EMTP Simulation of Interface Magnetics and Controls in Multi-Pulse High Power Static Var Compensators

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Abstract - **A simulation study of a multi-pulse STATCOM is discussed in this paper. It is based on the Electro Magnetic Transient Program (EMTP). Steady state simulation results are presented for a number of multipulse structures operating at very low switching frequencies and coupled to the transmission system by means of special transformer arrangements. Operation under transient conditions are illustrated. Results are extended the combination of series and shunt converters (UPFC).**

Keywords - AC transmission system, static compensator, GTO, FACTS, power converter, harmonics, EMTP.

I. INTRODUCTION

The control of reactive power is essential to the operation of power systems, for voltage support, var compensation and transient stability enhancement, among others. Conventional static var compensators (SVC) are based on thyristor controlled reactors (TCR) in parallel with thyristor switched capacitors (TSC). These VAR compensators are part of a larger class of power system compensators known as Flexible AC Transmission System (FACTS) devices [1].

Recent advances in power semiconductor technologies have allowed the implementation of compensators based on the principle of synchronous voltage sources (STATCOM) [2, 3]. The compensators consist in voltage source converters coupled to the transmission system by means of inductances, usually provided by the coupling transformers [4]. However, requirements for high voltage and current ratings can only be met by connecting switching devices or complete converter units in series and parallel. In addition, very high efficiencies can only be obtained by reducing the switching losses in the self commutated devices, and therefore switching at very low frequencies (a few hundred Hz). It can be shown that by associating a number of units gated appropriately, the compensator output voltage distortion, and therefore the distortion of the current injected into the ac system, can be significantly reduced.

This paper presents gating patterns and transformer connections appropriate for high power STATCOMs. Fixed and variable patterns are discussed. The topology presented is a 24 pulse system, but most of the results can be extended to higher pulse numbers. Evaluation of steady state characteristics and waveforms is carried out using the industry standard simulation software, the Electro Magnetic Transient Program (EMTP). Gating patterns, including Pulse Width Modulation (PWM), are presented. Transient responses to changes in the var reference are illustrated. Results are extended to the series-shunt configuration (UPFC), which combines shunt and series var compensation, and includes phase shifting capabilities [5]. These features can be used to damp out power oscillations and subsynchronous resonance phenomenon, enhance transient stability, regulate the bus voltages, and control the power flow.

II. PRINCIPLES OF ACTIVE COMPENSATION

A. Inverters

The basic converter topology consists of a number of three phase voltage source inverters operated from a common dc link capacitor, and composed of self commutated power semiconductor switches, typically gate turn of (GTO) thyristors, Fig. 1. More recently IGBTs have been proposed, which allow operation at higher switching frequencies. The basic converter discussed in this paper is of the 2 level type. Alternative arrangements include multilevel 3 phase structures and cascaded single phase full bridge inverters.

The same converter structure can be used in conjunction with a series transformer to implement series var injection, as in a Static Synchronous Series Compensator (SSSC). If a series and a shunt unit are connected to the same dc bus, the resulting system is known as the Unified Power Flow Controller (UPFC). This configuration allows the control of real power in the ac system, in addition to the control of reactive power on both the series and shunt sides.

B. Static Compensator (STATCOM)

The STACOM can be viewed as a static synchronous condenser, Fig. 2. By adjusting the converter output volt-

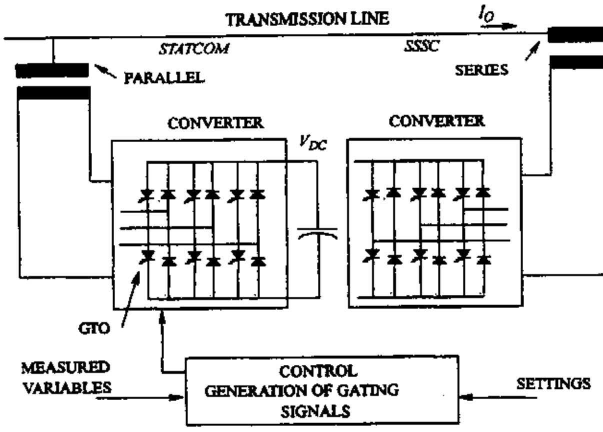


Fig. 1. Basic configuration of a STATCOM and an SSSC.

age, leading or lagging reactive current can be injected into the system. Voltage magnitude variation is obtained by changing the capacitor voltage, if a fixed pattern is used, or by modifying the pattern. In a three phase 2 level inverter, this requires pulse width modulation, with at least one notch in the pattern.

