THE UNIVERSITY OF MANITOBA

A NEW SHUNT STATIC REACTIVE POWER CONTROL DEVICE AND ITS APPLICATIONS

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A Thesis
Submitted to the Faculty of Graduate Studies
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To my parents . . . . .

ABSTRACT

Static shunt reactive power compensation schemes are being more and more widely considered for VAr control in power systems. They form in large a natural replacement for the traditional synchronous compensators with the promise of benefits in performance, reliability and cost.

A new generalized concept for static shunt VAr compensation is proposed which permits selection of an optimum design. With a slight increase in the VAr rating of the reactors this novel scheme should overcome the harmonics and thyristors rating problems of the existing devices.

A faithful analytical comparison with other known devices is made to show the superiority of the new device with respect to harmonics generation, control range and thyristor stresses during steady-state and overvoltage transient conditions.

In order to be able to verify the feasibility and the advantages of using thyristor controlled reactors in ac systems and at HVDC terminals different models are developed for the fundamental current behavior of these systems. A large scale load flow and transient stability program is developed based on these models and with unique features for the simulation of multi-terminal HVDC schemes and for ac/dc network solution algorithms. The program is then applied to various practical problems such as MANDAN to demonstrate the ability of static means for VAr control to enhance the performance of weak ac systems when connected to HVDC converters.

The application of thyristor controlled reactors at the terminals of superconducting generators is, for the first time, suggested and fully analysed.

The results of all the studies prove that the application of static reactive power schemes in ac and HVDC transmission systems do solve or reduce the major transmission problems; voltage control, and stability.

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LIST OF MOST-USED SYMBOLS

E_T	Synchronous or static VAr compensator model source Voltage (p.u.)
e_d, e_q	Direct and quadrature components of terminal voltage (p.u.)
e_f	Super conducting field voltage (p.u.)
f_o	Rated synchronous frequency (Hz)
G	Conductance (p.u.)
H	Inertia constant (sec.)
I_1	Magnitude of fundamental component of line current (p.u.)
I_n	Magnitude of nth harmonic component of line current (p.u.)
$i_1, i_2 ..$	Instantaneous currents of thyristors $T_1, T_2, ...$
i_A, i_B, i_C	Instantaneous 3-phase line currents (p.u.)
i_{dL}, i_{qL}	Direct and quadrature components of load current (p.u.)
i_d, i_q	Direct and quadrature armature current components (p.u.)
i_f	Super conducting field current (p.u.)
$i_{pd}, i_{pq}, i_{sd}, i_{sq}$	Direct and quadrature currents of screening and damping shields (p.u.)
K_α, K_w	Controller and stabilizer gains of a static compensator
K_e, K_{we}	Field forcing regulator and stabilizer gains
L	Inductance (p.u.)
N	Number of series bridges of a HVDC converter
n	Harmonic order
P_d	DC power (p.u.)
P_m	Mechanical power (p.u.)
p	d/dt operator

Q_c	Reactive power of a shunt capacitor (p.u.)
Q_d	Reactive power absorbed by a HVDC converter (p.u.)
Q_r	Reactive power absorbed by a thyristor controlled reactor (p.u.)
R	Resistance (p.u.)
T	HVDC converter transformer taps
T_e, T_m	Electrical and mechanical torques (p.u.)
t	Time (sec.)
V_a	RMS ac voltage (p.u.)
V_b	RMS ideal supply voltage (p.u.)
V_T	RMS terminal ac voltage (p.u.)
V_d	DC voltage (p.u.)
Vref	Reference voltage (p.u.)
v_A, v_B, v_C	Instantaneous 3-phase line voltages (p.u.)
X or X_T	Total reactance of thyristor controlled reactor (p.u.)
X_s	Synchronous or static compensator model reactance (p.u.)
X_e	Equivalent reactance of an ac system (p.u.)
x_1, x_2, x_3	Reactors of a Generalized UM-Concept for thyristor controlled reactors
x_d, x_q	Direct and quadrature armature reactances of a generator (p.u.)
x'_d, x''_d, x'''_d }	Transient and subtransient reactances of a super conducting turbo generator (p.u.)
x_f, x_p, x_s	Reactances of field& screening and damping shields of a super conducting turbo generator (p.u.)
Y	Admittance (p.u.)

