

S. RAO

# EHV-AC, HVDC

TRANSMISSION &  
DISTRIBUTION ENGINEERING



KHANNA PUBLISHERS

---

---

# **EHV-AC, HVDC TRANSMISSION AND DISTRIBUTION ENGINEERING**

---

---

*A textbook for B.E., M.E. (Electrical), AMIE, Technical Teachers' Training, Polytechnic, Power Engineers Training Courses and a Reference Book for Power Engineers in Electricity Boards, Projects, Consultants, Power Sector, Covering all the topics related with modern EHV-AC, HVDC Transmission, AC Networks and Distribution Systems.*

***Other Related Books of Special Interest***

- “Testing, Commissioning, Operation and Maintenance of Electrical Equipment”, *by S. Rao*
- “Power Transformers and Special Transformers”, *by S. Rao*
- “Electrical Substation Engineering Practice”, *by S. Rao*
- “Switchgear Protection Power System” (11th Ed. 1999), *by Sunil S. Rao*
- “Energy Technology — (Non-conventional, Renewable & Conventional)”, *by Dr. B.B. Parulekar and S. Rao*
- “Handbook of Electrical Engineering”, *by S.L. Bhatia*
- **“Electrical Safety, Fire Safety Engineering and Management” by Prof. H.L. Saluja & S. Rao, New Arrival, Jan. 1999.**

*Note* : This book is of Topical Interest to Students and Professionals.

---

# **EHV-AC, HVDC TRANSMISSION & DISTRIBUTION ENGINEERING**

**(Theory, Practice and Solved Problems)**

---

**S. RAO, M.E., M.I.E.**



## **KHANNA PUBLISHERS**

**Operational Office:** 4575/15, Onkar House, Room No. 3-4,  
Darya Ganj, New Delhi-110002  
Phone: 23243042 • Fax: 23243043

**Despatch Office:** 11, Community Centre, Ashok Vihar, Phase 2  
Delhi-110052. Phone : 27224179

**Regd. Office:** 2-B, Nath Market, Nai Sarak, Delhi-110006.

*Published by :*  
Romesh Chander Khanna  
for **Khanna Publishers**

Visit us at :  
[www.khannapublishers.in](http://www.khannapublishers.in)

*All Rights Reserved*

*[This book or part thereof cannot be translated or reproduced  
in any form (except for review or criticism) without the  
written permission of the Author and the Publishers.]*

**ISBN No : 81-7409-043-6**

***Third Edition***  
*Fifteenth Reprint : 2016*

***Price : Rs. 350.00***

*Text Composition by :*  
Narmada Computers

*Printed at :*  
**Tanya Printers**

## Preface to Third Edition

With the availability of modern tools like fiber optic cables for data communication, SCADA for National, Regional and Distribution Control Centers, Intelligent Substation Equipment, Satellite Communication and Information Technology, Microprocessor Based Controls and Protection, SF<sub>6</sub> Gas Insulated Substations, Power Electronic Devices in main EHV circuit, etc. *the Transmission Distribution and Network Automation Systems in India and other Developing Nations are in the process of rapid renovation and modernization (R & M).*

Capacitor Commutated HVDC Converters (CCC) offer superior and economical HVDC Systems for Transmission Networks. These are being introduced in the next generation of HVDC Systems by the 2000 AD.

*Rural and Urban Distribution Systems, Power Quality and Distribution Automation and Control (DAC)* have gained importance in the rapidly growing Power Sector of India. Transmission, Urban and Rural Distribution Sectors have become the energy routes of National Economy. The Power Sector Reforms and Restructuring of Transmission and Distribution Sectors initiated in India during early 1990s have given spectacular dividends to India's masses, rural/urban and industrial consumers.

This revised and enlarged edition covers *Modern Distribution Systems, Rural Distribution and Distribution System Automation* in a separate section and 5 detailed Chapters.

The recent advances in Transmission, Distribution and Network Automation towards 21st century have been covered in detail. *India's Transmission, Distribution and National Grid Planning under 9th five year plan (1998–2002) and 10th five year plan (2003–2007) have been reviewed.* Several new solved numerical examples have been added.

*Capacitor Commutated HVDC Converters* for 21st century, the avoidable occurrences of *Voltage Collapse and Voltage Instability* of Transmission Networks, *Intelligent Substations, Fiber-Optic Cable, Power Quality, Supply to Arc Furnaces and Load Management* have been covered in Section V.

I gratefully acknowledge the valuable suggestions of Professors Students and Professionals in Power and Energy Sector. I also thank M/S Khanna Publishers for this revised and updated edition being dedicated to India's Energy Sector during the turn of the century.