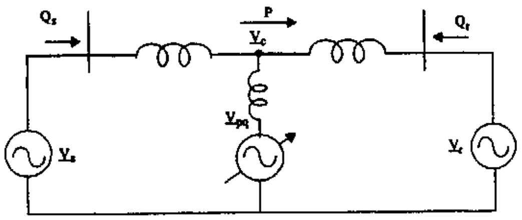
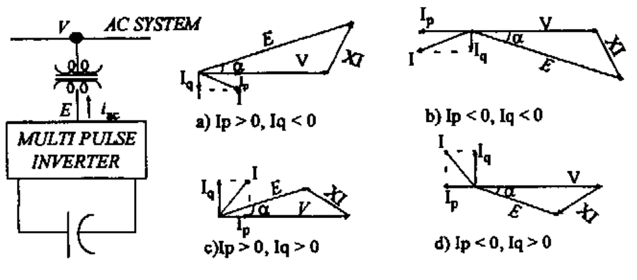


Fig. 2. Single phase equivalent of a STATCOM.

Since the dc bus is self controlled, only reactive power Q can be exchanged with the ac system. Active power P is however required to cover losses in the converter system. If dc bus capacitor voltage control is used, active power is also required to transiently change the capacitor voltage. In a synchronously rotating frame, and using the standard d-q or p-q system, total real and reactive power can be expressed as [6]:

$$P = \frac{3}{2}VI_p = \frac{3EV}{X}\sin\alpha \qquad Q = \frac{3}{2}VI_q$$

The p-axis current component, i_p, accounts for the instantaneous power, and the q-axis component, i_q, accounts for instantaneous reactive power.



a) Ip > 0, Iq < 0
b) Ip < 0, Iq < 0
c)Ip > 0, Iq > 0
d) Ip < 0, Iq > 0

Fig. 3. Principles of α control (*Ip*>0 for active power).

If the STATCOM is used only for reactive shunt compensation, the p-axis component of the inverter current will be zero is steady state for a lossless inverter.

Fig. 3 shows the single phase equivalent circuit of the STATCOM and the principle of active and reactive power control.

The dynamic equations of this system are nonlinear, if α is regarded as input variable. A functional control scheme for a STATCOM operated as shunt compensator is discussed in Section IV.

III. MULTILEVEL VOLTAGE PATTERNS

In a three-phase bridge, the voltage produced by gating the switches once per cycle, or fundamental frequency gating, is a square wave with a duty cycle of 120°. This waveform contains a large amount of low frequency harmonics, typically of order $(6k \pm 1)f$, resulting in large low frequency harmonic currents flowing in the line. To reduce the harmonic content of the voltage, multilevel or PWM patterns can be used. If the switching frequency must be kept low, multilevel patterns are preferable. These can be generated using either multilevel converters or by associating a number of units, usually coupled by means of transformers or an electromagnetic interface.

Multi-pulse converters have the advantage of being modular. Multi-pulse converters are connected together to form a complete system by means of transformers. The transformer configuration depends upon its functions. In addition to adding the voltages of individual units, transformers can also be used to cancel certain voltage harmonic components. A number of gating patterns suitable for converters switching at very low frequencies are presented. Waveforms were obtained using EMTP.

A. Fundamental frequency switching

The switches in each converter are gated once per cycle of the ac voltage, that is 180° for the top and bottom switches. The voltage at the output of each converter, on a line to line basis is a square wave. If the voltages of n converters are shifted by $60°/n$, and each transformer arrangement shifts the voltage back by an equal amount, it can be shown that harmonics are cancelled on the line side of the transformer. The pulse number on the dc side is $6n$, and the distortion harmonic components are of order $(6nk \pm 1)f$. This is illustrated in Fig. 4 for a 24 pulse converter. The inverter connection is shown in Fig. 5.

