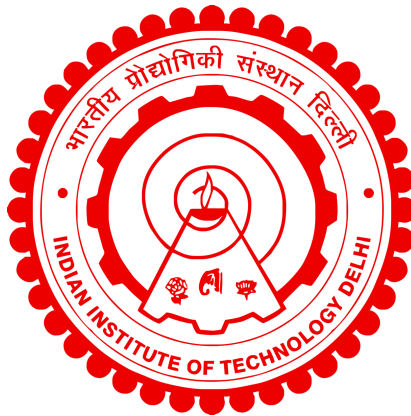


**MONITORING, OPERATION AND CONTROL
STRATEGIES FOR SMART ELECTRICAL SYSTEMS**

HIMANSHU GROVER



**DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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**Monitoring, Operation and Control Strategies for Smart
Electrical Systems**

by

HIMANSHU GROVER

DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING

Submitted

in partial fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to

My Parents & Brother

Certificate

This is to certify that the thesis entitled “**Monitoring, Operation and Control Strategies for Smart Electrical Systems**”, submitted by **Himanshu Grover** to the Indian Institute of Technology Delhi, is worthy of consideration for the award of the degree of **Doctor of Philosophy** and is a record of bona fide research work carried out by him. He has worked under our supervision and guidance, and has fulfilled the requirements for the submission of this thesis.

To the best of our knowledge, the results contained in this thesis have not been submitted elsewhere in part or full for the award of any degree or diploma.



Prof. Ashu Verma

Dept. of Energy Science and Engineering,
Indian Institute of Technology Delhi
Hauz Khas, New Delhi, 110016
India



Prof. T.S. Bhatti

Dept. of Energy Science and Engineering,
Indian Institute of Technology Delhi
Hauz Khas, New Delhi, 110016
India

Date:

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Himanshu Grover

Abstract

Motivated by the growing concerns over climate change and carbon emissions caused by excessive utilization of fossil fuels, the global energy sector is transitioning towards the adoption of clean energy sources such as solar photovoltaics (PV), wind, small hydro etc. The concept of microgrids (MG) has become an emerging trend as it facilitates large-scale penetration of renewable energy sources (RES) based distributed energy resources (DERs) and increased incorporation of information & communication technology (ICT). Since RES based generation systems inherently produce intermittent output characteristics, therefore, their integration in electrical systems results in greater challenges for the system operator, in terms of system stability and operation. Apart from having intermittent characteristics, renewable energy sources (RES) generation systems are interfaced through power electronics converters which have zero or low inertia. Such proliferation of power electronics devices reduces the overall system inertia in the network, which makes the system frequency and voltage more susceptible to instability issues. Accordingly, this thesis focuses on integration of smart infrastructure for real-time monitoring and information processing, and further develops fast and robust control strategies for reliable operation of microgrid while countering the effect of real-time uncertainties.

Smart buildings and homes are building blocks of the smart grid that enable interaction between utility and consumers in multiple ways such as real-time energy monitoring, demand response, demand-side management etc. A smart building unit includes the integration of numerous engineering technologies such as electrical power network with robust control and reliable two-way communication infrastructure with intelligent software and hardware systems. In view of this, firstly, this thesis develops a smart energy metering solution and an appliance control device for advanced monitoring and control infrastructure in smart grid environment. It upgrades the non-automated smart energy metering and appliance control to an IoT-enabled intelligent energy management system. It also reduces the peak load and overall energy consumption of a building by switching off non-essential appliances.

The real-time electrical parameters information acquired from smart energy metering solution is further utilised for development of an online algorithm for non-intrusive load monitoring (NILM) which helps system operator for the purpose of network support and demand response applications in an increasingly uncertain distribution network. Accordingly, this thesis further focuses on development of a multi-layered convolutional neural network (CNN) based NILM for load monitoring in smart buildings, through precise identification of appliances and their operational schedules during real-time operation.

