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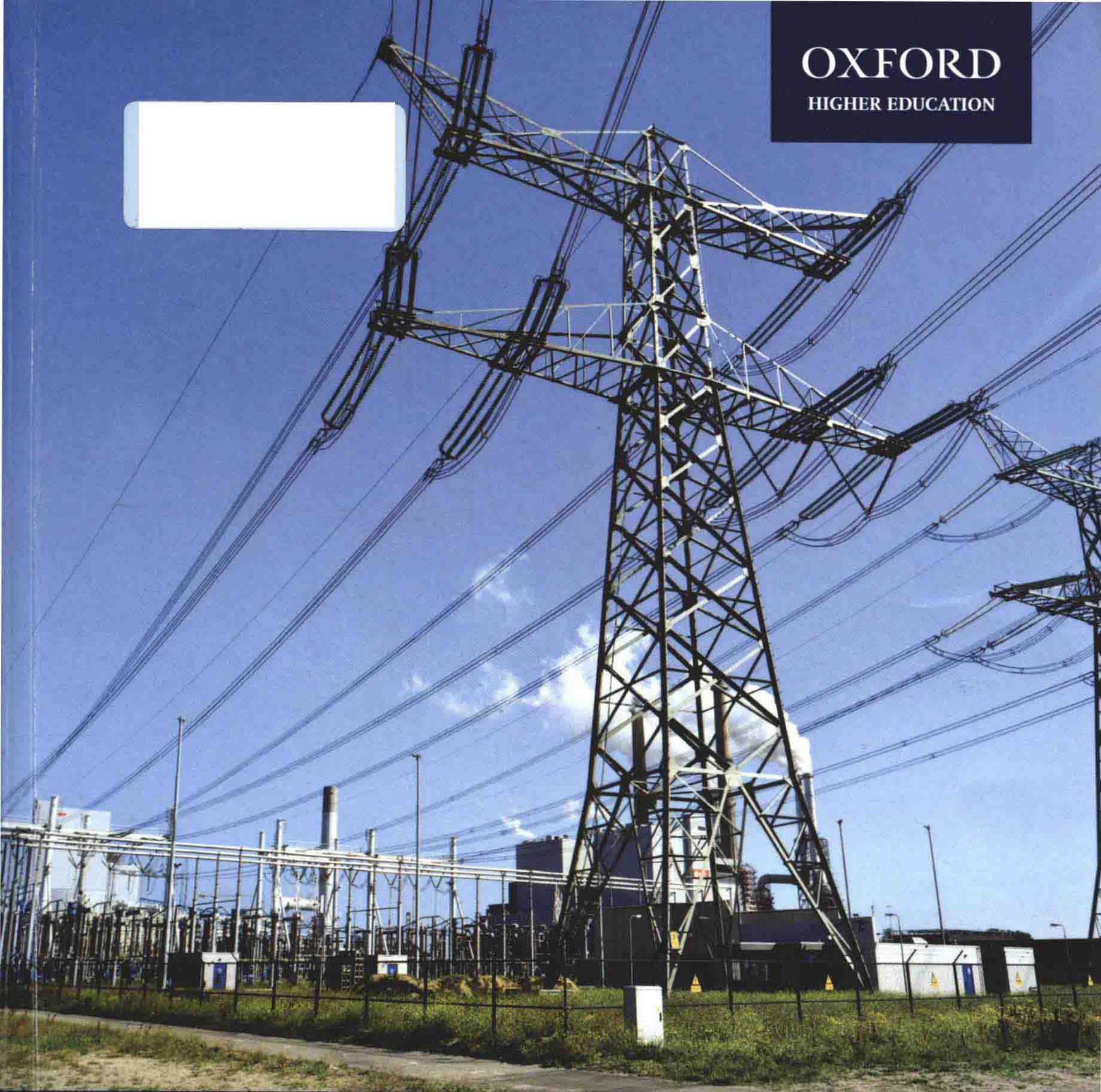