The magnetic interface can be implemented using the conventional phase shifting transformers, consisting in combinations of windings on the different phases of the magnetic core [7]. The transformer is complex and transformer utilization is not optimized.

Alternatively, the transformer system can be implemented using conventional three phase transformers with appropriate turns ratios and associated so as to give the required phase shift [8, 9], as shown in Fig. 6. Transformer utilization is significantly improved and the total transformer kVA therefore reduced.

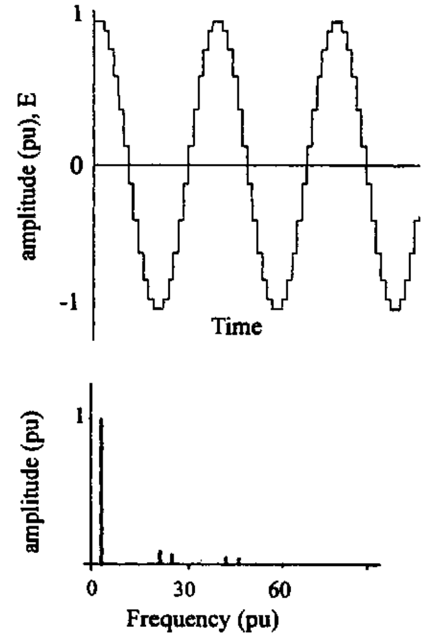


Fig. 4. Typical multi-level voltage pattern - 24 pulse converter. (a) Output waveform. (b) Spectrum.

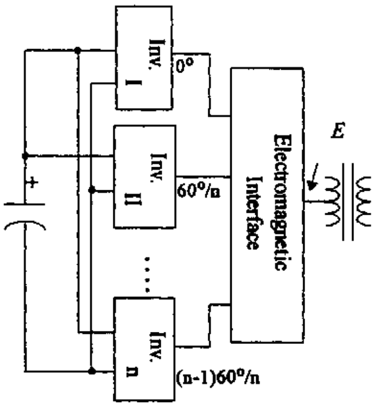


Fig. 5. Multi-pulse converter based on a phase-shifting electromagnetic interface.

Since the pattern is fixed, the rms value of the voltage reflected back on the ac side is fixed and depends upon the dc bus voltage. This value can therefore only be varied by changing the dc bus voltage.

B. Low frequency pulse width modulation

If the switching frequency is allowed to increase, for example from 1 pu to 3 pu (360 Hz), low frequency pulse width modulation (PWM) patterns can be implemented. PWM can be used to control harmonic components, including the fundamental component, of the converter output voltage. In particular, patterns, based on space vector modulation, can be derived to control the fundamental component. These patterns can be implemented with switching frequencies as low as 3 pu.

Space vector modulation is based on representing the output voltage of the three phase inverter by means of a space vector, V, as shown in Fig. 7 (a). The position and magnitude of this vector is translated into a set of converter states, Fig. 7 (b), from which gating patterns can be extracted. The reference space vector is sampled once every 60° and synthesized using the two adjacent active vectors, together with one zero vector. Each inverter has the same pattern and switches at 3 pu frequency. The resulting output voltage for a 4 pulse converter is shown in Fig. 7 (c).

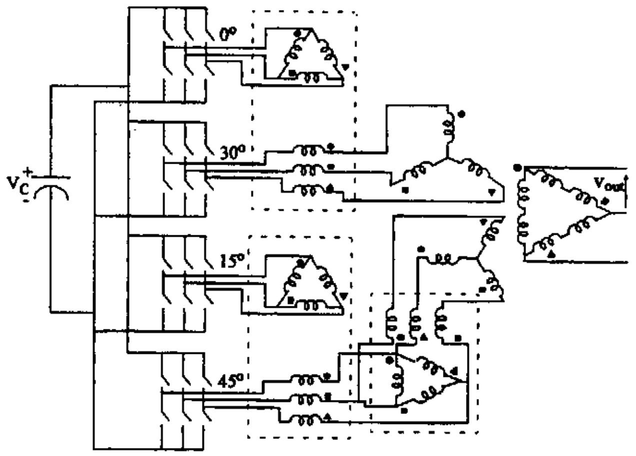


Fig. 6. Proposed phase shifting transformer connection.

