DATA RECONCILIATION AND DYNAMIC OPTIMIZATION FOR THE SUSTAINABLE OPERATION OF HYBRID RENEWABLE ENERGY SYSTEMS

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Dedication

To my beloved grandfather *Late Kishori Shyam Sharma* and my parents, who ignited the flame of exploration in my heart and taught me to see the world as an endless source of wonder and discovery. Your encouragement, wisdom, and unshakable faith in my potential have guided me on this remarkable journey.

As I embark on the pursuit of greater understanding and contribute to the world of research, I carry your legacy with me. This thesis is a testament to the values and aspirations you instilled in me a reminder that with passion, perseverance, and a thirst for knowledge, we can achieve great things.

Thesis certificate

This is to certify that the thesis titled **Data Reconciliation and Dynamic Optimization for the Sustainable Operation of Hybrid Renewable Energy Systems**, submitted by **Reena Sharma (2018CHZ8091)**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Abstract

Environmental degradation due to the increased use of fossil fuels has paved the growth in harnessing eco-friendly renewable energy resources. However, renewable energy sources are connected with the issues such as non-uniform power generation due to weather and seasonal variations. In this context, several renewable energy sources are integrated into a hybrid renewable energy system (HRES) framework to circumvent this limitation. Such integration enables higher efficiencies than those obtained from a single renewable resource considering their individual operating characteristics. Due to this advantage, HRES framework is becoming increasingly popular to meet the future demand. Hence, there is a potential to deploy HRES as it captures the best features of each renewable energy resource and can provide maximum non-interrupting "carbon-free" power. A typical HRES comprises renewable energy sources like wind, solar, fuel cell, electrolyzer, battery storage, and diesel generator as a backup power source. When HRES is dynamic mode, effective demand-side energy management and real-time power trading need correct estimate of real-time variables for each sub-component, which are usually corrupted by measurement errors.

First part of the thesis focuses on devising novel frameworks for reconciliation strategies that can be used to resolve sensor measurement inconsistencies. To make the study exhaustive, we considered various operational scenarios, such as single-rate sampling, multi-rate sampling, and sensor failure. Simulation based validation studies are performed to validate frameworks. Simulation results show that RPF provides the highest estimation accuracy for all three operational scenarios as compared to EKF and EnKF with only a small increase in computational time. Second part of the thesis deals with aims to develop a novel dynamic multi- objective receding horizon strategy for operational optimization of medium-scale HRES. As an extension to classical receding horizon strategy in which only one objective is used, in this part of the thesis three non-commensurate objectives are optimized simultaneously by using genetic algorithm to obtain the optimal control variable trajectories. The third part of the thesis results in development of tools for quantifying ecosystem services so as to include them as a potential unit operation in decision making, aiding sustainability. To this extent we employ i-Tree Eco model, developed by the United States by the U.S. Department of Agriculture (USDA) Forest Services, by suitably adapting to the conditions of Indian subcontinent by using remote sensing techniques. Fourth part of the thesis uses this quantified ecosystem services obtained in the third objective and bring in the notion of techno-ecological synergy (TES) in decision making. Further, we optimize the HRES operation to make positive environmental impact by including the TES based sustainable design of HRES and their surrounding ecosystems to mitigate emissions. This part of the thesis considered the forest ecosystem developed by different afforestation approaches as an additional unit operation and its growth dynamics have been incorporated in the system design.

KEYWORDS: Data reconciliation, Ensemble kalman filter, Particle filter, Regularised particle filter, Multi-objective optimization, Genetic algorithm, i-Tree Eco, Remote sensing, Landsat satellite image, Sustainability, Techno-ecological synergy, Miyawaki method