## Preface to Second Edition

The warm response to the first edition (1990) has promoted this revised edition. Every chapter has been improved by adding simplified derivations, new figures, up-to-date data, recent advances and *a few topical solved numerical problems*. The EHV AC and HVDC Phenomena and the interaction between AC Systems and HVDC Systems have been illustrated in detail. A new chapter has been added on Communication and Telecontrol in Power System Network. Chapter on RI, TVI, AN has been reshaped. The suggestions from teachers, students and professionals were very useful.

EHV AC and HVDC Transmission Technologies have now come of age in India and have become integral part of National Energy Sector. 400 kV AC Network has been well established.

800 kV AC lines will be introduced in 10th plan.  $\pm 500$  kV HVDC lines and HVDC Back-to-back Stations have been commissioned. The transmission efficiency and control of energy flow have gained more significance. Human Resource Development in Energy and Power Sector has gained importance. While the Energy Planning and strategies are covered in detail in the sister book “Energy Technology—Nonconventional, Renewable and Conventional”, the transport and control of energy in electrical form from generating stations to load centres *via* HVDC and EHV AC transmission systems are covered fully in this book. The details about Substation Engineering, Switchgear and Protection, Testing Commissioning, Operation and Maintenance have been covered in the sister books.

I extend my sincere thanks to all the readers for the warm response given to the first edition. I also thank M/S Khanna Publishers, for undertaking the difficult task of publishing this revised Edition. I would request the Readers to drop a line on any particular information desired, with comments.

June, 1996

*Author*

## Preface to First Edition

Electrical Power Transmission Technology is on the verge of a technological big leap forward. India's 'National Power Transmission Plan : 1990—2000' envisages installation of 50,000 circuit kilometers of 400 kV AC lines, 5000 ckt km of 765 kV AC lines, 4000 ckt km of HVDC lines and five Back-to-back HVDC coupling systems.

The National Grid of India will have additional generation capacity of 50,000 MW during eighth plan (1990—1995) and 65,000 MW during ninth plan (1995—2000) with total installed capacity of 185,000 MW by 2000 AD. This power will be transmitted by a strong network of 400 kV AC,  $\pm 500$  HVDC transmission lines, AC and HVDC Interconnecting links ; HVDC coupling stations and corresponding network of subtransmission lines at 220 kV, 132/110 kV, 66 kV and distribution lines. Prospects of introducing 765 kV AC lines are uncertain.

Every next higher voltage step brings forth new technical phenomena. These need careful study, analysis and clear understanding. 1200 kV AC line has been successfully commissioned in USSR during 1988. HVDC line rated  $\pm 600$  kV has been commissioned in Brazil. The highest rated voltages, power transfer capabilities of EHV-AC and HVDC lines are increasing during every decade.

The major problems associated with high power, long distance lines and system interconnecting lines include control of power flow during steady state and dynamic state, damping of power swings, control of reactive power, control of terminal voltages and voltage profile, switching surges, radio interference, audible noise, corona, etc. The long transmission lines transfer large blocks of power and influence the voltage stability, dynamic stability, interchange and overall performance of interconnected AC networks.

With the development of thyristor convertors during 1980's the HVDC technology has become commercially successful and is now preferred for system interconnections and very long lines.

During 1990's Flexible AC Transmission (FACT) systems will be introduced. New tools such as SVS, controllable series compensation, microprocessor based integrated control and protection systems, EHV-AC and HVDC cables, superior ZnO Arresters, etc. are now available to transmission planners. The choice of type of transmission system will depend on techno-economic considerations and available expertise.

With these technological advances, the human resources development needs an immediate reorientation and training of the personnel in planning, system analysis, system design, equipment design, manufacturing, installation, testing, commissioning, operation, Maintenance etc.

**HVDC technology** is based on operation of high power high voltage thyristor convertors and associated controls. This new technol-

ogy has been successfully adopted in transmission systems in the form of Bipolar HVDC transmission, Back-to-back HVDC and Multi-terminal HVDC transmission systems, frequency-conversion ties, etc.

HVDC technology involves several entirely new approaches and new system studies including AC and DC Harmonic Filter studies, Reactive Power Interactions, abnormal operating conditions, integrated control and protections, insulation coordination, dynamic damping control etc.

**The close interaction between EHV-AC HVDC transmission links and associated AC Networks calls for an integrated approach towards the study of transmission systems and power systems. With this background the curricula for final year electrical courses and post graduate courses in electrical power need immediate revision by encompassing various modern principles and practices in EHV-AC, HVDC and FACT systems.**

This book has been written especially to meet this new requirement.