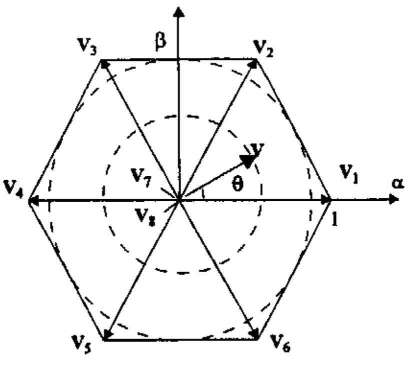
Output voltage is controllable from 0 to maximum corresponding to the square wave patterns of the fundamental switching frequency technique. Harmonic reduction is carried out in a manner similar to that used in fundamental frequency switching, that is phase shifting transformers. The arrangement of Fig. 6 has been used [9]. A typical output patterns is shown in Fig. 7. Patterns are similar to those of Fig. 4 for modulation indices equal to k/n.

C. Phase shifted PWM patterns

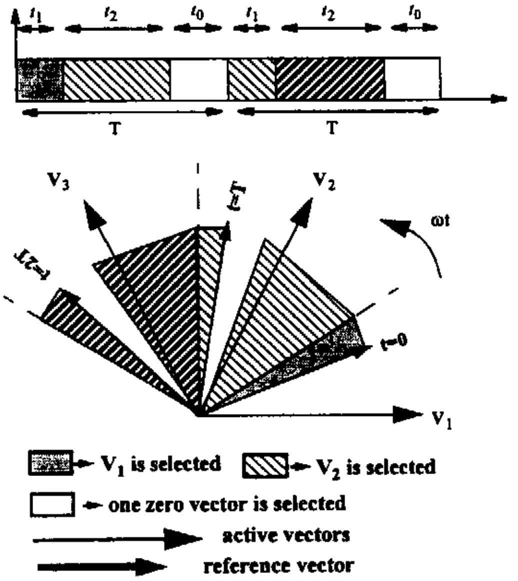
The standard method for obtaining patterns that produce voltages in phase but having phase shifted harmonic components is by means of carrier PWM techniques. When the voltages of individual converters are added, harmonic components cancel up to an order that depends on the carrier frequency and on the number of units in series.

A similar result can be obtained using space vector modulation, Fig. 7 (a) [10]. Amplitude control is obtained by the depth and position of the notches created in the voltage pattern. By varying these from one converter to another, harmonic components are phase shifted and cancel in the complete system. More specifically, each inverter has a switching pattern such that the fundamental components are equal. However, the sampling of the reference space vector for each inverter is delayed by $60^\circ/n$ for n inverters. The harmonic components of each inverter are therefore shifted, leading to cancellation of low order harmonics. The dominant harmonic components for n inverters are of order $(6n \pm 1)f$. Switching frequencies can be as low as 3 pu, and the amplitude of the fundamental is controllable form 0 to a maximum corresponding to square wave operation.

No special transformer is required, since the voltages of individual converters are simply added.

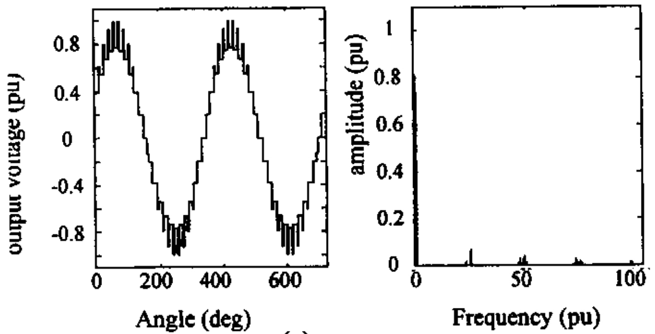


(a)



Cycle periods, reference vector, decision areas, and selection of switching state vectors in the proposed technique

(b)



(c)

Fig. 7. Space vector modulation patterns for multi-pulse converters - amplitude control ($n = 4$, $M = 0.8$). (a) Space Vector. (b) Selection of switching states. (c) Output.