Power System Analysis

SECOND EDITION

T. K. Nagsarkar ▪ M. S. Sukhija

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To my parents
Late Ramakanta Nagsarkar
and
Late Shova Nagsarkar

T.K. Nagsarkar

Humbly dedicated to
the greatest Master for penning a
destiny of unmitigated joy

M.S. Sukhija

Preface to the Second Edition

Our title *Power System Analysis* was published in 2007 and since then it has been readily accepted as a standard textbook both at the graduate and postgraduate levels. This second edition is a gradational revision of the power systems analysis course. Without disturbing the simple and mellifluous flow of the language, the second edition aims to fulfil the following objectives:

- Reflect the overall changes in the energy sector scenario which have come about during the past five years or so
- Further fortify the understanding of principles of power system analysis
- Expose readers to current topics such as *voltage stability* which have acquired significance in the context of large integrated power systems operating close to their maximum capacity

New to the Second Edition

The purpose of revising the already accepted title *Power System Analysis* was to see it as an opportunity to bring about improvements. Therefore, the changes which have been incorporated in the second edition are largely based on the following:

- Suggestions from students and faculty members in various institutions
- Our continual references to look for 'chinks in the armour' in our work
- Periodic comments from the publisher's reviewers

Common Features

The most important change in the second edition is the inclusion of the following in each of the chapters:

- *Learning Outcomes* at the beginning of each chapter defines the results a reader will be able to achieve following a study of the chapter.
- End chapter *Summary*, along with *Significant Formulae*, provides a recapitulation of the chapter.
- Descriptive questions have been included in the chapter end *Exercises*.
- *Multiple Choice Objective Questions*, with one correct answer, have been added to enable a reader to quickly gauge his/her understanding and retentivity of the principles and laws of power system analysis.
- Existing terminology, principles, laws, symbology, etc., wherever required have been further clarified.

Extended Chapter Material

Chapter 1 (*Power Sector Outlook*) Data related to the energy sector has been updated along with a brief description of Vision 2020. Additionally, solar power and magneto-hydro-dynamic (MHD) power generation have been included.

Chapter 2 (*Basic Concepts*) Comparison of single- and three-phase power transmission, along with typical solved examples, have been included.

Chapter 3 (*Transmission Line Parameters*) Overview has been re-drafted to highlight the importance of transmission lines in power transmission and the electrical properties of commonly used conductor materials are shown in tabular form. A separate section is included to explain at length skin, proximity, and spirality effects which lead to non-uniform distribution of alternating current in a conductor.

Chapter 4 (*Transmission Line Model and Performance*) Overview has been re-written to bring out the effect of distributed line parameters. Significance of ultra-fast transients leading to overvoltages has also been stated. Significance of propagation constant and Ferranti effect have been explained at length along with the inclusion of several typical solved examples.

Chapter 6 (*Formulation of Network Matrices*) Overview has been expanded to emphasize the formulation of network matrices based on graph theory.

Chapter 7 (*Power Flow Studies*) A new section to explain the simulation of DC power flow solution has been added. Similarly, a detailed comparison of the various power flow solution methods has been provided in tabular form.

Chapter 10 (*Symmetrical Components and Unsymmetrical Fault Analyses*) A table summarizing the phase shift between primary and secondary voltages of three-phase transformers, according to different vector groups, has been added for easy simulation for fault analysis.

Chapter 12 (*Voltage Stability*) Keeping in mind the several collapses of major power networks worldwide due to voltage instability, this new chapter has been included. After explaining and defining voltage stability and voltage collapse, the former is classified as large disturbance and small disturbance voltage stabilities. Formulation of transient voltage stability problem, due to a small disturbance, has been discussed along with techniques for performing transient voltage stability studies. Appropriate typical solved examples explain the application of the techniques.

