Electrical Power Engineering Reference & Applications Handbook

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Dedicated

to my parents with

A Guilt of Neglect

Had I cared them a little more,

Had I loved them a little more!

My loving parents have gone,

And so goes my heart!

The memories would stay and

So will the *Guilt*.

K. C. Agrawal

Contents

Preface to this edition

Since time immemorial pursuit to knowledge has been a never ending process for the man. The man has always been capable of evolving new methods and techniques to overcome his difficulties. In earlier times the means were primitive but with the advancement of science and technology, applications of safety measures and man's own disciplines and controls, situation today is far more redeeming yet quite alarming in many fields. Of all fields, degeneration of environment is the most alarming, caused by emission of toxic gases and discharge of effluents and most importantly generation of excessive heat due to excessive loss of energy by all equipment and devices consuming energy in whatever form. Electromagnetic (EM) emissions also cause environmental pollution affecting performance of equipment and devices operating in their vicinity.

The gradual rise in human awareness even about his own callousness towards contributing to the above causes, he is now getting intensely engaged in containing the causes and mitigating their effects as far as possible. Rigorous R&D in various fields around the world by those who are more aware and concerned is now the order of the day. Emphasis is on controlling all kinds of pollutions and all such emissions that contribute to global warming or health hazard at source itself. Similarly, energy and space saving. All such requirements can form the eco norms. These issues are discussed in this handbook to the extent related to the topics covered to keep the readers abreast with the latest technological philosophies and the disciplines that one is required to observe. For more information refer to 'Kyoto Protocol'*.

The present edition is a thoroughly revised and upgraded version of the earlier handbook 'Industrial Power Engineering and Applications Handbook'. It accounts for technological changes, product developments and new applications that have taken place in the last one decade. This also takes account of upgraded and new national and international Standards that have become available in this period. Some of the new topics that have been added are noted in Table P-1. It has been done to keep the readers well informed of the latest technologies and practices being adopted worldwide in the field of Electrical and Electronic Power Engineering. Energy saving and space saving are buzzwords in today's world. All these aspects have been given due consideration in the present handbook and accordingly special thrust is laid on,

– Energy conservation
– Use of energy efficient electrical and electronic equipment and devices
– Environment and pollution controls
– Space saving

Energy conservation

All efforts have been made to identify areas, equipment and devices that can save energy. Some such areas discussed in this book are

– Energy efficient motors (EEM)
– Soft starters and energy feedback through static drives
– Energy efficient and space saver belt drives
– Fluid couplings for soft starting and energy saving
– Power cables, busbars and gas or fluid pipelines
– Air insulated and gas insulated switchgears (GIS) and general guidelines to save energy where possible.
– Compact and sandwich low loss busbar systems
– Retrofitting of old installations, equipment and devices with energy efficient and space saving equipment and devices

It is suggestive that manufacturers and equipment suppliers, who deal with energy efficient products or technologies, as customary, provide repayment schedule to their users for encouraging them use energy efficient products and technologies and enable them take a more pragmatic decision while making the purchases.

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* **Kyoto Protocol** was opened up for signature on Dec. 11, 1997 at Kyoto, Japan and came into force with effect from Feb. 16, 2005. In all 141 countries have presently ratified the protocol.
It is an amendment to the United Nations Framework Convention to Climate Change (UNFCCC), an international treaty on global warming. It also reaffirms sections of the UNFCCC countries who have ratified this protocol and commit to reduce the emission of green house gases (GHG) (the major gases being water vapours (36–70%), CO_2 (9–26%), Ozone (3–7%), and minor gases being methane (CH_4), Nitrous oxide (N_2O), Sulphur hexafluoride (SF_6), Chlorofluorocarbons (CFC 11 to 115, Section 13.10.1) and many more).

Environment

– Similarly, thrust is on environmental and pollution controls by way of effluent treatment of waste water and disposal of wastes.
– Also practising EMC/EMI norms to control electromagnetic and radiated field environmental pollutions.
- Restrictions on the use of certain hazardous substances (RoHS) in the manufacture of electrical and electronic equipment (EEE) and their waste management (WEEE) – (collection, treatment, recycling and disposal under controlled conditions).