α	Firing (or control) angle of thyristor
β	Advance angle of an inverter
γ	Extinction angle of a HVDC inverter
δ	Rotor angle
θ	Voltage angle
ϕ	Power factor angle of a dc converter
Ψ_d, Ψ_q	Direct and quadrature components of flux linkages
Ψ_f	Super conducting field flux linkage
$\left.\begin{matrix}\Psi_{pd}, \Psi_{pq}, \\ \Psi_{sd}, \Psi_{sq}\end{matrix}\right\}$	Direct and quadrature flux of screening and damping shields
τ_α	Controller time constant of a static compensator system
τ_f, τ_p, τ_s	Time constants of field, screening and damping shields
ω	Angular speed (rad/sec)
ω_0	Rated synchronous angular speed (rad/sec)
ζ	Damping ratio
Δ	A small change in a variable

chapter one

INTRODUCTION

1.1 General

Controlling the reactive power generation and flow in an energy transmission system is of an immense importance. The influence of the balance and flow of reactive power in EHV transmission lines in terms of voltage is easy to visualize. External sources and sinks of reactive power provided at chosen points in a transmission network are therefore used for controlling the voltage and the power transmission efficiency and capability. Fixed elements (capacitors or reactors) have an inherent generation or absorption characteristics dependent upon terminal voltage and hence are of limited effectiveness. The availability of fully controllable VAr systems multiplies the value of reactive power control by providing an alternative method of system stabilization in addition to an optimum control of voltage and power transmission capability.

While the virtue of reactive power control is easy to visualize for an ac transmission system it is not very difficult to see its value for an ac/dc system. A HVDC converter requires, for its commutation process, an amount of reactive power which is dependent upon the active power transmitted on the dc side and which must be supplied from the ac side. Fully controllable reactive power sources at the HVDC converter terminals are, therefore, the best choice to enhance the performance of both ac and dc systems.

Up till now synchronous compensators have been the major fully controllable reactive power device. However , during the last few years a number of static reactive power compensators have emerged which appear to be technically superior to the traditional synchronous compensators in many ways and are economical too. Hence, a systematic evaluation of the performance of the static VAr controlling devices and that of the system in which they are employed is very timely and much needed.

The research work described in this thesis is devoted to this end and has resulted in the following major contributions:

(1) A new design of thyristor phase-controlled static VAr compensator has been invented which upon analysis is shown to be superior when compared to those available. In this connection a generalized concept has been put forward which permits selection of an optimum design.

(2) The application of static VAr compensation systems at the converter terminals of interconnected ac/dc networks has been thoroughly investigated and in the process a large scale load flow and transient stability program for power systems incorporating multiterminal dc schemes has been developed.

(3) While investigating the application of static VAr compensators, for the first time a suggestion has been made and fully analysed for their application at the terminals of a superconducting alternator.

The major emphasis of the thesis is, thus, on the development of a new type of compensator and its novel applications.

In Section 1.2 of this chapter a summary and brief critical evaluation of available VAr compensators are presented. Section 1.3 deals briefly with the application of VAr compensators in ac transmission systems. This part of the investigation has been kept very brief on purpose keeping in view the reporting of the major contributions.

Chapter 2 is devoted to the development and analysis of the new type of thyristor phase controlled VAr compensator.

Chapters 3 and 4 investigate the impact of applications of static means of reactive power control at the terminals of HVDC converters and superconducting alternators respectively. The overall conclusions and major contributions achieved in the thesis are summarized in Chapter 5.

1.2 Reactive Power Systems; Critical Evaluation

In the following an evaluation of the known types of reactive power systems is undertaken.

1.2.1 Rotating Synchronous Machines[2,3,4]

Excitation control of a synchronous machine connected to an ac bus allows a controlled reactive power supply. The machines specially designed for the control of reactive power are known as synchronous compensators.

Typically a synchronous compensator when under-excited can absorb about half of its over-excited MVAr rating.

The response time for changing its output from no-load to rated reactive load is generally in the range from 0.10 to 2.00 seconds depending on the field time constant, excitation system and voltage regulator of the machine and the nature of the network disturbance initiating the change.

Unlike static devices, synchronous compensators have stored kinetic energy in their rotors, and hence can exhibit transient oscillations of real power about a mean value of zero, during or following disturbances.