Owing to the increased penetration of distributed RES, the system frequency and voltage stability are increasingly susceptible to disturbances under uncertain environments. In this regard, a fast and robust auxiliary control for voltage and frequency regulation has been integrated to the existing conventional controllers, which improves the system performance without additional computational burden. A single-input and single-output linear disturbance observer-based control has been proposed to regulate system frequency and voltage within prescribed under uncertain environment. Furthermore, the performance of the proposed control have been evaluated under noisy load and communication delays.

This thesis further focuses on utilization the information of appliance switching through appliance control board in an energy internet environment. In this regard, a multi-timescale coordinated control scheme has been proposed to optimally control inverter-based resources in different timescales. Accordingly, a two-stage stochastic optimization framework has been developed for optimal operation of battery energy storage system (BESS) and voltage source converters (VSC) in hour-ahead and intra-hourly timescales, to counteract the effects of

uncertainties in solar photovoltaic (PV) and load. Additionally, a novel real-time coordination framework has been developed for fast frequency control, triggered by appliance switching/scheduling information through energy internet. Thus, real-time control is implemented as a pre-disturbance preventive action, appropriately acting with the load switching event. Furthermore, the proposed real-time frequency control is developed as a coordination strategy for primary regulation by adaptive VSC control and recovery control by the grid.

Virtual synchronous generator (VSG) is an emerging approach for grid-forming inverters that imparts stability to low-inertia microgrids. In view of this, an adaptive VSG concept has been proposed to enhance system stability in islanded microgrids. Accordingly, a two-layered coordinated control strategy for optimal operation of renewable energy sources (RES) integrated microgrids has been developed. At the first layer, a voltage control scheme has been developed for radial distribution networks through reactive power support using inverter-based resources. The second layer develops an adaptive approach for VSG parameter tuning for frequency regulation in islanded networks, considering load and generation uncertainty. Accordingly, a bi-level optimization model has been developed, wherein the first level evaluates robust VSG parameters, and the second level develops a stochastic programming model for adaptive tuning of VSG parameters to counteract the effects of network uncertainties during islanding.

Performance of the control and optimization strategies developed in this thesis have been verified through extensive simulations on standard data sets and test systems. Furthermore, effectiveness of the proposed control approaches have been validated on hardware-in-loop simulation on OPAL-RT and laboratory-scale hardware experimental setup.

सार

जीवाश्म ईंधन के अत्यधिक उपयोग के कारण कार्बन उत्सर्जन एवं जलवायु परिवर्तन पर बढ़ती चिंताओं से प्रेरित होकर, वैश्विक ऊर्जा क्षेत्र में स्वच्छ ऊर्जा स्रोतों जैसे कि सौर फोटोवोल्टिक (पीवी), पवन, लघु जलविद्युत आदि को अपनाने की दिशा में परिवर्तन हो रहे हैं। माइक्रोग्रिड्स (एमजी) की अवधारणा एक उभरती हुई प्रवृत्ति बन गई है क्योंकि यह नवीकरणीय ऊर्जा स्रोतों (आरईएस) पर आधारित वितरित ऊर्जा संसाधनों (डीईआर) के बड़े पैमाने पर प्रवेश की सुविधा प्रदान करती है और सूचना और संचार प्रौद्योगिकी (आईसीटी) को शामिल करती है। चूंकि आरईएस आधारित प्रणालियों का उत्पादन आंतरायिक होता है, इसलिए, विद्युत प्रणालियों में उनका एकीकरण सिस्टम ऑपरेटर के लिए सिस्टम स्थिरता और संचालन के संदर्भ में अधिक चुनौतियों का कारण बनता है। आंतरायिक अभिलक्षणों के अतिरिक्त, नवीकरणीय ऊर्जा स्रोत (आरईएस) उत्पादन प्रणालियां पावर इलेक्ट्रॉनिक्स कन्वर्टर के माध्यम से इंटरफेस की जाती हैं जिनमें शून्य या निम्न जड़ता होती है। विद्युत संबंधित इलेक्ट्रॉनिक्स उपकरणों के इस तरह के प्रसार से नेटवर्क में समग्र निकाय की जड़ता कम हो जाती है, जिससे सिस्टम आवृत्ति और वोल्टेज अस्थिरता के मुद्दों के प्रति अधिक संवेदनशील हो जाती है। तदनुसार, यह शोध ग्रन्थ रियल टाइम निगरानी और सूचना प्रसंस्करण के लिए स्मार्ट बुनियादी ढांचे के एकीकरण पर केंद्रित है, और तत्कालीन अनिश्चितताओं के प्रभाव को घटाते हुए माइक्रोग्रिड के विश्वसनीय संचालन के लिए तेजी से और मजबूत नियंत्रण रणनीतियों को विकसित करता है।

