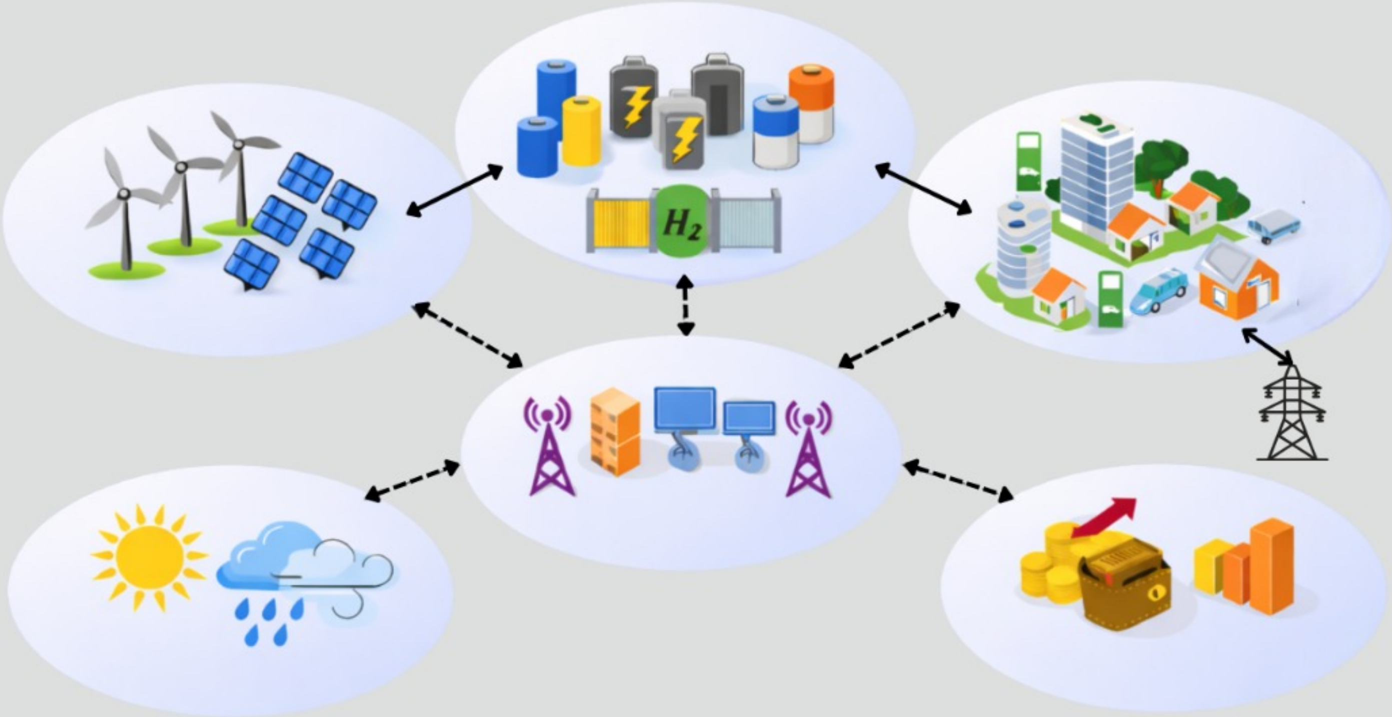

MICROGRIDS

Key Operational Strategies & Avenues for Grid Support Services

PRABODH BAJPAI

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Key Operational Strategies and Avenues for Grid Support Services

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Prabodh Bajpai

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Foreword by
Dr. Suresh Chandra Srivastava

Through rigorous survey of innovative strategies to enhance Microgrid systems for smart grid realization, author has attempted to provide an invaluable resource for researchers, industry leaders and policymakers committed to driving impactful change. Major contribution in this monograph includes detailed study of key operational strategies for all possible operational modes of Microgrids and various opportunities for providing grid support services using Microgrids. This monograph will inspire collaboration and catalyse meaningful advancements, both in research and practice, as we collectively work towards achieving global sustainability goals.

Microgrids as a major application domain will play a critical role in transforming energy systems as a novel distribution network architecture within the broader smart grid concept. I am confident that this monograph will serve as an exceptional resource for academicians, researchers, students and postdocs, and clean energy professionals working towards a sustainable energy transition and building a cleaner and greener world.