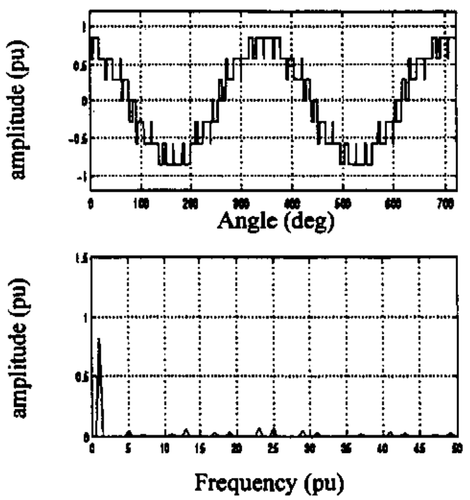


Fig. 8. Space vector modulation patterns for multi-pulse converters - phase shifted patterns ($n = 4$, $M = 0.8$).

IV. SYSTEM SIMULATION STUDIES

A. STATCOM operation

The Electro Magnetic Transient Program (EMTP) provides an appropriate environment for studying the behavior and the performance of power systems for both transient and steady state operation. It allows an exact representation of power system components as well as the control units. It is therefore a powerful simulation tool for power system analysis. In addition to simulation conventional power system components, it is possible, by means of ideal switches, to develop models for self commutated converters.

The complete 24 pulse STATCOM, including inverters, transformers and control loops has been implemented in EMTP. Standard models are used for transformers, including saturation and impedances, and lines.

The inverters use ideal switches (type 13, with appropriate snubber circuits). The 24 pulse configuration is readily extended to higher pulse converters. The control system is based on standard models modified to suit the control strategy.

Transient operation results were obtained for a multi-pulse converter gated at fundamental frequency, that is using dc capacitor voltage control for output control. The

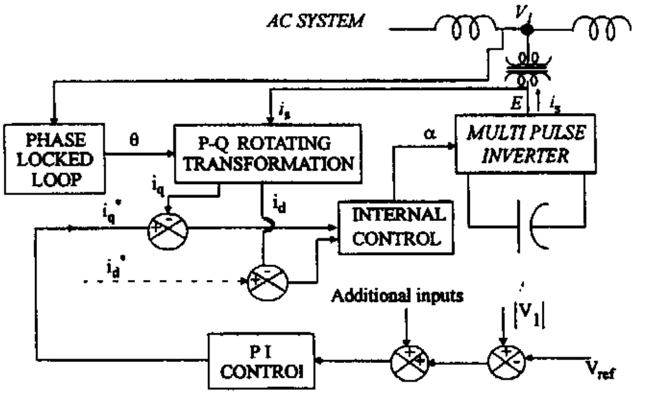


Fig. 9. STATCOM control system.

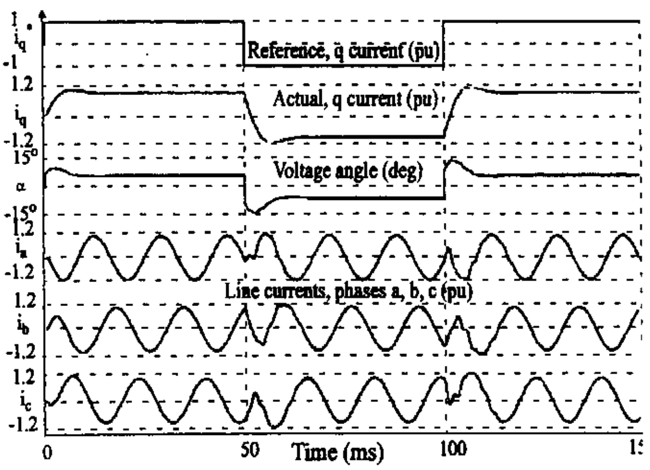


Fig. 10. Transient response of the current control loop.