This book has been recommended for final year degree and polytechnic courses, post graduate courses in electrical engineering and for engineers in power sector.

Basic principles, theory and background have been explained carefully and clearly with the help of numerous figures, graphs, tables, data, the equations and solved examples.

Special features of this book include up-to-date terms and definitions, description of modern equipment and practical aspects. A very vast coverage has been presented in a single volume. A large number of typical solved examples have been given for gaining mastery over the transmission engineering calculation procedures.

The vast coverage has been spread over 51 chapters covered under four major sections.

**Chapter 1 and Chapter 30**, give the General Background and present state-of-art.

**Section I, Chapter 2 to 19**, covers the principles and practices of HVDC transmission systems. The topics include types of HVDC systems, AC Harmonic Filters, Earth Return, HVDC switching arrangements, HVDC Insulation-Coordination, Surge protection by ZnO Arresters, Reactive power requirements, station layout, control and protection of bipolar HVDC systems, HVDC circuit breakers for Metallic Return Transfer etc.

**Section II, Chapter 20 to 29**, covers HVDC Terminal Equipment including Converter-Transformers, Smoothing Reactor, Thyristor Valves, DCCT, DCVT, Testing of HVDC equipment, computer aided system studies etc. have been covered.

**Section III, Chapter 31 to 45**, deals with Engineering aspects

of EHV-AC Transmission including Power Transfer Ability, Voltage Control and Reactive Power Compensation, Corona, RI, TVI, ROW, AN etc.

**The types of transmission towers, the configurations, design based on lightning surges and switching surges has been covered in detail along with practical data regarding construction, clearances, foundation, planning, installation etc. The design and constructional aspects about bundle conductors, string insulators etc. have been covered in separate chapters.** Project Planning, Substation Planning, Operation. Maintenance topics have been covered.

The theoretical aspects regarding voltage profile of long AC lines, reactive power compensation SVS, Series Compensation Schemes, etc. have been covered in details in separate chapters.

**Chapter 44** covers EHV-AC and HVDC Cables of various types including oil filled, XLPL and SF<sub>6</sub> filled cables.

**Section IV, Chapter 46 to 49**, deals with Equations and calculations for medium and long AC lines. The fundamentals of line parameters, network modelling, basic calculation techniques have been covered. The application of nominal  $\pi$ ,  $T$  and Equivalent  $\pi$ ,  $T$  networks,  $ABCD$  constants, Power Circle Diagrams, Rigorous Solution for long lines, has been explained by means of phasor diagrams, equivalent circuits, equations, derivations and typical solved problems.

**Chapter 50** deals with wave equations for long lines, and the concept of standing waves on long AC lines.

**Chapter 51** covers Telecontrol and communication systems in Network.

The associated aspects about flashover characteristics of air and solid insulation, clearances, creepages, causes of failures, high voltage testing etc. have also been covered.

Two important practical problems faced by Power Engineers are Load-Frequency Control and Voltage Control. These have been dealt in Ch. 15 and Chapter 41. Another difficult task is control of reactive power flow of long EHV-AC lines. This has been covered in Chapter 19 and Ch. 40. Dynamic control of power swings has been dealt in Ch. 15.

The help by Manufacturing Organisations, Standards Organisations, CPRI, CEA, Electricity Boards, etc. is gratefully acknowledged.

Thanks are expressed to the Technical Editor and Staff of M/s Khanna Publishers for bringing out this large book.

The book is topical will benefit Electrical Engineering Students and Power Engineers. Comments and suggestions are eagerly awaited.