स्मार्ट बिलिंग और घर स्मार्ट ग्रिड के महत्वपूर्ण अंग हैं जो विद्युत आपूर्ति इकाइयों और उपभोक्ताओं के बीच समयोचित ऊर्जा निगरानी, मांग प्रतिक्रिया, मांग-पक्ष प्रबंधन आदि जैसे कई तरीकों से आपसी व्यवहार को सक्षम करते हैं। एक स्मार्ट बिलिंग इकाई में कई इंजीनियरिंग तकनीकों का एकीकरण शामिल है जैसे की मजबूत नियंत्रण के साथ विद्युत शक्ति नेटवर्क और बुद्धिमान सॉफ्टवेयर और हार्डवेयर सिस्टम के साथ विश्वसनीय दो-तरफा संचार अवसंरचना स्थापित करना। इसे ध्यान में रखते हुए, सर्वप्रथम, यह शोध ग्रन्थ स्मार्ट ग्रिड पर्यावरण में उन्नत निगरानी और नियंत्रण बुनियादी ढांचे के लिए एक स्मार्ट ऊर्जा मीटरिंग समाधान और एक उपकरण नियंत्रण युक्ति विकसित करती है। यह गैर-स्वचालित स्मार्ट ऊर्जा मीटरिंग और उपकरण नियंत्रण को आईओटी-सक्षम बुद्धिमान ऊर्जा प्रबंधन प्रणाली में अपग्रेड करता है। यह हस्तक्षेप बिना किये हुए अनुपयोगी उपकरणों को बंद करके बिलिंग के पीक लोड और समग्र ऊर्जा खपत को भी कम करता है।

स्मार्ट ऊर्जा मीटरिंग समाधान से प्राप्त विद्युत पैरामीटर सम्बंधित रियल-टाइम जानकारी का उपयोग एक ऐसे विद्युत आपूर्ति नेटवर्क जिसमें अनिश्चितता बढ़ते जा रही है उसमें लोड निगरानी (एनआईएलएम) के लिए एक ऑनलाइन एल्गोरिदम के विकास के लिए किया जाता है जो सिस्टम ऑपरेटर को नेटवर्क

समर्थन और मांग प्रतिक्रिया अनुप्रयोगों में मदद करता है। नेटवर्क। तदनुसार, यह शोध ग्रन्थ रियल-टाइम संचालन के दौरान उपकरणों की सटीक पहचान और उनके परिचालन कार्यक्रम के माध्यम से, स्मार्ट इमारतों में लोड की निगरानी के लिए एक बहु-स्तरीय दृढ़ तंत्रिका नेटवर्क (सीएनएन) आधारित एनआईएलएम के विकास पर केंद्रित है।

आरईएस आधारित वितरित ऊर्जा संसाधनों की बढ़ती पैठ के कारण, सिस्टम आवृत्ति और वोल्टेज की स्थिरता अनिश्चित वातावरण के कारण अतिसंवेदनशील होती है। इस संबंध में, वोल्टेज और आवृत्ति विनियमन के लिए एक तेज़ और मजबूत अतिरिक्त नियंत्रण के प्रावधान को मौजूदा पारंपरिक नियंत्रकों में एकीकृत किया गया है, जो अतिरिक्त कम्प्यूटेशनल आवश्यकता के बिना सिस्टम के कार्य में सुधार करता है। अनिश्चित वातावरण के तहत निर्धारित प्रणाली आवृत्ति और वोल्टेज को विनियमित करने के लिए एक एकल-इनपुट और एकल-आउटपुट रैखिक बाँधा पर्यवेक्षक-आधारित नियंत्रण प्रस्तावित किया गया है। इसके अतिरिक्त, शोर भार और संचार विलंब के तहत प्रस्तावित नियंत्रण प्राविधान के कार्य का मूल्यांकन किया गया है।