Technical information

To compile all these details a lot of research and hard labour has gone into obtaining vital data and details from different leading manufacturers and users worldwide. The basic thrust of the book is to provide such information that is not easily available. All topics are backed up with extensive study and research by the author and information provided by leading manufacturers and consultants. Utmost care has been taken to ensure authenticity of text in technical discussions, inferences drawn and applications on a particular subject matter. All data provided and recommendations made are corroborated through relevant IEC and other Standards and generally accepted practices worldwide. Presenting all such Standards in a tabular form with their equivalent BS, IS, IEEE, NEMA and ANSI Standards, as practised by different countries, for each chapter and each topic is a unique feature of the handbook and shall greatly help a practising engineer, consultant or a design engineer, student or research scholar in their day to day working and handling of these subjects and machines.

All this has been done to benefit the readers and provide them such vital data and details so handy. The language is simple and distinct and easily comprehensible. Those who like to learn and be abreast with the technological advances, modern practices and applications will find the handbook extremely informative and useful. Masters in their fields surely know all this. The topics added in the present addition are shown in Table P-1.

Standards

There is a continuous upgradation of Standards and products. It is therefore advisable that the user of a product may consult the latest Standards for the latest specifications. The main thrust is on IEC Standards but NEMA, ANSI and IEEE Standards that are more prominent in many countries are also considered and given due reference. BS and IS Standards are gradually adapting to IEC Standards, their equivalent are also mentioned where possible. Similarly, more prominent ISO Standards are also mentioned.

Tables and data

All tables and data obtained from manufacturers are for general reference only. With continuous improvements and advancements in technology and product the data and applications may vary. The user must consult the manufacturer for accurate data.

Mathematical and voltage systems

Endeavour is to provide as much information with as much clarity as possible. Different countries may adapt to different mathematical systems (like MKS or FPS), 50 Hz or 60 Hz and also different voltage systems (new voltage systems are mentioned in the Introduction). While MKS and 50 Hz system has been chosen in the book for all explanations, where possible data are provided for FPS as well as 60 Hz systems also. It has been done to help the readers find it easy to comprehend the subject matter and translate it to their system easily.

Similarly, there may be variations in basic components and raw materials from country to country, but it would be easy to apply the practical approach of this book and use only the available raw materials and components.

Cross-references

The cross-references should not be hindrance to smooth reading. They are aimed to provide more details to the reader on a particular subject or its additional applications, and in the process providing more clarity on the subject. This is a unique feature of the handbook and it is hoped the readers will like it.

Index

The book contains enormous amount of rare and valuable information. To make it convenient for the reader to search out an information, we have tried to provide an exhaustive index to enable him locate his information promptly.

It is hoped the readers will find the book unique and useful.

K.C. Agrawal
(2007)

Table P-1 Topics added

Part I	*Part II*	*Part III*	*Part IV*	*Part V*
Electric motors, drives and energy saving – Energy saving – Energy efficient motors (EEM) – Developments in semi-conductor devices and their applications in ac/dc drives, HV dc transmission, SVC's and other power applications – Shielding of signals and isolated or clean grounding of power electronic circuits – Prevention from bearing currents caused by PWM inverters – Transition from ISO 9000 (1994) to ISO-9001 (2000) – Energy efficient and space saver power-transmission belts – Microprocessor based switching devices (IEDs) – Intelligent starters	***Switchgear assemblies and captive (emergency) power generation*** – Energy based discrimination of current limiting breakers – Compact switchgear assemblies – Protection schemes – Intelligent switchboards – Additional tests on switchgear assemblies like • impact test, internal arcing test and separators for operational safety, glow wire test • Impulse test on LV system • Restrictions on use of hazardous substances (RoHS) – Some new techniques of recording and predicting an earthquake – Passing reference to tsunami warning systems – Non-conventional methods of current measurement – Hybrid current sensors – Hall effect sensors, Rogowski coils and Digital optical instrument transformers – EMC/EMI testing requirements – Generator grounding and reactive load sharing	***Voltage surges, over-voltages, circuit interrupters and grounding practices*** – Gas insulated compact sub-stations (GIS) – LV surge protection and surge protection devices (SPDs) – Metal oxide distribution class surge arresters – HV and LV vacuum contactors – Grounding systems	***Power capacitors and reactive power controls*** – Special purpose capacitors – Auto-reclosure scheme for transient stability and – Use of Supervisory Control and Data Acquisition (SCADA) system for dynamic stability of a power network – Serial data transmission, communication interfaces and protocols – EMC/EMI (Electromagnetic compatibility and interferences) – EMC/EMI norms	***Busbar systems*** – Sandwich and compact low loss bus systems – Partially isolated bus-systems – More tables and details on copper busbar systems – Designing of copper bus systems – New safety measures and tests prescribed by IEC
And many more small and relevant topics				