Chapter 13 (*Contingency Analysis Techniques*) A typical solved example has been included to further explain the method of performing contingency analysis.

Chapter 14 (*State Estimation Techniques*) Variations in Examples 14.1 and 14.2 have been introduced to further explain the method of weighted least squares and the application of line power flow estimator for computing the system variables respectively.

Chapter 15 (*An Introduction to HVDC Power Transmission*) A whole new section explaining the operation of HVDC converter, in detail, has been included. Additionally, typical solved examples have been added. These examples further clarify the principles of HVDC operation.

Academic Capacity Test (ACT) has been provided as an online resource for students. It consists of 100 multiple choice objective questions, randomly selected from all the chapters in the textbook. ACT has been designed to enable a reader to identify chapter-wise strengths and weaknesses.

Acknowledgements

Words may not be enough to express our sense of gratefulness to our innumerable readers who took time out to provide priceless inputs. In particular we would like to acknowledge our gratitude to our colleagues, reviewers, and the staff of OUP who provided invaluable constructive criticism. Finally, last but not the least, we are indebted to the countless faculty members and young readers for their eager acceptance of our work.

T.K. Nagsarkar
M.S. Sukhija

Preface to the First Edition

The enjoyable experience of writing our first book *Basic Electrical Engineering* and its ready acceptance by the engineering faculty has inspired us to author our second book *Power System Analysis*. Written with the objective of assisting students to acquire the concepts and tools of analyses, it will also equip them in finding solutions to power system engineering problems in practice. In view of this objective, the language and style of writing this book is completely student oriented.

The growth of modern-day integrated power systems has fortunately been accompanied by the development of fast interactive personal computers. The latter has necessitated the integration of personal computers into the curricula of power system engineering programmes and has enabled the teachers to augment the learning process through the simulation and designing of more practice-oriented problems and taking up more complex topics for analyses.

Matrix laboratory (MATLAB) is a very powerful matrix oriented software package for numerical computations. It is a handy tool for solving numerical problems requiring numerous matrix operations, and therefore, a boon for analysing power system problems. Keeping in mind the current developments and future requirements, the book has an intentional bias towards computer simulation of power systems and the application of MATLAB for analyses and solutions of complex problems. The text integrates, through examples, several executable MATLAB functions and scripts. This will help the readers to comprehend not only the translation of a simulation into an executable MATLAB solution but will also encourage them to modify and even develop their own programmes. The MATLAB commands and their effects have been explained wherever they have been used in the text. Each chapter includes several such examples and unsolved problems with answers.

About the Book

Power System Analysis aims at providing a comprehensive coverage of the curricula and will serve as a very useful textbook for electrical engineering students at the undergraduate level. The book provides a thorough understanding of the basic principles and techniques of power system analysis. Beginning with basic concepts, the book gives an exhaustive coverage of transmission line parameters, symmetrical and unsymmetrical fault analyses, power flow studies, power system control, and stability analysis. With the inclusion of some advanced topics such as state estimation, stability analysis, contingency analysis, and an introduction to HVDC and FACTS, it would also serve the requirements of teachers and students alike at the postgraduate level.

Content and Coverage

The book comprises 15 chapters and three appendices. Each chapter in this book commences with an overview, which briefly outlines the topics covered in the chapter, and ends with numerous unsolved problems which help the readers to assess their comprehension of the subject matter studied in the chapter.

Chapter 1 in addition to tracing the history of the growth of the power sector outlines its structure and its present state. Statistical data is included to provide a perspective of the Indian power sector and its future plans for meeting the load demand and making it more energy efficient. The concept of deregulation of the power industry is also covered.

Chapter 2 covers the representation of power system elements suitable for circuit analysis. A review of phasor notation, phase shift operator for three-phase systems, and the power in single-phase and three-phase circuits is presented. It describes per unit representation of power systems and its advantages in power system analysis.

