shunt compensator. (b) Transfer characteristics of a TCR with fixed capacitor. (c) Thyristor-controlled series capacitor compensator (TCSC).

3. AC controller-based structures

3.1 Conventional thyristor-controlled reactor

The basic scheme, figure 2a, consists of an *ac* controller which varies the apparent inductance of the inductor as reflected onto the *ac* line (Gyugyi 1979). The thyristor-controlled reactor (TCR) provides continuously controllable lagging vars and is biased using fixed, or more often, thyristor-switched capacitors (TSC). The injected vars can therefore be continuously adjusted from leading to lagging, figure 2b. However, the var injection or voltage regulation capability of the compensator is limited by the value of the reactance and is therefore line voltage dependent, figure 2b. Advantages of the system however include ruggedness, high efficiency, good dynamic performance and competitive cost. The disadvantages include injection into the line of large low frequency harmonic currents, dominant being the 5th and 7th components (300 and 420 Hz for a 60 Hz system) for the basic *ac* controller. Harmonics can be moved to higher frequencies by paralleling units and using special transformer configurations. Harmonic currents can be reduced by means of tuned LC filters. These however are costly and can cause voltage oscillations resulting from the added system resonant frequencies.

3.2 Force-commutated *ac* controller structures

An alternative to the thyristor-based *ac* controllers is the force-commutated *ac* controller, figure 3a (Jin *et al* 1994; Venkataramanan & Johnson 1997). The use of force-commutated switching devices removes the requirement for operating the converter in synchronism with the *ac* supply and allows gating the switches more than once per cycle. Arbitrary gating patterns can be implemented, particularly PWM patterns (Jin *et al* 1994). The principles of

Figure 3. Variable reactance scheme based on force-commutated *ac* controllers (Bias capacitors are not shown). (a) Basic *ac* controller structure. (b) Multi-module converter.

PWM pattern generation are explained in § 6.2. Assuming the inductor current is sinusoidal, a pattern with constant duty cycle yields *ac* line side currents that only contain harmonics around the switching frequency and its multiples. This pattern is simple to implement and allows control of the equivalent inductance; therefore, the amount of vars absorbed can be varied from 0 to a maximum value. Since losses associated with switching large currents at high voltages increase significantly with switching frequency, this frequency must be kept low, typically a few hundred hertz for GTOs. In order to reduce the distortion of injected currents, while keeping the switching frequency low, elementary modules are connected in parallel, figure 3b, and gated so that harmonics are minimized (see discussion in § 7). This also allows the realization of var compensators of large ratings (Lopes *et al* 1996).

3.3 Thyristor series controlled capacitor

The dual of the TCR is the thyristor-controlled series capacitor (TCSC), figure 2c. It uses a thyristor-based *ac* controller to continuously adjust the apparent reactance seen from the line. Such units have been successfully installed in transmission systems. However, they have the same limitations as TCRs, including harmonic injection. Performance and harmonic reduction may be enhanced by using force-commutated switches.

Although *ac* controller-based compensators are rugged and simple to control, operating regions are determined by the reactances used and by the line conditions, figure 2b. Converter-based structures are more versatile and flexible and are therefore receiving more attention.

4. Active compensator topologies

The availability of controllable voltage and current sources, realized using static power converters, allows the implementation of static compensators which can emulate the characteristics of a variable reactance, (figure 4). Advantages over the variable reactance structures include the following.

- (a) The performance characteristics are improved, particularly reactive power generation Q_{ref} capability, and are independent of the line parameters and line steady state operating voltages and currents, figure 5b.
- (b) Energy storage devices, such as battery banks (Walker 1990) and superconducting magnet energy storage systems (SMES) (Zhang & Ooi 1993) can be incorporated into the units. This allows the absorption and generation of real power, P_{ref} , which can be used for power system damping and voltage support under fault conditions.

In the shunt connection, figure 4a, the power converter system behaves in a manner similar to a synchronous machine operated as a synchronous condenser. If the converter is considered a voltage source behind an inductance, varying the output voltage is equivalent to varying the internal voltage of the synchronous generator, figure 5a. The shunt connection

Figure 4. Principles of active compensation based on static power converters. (a) Shunt connection. (b) Series connection. (c) Series-shunt connection (UPFC).

has long been the preferred connection: one end of the compensator can be connected to ground and fault currents do not flow through the compensator.

The series connection, figure 4b, offers a number of advantages over passive series compensation at a cost that is becoming competitive in demanding applications (Gyugyi *et al* 1996). These include: (i) the elimination of the risk of resonance normally associated with fixed series compensation (SSR); (ii) the possibility of injecting real power into the system and modifying the apparent resistance of the line. This improves the power transmission system characteristics, including the possibility of increasing the X/R ratio.