Preface to the first edition

The author has had a long association with the machines described in this book. The book is the result of this experience and the overwhelming help and support extended to him by his colleagues, friends and business associates over the last twelve years. The purpose of this book is to share the experience of the author with those in the field. It is an attempt to make these subjects simple and interesting. The book should provide an easy approach to answer the problems an engineer or engineering student may face when handling these machines.

The author is sure that the readers will find ample opportunity to learn from his experience and apply this information to their field of activities. The book aims to provide a bridge between the concept and the application. With this book by his or her side, an engineer should be able to apply better, design better and select better equipment for system needs and ambient conditions. It should prove to be a handy reference to all those in the field of design and application, protection and testing, production, project engineering, project implementation or maintenance, in addition to the sales and purchase of these products.

Devoted Engineers and Scientists have done an incredible job by inventing new technologies and bringing them, over the years to their present level. Research and development work by a dedicated few Engineers and Scientists has been a relentless and untiring journey which has provided us with more advanced forms of technologies from time to time. The credit for this book goes to these Engineers and Scientists throughout the world. The author is not an inventor, neither has he done anything new in these fields. He has only attempted to bring together such advances in a particular field in one book for their better applications and uses. The author's contribution is only appropriate selection and application of the available technology and products for their optimum utilization.

All relevant aspects of a machine, including design, have been discussed but greater emphasis is laid on selection and application. Since this is primarily a reference book the basic theory is assumed to be known to a student or a practising engineer handling such machines and/or technologies, yet brief theory has been discussed wherever considered necessary to refresh one's memory.

In the academic world the derivation of a formula from fundamentals is regarded as most important. In practice, this formula matters more rather than its origin. But for those who wish to know more of the reasoning and the background of a formula, care is taken that such supportive information is also covered. The author hopes that readers will be satisfied to have most of their queries answered.

The book has been written so that it refreshes and awakens the engineer within a reader. The author is confident that this is what readers will feel as they progress through this book. A cursory reading will bring them abreast with the subject and enable them tackle problems with ease and simplicity. The author's efforts will be defeated if this book falls short of this aim.

The endeavour has been to provide as much information as possible on the application of available technology and products. It should help application engineers to select and design a more suitable machine or power system for their needs. As mentioned above, the text may not cover the full engineering derivations, yet all fundamentals have been provided that are considered relevant to engineer any machine or system covered in this book. To augment the information, 'Further Reading' has also been provided to support the text and to answer queries that may arise on a particular subject. For detailed engineering, the manufacturers are still the best guide. Detailing and engineering must be left to them. In this book, the author has tried to make the subject comprehensive yet concise and easy to understand, so that one can easily refer to it at any time. The references drawn are brief, but pertinent, and adequate to satisfy a query.

This book may prove to be a boon to young engineers entering the field. With it by their sides they can comprehend the theory of their classrooms with applications in the field.

Whereas all aspects that were thought necessary have been considered, it is possible that some have been omitted. The author would be grateful to receive suggestions from readers for any additions, deletions or omissions to make the book even more useful and up-to-date next time.

K.C. Agrawal
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Standards

ANSI	American National Standards Institute – USA
BS	British Standards – UK
IEC	International Electro Technical Commission – Switzerland
IEEE	The Institute of Electrical and Electronics Engineers – USA
IS	Indian Standards – India
ISO	International Standards Organisation – Switzerland
NEMA	National Electrical Manufacturers' Association – USA

Introduction

This book is built into five parts. A summary of each part follows.