Dr. Suresh Chandra Srivastava
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Retired Professor, Department of Electrical Engineering,
Ex Director, IIT Kanpur-La Trobe University Research Academy,
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Kanpur, Uttar Pradesh, India

Foreword by
Dr. Narayana Prasad Padhy

This monograph on *Microgrids: Key Operational Strategies & Avenues for Grid Support Services* is created by the author through extensive review of the research work carried out by the research project team. The monograph is based on the recently published research work of project team members from leading academic institutions of India and Australia. This monograph is focused on the Microgrid control approaches for instantaneous power management and long-term energy management, along with challenges related to multi-microgrid coordination. Further, its emphasis is on various opportunities for providing grid support services using Microgrids, including demand response, peer-to-peer energy trading, and ancillary services such as frequency and voltage support, as well as resilient microgrid operation.

Microgrids are being expended and developed globally as fundamental and essential building block for future smart power systems with the increased penetration of distributed generation that has changed the control and operational concepts. Key issues of these new systems include integration technologies, control techniques and optimization methods in presence of Microgrids that can connect and disconnect from the main grid as physical and /or economic conditions dictate.

I strongly believe that this monograph will help as state-of-the-art resource for research community and industry practitioners to collaborate and work towards critical future prospects of Microgrid research challenges. This will help improve the grid support services for the Microgrid as well as explore new opportunities for such avenues.

Dr. Narayana Prasad Padhy
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Professor, Department of Electrical Engineering,
Indian Institute of Technology Roorkee, Uttarakhand, India.

Preface

The electric power grid transformation is necessary to make it smarter and more resilient using cutting-edge technologies. Smart grid technologies are being implemented in developed as well as developing countries and various smart grid components are being adopted in to their electrical power systems. The development of Microgrids as a novel distribution network architecture could facilitate the smart grid, which is conceived to improve the instantaneous power balance and demand response. Microgrids will help deploying large amounts of renewable energy sources to improve the reliability and resilience of the main utility grid, if their ostensible benefits offset the costs compared to alternative smart grid architypes. Microgrid consists of distributed generation units, loads, energy storage elements, protection equipment and control scheme to ensure the regulation of the power flow, and voltage and frequency profiles within a defined region as well as energy exchange with the main utility grid.

This monograph is based on extensive research work carried out by the Indo-Australian joint research project team. The domain of the monograph is designed to connect few important aspects of Microgrid operational challenges with grid support service opprotunities for Microgrids. Major content of this monograph is reworked from the published literature of project research team members. This monograph will inspire collaboration and catalyse meaningful advancements, both in research and practice, to achieve our sustainability goals.

The evolution of Microgrid concept is presented in chapter 1 along with its detailed classification, design aspects and associated technologies. Chapter 2 includes major control approaches for instantaneous power management and long-term energy management along with multi-microgrid coordination approach. Chapter 3 presents operational challenges and proposed methodologies for four possible operating states of a Microgrid, beginning with grid-connected operation, transitioning through islanding, stand-alone operation, and finally synchronization for reconnection to the main grid. Chapter 4, focuses on grid support services provided by microgrids, including dynamic operating envelope-based operation, demand response, peer-to-peer energy trading, and ancillary services such as frequency and voltage support, as well as resilient microgrid operation. Finally, Chapter 5, concludes the monograph with discission on some of the critical future prospects of Microgrid research.

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This work is supported by the Government of India under the Scheme for Promotion of Academics and Research Collaboration (SPARC) project grant No. SPARC/2019-2020/P1599/SL. This project is led by IIT Kanpur, India as the leading Institute with the University of Queensland (UQ), Australia as International collaborating institute and IIT Kharagpur, India as Indian collaborator. The project team has contributed extensively through their research work in the domain of this monograph. Some parts of this monograph is reworked from the recently published literature of project research team members with proper citations.

I am sincerely grateful to all the subject experts, who have contributed through their research publications in this monograph. Their details are given below and they have participated from their respective institutes as collaborator of the above mentioned SPARC project.

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I am also thankful to two major contributors as project facilitators in preparing this monograph. Their affiliation details are given below.

Name	**Affiliation**
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Mr. Amit Kumar	PhD Scholar, Sustainable Energy Engineering Department, IIT Kanpur, India

Most of the references are the publications of the above listed project research team members for the relevent topic in this monograph. Content is used in this monograph with proper citations of all appropriate references in relevant sections.

I acknowledge the consistent support and motivation from my beloved family members and aspiring friends for publishing this monograph.

