REACTIVE POWER CONTROL IN ELECTRIC SYSTEMS

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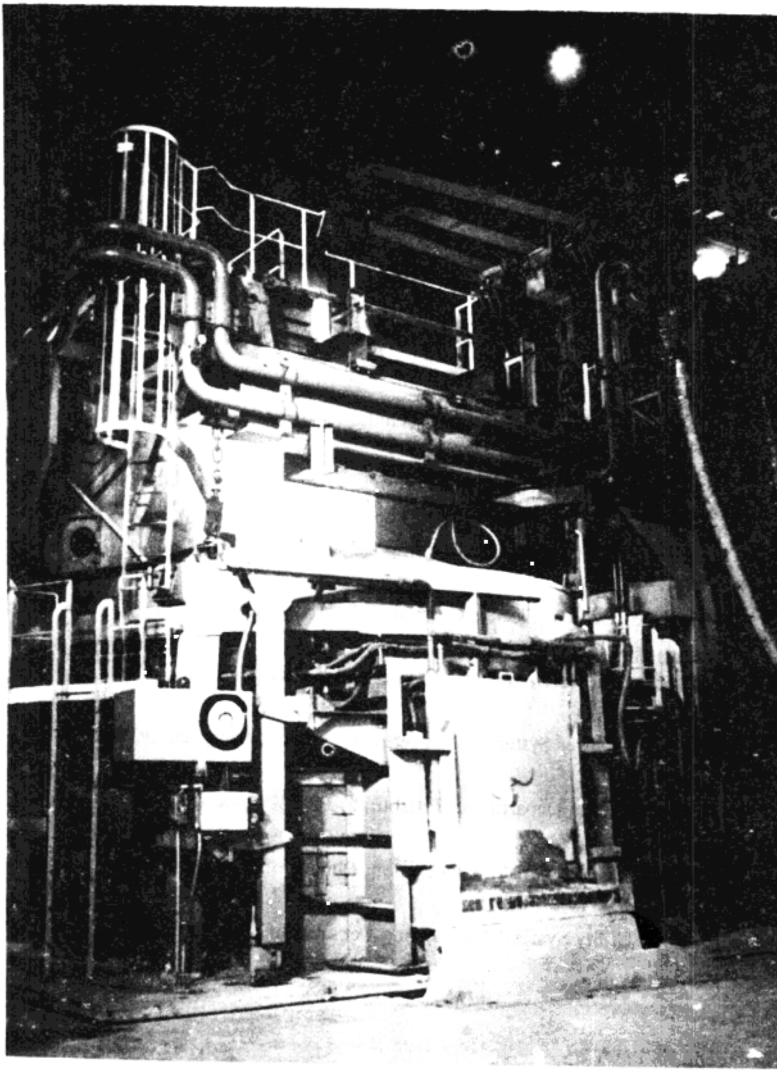

Large electric arc furnace used in steel production. Such loads on the electricity supply system often require reactive power control equipment of the type described in Chapter 9.

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FOREWORD

Reactive power has been recognized as a significant factor in the design and operation of alternating current electric power systems for a long time. In a very general and greatly oversimplified way, it has been observed that, since the impedances of the network components are predominantly reactive, the transmission of active power requires a difference in *angular phase* between the voltages at the sending and receiving points (which is feasible within rather wide limits), whereas the transmission of reactive power requires a difference in *magnitude* of these same voltages (which is feasible only within very narrow limits).

But why should we want to transmit reactive power anyway? Is it not just a troublesome concept, invented by the theoreticians, that is best disregarded? The answer is that reactive power is consumed not only by most of the network elements, but also by most of the consumer loads, so it must be supplied somewhere. If we can't transmit it very easily, then it ought to be generated where it is needed.

Of course, the same might be said about active power, but the constraints on its transmission are much less severe and the penalties on inappropriate generator siting (and sizing) much more severe. Still, the differences are only quantitative.

It is important to recognize that, when we speak of transmission of electricity, we must speak of *electrical* distances. For example; the reactance of a transformer may be as great as that of 50 miles of transmission line. Thus, when we consider that the average transmission distance in the United States is only of the order of 100 miles, it is evident that we do not really avoid transmission entirely unless the generation of reactive power is at the same voltage level as is the consumption to be supplied. This partially explains the superficially strange fact that we can often observe in the same network, shunt compensation in the form of capacitors in the distribution system and shunt inductors in the transmission system.

There is a fundamental and important interrelation between active and reactive power transmission. We have said that the transmission of active power requires a phase displacement of voltages. But the magnitudes of these voltages are equally important. Not only are they necessary for power transmission, but also they must be high enough to support the loads and low enough to avoid equipment breakdown. Thus, we have to control, and, if necessary, to support or constrain, the voltages at all the key points of the network. This control may be accomplished in large part by the supply or consumption of reactive power at these points.