इस शोध ग्रन्थ में एक ऊर्जा इंटरनेट वातावरण में एक उपकरण नियंत्रण बोर्ड के माध्यम से उपकरण स्विचिंग की जानकारी के उपयोग करने की दिशा में कार्य किया गया है। इस संबंध में, अलग-अलग समय-सीमाओं में इन्वर्टर-आधारित संसाधनों को बेहतर ढंग से नियंत्रित करने के लिए एक बहु-स्तरीय समन्वित नियंत्रण योजना प्रस्तावित की गई है। तदनुसार, बैटरी एनर्जी स्टोरेज सिस्टम (बीइएसएस) और वोल्टेज स्रोत कन्वर्टर्स (वीएससी) के इष्टतम संचालन के लिए एक दो-चरण स्टोकेस्टिक ऑप्टिमाइजेशन फ्रेमवर्क विकसित किया गया है, जो एक घंटा पूर्व एवं एक घंटे के समय अंतराल के बीच पीवी में उत्पादन एवं लोड में अनिश्चितता के प्रभावों का प्रतिकार करने के लिए है। इसमें अतिरिक्त प्रस्तावित नियंत्रण प्राविधान के कार्य का मूल्यांकन संचार में विलंब एवं नोइज़ी लोड की उपस्थिति में किया गया है। इसके अतिरिक्त, ऊर्जा इंटरनेट के माध्यम से उपकरण स्विचिंग/शेड्यूलिंग जानकारी द्वारा ट्रिगर किए गए तेज आवृत्ति नियंत्रण के लिए एक नया रीयल-टाइम समन्वय ढांचा विकसित किया गया है। इस प्रकार, रीयल-टाइम नियंत्रण को पूर्व-विसोय निवारक कार्रवाई के रूप में कार्यान्वित किया जाता है, जो लोड स्विचिंग होने पर उचित रूप से कार्य करता है। इसके साथ-साथ, प्रस्तावित रियल टाइम समय आवृत्ति नियंत्रण को अनुकूली वीएससी नियंत्रण और ग्रिड द्वारा पुनर्प्राप्ति नियंत्रण द्वारा प्राथमिक विनियमन के लिए एक समन्वय युक्ति के रूप में विकसित किया गया है।

ग्रिड फॉर्मिंग इनवर्टर में बनाने के लिए वर्चुअल सिंक्रोनस जेनरेटर (वीएसजी) का उपयोग प्रचलित होने लगा है, वर्चुअल सिंक्रोनस जेनरेटर (वीएसजी) ग्रिड बनाने वाले इनवर्टर के लिए एक उभरता हुआ दृष्टिकोण है जो निम्न-जड़ता वाले माइक्रोग्रिड को स्थिरता प्रदान करता है। इसे देखते हुए, ग्रिड की