Chapters 3 and 4 deal with the parameters of transmission lines and steady-state performance and analysis of transmission lines, respectively. Chapter 3 outlines the computation of the parameters of transmission lines. Chapter 4 covers their simulation as short, medium, and long lines. Power handling capability and reactive line compensation of lines are discussed. The phenomenon of travelling waves on transmission lines is also included in the chapter.

Chapter 5 covers the representation of synchronous machines, transformers, and loads in the steady state and transient analysis.

Chapter 6 introduces graph theory along with the commonly employed terminology in the formulation of network matrices. Since network matrices form the basis of power system analyses, the chapter comprehensively covers the formulation of bus admittance and bus impedance matrices of a power system network. The chapter also includes the formulation of nodal equations, both in the admittance and impedance frames of reference, and their solutions by direct and indirect methods. Sparsity techniques for storing non-zero elements, network reduction, and optimal numbering schemes are also covered in the chapter.

Chapter 7 on power flow studies of integrated power systems, under normal operating conditions, provides a detailed description of the formulation of power flow equations. Solutions of these power flow equations by the well-accepted Gauss, Gauss–Seidel, and Newton–Raphson methods have been presented in detail in this chapter. Fast decoupled method for solution of power flow problems suitable for online studies has also been presented.

Chapter 8 deals with the maintenance of active power balance and control of voltage magnitude and power frequency, within specified limits, when a system is operating in the steady state. Beginning with the basic control loop in a generator, the automatic voltage control (AVC) and load frequency control (LFC) loops are described and their steady-state and dynamic performances are outlined in detail. The LFC of a single control area is first discussed and then extended to a two-area control system. Tie-line bias control and its application to a two-area control system are also presented in detail.

Chapter 9 deals with the methodical computation of bus voltages and line currents under balanced three-phase fault conditions. Impedance matrix for three-phase faults and computations of three-phase fault currents are also included.

Chapter 10 covers the analysis of power systems under unsymmetrical fault conditions. Symmetrical components which transform unbalanced currents and voltages into sets of three balanced components are employed as a tool for transforming an unbalanced circuit into a balanced circuit. The latter transformation makes it feasible to analyse the faulted network on per phase basis. The application of symmetrical components to various types of unbalanced faults, along with computational algorithms, has been detailed. Series faults such as one-conductor or two-conductors open are discussed. Generalized formulation for unbalanced short circuit computation using bus impedance matrix is also given at the end.

Chapter 11 commences with the assumptions commonly made in stability studies, followed by the derivation of the swing equation based on an analogy with the laws of rotational mechanics. The chapter includes an analysis of the single machine transient stability problem based on the equal area criterion. The solution of swing equation by conventional step-by-step method as well as modified Euler method has been presented. An algorithm for studying the multi-machine transient stability of a power system is also included. Numerical solutions of the non-linear algebraic equations are explained. MATLAB functions and scripts have been included to demonstrate their utility in obtaining numerical solutions and plotting the swing equation. Linearization of the swing equation and its solution for performing steady-state stability analyses are explained in detail. Some methods for improving stability are discussed.

Chapter 12 covers the contingency analysis of a power system and it deals with the determination of line currents following a line outage or a switching operation. The concepts of compensating currents, distribution factors, and their computation by employing the ***Z***-bus matrix are explained in detail. Contingency analysis of interconnected power systems by network equivalents is also presented.

Chapter 13 provides techniques to estimate the state of a power system using measured quantities such as P, Q, and line flows. Quantitative techniques to test the goodness of the state estimates from measurements and the elimination of bad data are also comprehensively described.

High voltage direct current (HVDC) systems operate in conjunction with ac systems to transmit bulk power in present day power systems.

Chapter 14 provides a historical perspective on the HVDC transmission, followed by a comparison of the ac and dc transmission systems. Typical configurations of HVDC converter stations and various types of dc links are also described.