Although these aspects of reactive power have long been recognized, they have recently acquired increased importance for at least two reasons: first, the increasing pressures to utilize transmission capacity as much as possible; and second, the development of newer static types of controllable reactive-power compensators. Many years ago, when the growing extent of electric power networks began to justify it, synchronous condensers were used for voltage support and power transfer capability improvement. At the same time, shunt capacitors began to be installed in distribution circuits to improve voltage profiles and reduce line loading and losses by power-factor improvement. The rapid development and relative economy of these shunt capacitors led to their almost displacing synchronous condensers in the transmission system also. It was found that practically as much could be gained by switched capacitors as by synchronous condensers, and at a much lower cost. Now there are signs that the tide may have turned again, and controlled reactive-power supplies are beginning to return in the form of static devices. However, from an economic point of view, it is still the job of the system engineer to determine how much can be accomplished by fixed capacitors (and inductors), how much needs to be switched, and finally how much needs to be rapidly and continuously controlled, as, for example, during disturbances. Of course, there also remains the question of how much, if any, reactive power should be obtained from the synchronous generators themselves.

We have so far discussed reactive power as being supplied to, or from, the network. However, at the beginning of this Foreword it was pointed out that some of the consumption of reactive power is in the network series elements themselves, for example, in transmission lines and transformer leakage reactances. Thus, a direct way of increasing power transfer capacity in transmission systems, and of reducing voltage drop in distribution systems, is to compensate part of the series inductive reactance by series capacitors. Ordinarily, this is looked at from the standpoint of reducing the net inductive reactance, rather than in terms of reactive-power supply. Operating problems have been encountered, and applications to distribution systems have become rare, but the series capacitor remains the best way to increase transmission capacity in many cases. It has also been used to balance line loadings among network branches. As a corollary to this, in a meshed network the application of series capacitors must be coordinated in order to preserve, or obtain, a proper distribution of line loadings, while a shunt capacitor (or other means of voltage support) can often be applied with benefit at a single point.

The present book includes both theoretical and practical accounts of reactive power control and compensation, as well as a detailed chapter on harmonics. There is no doubt that the subject of reactive power control is increasing in importance, and the book is therefore particularly appropriate at this time. The authors are all practising power-system engineers who have had a total of many decades of experience in the technologies related to reactive power.

CHARLES CONCORDIA

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PREFACE

About thirty percent of all primary energy resources worldwide are used to generate electrical energy, and almost all of this is transmitted and distributed by alternating current at 50 or 60 Hz. It is now more important than ever to design and operate power systems with not only the highest practicable efficiency but also the highest degree of security and reliability. These requirements are motivating a wide range of advances in the technology of ac power transmission and the purpose of this book is to describe some of the more important theoretical and practical developments.

Because of the fundamental importance of reactive power control, and because of the wide range of subjects treated, as well as the method of treatment, this book should appeal to a broad cross section of electrical, electronics, and control engineers. Practising engineers in the utility industry and in industrial plants will find both the theory and the description of reactive power control equipment invaluable in solving problems in power-factor correction, voltage control and stabilization, phase balancing and the handling of harmonics. In universities the book should form an ideal basis for a postgraduate or even an undergraduate course in power systems, and several sections of it have already been used for this purpose at the University of Wisconsin and in the General Electric Power Systems Engineering Course.

Reactive power control, which is the theme of the book, has grown in importance for a number of reasons which are briefly as follows. First, the requirement for more efficient operation of power systems has increased with the price of fuels. For a given distribution of power, the losses in the system can be reduced by minimizing the total flow of reactive power. This principle is applied throughout the system, from the simple power-factor correction capacitor used with a single inductive load, to the sophisticated algorithms described in Chapter 11 which may be used in large interconnected networks controlled by computers. Second, the extension of transmission networks has been curtailed in general by high interest rates, and in particular cases by the difficulty of acquiring right-of-way. In many cases the power transmitted through older circuits has been increased, requiring the application of reactive power control measures to restore stability margins. Third, the exploitation of hydropower resources has proceeded spectacularly to the point where remote, hostile generation sites have been developed, such as those around Hudson Bay and in mountainous regions of Africa and South America. In spite of the parallel development of dc transmission technology, ac transmission has been preferred in many of these schemes. The problems of stability and voltage control are identifiable as problems in reactive power control, and a wide range of different solutions has been developed, ranging from the use of fixed shunt reactors and capacitors, to series capacitors, synchronous condensers, and the modern static compensator. Fourth, the requirement for a high quality of supply has increased because of the increasing use of electronic equipment (especially computers and color television receivers), and because of the growth in continuous-process industries.