However, starting of such a machine can create a substantial voltage dip, and when running, the synchronous compensator due to its inertia has its own stability problem in the event of a system fault.

A synchronous compensator reduces the system reactance while it regulates the reactive power.[6]

Reduction of system equivalent Thevenin's reactance minimizes the alternating voltage phase angle fluctuations in case of any disturbance , it, however, causes an increased short circuit level and circuit breaker duty.

The high capital investment, running and maintenance costs and losses of a synchronous compensator add to its shortcomings and must also be taken into account for the selection of compensators.

1.2.2 Static Compensators[1,5]

Generally these types of shunt VAr compensators do not contribute to the system short circuit capacity, have lower initial investment and losses per KVAr and are less costly to operate and maintain compared to synchronous compensators. Static compensators can be divided into two main classes: Fixed Elements and Controllable Devices.

i. Fixed Elements

(a) Shunt Capacitors:[7]

Shunt Capacitor banks are used with mechanical switches to compensate the inductive reactive power at HVDC terminals or major load terminals in order to maintain the ac voltage at the rated value.

It may however lead to excessive voltage rise on account of a sudden loss of load.

(b) Linear Shunt Reactors:[7,8]

The inductance of these reactors is independent of their loading. They often are air-cored or gapped type reactors.

Permanently connected linear reactors are used to compensate the excessive capacitive reactive power on long ac transmission lines and thus suppressing the voltage along the line and its terminals under light load conditions. This, however, reduces the maximum power transfer capability of the line.

Optimum line compensation requires shunt reactors to be switched out of service under heavy load transmission. This leaves the system open to transient overvoltages in case of a severe loss of load in addition to an undesirable step voltage variation due to switching-in of the reactors.

(c) Saturable (or Saturation) Shunt Reactors:[9,10]

This refers to the EHV line connected reactors with a saturation knee at 1.1 the normal system voltage, thus restricting power frequency overvoltages under abnormal conditions.

The non-linear reactor is less effective in limiting instantaneous overvoltages than it might seem, since a specific voltage-time area is required for changing the reactor magnetic state. Furthermore, with linear transmission systems this type of reactor, in conjunction with the saturation effects of transformers, introduces some risk of sub-harmonic instabilities because overvoltages are possible due to partial shunt compensation not eliminating the Ferranti effect under light-load conditions.

(d) Gap-Connected Shunt Reactors:[11]

An arc gap is used to either switch a line shunt reactor in or out. The reactor assembly may take either form (a) or (b) as shown in Figure 1.1. The gaps are shunted by circuit breakers which are switched on by a trigger derived from the gap breakdown current.