Part I Electric motors, drives and energy saving

This part deals with three- and single-phase a.c. machines, and their protective switchgears. However, reference is made to and comparisons drawn of a d.c. motor with an a.c. motor, to assist a user make a proper choice of machine. Energy conservation, energy auditing and energy efficient motors (EEM).

However simple a motor is, it requires careful handling to ensure optimum performance and long years of trouble free operation. A small drive, failing while in operation, may bring the entire process to a halt. One can visualize the loss of production that can result. Power plants, chemicals, fertilizers, petrochemicals, paper and cement mills all require careful selection of equipment to avoid breakdown or malfunctioning during operation. Motors and their controlgears are core components that require special attention:

- It deals with the specifications, performance, characteristics and behaviour of motors under different operating conditions, their application and selection. It also covers aspects such as shock loading, motors for hazardous locations and open transient conditions in MV motors during a switching sequence.
- This part-also deals with static controls and drives, soft starting and process control through solid-state technology (phasor and field-oriented controls) using IGBTs, IGCTs, SGCTs. Energy conservation. Developments and applications of solid state technology. Grounding practices and shielding of signals. Prevention from bearing currents.
- There is special coverage of fluid couplings for soft starting and speed control. A comparison between static drives and variable-speed fluid couplings is made.
- Windmills (induction generators) as an unconventional energy source, vertical hollow shaft motors and submersible pump sets, selection of energy efficient and space saver belts for transmission of load, the phenomenon and remedy of shaft currents.
- The text especially covers testing requirements and an introduction to quality assurance systems and application of ISO 9001(2000).
- Special coverage of impulse testing of resin-rich formed coils and their in-house testing requirements.
- In Chapter 12 a detailed analysis is made of all unfavourable operating conditions and their effect on the performance of the motor and its protection for optimum utilization. The precautions also cover surge protection for MV motors. The details provided cover the smallest-influence that a particular parameter can have on the machine. Microprocessor based switching devices (IEDs) and intelligent starters.

Part II Switchgear assemblies and captive (emergency) power generation

The subjects covered aim at providing methods to form specifications and design a switchgear assembly for all power distribution needs. The text covers compact assemblies and intelligent switchboards. It also provides coverage of draw-out assemblies. Establishing the fault level of a system is described including the electrodynamic and electromagnetic forces that arise. Protection schemes and energy based discrimination of current limiting breakers.

- An introduction to RoHS (restrictions on use of hazardous substances)
- Testing procedures are informative and elaborate
- Introduction to EMC/EMI testing
- Seismic effects and earthquake engineering is covered in this part to study the behaviour of an object under seismic conditions and its suitability for critical installations. The formation of the earth and movements of tectonic plates that cause earthquakes, tsunamis and volcanic eruptions are described
- Instrument transformers (CTs, class PS CTs, VTs and CVTs, etc.) form important components of a switchgear assembly for measurement and protection. They are covered for their specifications, selection and application.
- Design of class PS CTs, non-conventional current measurements, current sensors and transducers. Rogowski coils (RCs)
- Captive (emergency) power generation covers the

application of a diesel generating set, its starting, protection, grounding, synchronizing and load sharing. This forms an important part of power distribution at any installation to provide a standby source of supply.
- The entire painting procedure and effluent treatment is covered for those in the field of manufacturing such assemblies and to also save environment.
- In an attempt to provide as much information on the related subjects as possible and to make the book more complete for a project or a design engineer we have provided data and tables on PVC, paper insulated and XLPE cables and described in detail the procedure for selecting the type and size of LV and HV power cables.

Part III Voltage surges, over-voltages, circuit interrupters and grounding practices

This part is complementary to Part II and provides technical support to switchgear assemblies and machines fed by them for surge and over-voltage protection. It is a very useful part for all those handling HV and EHVpower systems and their surge and over-voltage protection.