सारांश

जीवाश्म ईंधन के बढ़ते उपयोग के कारण पर्यावरणीय गिरावट ने पर्यावरण-अनुकूल नवीकरणीय ऊर्जा संसाधनों के दोहन में वृद्धि का मार्ग प्रशस्त किया है। हालाँकि, नवीकरणीय ऊर्जा स्रोत मौसम और मौसमी बदलावों के कारण गैर-समान बिजली उत्पादन जैसे मुद्दों से जुड़े हुए हैं। इस संदर्भ में, इस सीमा को दूर करने के लिए कई नवीकरणीय ऊर्जा स्रोतों को एक हाइब्रिड नवीकरणीय ऊर्जा प्रणाली (एचआरईएस) ढांचे में एकीकृत किया गया है। इस तरह का एकीकरण उनकी व्यक्तिगत परिचालन विशेषताओं को ध्यान में रखते हुए एकल नवीकरणीय संसाधन से प्राप्त दक्षताओं की तुलना में अधिक दक्षता प्रदान करता है। इस लाभ के कारण, भविष्य की मांग को पूरा करने के लिए एचआरईएस ढांचा तेजी से लोकप्रिय हो रहा है। इसलिए, एचआरईएस को तैनात करने की संभावना है क्योंकि यह प्रत्येक नवीकरणीय ऊर्जा संसाधन की सर्वोत्तम विशेषताओं को पकड़ता है और अधिकतम गैर-बाधित "कार्बन-मुक्त" बिजली प्रदान कर सकता है। एक विशिष्ट एचआरईएस में बैकअप पावर स्रोत के रूप में पवन, सौर, ईंधन सेल, इलेक्ट्रोलाइज़र, बैटरी भंडारण और डीजल जनरेटर जैसे नवीकरणीय ऊर्जा स्रोत शामिल होते हैं। जब एचआरईएस गतिशील मोड होता है, तो प्रभावी मांग-पक्ष ऊर्जा प्रबंधन और वास्तविक समय बिजली व्यापार के लिए प्रत्येक उप-घटक के लिए वास्तविक समय चर के सही अनुमान की आवश्यकता होती है, जो आमतौर पर माप त्रुटियों से दूषित होते हैं।

थीसिस का पहला भाग सामंजस्य रणनीतियों के लिए नवीन रूपरेखा तैयार करने पर केंद्रित है जिसका उपयोग सेंसर माप विसंगतियों को हल करने के लिए किया जा सकता है। अध्ययन को संपूर्ण बनाने के लिए, हमने विभिन्न परिचालन परिदृश्यों पर विचार किया, जैसे एकल-दर नमूनाकरण, बहु-दर नमूनाकरण और सेंसर विफलता। फ्रेमवर्क को मान्य करने के लिए सिमुलेशन आधारित सत्यापन अध्ययन किए जाते हैं। सिमुलेशन परिणाम दिखाते हैं कि आरपीएफ, कम्प्यूटेशनल समय में केवल थोड़ी सी वृद्धि के साथ ईकेएफ और एनकेएफ की तुलना में सभी तीन परिचालन परिदृश्यों के लिए उच्चतम अनुमान सटीकता प्रदान करता है। थीसिस का दूसरा भाग मध्यम स्तर के एचआरईएस के परिचालन अनुकूलन के लिए एक उपन्यास गतिशील बहुउद्देश्यीय घटती क्षितिज रणनीति विकसित करने के उद्देश्य से संबंधित है। शास्त्रीय घटती क्षितिज रणनीति के विस्तार के रूप में जिसमें केवल एक उद्देश्य का उपयोग किया जाता है, थीसिस के इस भाग में इष्टतम नियंत्रण चर प्रक्षेपवक्र प्राप्त करने के लिए आनुवंशिक एल्गोरिदम का उपयोग करके तीन गैर-अनुरूप उद्देश्यों को एक साथ अनुकूलित किया जाता है। थीसिस के तीसरे भाग में पारिस्थितिकी तंत्र सेवाओं की मात्रा निर्धारित करने के लिए उपकरणों के विकास का परिणाम है ताकि उन्हें निर्णय लेने में संभावित इकाई संचालन के रूप में शामिल किया जा सके, जिससे स्थिरता में सहायता मिल सके। इस हद तक हम रिमोट सेंसिंग तकनीकों का उपयोग करके भारतीय उपमहाद्वीप की परिस्थितियों को उपयुक्त रूप से अनुकूलित करके, अमेरिकी कृषि विभाग