Chapter 15 outlines the use of flexible ac transmission systems (FACTS) technology for enhancing transmission capability and improving grid reliability. The chapter highlights the restrictions in ac power flow in existing transmission systems due to parametric limitations and then explains how

FACTS technology can be employed to change the power flows by varying the parameters such as line reactance and voltage magnitudes. The various types of FACTS controllers employed for parametric variation have been described.

Three appendices are given at the end of the book. Appendix A defines the various types of matrices encountered in the modelling of complex engineering problems and outlines the matrix algebra involved in finding their solutions. Creation of matrices and the use of MATLAB commands have been demonstrated through examples. Numerous unsolved problems are provided at the end of the appendix. Appendix B comprises test data for power flow and the results for standard IEEE test systems. Solutions to end chapter exercises are provided in Appendix C.

We are confident that this book will enable students to achieve a better understanding of complex power system problems and help them solve these problems by utilizing the existing MATLAB functions and scripts. Students will become adept at developing their own functions and scripts independently, essentially after solving the problems at the end of each chapter. The faculty teaching the power systems engineering programme, on the other hand, will be able to enhance the teaching process by taking up modelling and analyses of problems which are encountered in the operation and control of power systems in practice.

We have developed this book over the past many years while teaching this subject to the students of electrical engineering at the postgraduate and undergraduate levels. The text has been written to match the evolving curriculum of the subject taught in universities in India and abroad. We acknowledge that the book is greatly influenced by earlier texts and literature written on diverse aspects of power systems by many outstanding professors and engineers. The details of the sources have been compiled in the bibliography at the end of the book. We wish to thank these individuals who have been instrumental in the development of this book. We are also grateful to our colleagues and friends who have provided valuable suggestions and criticism in formulating the contents of this book.

T.K. Nagsarkar
M.S. Sukhija

Symbols and Acronyms

Δf frequency deviation

ΔI_{ij} current changes in the line connected between buses *i-j*.

ΔP, $\Delta\delta$, $\Delta|V|$ deviations from normal operating values of power, angle, and voltage magnitude, respectively

ΔP_{1-2} change in tie-line power

ΔP_G increase in the generated power

ΔP_i, ΔQ_i active and reactive power mismatch respectively at bus *i*

ΔP_L increase in the load demand

ΔP_{ref} change in reference power setting; deviation in speed changer or reference position

ΔP_T change in the turbine power

ΔP_{tie} tie-line power deviation

ΔP_V signal that regulates the control valves of steam or hydro turbine unit

ΔS_i complex power mismatch at bus *i*

Δt uniform step time interval

ΔV vector of the changes in bus voltages due to compensating currents

Δx elemental strip length

Δx_i^0 addition to be made to the initial estimate of the state variable x_i^0

Δy_A change in position of point *A* corresponds to a change in ΔP_{ref}

Δy_C change in governor output command ΔP_g

Δy_E a change in valve position command ΔP_V

$\Delta\delta_1$, $\Delta\delta_2$ small changes in voltage angles

$\Delta\delta_n$ change in δ during the *n*th interval

α electrical angular acceleration (rad/s^2); attenuation constant, reflection operator for waves approaching from the left; acceleration factor in power flow study; damping factor

α_{n-1} acceleration at time $t = (n-1)\Delta t$

α_0 temperature coefficient of the conductor resistance at 0°C.

α_m rotor angular acceleration (mech. rad/s^2)

α_R receiving end reflection coefficient

α_S sending end reflection coefficient

α' reflection operator for waves approaching from the right

β area frequency response characteristic (AFRC); phase constant; refraction operator for waves approaching from the left

β' refraction operators for waves approaching from the right

γ natural frequency of oscillations; propagation constant $= \alpha + j\beta = \sqrt{yz}$

δ_m rotor angular position with respect to synchronously rotating reference (mech. rads)