- The part deals with the BIL of a system, protective margins and insulation coordination. LV surge protection and surge protection devices (SPDs)
- It also deals with electric motors as they are typical for their surge behaviour and protection.
- It also covers the steepness of TRVs, their significance and methods of taming them. Reflections of travelling waves and surge transferences are also described.
- This part specifically considers the application and selection of surge capacitors and surge arresters. Since the internal causes of surge generation are a consequence of switching operation and type of interrupter, this part provides details of the various types of interrupters in use, their switching behaviour, current chopping and quenching of arc plasma. It also makes a detailed comparison of the various types of interrupters available in the market to facilitate their selection and adaptation to a more appropriate surge protection scheme. Gas insulated switchgears (GIS). HV and LV vacuum contactors.
- Temporary over-voltages are different from surges as are their causes. Therefore temporary over-voltages also form an important parameter in a system design and its grounding method. This topic is therefore complementary to surge protection and has been dealt in detail to make a practising engineer or engineering student more aware of the behaviour of an HV system, particularly on a ground fault.
- Exposure of a human body to touch and step voltages and methods to deal with these are also covered. Grounding and ground fault protection schemes are described in detail with illustrations to help an engineer select the most appropriate grounding method and ground fault protection scheme for a machine or a system.
- The use of CBCTs is covered.
- Grounding systems, their choice and protection from transferred surges and over-voltages
- Grounding practices of industrial installations and power generating stations.

Part IV Power capacitors and reactive power controls

Reactive control is an important tool for voltage regulation and for optimizing available power utilization. It can also be used for attaining better stability of the system. It has therefore become a very important technique to improve an old distribution network that is being overutilized and is ailing with recurring problems such as flickering of voltage, frequent system outages and a normally low voltage at the consumer end. The author has attempted to apply reactive control to improve power distribution networks which are over-loaded and are ailing with such problems.

In this part the author provides all relevant aspects of a reactive control and carries out an exhaustive analysis of a system for the most appropriate control. Harmonic effects and inductive interferences as well as use of filter and blocking circuits are covered. EMC/EMI (Electromagnetic compatibility and interferences). Capacitor switching currents and surges and methods of dealing with these are also described.

This part considers reactive power control with the use of shunt and series capacitors. The controls may be manual or automatic through electromagnetic or static devices. Protection of capacitors and capacitor banks as well as design, manufacturing and test requirements, installation and maintenance are also covered, the main thrust being on the application of power capacitors.

- Application of series capacitors and analysis of an uncompensated transmission line and the capability of power transfer and system regulation with and without series compensation are also presented. Auto-reclosure scheme for transient stability and SCADA system for dynamic stability of a power network. Serial data transmission, communication interfaces and communication protocols.
- To clarify the subject the basics and the behaviour of power capacitors in operation are also discussed.
- This part also briefly describes different types of power reactors required to control inrush currents, suppress system's harmonic disorders, limit system fault level and absorb the excessive charging currents on an EHV system.

Part V Busbar systems

Power transfer is a very important area of a power system. In this part it is dealt with in detail for both LV and HV systems and for all current ratings. For large to very large ratings, skin and proximity effects are also discussed to arrive at a design to transfer large amounts of power, without great loss, voltage drop or voltage unbalance. Technical data and current ratings for various sizes and sections of copper and aluminium are provided. The text provides material to design, engineer, manufacture and test a bus system of any current and voltage rating.

This part specifically deals with

- Design parameters
- Sandwich, compact and partially isolated low loss bus systems
- Short-circuit effects
- Electrodynamic and electromagnetic forces
- Effects of proximity and reducing this by phase interleaving or phase transposition
- Designing a reactor for the middle phase to balance a large unbalanced current-carrying system
- Recommended practices to mount buses and make bus connections
- A detailed discussion on the isolated phase bus system concentrating on continuous enclosures and their design aspects
- Sample calculation to design an IPB
- Testing of bus systems.