The combination of series and shunt connected converters, connected to a common dc bus, figure 4c provides the advantages of both the series and the shunt configuration and adds another degree of control. This structure is known as the Unified Power Flow Controller or UPFC (Gyugyi 1992). In addition to its operation as a var compensator, this scheme can also be used as a phase shifter. Although the dc bus can be either of the voltage or current source type, most of the structures that are investigated are based on the voltage source configuration. The voltage source dc bus, figure 4c, is the standard configuration for the UPFC structure. Inverter structures and their characteristics are discussed in § 5.

Figure 5. Operation of a voltage source-based compensator. (a) Phasor diagram illustrating var generation principles. (b) Transfer characteristics.

5. Converter structures

5.1 Current source type structures

In a thyristor-based implementation of the compensator, the basic converter structure consists of a 6-pulse *ac/dc* rectifier/inverter loaded with an inductor. Only controlled reactive power is exchanged between the *ac* line and the inverter and the compensator draws the real power required to supply inductor and inverter losses from the *ac* source. The *dc* bus is of the current source type and the converter structure is similar to that of figure 6a. However, thyristor-based units can only provide lagging reactive power and line side current harmonics are large, figure 7. The compensator has been used in special cases, such as SSR mitigation, for power system damping.

Figure 6. Static power converter structures. (a) Current source converter. (b) Voltage source converter.

Figure 7. Static power converter output waveforms. AC line voltage for voltage source or *ac* line current for current source. (a) Waveforms for single pulse patterns and pulse width modulation (SHE) patterns (5th and 7th harmonic elimination). (b) Harmonic spectrum for single pulse patterns and pulse width modulation (SHE) patterns.

The lagging reactive power limitation is removed when thyristors are either force-commutated (Walker 1986), or replaced by force-commutated devices, such as GTOs, figure 6a (Edwards *et al* 1988). The use of such devices also allows the implementation of PWM patterns to (a) control the level of injected current, (b) limit the amount of harmonic currents generated (Moran *et al* 1989a; Espinoza & Joos 1994). However, the structure requires an input capacitor and a line filter reactor, with the associated resonant frequency. Furthermore, in the standard control scheme, the current in the *dc* inductor is maintained constant at the rated value, resulting in significant losses, even when the compensator supplies no reactive power. This has led to the development of compensators based on superconducting magnet energy storage devices, SMES (Zhang & Ooi 1993). This technology however is complex and costly and the preferred compensator configuration is based on voltage source structures.

5.2 Voltage source type structures

These structures use a voltage source, a capacitor or a battery bank, on the *dc* side of the *ac/dc* inverter and reflect an *ac* voltage on the line side, figure 6b. Therefore, an *ac* inductor must be used to couple the converter to the line. Part or, in some implementations, all of the inductance is provided by the transformer leakage reactance. As such, the structure is similar to that of a synchronous condenser, and the converter may be referred to as a synchronous voltage source.

As in a synchronous condenser, the current injected into the *ac* supply is controlled by the magnitude of the reflected voltage, figure 5a: a voltage larger than the *ac* supply results in injected vars (leading or capacitive); the converse, or lagging reactive power, results if the voltage is smaller. Methods for controlling this voltage are explained in § 6.3. Since the *dc* bus voltage is controlled and independent of the line voltage, the steady state operation

of the compensator, in particular the compensating capability, illustrated in figure 5b, is independent of the line conditions (compare with figure 2b for a TCR-TSC conventional compensator). The compensator therefore provides a better dynamic response and the voltage support in the case of operation of the power system under fault conditions is improved.

The converter operates as a reactive power source, and in steady state does not supply or absorb real power. Losses however must be supplied either: (i) from the *ac* supply for a self-controlled *dc* bus, the preferred solution, in which case an additional *dc* capacitor voltage control loop must be used and a small amount of real power flows into the converter to cover losses (Moran *et al* 1989b); (ii) from a separate *dc* source, usually an *ac/dc* rectifier. If the var compensator is required to supply real power under transient conditions, battery banks can be connected on the *dc* side (Walker 1990).

Advantages of the scheme include low harmonic current injection, if harmonic voltage components are minimized (see §§ 6.2 and 7), and high dynamic performance. Losses are lower than for current source structures. Weaknesses include the risk of *dc* short circuits, when both switches in a leg conduct, and the requirements for output short circuit protection. Current source structures are more rugged: the short circuit current is limited, the *dc* bus being a current source.