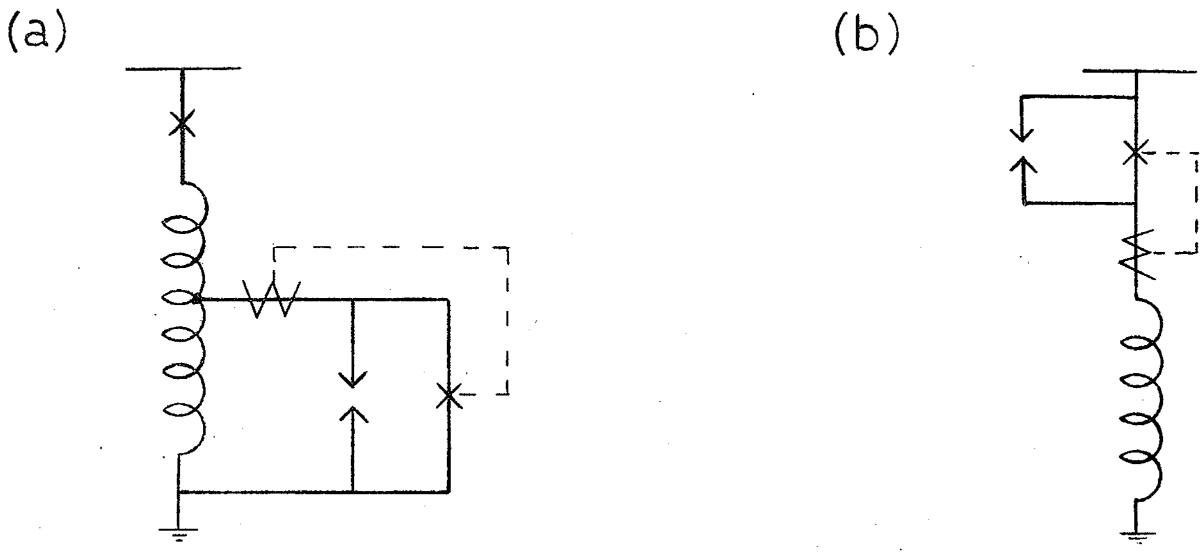

Figure 1.1 *Gap connected reactors*

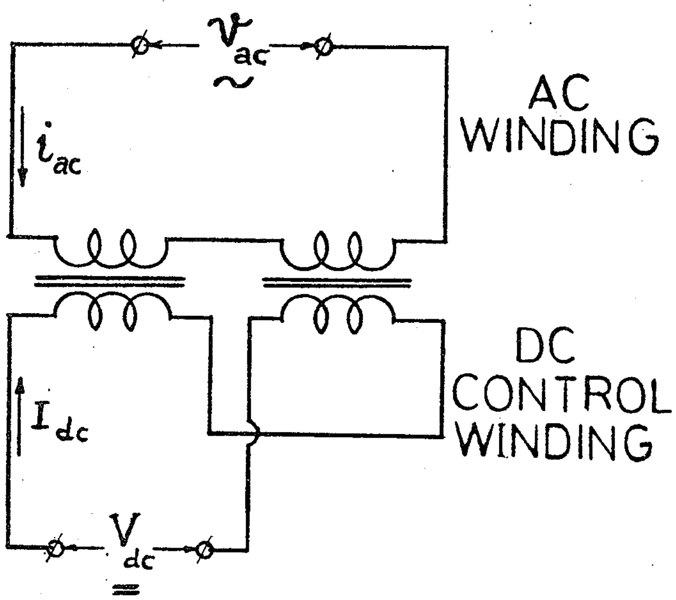

Figure 1.2 *Single phase transductor schematic diagram*

At first sight such a device may appear trivial. However, a number of studies (as will be discussed in Chapter 4) show that in many applications, involving severe disturbances, even controllable static VAr compensators behave in a bang-bang fashion.

Gap connected reactors provide an economic but crude compensation means.

ii. Controllable Devices

(a) Transductors:[12,15]

A transductor is a reactor with direct current controlled saturation, i.e. the effective reactor impedance and the primary alternating current are controlled by a direct current fed into a separate winding. (Figure 1.2)

The increase of direct current causes an increase of the unidirectional flux in the reactor iron cores. As a consequence the superimposed alternating flux tops are raised beyond the magnetic saturation limits giving rise to the fundamental alternating current nearly proportional to the dc current.

Odd current harmonics are generated in the ac circuit while even harmonics are produced in the dc control circuit.

Another device can be used utilizing the principle of a rotating magnetic field created by a 3-phase wound stator.[13] The saturation level of the magnetic circuit of the stationary rotor is controlled by dc winding.

The stator windings and slots are arranged in such a way that the alternating current contains minimum amount of harmonics.

The above controlled saturation compensators have the major drawback of slow response compared to the other types of controllable compensators due to the dc circuit time constant and the dead time required to build up the direct flux in the magnetic core. However, when a thyristor rectifier with a high ceiling voltage for forcing the control current is used, total time to change the primary ac current can be substantially reduced.

Unfortunately, under system fault conditions the dc control winding is difficult to protect.

(b) Saturated Reactors: (inherently controlled devices)[13-29]

The saturated reactor is designed to operate in the saturated region at normal operating voltages. With a series and shunt capacitors combination it automatically varies the reactive power output over a wide range and holds the terminal voltage constant.

The device elements and the corresponding V-I characteristics are illustrated in Figures 1.3 and 1.4 respectively.

Special measures must be taken; especially for applications in weak ac systems, to decrease the high current harmonic content due to the saturated reactor and to avoid the possiblity of ferroresonant sub-harmonic instability arising from the presence of the slope correcting series capacitor.