अनुपस्थिति में माइक्रोग्रिड्स की स्थिरता को बढ़ाने के लिए एक अनुकूली वीएसजी अवधारणा प्रस्तावित की गई है। तदनुसार, नवीकरणीय ऊर्जा स्रोतों (आरईएस) पर आधारित एकीकृत माइक्रोग्रिड्स के इष्टतम संचालन के लिए एक दो-स्तरीय समन्वित नियंत्रण युक्ति विकसित की गई है। पहली सतह पर, इन्वर्टर-आधारित संसाधनों का उपयोग करके प्रतिघाती शक्ति समर्थन के माध्यम से रेडियल वितरण नेटवर्क के लिए एक वोल्टेज नियंत्रण योजना विकसित की गई है। दूसरी सतह लोड और उत्पादन अनिश्चितता पर विचार करते हुए ग्रिड रहित प्रतिलिपित नेटवर्क में आवृत्ति विनियमन के लिए वीएसजी पैरामीटर ट्यूनिंग के लिए एक अनुकूली दृष्टिकोण विकसित करती है। तदनुसार, एक द्वि-स्तरीय अनुकूलन मॉडल विकसित किया गया है, जिसमें पहला स्तर मजबूत वीएसजी मापदंडों का मूल्यांकन करता है, और दूसरा स्तर द्वीपीकरण के दौरान नेटवर्क अनिश्चितताओं के प्रभावों का मुकाबला करने के लिए वीएसजी मापदंडों के अनुकूली ट्यूनिंग के लिए एक स्टोकेस्टिक प्रोग्रामिंग मॉडल विकसित करता है।

इस शोध ग्रन्थ में विकसित नियंत्रण और अनुकूलन युक्तियों का परिक्षण करने के लिए उन्हें मानक डेटा सेट और टेस्ट सिस्टम पर व्यापक सिमुलेशन के माध्यम से सत्यापित किया गया है। इसके अतिरिक्त, ओपल-आरटी और प्रयोगशाला-स्तरीय हार्डवेयर प्रयोगात्मक सेटअप पर हार्डवेयर-इन-लूप सिमुलेशन पर प्रस्तावित नियंत्रण युक्तियों की प्रभावशीलता को मान्यकरण किया गया है।

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Abbreviations

AC	Air conditioner
AHU	Air handling unit
AVR	Automatic voltage regulator
BDC	Bi-directional converter
BESS	Battery energy storage system
BFOA	Bacteria foraging optimization algorithm
CF	Ceiling fan
CHIM	Convex hull of individual minima
CNN	Convolution neural network
DAE	De-noising auto encoder
DER	Distributed energy resources
DG	Diesel generator
DLMS	Device Language Message Specification
DOBC	Disturbance observer-based control
DR	Demand response
DSM	Demand side management
EK	Electric kettle
EV	Electric vehicle
FC	Fuel cell
GUI	Graphical user interface
HVAC	Heating ventilation and air conditioning
IAE	Integral of absolute value of error
IB	Incandescent bulb
ILM	Intrusive load monitoring
IMC	Internal mode control
INC	Incremental conductance

Abbreviations

IoT	Internet of things
IPSO	Improved particle swarm optimization
ISE	Integral of the square of the error
ITAE	Integral of the time-multiplied absolute value of error
ITSE	Integral time-multiplied of the square of the error
MO	maximum overshoot
LT	LED tube
LFC	Load frequency control
LHC	Lecture hall complex
LPF	Low-pass filter
LV	Low voltage
MAE	Mean of absolute error
MCS	Monte Carlo simulation
MG	Microgrid
MGCC	Microgrid central controller
ML	Machine learning
MPC	Model predictive control
MPP	Maximum power point
MPPT	Maximum power point tracking
MT	Micro-turbine
MW	Microwave
NBI	Normal boundary intersection
NILM	Non-intrusive load monitoring
NLTA	Non-linear threshold accepting algorithm
NN	Neural network
OH	Oil heater
PCC	Point of common coupling
PDF	Probability distribution function
PID	Proportional-integral-derivative
PLL	Phase-lock loop
PV	Photovoltaic
RES	Renewable energy sources
RF	Refrigerator
RNN	Recurrent neural network
RoCoF	Rate of change of frequency

Abbreviations

RTDS	Real time digital simulator
SAE	Signal aggregate error
SG	Synchronous generator
SM	Sliding Mode
SOGI	Second order generalized integrator
STC	Standard testing conditions
ToU	Time-of-use
UK-DALE	UK Domestic Appliance-Level Electricity
ULFS	Under-frequency load shedding
VSG	Virtual synchronous generator
VSC	Voltage source converter
WTG	Wind turbine generators