6. Converter control techniques

The basic requirement of the compensator is to generate vars, by controlling either the voltage or the current generated by the converter. Since most of the compensators are based on the voltage source topology, the discussion on control techniques will focus on this topology. However, the conclusions regarding gating patterns are equally applicable to the current source topology: by virtue of duality, current source inverter (CSI) current patterns are identical to the line to line voltage patterns of the voltage source inverter (VSI). However, the gating of a VSI is generally simpler than that of a CSI: this is the result of the bidirectional current capability of the switches in the VSI, which ensures that there always is a return path for the *dc* bus current; therefore, there are no restrictions on the gating pattern. Switches in the CSI however are unidirectional devices and therefore require complementary gating to satisfy the requirements for *dc* bus current continuity.

6.1 Single pulse gating

Thyristors in rectifiers and inverters can only be gated once per cycle and line current must always be lagging the voltage to ensure line commutation. If thyristors are replaced by force-commutated switches such as GTOs, this restriction is lifted and both leading and lagging currents can be generated. Gating of each switch in a leg for half the *ac* supply period leads to a single pulse per period: this is the conventional means of controlling large static synchronous condensers, figure 7. An important advantage is that this method leads to the lowest switching losses and the highest efficiency. However, the pattern is fixed and the fundamental or desired component of the voltage (or current in a CSI) depends upon the *dc* bus voltage (or current). Furthermore, the harmonic content of the inverter

Figure 8. Multi-module pattern generation by carrier phase shifting. (a) Principles of Sine Pulse Width Modulation (SPWM) and phase shifted carriers (8 carriers, with only 3 shown). (b) Output voltage of individual modules and harmonic spectrum (carrier to fundamental frequency = 9). (c) Total output voltage and harmonic spectrum (4 units).

Figure 9. Multi-pulse compensator – voltage source topology. (a) Structure of individual units and output voltage waveforms. (b) Harmonic cancellation by transformer phase shifting and inverter output voltage waveform (24 pulse, $n = 4$, dominant harmonics at the 23rd and 25th).

output voltage is large resulting in large injected harmonic currents. Methods to reduce the harmonic content include large filters, a solution that is uneconomical or multi-pulse techniques, discussed in § 7.

6.2 PWM techniques

In order to vary the fundamental component of the output voltage for a fixed dc bus voltage, Pulse Width Modulation (PWM) is used. A number of techniques have been developed, among which: (i) selective harmonic elimination (SHE), (figure 7) (Kojori *et al* 1990), (ii) carrier PWM, the most common being the sine PWM (SPWM), (figure 8a) (Kuang & Ooi 1994; Suzuki *et al* 1997), and (iii) space vector modulation (SVM) (Bakhshai *et al* 1997). For high power applications, SHE has been successfully applied, since it minimizes switching frequency for a given harmonic content. Criteria for selecting an appropriate PWM pattern generation scheme, for voltage source inverters for example, include the following.

(a) *Instantaneous on-line control*: SPWM and SVM allow instantaneous control of the inverter output voltage; patterns generated by a SHE algorithm are generally stored in an EPROM or equivalent, which leads to a slower dynamic response.

(b) *Harmonic minimization*: Direct, selective and precise harmonic elimination can only be obtained with the SHE techniques; other patterns rely on the fact that the dominant harmonics are related to the switching frequency and its multiples. The switching frequency is equal to the carrier frequency for SPWM, as shown in figure 9, or to 2/3 of the cycle time for SVM.

(c) *Maximum inverter output in the controllable range*: Patterns that are generated on a three phase basis (SVM and SHE) maximize the output voltage for a given dc bus voltage; in SPWM, patterns are usually produced on a per leg basis, resulting in redundant switching on a line to line basis and a reduction in the output voltage. However, this value can be increased by injecting a third harmonic component in the modulating reference voltage.

6.3 Output control

The fundamental component of the output voltage of the inverter, $V_{i,1}$ (line to line peak), can be controlled, as required for var compensation purposes, figure 5c, either by changing the dc bus voltage V_{dc} or the PWM pattern, through modulation index control, M :

$$V_{i,1} = K_{ac} M V_{dc},$$

where K_{ac} is the gain of the converter, which depends upon the PWM pattern. For a three-phase inverter, the gain K_{ac} varies between 0.86 for SPWM, and 1.03 for SHE, SPWM with third harmonic injection and SVM.

The dynamic performance of the compensator depends largely on the control technique chosen.

(a) *DC bus voltage control*: If no PWM or a fixed SHE pattern designed for harmonic elimination only are used, output voltage control is obtained by varying the dc bus capacitor voltage V_{dc} . This is achieved by charging or discharging the dc capacitor; this can result in a slow response which depends upon the dc capacitor value, the dc voltage and the ac inductor (Joos *et al* 1991);

(b) *PWM pattern control*: If the PWM pattern is varied to produce a variable voltage from the fixed dc bus voltage, response can be very fast, in the order of the switching period. Instantaneous control of the injected current can then be implemented, and response is much faster than with conventional TCRs.