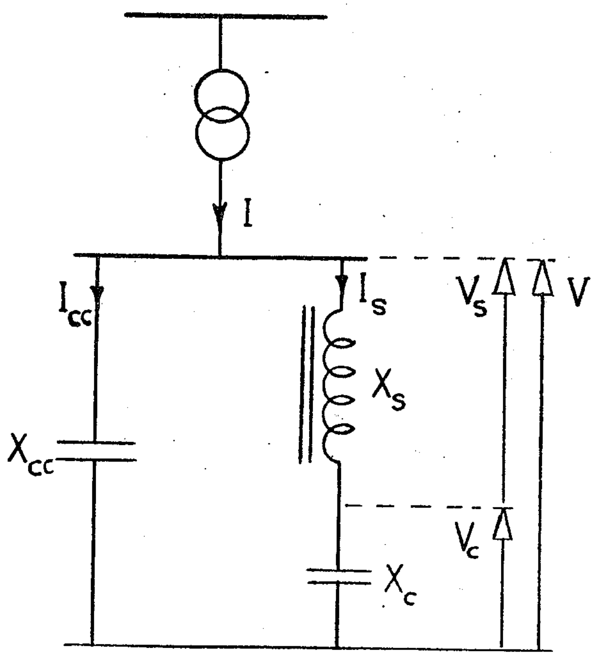

Figure 1.3 Saturated reactor scheme

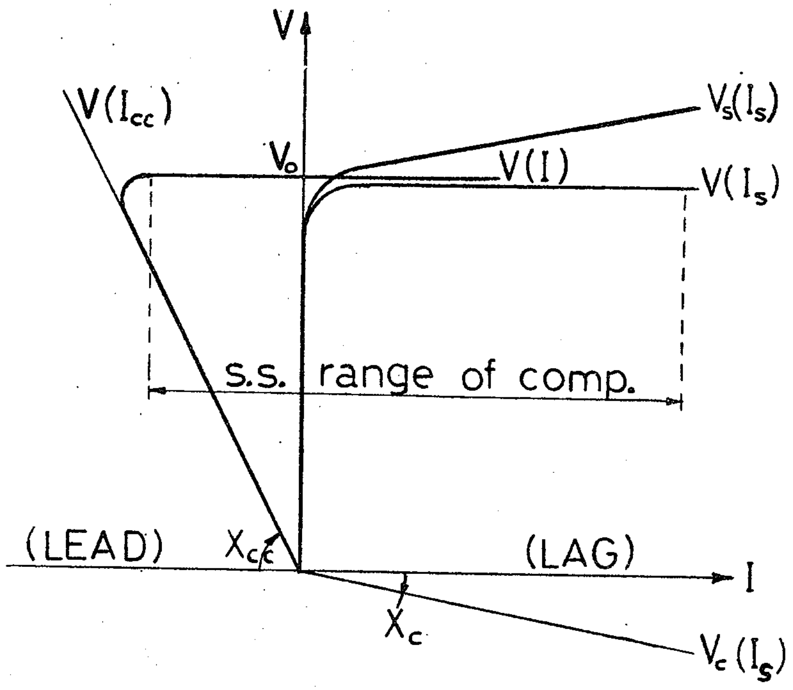

Figure 1.4 Saturated reactor steady state characteristics

In this regard, techniques employing complex multi-core, multi-winding designs are used to cancel the current harmonics internally by suitable choice of the flux phase-shifts between cores and by an appropriate flow of the magnitude of triplen harmonic currents in the secondary windings. (e.g. Quin, Twin-tripler and treble-tripler types of harmonic compensated ac saturated reactors.)

However this multiphase construction reduces the potentiality of the device for unsymmetrical compensation of unbalanced loads. Although the transient response of the compensator is of the order of one to two cycles of the supply voltage, capacitive compensation of the slope reactance introduces transiently higher reactances. When the current through the slope correcting capacitor exceeds a predetermined value, during a transient overvoltage condition, part or all of the latter may be short circuited, thus increasing the slope of the compensator from (X_s-X_c) to X_s (in Figures 1.3 and 1.4) or to some intermediate value.[5]

(c) Thyristor-Switched Shunt Reactors:

Thyristor valves are used as fast switches to connect, in a coordinated manner, a number of shunt reactors in small steps (Figure 1.5). The switching is performed at voltage peaks to avoid dc current components injected into the ac system. This form of discrete control requires a large number of components and hence increases the cost and deteriorates the reliability of the device.