Voltage or frequency depressions are particularly undesirable with such loads, and interruptions of supply can be very harmful and expensive. Reactive power control is an essential tool in maintaining the quality of supply, especially in preventing voltage disturbances, which are the commonest type of disturbance. Certain types of industrial load, including electric furnaces, rolling mills, mine hoists, and dragline excavators, impose on the supply large and rapid variations in their demand for power and reactive power, and it is often necessary to compensate for them with voltage stabilizing equipment in the form of static reactive power compensators. Fifth, the development and application of dc transmission schemes has created a requirement for reactive power control on the ac side of the converters, to stabilize the voltage and to assist the commutation of the converter.

All these aspects of ac power engineering are discussed, from both a theoretical and a practical point of view. Chapters 1 through 3 deal with the theory of ac power transmission, starting with the simplest case of power-factor correction and moving on to the detailed principles on which the extremely rapid-response static compensator is designed and applied. In Chapter 2 the principles of transmitting power at high voltages and over longer distances are treated, and Chapter 3 deals with the important aspects of the dynamics of ac power systems and the effect of reactive power control. The unified approach to the "compensation" problem is particularly emphasized in Chapter 2, where the three fundamental techniques of compensation by sectioning, surge-impedance compensation, and line-length compensation are defined and compared. Chapter 1 is also unified in its approach to the compensation or reactive power control of loads; the compensating network is successively described in terms of its power-factor correction attributes, its voltage-stabilizing attributes, and finally its properties as a set of sequence networks capable of voltage stabilization, power-factor correction, and phase balancing, both in terms of phasors and instantaneous voltages and currents.

Chapter 4 introduces and describes in detail the principles of modern static reactive power compensators, including the thyristor-controlled reactor, the thyristor-switched capacitor, and the saturated reactor. Particular attention is given to control aspects, and a detailed treatment of switching phenomena in the thyristor-switched capacitor is included.

The modern static compensator receives further detailed treatment in Chapters 5 and 6. Chapter 5 describes the high-power ac thyristor controller and associated systems, while Chapter 6 gives a complete description of a modern compensator installation including details of the control system and performance testing.

In Chapter 7 the series capacitor is described. The solution of the subsynchronous resonance (SSR) problem, together with the introduction of virtually instantaneous reinsertion using metal-oxide varistors, have helped restore the series capacitor to its place as an economic and very effective means for increasing the power transmission capability and stability of long lines. Both the varistor and the means for controlling SSR are described in this chapter.

Chapter 8 on synchronous condensers has been included because of the continuing importance of this class of compensation equipment. As a rotating machine the synchronous condenser has a natural and important place in the theory of reactive power control, and several of the most recent installations have been very large and technically advanced. Rapid response excitation systems and new control strategies have steadily enhanced the performance of the condenser.

In Chapter 9 there is a detailed treatment of reactive power control in connection with electric arc furnaces, which present one of the most challenging load compensation problems, requiring large compensator ratings and extremely rapid response to minimize "flicker." Chapter 9 will be of interest to the general reader for its exploration of the limits of the speed of response of different methods of reactive power control. It also shows clearly the advantages of compensation on the steel-producing process, which exemplifies the principle that the performance of the load is often significantly improved by voltage and reactive power control, even when these are required for other reasons (such as the reduction of flicker).

The subject of reactive power control is closely connected with the subject of harmonics, because reactive power compensation and control is often required in connection with loads which are also sources of harmonics. A separate reason for the importance of harmonics in a book on reactive power control is that reactive compensation almost always influences the resonant frequencies of the power system, at least locally, and it is important that capacitors, reactors, and compensators be deployed in such a way as to avoid problems with harmonic resonances. Chapter 10 deals with these matters, and includes a treatment of filters with practical examples.

The final chapter, Chapter 11, deals with the relatively new subject of reactive power coordination, and describes a number of systematic approaches to the coordinated control of reactive power in a large interconnected network. Minimization of system losses is one of several possible optimal conditions which can be determined and maintained by computer analysis and control. This promising new subject is given the last word in leaving the reader to the future.

Many people have contributed to the writing and production of this book, and the editor would like to record his warmest thanks for all contributions great and small. Special thanks are due to Dr. Eike Richter of the General Electric Research and Development Center for his generosity and sustained support of the project, and also to Dr. F. J. Ellert, D. N. Ewart, D. Swann, Dr. P. Chadwick, R. J. Moran, D. Lamont, and Dr. E. P. Cornell.

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No book is the sole work of its named authors, and acknowledgment is made to the many unnamed contributors to the technology and application of reactive power control. This book does not attempt to set out hard-and-fast rules for the application of any particular type of equipment, and in particular the authors accept no responsibility for any adverse consequences arising out of the interpretation of material in the book. The chapters are all written from the individual points of view of the authors, and do not represent the position of any manufacturing company or other institution.

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