7. High power structures

In order to increase the power rating of the compensator to power system levels, typically 100 MVAR or more, available power switching devices must be combined in series and in parallel. However, advantage can be gained by combining converter units rather than individual devices: these units are associated so as to minimize harmonic injection while

maintaining switching losses low. This significantly increases compensator efficiency, which must be kept very high (ideally 98% or higher).

Multi-stepped voltage waveforms that more closely approximate a sinusoidal voltage can be obtained in a number of ways, among which are multi-level and multi-pulse or multi-module structures. In addition to providing flexibility in the control of the fundamental and harmonic components, these structures allow the increase of the voltage and current rating to levels required for transmission systems. They also provide the option of removing the coupling transformer used for voltage matching, which may reduce the cost of the installation (Hochgraf & Lasseter 1996). A number of structures are presented below, based on voltage source inverters, and the implementation of harmonic cancellation is discussed.

7.1 *Multi-pulse and multi-module structures*

Rather than increasing the frequency of the PWM pattern to reduce the harmonic content of the output voltage, a number of units can be connected in series through a magnetic interface circuit, figure 9b. Voltage distortion is reduced by harmonic cancellation or minimization. Some multi-pulse structures use PWM. If no PWM is used, output voltage control must be implemented by *dc* capacitor voltage control, as described in § 6.3 (Schauder *et al* 1995; Agaki *et al* 1990).

In general, harmonic cancellation is achieved by phase shifting the harmonic components to be cancelled so that, when the output voltages of individual units are added, these components cancel. This can be obtained by using the following.

(a) *Phase-shifted transformer windings*: Converter units are identically gated, figure 9a, but the fundamental component of the output is shifted by $60^\circ/n$ for n converters and applied to transformers with a phase shift of $60^\circ/n$, figure 9b; this allows total harmonic cancellation (Mori *et al* 1993).

(b) *Patterns with phase-shifted harmonics*: Phase-shifted carrier techniques, as shown in figure 8a for 8 units, exhibit this feature; these techniques however only provide harmonic minimization; for example, in figure 8b, individual converters have harmonic components around the 9th and multiples, whereas the combined output of 4 units, figure 8c, only contains dominant components around the 36th and multiples (Kuang & Ooi 1994); transformer configurations are similar to that of figure 9b, but no phase shift is required and standard transformers can be used.

7.2 *Multi-level structures*

By splitting the *dc* bus capacitor, figure 10a, it is possible to generate a stepped voltage similar to that in figure 8b. A number of topologies are available among which the Diode Clamped Capacitor Multilevel Inverter (DCMLI), figure 10b and the Flying Capacitor Multilevel Inverter (FCMLI) (Hochgraf *et al* 1994). Typically 3 to 7 level converters have been investigated. The number of levels can be chosen to satisfy the waveform distortion and output voltage level requirements (Menzies & Zhuang 1995).

Figure 10. Multi-level compensator-voltage source topology. (a) General three-phase structure. (b) Power circuit for one-leg of a 4-level diode clamped converter.

7.3 Single phase structures

The structures presented above are based on three-phase converter units. This is the natural choice for three phase systems. However, implementations based on single-phase converters of the voltage source type have been proposed, figure 11 (Lai & Peng 1996; Peng & Lai 1996). Advantages include: (i) modularity and ease of expansion, obtained by stacking units, particularly to meet voltage ratings; (ii) control flexibility, since control is implemented on a per phase basis and unbalances are more easily handled. Output voltage waveforms are similar to that of figure 9b for a single pulse operation (Lai & Peng 1996). PWM can also be used.

8. Summary

Force-commutated static power compensators, part of the FACTS devices family and based on GTOs and on IGBTs, offer an interesting alternative to conventional shunt or series, fixed or variable, reactance compensation. They are capable of producing the required amount of reactive power independently of the line voltage or current: this is the result of their voltage or current source nature. They can both supply and absorb reactive power. Furthermore, as required, they can supply real power if equipped with energy storage devices. They have almost instantaneous response to control variable changes. Unlike systems based on passive components, they do not introduce potentially damaging resonant frequencies. Advanced static compensators are therefore one of the key elements in enhancing the power transfer capacity and the security of large power systems and a number of prototype units are being installed.

Figure 11. Multi-module compensator based on single phase units – voltage source topology. (a) Three-phase structure. (b) Multi-module single phase converter, series connection – one leg. (c) Circuit topology of each unit.

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