δ_{n-1} angular position at time $t = (n-1)\Delta t$

δ_0 initial rotor angle position of the machine

δ_1, δ_2 voltage angles of $|E_1|$ and $|E_2|$, respectively
δ_c fault clearing angle
δ_{crit} critical fault clearing angle
δ_i voltage phase angle at bus i
δ_m angle (mech. rads)
ε permittivity constant (F/m); convergence tolerance
ε_0 permittivity constant for free space = 8.854×10^{-12} F/m
ζ vector of random errors or noise of measured physical quantities
ζ_i error or noise of ith measured variable
$\hat{\zeta}$ noise vector
η efficiency
θ angle in electrical radians measured from the rotor pole axis
θ_1, θ_2 angles of phase displacement from the reference
θ_{im} admittance angle of transfer admittance Y_{im}
θ_m rotor angular position; angular displacement of rotor with respect to stationary reference axis (rad/s)
μ mean; permeability constant of the medium
μ_0 $4\pi \times 10^{-7}$
μ_r relative permeability
3ϕ three-phase
φ phase angle between the voltage and current phasors
ϕ total flux (Wb)
ϕ_{ar} armature reaction flux per pole
ϕ_f flux per pole; rotor field flux
ϕ_{fa} flux linking the rotor field and the armature
ϕ_r resultant air-gap flux
ρ resistivity of conductor material (Ω m)
σ standard deviation
σ_i^2 variance
τ''_d short circuit sub-transient time constant
τ'_d direct axis short circuit transient time constant
τ'_{do} direct axis open circuit transient time constant
$\chi^2_{k\alpha}$ chi-square distribution
Ψ flux linkages (WbT)
ψ_{12} total flux between two points A_1 and A_2
ψ_{int} total internal flux linkages (WbT/m)
ω angular speed (radians/sec)
ω_s synchronous speed (elect. rad./s)
ω_{sm} angular synchronous speed (mech. rad/s)
$|E_1|$, $|E_2|$ magnitudes of the end voltages of control areas 1 and 2, respectively
$|I|$ effective or root mean square (rms) value of the sinusoidal current $\left(= I_m/\sqrt{2}\right)$
$|S_i|$ absolute value of the ith measurement of real and reactive power flow
$|V_i|$ magnitude of voltage at bus i
$|V_{R(FL)}|$ receiving end voltage at full load
$|V|$ effective or root mean square (rms) value of the sinusoidal; voltage magnitude $\left(= V_m/\sqrt{2}\right)$
$|V|_{ref}$ reference voltage
$|Y_{im}|$ magnitude of transfer admittance between bus i and bus m
$|_{\hat{x}}$ indication that the equations are evaluated from the elements of state estimate vector $\hat{x}$
0^+ and 0^- instant of time just after and just before the instant $t = 0$
A cross-sectional area (m^2)
$\mathbf{A}$ element-bus incidence matrix or bus incidence matrix; symmetrical components transformation matrix
$\bar{\mathbf{A}}$ element-node incidence matrix
$a + jb$ complex turns ratio of phase shifting transformer