STATCOM control system is shown in Fig. 9.

Two sets of simulation results are presented in Figs. 10 and 11 to illustrate the dynamic response of the current controller and to verify the voltage regulation respectively. In Fig. 10, the operation of the current control loop is illustrated.

In Fig. 11, both capacitive and inductive modes of operation are investigated. The control system is fast, and the variables reach their steady state values in less than a cycle. The response is a function of inverter gating delays, but more importantly of the system parameters, namely dc capacitor and ac inductance, since the output voltage is controlled by the load angle. Response times in PWM systems are faster, since gating pattern changes required for voltage control can be implemented instantaneously. The operation of the control system however is identical.

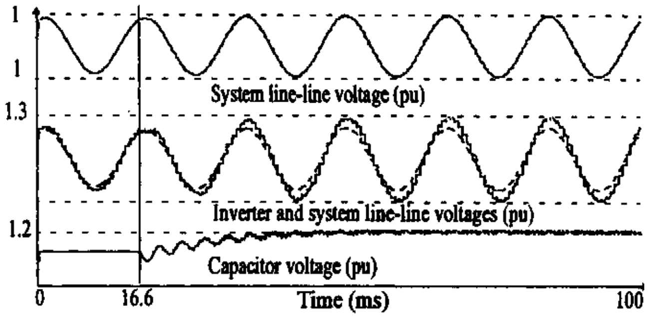
Harmonic distortion of the injected current is low, and decreases as the pulse number increases. The amplitude depends upon the equivalent synchronous link reactance (transformer leakage reactance) and the line reactance.

B. Unified Power Flow Controller (UPFC)

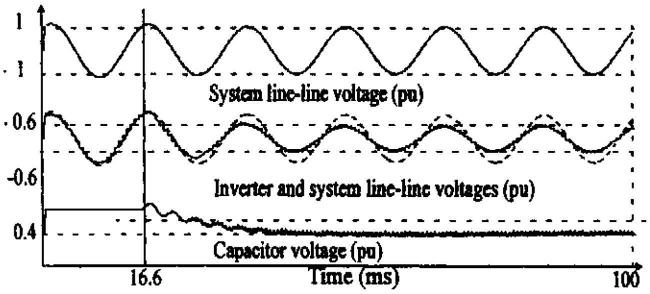
The techniques presented for the STACOM are extended in Fig. 12 to the combination of series and shunt compensators connected to the same dc bus (or UPFC). The control system of each component of the UPFC uses principles similar to that of the STATCOM. The external controls generate the demands for series injected voltage, v_{pq}^*, and the shunt reactive current, i_q^*. The local or internal controls operate the inverters so as to adjust the desired series injected voltage, and the commanded shunt reactive current.

In the proposed implementation, Fig. 12, the real and reactive power control functions are carried out by the series converter, the shunt converter being operated at unity power factor.

To verify the appropriate control action, digital simulation were performed using EMTP, and sample results are shown in Figs. 13 and 14.



(a) Voltage control by var injection.



(b) Voltage control by var absorption.

Fig. 11. STATCOM voltage regulation.

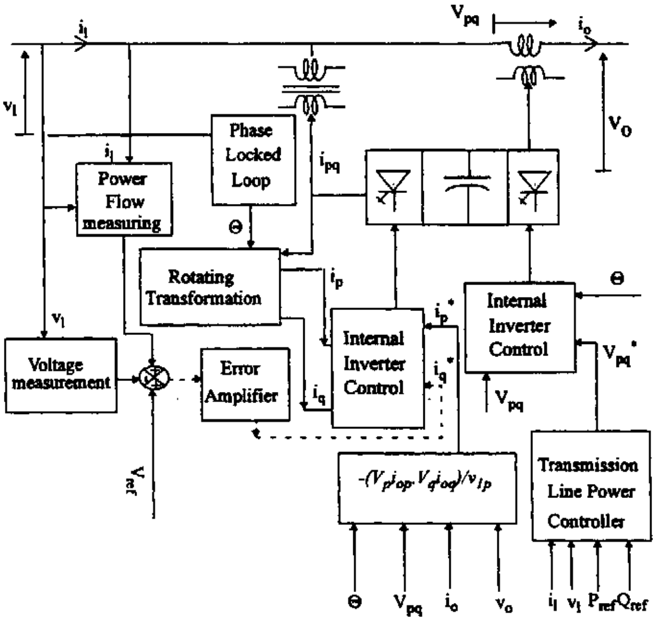


Fig. 12. UPFC control system.