*Dedicated to*  
**MY WIFE**

## CONTENTS

<i>Chapter</i>	<i>Page</i>
<b>1. General Background</b> Energy Transmission. Hierarchical AC Transmission voltages levels. Tasks. Choice. Applications. <b>EHV-AC transmission</b> . Configuration, Engineering Features, Rated voltages, Number of Circuits, Intermediate Substations, Compensation of Reactive power. <b>HVDC systems</b> . Applications & Types, Bipolar, Back-to-Back, Multi-Terminal HVDC. Criterion of Choice. Limitations, Configuration, Equipment in HVDC Substations, HVDC Cable transmission. <b>Interconnected AC Networks</b> . Voltage control and frequency control. Power flow in AC line and in HVDC line. AC and HVDC Interconnections. EHV-AC versus HVDC. Economic Comparison. Prospects of HVDC. <b>Transmission Planning</b> . Communication in Transmission Network. Scope of Subject. Summary and Questions.	<b>1—53</b>
<b>HVDC Transmission</b>	
<b>2. HVDC Power Flow</b> Subscripts and Symbols. Thyristor principle and control. Power conversion principle. Direct Voltage $U_{d1}$ and $U_{d2}$ . Power at Rectifier-end $P_{d1}$ . Power at Inverter-end $P_{d2}$ . Power loss in DC system. Power in middle of HVDC line. Power at sending end. Power at receiving end. General equations. <b>Solved Numerical Examples on <math>P_d</math> and <math>U_d</math></b> . Summary and Questions.	<b>54—65</b>
<b>3. Steady State <math>U_d/I_d</math> Characteristic</b> Functional requirements. AC and DC Quantities. Steady state $U_d/I_d$ Characteristics. Principle of Stable Operation. Intersection of Rectifier and Inverter Characteristics. Margin Control. Setting of rectifier Control and Inverter Control. Reversal of HVDC power flow. Operating Modes of Bipolar 2 T HVDC System. Starting and Loading and Stopping of HVDC Power Flow. Summary.	<b>66—80</b>
<b>4. Converter Connections, Rectifier and Inverter Waveforms</b> Rectifier Bridge Connections and waveforms on AC and DC side. Six Pulse Bridge (Graetz Bridge). 12-Pulse Bridge. Phase control and Delay Angle. Effect of phase control on DC Voltage. Valve Voltage. Inversion. Connections of Converter Bridge. Commutating Reactance. Angle of Overlap Extinction Angle. Significance of Delay	<b>81—99</b>

Angle and Extinction Angle. Control of DC Voltage. Configuration of Bipolar 2T HVDC System, Valves and Converters. Summary and Questions.

---

**5. Equations of Voltage and Current on AC and DC Side** **100—134**

Assumptions. Average and RMS Value. Symbols. Rectifier No load Voltage Equation with Zero Delay Angle and with Delay Angle. Control DC Voltage. Voltage Eqn. for S-unit Converter. Rectifier Voltage with  $\alpha$  and  $u$ . Current on primary and secondary sides. Fundamental component of Current. Rating of Converter Transformer. Equivalent Circuit of Rectifier. Characteristics of Rectifier. Equation of Inverter Equivalent Circuit of Inverter. Complete Equivalent Circuit of HVDC System. Terms and Definitions. Rectifier and Inverter Equations. Minimum Extinction Angle. Practical Significance of Equations Summary and Questions.

---

**6. Fundamental of Harmonics and Network Harmonic Impedance** **135—166**

Fourier Analysis. Characteristic Harmonics. Terms and definitions. Fourier Series. Characteristics AC Current Harmonics. Non-characteristic AC Current Harmonics. Harmful effects. Interaction with AC Network. Adequateness of AC Harmonic Filters. Summary and Questions.

---

**7. Harmonic Filters** **167—199**

Terms and definitions. Filters, Surge Suppressors, Damping Circuits. Resonance. Quality Factor. Bandwidth. Shunt filters. Series Filters. Acceptable level of Harmonics. Configuration of AC Filters. Design of AC Filters. Design of single frequency tuned filters. Double frequency Tuned Filters. High pass filter. Cost considerations of AC Harmonic Filters. Ratings of AC Capacitors in Tuned Branch. Harmonics in DC Voltage. DC Harmonic Filters. Summary and Questions.

---

**8. Reactive Power Compensation in HVDC Substations** **200—219**

Reactive power requirements of HVDC Converters, P. Q. S, Reactive power Q required by converter, and HVDC Substation. Reactive power equations. Effect of Delay angle and Extinction angle. Short Circuit Ratio (SCR). Impedance of AC Network. Equivalent Short Circuit Ratio. SCR in Planning of HVDC. Transient Voltage Rise. Summary and Questions.

**9. Earth Electrode and Earth Return 220—239**

Terms and definitions. Objectives. Location and Configuration of Earth electrode. Material of Anode. Sea electrode. Current density. Resistance of Earth Electrode. Earth resistance of Straight Electrode. Troubles by Earth currents and remedial measure. Electrode line. Summary and Questions.

---

**10. Configuration and Layout of HVDC Terminal 240—266**

Configuration of terminal station. Layout of a Bipolar Terminal Station. Concept behind layout. Choice of Converter Connections. Valve hall and Control Building. Converter Valves. HVDC Yard. Rihand Delhi Bipolar HVDC System. Back to Back HVDC Coupling Station. Summary and Questions.

---

**11. HVDC Circuit-Breaker and Metallic Return Transfer Breaker and Parallel Tap Circuit Breaker 267—282**

Application of MRTB and Parallel Tap. Interruption of DC Currents of high switching energy. Commutation principle. Commutation circuit. Switching Energy Main Circuit Breaker. Metallic Return Transfer Breaker (MRTB). Types of HVDC Circuit Breakers A, B. Capability and Characteristics of HVDC Breaker. Switching Times. Short Circuit Ratio. Effective Short Circuit Ratio. Parallel tapping of HVDC Line. Summary and Questions.