IEC 60038 New voltage systems

In pursuit of bringing more uniformity in voltage systems and promoting international understanding and business amongst various countries, IEC in consultation with experts of many countries has made an attempt to club dissimilar voltages practised by different countries into just a few slabs to narrow down this disparity for the advantage of all. The new voltage systems are noted in the Table I-1 for LV and Tables I-2 and I-3 for HV and EHV systems. These voltage systems are to be followed by all member countries who follow international practices in design and manufacture of their products to facilitate better understanding and business relations with other countries. With a view to making transition easier, higher voltage variations (as noted in the tables) are now prescribed for all new equipment and devices manufactured as per the new voltages to facilitate easy retrofitting of the old equipment and devices with the new ones without calling for two designs to meet the situation.

All countries following international Standards were required to follow the revised voltage systems by 2003. But many of them have not been able to do so as yet, because of practical problems. Although the maximum change is only in LV voltages, it too demands for change in design and change of existing equipment and devices besides the change of supply voltage in the existing distribution networks and all that is not an easy task. Nevertheless most countries are endeavouring to fall in line sooner or later. We have therefore retained our earlier tables. They will stand modified in proportion to the change in voltages. For exact details, one may refer to the relevant Standards. To identify the voltage level, the nomenclatures used by us are shown in Table I-4.

Table I-1 IEC 60038 New voltage systems

Nominal voltages (V_r)	
Series I (50 Hz)	*Series II (60 Hz)*
–	120/208
–	240
* 230/400	277/480
*400/690	480
–	347/600
1000	600

* The manufacturers and users shall endeavour to change over by 2003 from the existing 220/380 V and 240/415 V systems to the new voltage system of 230/400 V (+6%, –10%) or (+10%, –6%) respectively. The first step shall be taken by the electricity supply authorities of a country to adjust their voltages to the revised level to be followed suit by the manufacturers and users of equipment and devices.

Table I-2 Series I or II (50 Hz or 60Hz)

Series I (50 Hz)			*Series II (60 Hz)*	
*Highest voltage for equipment *V_m kV*	*Nominal system voltage (**V_r) kV(± 10%)*		*Highest voltage for equipment V_m kV*	*Nominal System voltage (V_r) kV (+5%, –10%)*
3.6	3.3	3	4.40	4.16
7.2	6.6	6	–	–
12	11	10	–	–
–	–	–	13.2	12.47
–	–	–	13.97	13.2
–	–	–	14.52	13.8
(17.5)	–	(15)	–	–
24	22	20	–	–
–	–	–	26.42	24.94
36	33	–	–	–
–	–	–	36.5	34.5
40.5	–	35	–	–

* V_m – represents the dielectric strength of an equipment, device or power system for which it is designed.

** V_r – nominal or rated system voltage at which an equipment, device or power system shall usually operate.

Table I-3 Series I or II (50 Hz or 60 Hz)

Highest voltage for equipment $*V_m$ *kV*	*Nominal system voltage* ($**V_r$) *kV*		
(52)	(45)	–	
72.5	66	69	
123	110	115	(i)
145	132	138	
(170)	(150)	–	
245	220	230	(ii)
(300)			
362			(iii)
420			(iv)
550 (or 525)			
800 (or 765)			(v)
1050 (or 1100)			
1200			

1. Values in parentheses are not the preferred values.
2. Wherever two voltage systems for one V_m have been prescribed a country may adopt to any one of them.
3. For more details refer to IEC 60038

* V_m – represents the dielectric strength of an equipment, device or power system for which it is designed.

** V_r – nominal or rated system voltage at which an equipment, device or power system shall usually operate.

Notes

i, ii, iii, iv – For one country one must choose only one voltage system from one group

v – Countries using 1050 kV should not use 800 or 1200 kV.

Table I-4 Nomenclatures used to represent different voltage levels

System	*Nominal voltage* (V_r) *kV*
LV	$V_r \leq 1$
MV	$1 < V_r \leq 35$
HV	$35 < V_r \leq 230$
EHV	$230 < V_r \leq 800$
UHV	$V_m = 1050$ or 1200 kV (practised in USA)

Note

For all voltages above LV we have used the nomenclature as HV unless where the voltage range is specific such as for motors and generators we have used MV. Similarly we have identified,

Transformer voltages as: Lower voltage side – LV

Higher voltage side – HV

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