I am grateful to all the anonymous referees for carefully reviewing this monograph. I am also thankful to IIP team for their guidance throughout the publishing process and timely completion of this monograph publication.

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List of Abbreviations

ABT-Availability based tariff
AC-Alternating current
ADMM-Alternative direction method of multipliers
ADN-Active distribution networks
ADP-Adaptive dynamic programming
AMR-Automated meter reading
APC- Abnormal performance category
AS-Ancillary services
BAU-Business as usual
BESS-Battery energy storage systems
BFM- Branch flow model
BIM- Bus injection model
CB-Circuit breaker
CC-Centralized controller
CCG-Canonical coalition game
CERC-Central electricity regulatory commission
CHP-Combined heat and power
CL-Critical load
CSC-Currentsource converter
DC-Direct current
DER-Distributed energy resource
DFT-Discrete fourier transform
DG-distributed generation
DLC-Direct load current
DN-Distribution network
DNO- Distribution network operator
DNSP-Distribution network service provider
DOE-Dynamic operating envelop

DOL-Dynamic operating limit

DPC-Diamond pairwise comparison

DP-Dynamic programming

DR-Demand response

DRA-Demand response aggregator

DSM-Demand side management

DSO-Distribution system operator

DVS- Dynamic voltage support

EIS-Energy information systems

EMCS-Energy management control systems

EMS-Energy management system

ESS-Energy storage system

EV-Electric vehicle

FC-Fuel cell

FFRT-Frequency fault ride-through

GA-Genetic algorithm

GHG-Green house gas

GPS-Global positioning system

HEMS-Home energy management system

HFT-High-frequency three-winding transformer

HIL-Hardware in loop

HILP-High-impact, low-probability

HVFRT-High voltage fault ride-through

IBDR- Incentive-based demand response

IDEMS-Intelligent dynamic energy management system

IGBT-Insulated gate bipoar transistor

LDR-Load demand response

LC-Local controller

LEM-Local electricity markets

LSI-Line strength index

LVFRT-Low voltage fault ride-through

LV-Low voltage

MG-Microgrid

MGCC-Microgrid central controller

MGO-Microgrid operator

MILP-Mixed- interger linear programming

MIQP-Mixed-integer quadratic program

MM- Mobile microgrid

MPC-Model predictive control

MPPT- Maximum power point tracking

MV-Medium voltage

NN-Neural network

OE-Operating envelope

OPDN-overhead power distribution networks

OPF-Optimal power flow

P2P-Peer to Peer

PBDR-Price-based demand response

PCC-Point of common coupling

PCWL- Path combination without loop

PEMFC-Proton exchange membrane fuel cell

PF-Power flow

PFS-Primary frequency support

PLL- Phase-locked loop

PMO-P2P market operator

PMS-Power management strategy

PN-Possible networks

POC-Point of connection

PoI- Point of interconnection

PSI-Pole strength index

PV-Photovoltaic

PWM-Pulse width modulation

RBMPC-Rate based model predictive control

RCS-Reference current signal
RES-Renewable energy source
RTP-Real time pricing
SC- Supercapacitor
SDFT-Sliding discrete fourier transform
SDP-Semi-definite programming
SDS-Static disconnect switch
SIL-Software in loop
SOC-State of charge
SPWM- Sinusoidal pulse width modulation
SS-Static switch
TN-Transmission network
TOU-Time of use
TSO-Transmission system operators
VFRT-Voltage fault ride-through
VR-Voltage regulation
VSC-Voltage source converter
VSI- Voltage source inverter

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He has served as a researcher, educator and administrator during his professional carrier in highly reputed academic Institutions of India. He has delivered research outcome through several sponsored research and consultancy projects with substantial funding support from Government organizations as well as research and industrial organizations. He has made significant publications in various reputed international journals and conferences, book chapters and white paper. He has also published several patents.

He has received Faculty Excellence Award Fellowship for outstanding contribution towards teaching, research and institutional development by IIT Kharagpur. He has received Bhaskara Advanced Solar Energy Fellowship Award from Department of Science and Technology (DST), Government of India. Additionally, he has awarded with Sr. Research Fellowship from PMI, NTPC Ltd., India.

His research interests include renewable energy systems, power system restructuring, smart grid, microgrids, electricity markets and solar PV applications.

His full and updated details are available on his homepage: **https://home.iitk.ac.in/~pbajpai/**

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