---

**12. Multi-Terminal HVDC Systems 283—298**

Two pole HVDC with earth return, Substation poles in different locations. MTDC System with series connected converters. MTDC System with parallel connected converters. Control of Parallel connected HVDC System. Reversal of power in a terminal of HVDC System. Three TDC System with parallel tapping. Two pole reversal in 3 TDC System. HVDC Breakers in MTDC System. Applications of MTDC Systems. World's First Commercial 3 TDC System. World's First 5 TDC System. Configuration and Type of HVDC System. Summary and Questions.

---

**13. Protective Zones and Protective Systems in HVDC Substations 299—320**

Faults in HVDC Systems. Fault clearing of DC Transmission line. Protective zones in HVDC Systems. Protection systems in HVDC Substation. HVDC line pole protection,

Clearing of line faults and re-energising of line. Abnormal operating conditions in convertor valves. Convertor Faults and protection systems. Convertor transformer protection. AC filter protection. Protection of AC Busbars and AC Yard equipment. Summary and Questions.

---

## **14. HVDC System Control**

**321—356**

Control requirements. Alternative principles of HVDC Control. Terms and definitions. Hierarchical levels of HVDC Control : HVDC System Control-HVDC Master Control-Substation Control-Pole Control-Convertor Control-Monitoring. Hybrid Control. Schematic Diagram of current control in two terminals and telecommunication channel. Control loop current control system. Convertor unit tap changer control. Valve unit firing control. Terms and definitions control. Equidistant firing control. Convertor firing control reviewed commutation margin control. Triggering logic in valve firing control. Transition between current control and commutation margin control. Station control in lead station and trail station. Power order setting. Power flow through synchronous HVDC link. Power flow through interconnection by non-synchronous HVDC link, Summary and Questions.

---

## **15. AC Network Frequency Control and Stabilisation by HVDC Damping Control and Power Modulation**

**357—384**

Load frequency relation in AC Network. Power deficit and frequency deviation. Frequency control in AC Networks. Power flow through AC Interconnection, Stability limit. Power swing through AC Tie line. Interconnection between three AC Networks. Frequency deviation of AC network. Frequency Control (Steady State) by HVDC power control. Block diagram of control system. Stabilisation or Damping of AC Network Oscillations. Transient Stability. Transient Instability. Dynamic Instability. Stabilising effect of HVDC Control Damping of Oscillations; Modulation signal Asynchronous HVDC link, Stabilisation of AC line. Control system for Frequency control and damping control. Subsynchronous Resonance (SSR) and its Damping. Harmonic Instability. Saturation of Convertor Transformer Core. Special control features in Rihand Delhi HVDC System. Voltage Stability of AC Network and reactive Power Compensation in HVDC Substation. Summary and Questions.

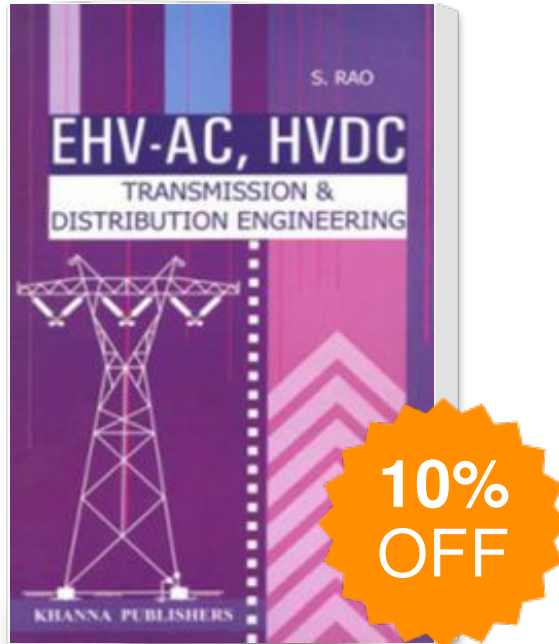
---

## **16. Insulation Coordination and Surge Arrester Protection in HVDC and EHV AC Substations**

**385—423**

Overview. Overvoltages in HVDC and EHV AC Systems.

# EHV-AC, HVDC Transmission And Distribution Engineering



Publisher : KHANNA  
PUBLISHERS

ISBN : 9788174090436

Author : S. Rao

Type the URL : <http://www.kopykitab.com/product/22273>



Get this eBook