$\boldsymbol{a}$	phase shift operator; turns ratio
ABCD	constants of a two-port network
AVC	automatic voltage control
B	magnetic flux density (Wb/m^2)
B_1, B_2	tie-line bias parameters
B_m	maximum value of flux density at the centre of the pole; magnetizing susceptance of a transformer
B_x	flux density at a distance x metres from the centre of the conductor
c_1	accuracy constant, in decimal, of the measurement (for real and reactive power flow measurements, typical values of c_1 are 0.01 or 0.02)
c_2	constant to account for transducer, and analogue to digital converter accuracy (typical values of c_2 are 0.0025 or 0.005)
C_{ab}	capacitance between conductors *a* and *b*
CCC	capacitor commuted converters
`col`	a row vector which provides the column number of $\boldsymbol{Y}_{\text{bus}}$
$\cos\varphi$	power factor
C_R	centre of the receiving end power circle
C_S	centre of the sending end power circle
d	distance between adjacent conductors of a bundled conductor
D	uniform electric flux density (C/m^2)
D_1, D_2	distances of two points A_1 and A_2 respectively from the conductor surface
D_f	electric flux density on a cylindrical surface
d/dt	operator p
D_m	geometric mean distance (GMD) between conductor X and conductor Y
D_s	GMR of individual conductors
$D_s^{\ b}$	GMR of a bundled conductor
D_{sX}	self-GMD
$d\phi$	flux in the tubular element of thickness dx
e	emf induced in the stator coil
E	field of electric intensity (V/m); rms value of the induced phase emf
$\boldsymbol{E}, \boldsymbol{E}_{\text{ar}}, \boldsymbol{E}_r$	phasor voltages proportional to the flux phasors ϕ_f, ϕ_{ar}, and ϕ_r respectively
$\boldsymbol{e}, \boldsymbol{j}$	specified voltage and current vectors respectively
E, V	internal emf and terminal voltage respectively of generator
$\boldsymbol{E}[z]$	expected value of z
e_1, e_2	emf induced in the primary and secondary windings respectively
E_1, E_2	rms emf induced in the primary and secondary windings respectively
e_i, f_i	real and imaginary parts of complex voltage of bus i
e_{km}	source voltage connected in series with the element
B'_{im}, B''_{im}	elements of [$-\boldsymbol{B}$] matrix
`elemz`	a row vector which stores the primitive impedance of the lines
E_m	peak value of induced emf
$\boldsymbol{E}_m$	vector of measured voltage differences linked with each power flow measurement
E'	voltage behind transient reactance of the machine
E''_G, E''_M	pre-fault internal voltages behind the sub-transient reactance of the machines
f	frequency (Hz)
$\hat{f}$	performance function
$\mathcal{F}$	magneto motive force (mmf) (AT)
f_0	constant frequency; nominal frequency (50 Hz)
FACTS	flexible ac transmission systems

f_r sub-synchronous frequency

FSD full scale deflection of the instruments such as watt and var meters

$\boldsymbol{G}$ symmetric gain matrix

G_C equivalent conductance to represent core loss in a transformer

G_{ii}, B_{ii} self-conductance and self-susceptance of bus *i*

G_{im}, B_{im} transfer conductance and transfer susceptance between bus *i* and bus *m*

GMD geometric mean distance

GMR geometric mean radius

$G_{SG}(s)$ transfer function of speed governing mechanism

$G_T(s)$ transfer function of a hydro-turbine

GTO gate turn-off thyristors

$\boldsymbol{H}$ coefficient matrix of dimension $m \times n$

H constant related to inertia (MJ/MVA or s); inertia constant (s); magnetic field intensity (AT/m)

HVDC high voltage direct current

H_x magnetic field intensity at a distance *x* metres from the centre of the conductor

$\boldsymbol{I}$ identity matrix

I current phasor

$I(x)$ current flowing through the elemental length Δx

$I(x, s)$ Laplace transforms of the current at position *x*

$i(x, t)$ instantaneous current as a function of *t* and *x*

I_0 no-load current in transformer

$\boldsymbol{I}_{012}$ column vector of symmetrical components of currents

I_1, I_2 rms current in the primary and secondary windings respectively

I_a current flowing from bus *i* to bus *j*

$\boldsymbol{I}_a$ rms phase current

$\boldsymbol{I}_{abc}$ column vector of three-phase currents

$\boldsymbol{I}_{abc,\,k\,(F)}$ column vector of three-phase post-fault currents at bus *k*

I_b current flowing from bus *p* to bus *q*

I_{base} base current

$\boldsymbol{I}_{\text{bus}}$ vector matrix of injected bus current for the network