In order to have independent control of the series and shunt injections, the output voltage of the series and shunt controllers must be controllable independently. With three phase 2 level inverters, this requires PWM patterns. In a typical implementation, the shunt converter maintains de dc bus voltage constant. The shunt and series reactive power are controllable, as is the power being injected in series, as is required for phase shifting purposes for example.

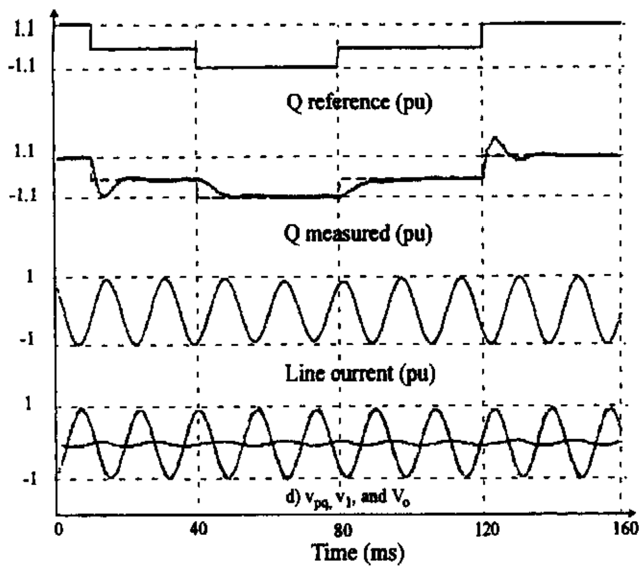


Fig. 13. Simulation results for step changes in Q.

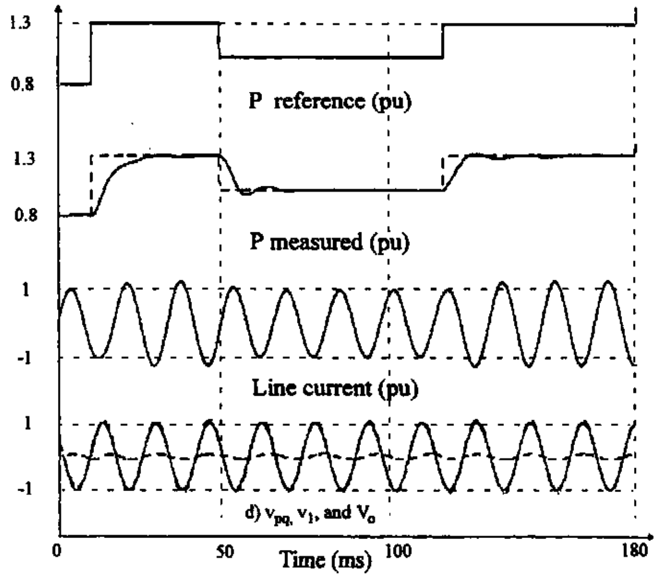


Fig. 14. Simulation results for step changes in P.

V. CONCLUSIONS

This paper has investigated the operation of high power static var compensators using the EMTP simulation package. It is shown that the requirement for high voltage and current capability can be met by using multi-pulse voltage source structures. A number of switch gating options are presented, including fundamental frequency gating and low frequency pulse width modulation, based on space vector modulation techniques. Harmonic distortion of the injected current is controlled either by phase shifting transformers or by means of PWM. Typical waveforms confirm that the compensator output voltage distortion is reduced. Therefore the injected current and voltage distortion can be kept low.

EMTP simulations of the complete compensator demonstrate the features of high power STATCOMs. The results can be extended to series compensators and are shown for the series-shunt combination (UPFC).

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