$\boldsymbol{I}_C$ compensating current vector

I_{ch} charging current

i_f generator field current

IGCT integrated gate-commutated thyristors

I_k per unit current injections in bus *k*

i_{km} current through the element *k-m*

I_{km} short circuit current in the line flowing from bus *k* to bus *m*

IPFC interline power flow controller

I_{pu} current in per unit

I_q, I_d quadrature axis and direct axis components of the armature current I_a

$\boldsymbol{I}_{S,\,\text{bus}\,(F)}$ post-fault symmetrical component bus current vector

I_S, I_R currents at the sending end and receiving end respectively of a transmission line

$\boldsymbol{I}_{S,\,k(F)}$ column vector of symmetrical component post-fault currents at bus *k*

IT iteration count

J_m total moment of inertia of the rotor masses (kgm^2)

$\boldsymbol{J}$ Jacobian matrix of partial derivatives

$\boldsymbol{J}_1$ sub-matrix of the partial derivative of *P's* with respect to relevant δ's

$\boldsymbol{J}_2$ sub-matrix of the partial derivative of *P*'s with respect to relevant *V*'s

$\boldsymbol{J}_3$ sub-matrix of the partial derivative of *Q's* with respect to relevant δ's

J_4 sub-matrix of the partial derivative of Q's with respect to relevant V's

j_{km} source current connected in parallel with the element k-m,

k iteration count

K_A, T_A transfer function gain and time constant respectively of the amplifier

K_E, T_E gain constant and time constant respectively of the exciter

K_I integral gain constant

$K_{I,\text{crit}}$ critical gain setting

K_{I1}, K_{I2} integrator gains

K_{ij-k} current-injection distribution factor

K_{SG} static gain of speed governing mechanism

K_T gain constant of the turbine

kV_{base} base kV

$kV_{\text{base-LL}}$ line-to-line base kV

$kV_{\text{base-LN}}$ line-to-neutral base kV

K_w winding factor

K'_{rs-p}, modified generation shift

K'_{rs-q} distribution factors

1LO one-line conductor open

2LG double line-to-ground

2LO two-line conductors open

L inductance of a circuit (H)

l length (m); length of line; length of the conductor or the axial stator length

L_{12} inductance due to the external flux included between A_1 and A_2

L_{fa} mutual inductance between the rotor field and stator armature

LFC load frequency control

L_{ij-pq} line-outage distribution factor

L_{int} inductance of conductor due to internal flux linkages

LL line-to-line

`loc` a row vector which stores the start of each row of $\boldsymbol{Y}_{\text{bus}}$

`locs` gives the size of the `loc` vector

M angular momentum of the rotor $= J_m\omega_m$; inertia constant

m number of measurements

MTO MOS turn-off thyristors

MVA_{base} base MVA

$MVA_{\text{base-}1\phi}$ single-phase base MVA

$MVA_{\text{base-}3\phi}$ three-phase base MVA

m/n redundancy factor

$(n-m)$ redundancy or degrees of freedom

n number of state variables

N number of turns of a conductor

N_1, N_2 number of turns in the primary and secondary windings respectively

`nbus` number of buses in the system

N_S speed in rpm

P number of poles of the alternator; average real power over one cycle in a single-phase circuit

$p(t)$ instantaneous power in single-phase circuit

$p(z)$ Gaussian or normal probability density function

P, f, δ, $|V|$ actual values of the power, frequency, angle, and voltage magnitude respectively

P_{1-2} transfer of power over the tie-line connecting area 1 with area 2

$P_{3\phi}$ average three-phase power

$p_{3\phi}$ total instantaneous three-phase power

P_a accelerating power which accounts for any unbalance between P_m and P_e (W)

$P_{a,\text{pu}}$, $P_{i,\text{pu}}$, $P_{u,\text{pu}}$ per unit accelerating, mechanical, and electrical power, respectively

P_d coefficient of damping power

$P_{G(0)}$ constant generator power output

P_{Gi}, Q_{Gi} generated active and reactive power respectively at bus i