(यूएसडीए) वन सेवाओं द्वारा संयुक्त राज्य अमेरिका द्वारा विकसित आई-ट्री इको मॉडल को नियोजित करते हैं। थीसिस का चौथा भाग तीसरे उद्देश्य में प्राप्त इस मात्रात्मक पारिस्थितिकी तंत्र सेवाओं का उपयोग करता है और निर्णय लेने में तकनीकी-पारिस्थितिकीय तालमेल (टीईएस) की धारणा लाता है। इसके अलावा, हम उत्सर्जन को कम करने के लिए एचआरईएस और उनके आसपास के पारिस्थितिकी तंत्र के टीईएस आधारित टिकाऊ डिजाइन को शामिल करके सकारात्मक पर्यावरणीय प्रभाव बनाने के लिए एचआरईएस ऑपरेशन को अनुकूलित करते हैं। थीसिस के इस भाग में विभिन्न वनीकरण दृष्टिकोणों द्वारा विकसित वन पारिस्थितिकी तंत्र को एक अतिरिक्त इकाई संचालन के रूप में माना गया है और इसकी विकास गतिशीलता को सिस्टम डिजाइन में शामिल किया गया है।

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[1]This work is published in ISA Transactions.
"Sharma, R., Agrawal, D., Kodamana, H. (2022). Data reconciliation frameworks for dynamic operation of hybrid renewable energy systems. ISA transactions, 128, 424-436".

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[2]The part of this work is published in Chemical engineering and processing - process intensification and Chemical Engineering Research and Design.
"Sharma, R., Kodamana, H., Ramteke, M. (2022). Multi-objective dynamic optimization of hybrid renewable energy systems. Chemical Engineering and Processing-Process Intensification, 170, 108663".
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[3]The work reported in this Chapter is under revision.

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[4] Part of the work reported in this Chapter is presented in PSE Asia conference 2022 in IIT Madras and is under revision.

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Abbreviations

ALS	Airborne laser scanning
AKF	Adaptive Kalman filter
AEs	Algebraic equations
BVOCs	Biogenic volatile organic compounds
CHM	Canopy height model
DBH	Diameter at breast height
DSM	Digital surface model
DTM	Digital terrain model
DAEs	Differential algebraic equations
EKF	Extended Kalman filter
EnKF	Ensemble Kalman filter
ETM+	Enhanced thematic mapper plus
EWMA	Estimate weighted moving average
EVI	Enhanced vegetation index
ESRI	Environmental systems research institute
GCI	Green chlorophyll index
GLCM	Gray level co-occurrence matrix
HSR	High spatial resolution
HRES	Hybrid renewable energy system
HES	Hybrid energy System
IV	Importance values
ISRO	Indian space research organisation
IRS 1C	Indian remote sensing satellites-1C
IRS 1D	Indian remote sensing satellites-1D
KF	Kalman filter
LiDAR	Light detection and ranging
LAI	Leaf area index
LMTD	Log mean temperature difference
MPPT	Maximum power point tracking
MAP	Maximum a posterior
MO DIS	Moderate-resolution imaging spectroradiometer
NDVI	Normalized difference vegetation index
NEON	National ecological observatory network

NOAA	National oceanic and atmospheric administration
NASA	National aeronautics and space administration
OLI	Operational land imager
PV	Photovoltaic
PEMFC	Proton exchange membrane fuel cell
QGIS	Quantum geographic information system
RES	Renewable energy sources
RPF	Regularized particle filter
STC	Standard test condition
SCR	Selective catalytic reduction
SA	Stand alone
SAVI	Soil adjusted vegetation index
SCP	Semi-automatic classification plugin
SAGA	System for automated geo scientific analyses
TDs	time delays
TES	Techno-ecological synergy
USDA	United States Department of Agriculture
US	United States
USGS	United States geological survey

Notation

I_{pc}	Photo current
$I_{pc,Ref}$	Photo current at STC
I_r	Reverse saturation current
r_s	Series resistance
r_p	Parallel resistance
n	ideality factor
$V_{mp,Ref}$	Voltage at maximum power at STC
$I_{mp,Ref}$	Current at maximum power at STC
$I_{sc,Ref}$	Current at short circuit at STC
$V_{oc,Ref}$	Voltage at open circuit at maximum power at STC
n_{Ref}	ideality factor at STC
E	Irradiance
E_{Ref}	Irradiance at STC
T_{cell}	Cell temperature
$T_{cell,Ref}$	Cell temperature at STC
V_{rev}	Reversible cell voltage
z	Number of electron transferred
F	Faraday's constant
ΔG	Gibbs free energy change
V_{el}	Voltage applied to the electrolyzer
$\dot{\eta}_{H_2}$	Hydrogen production rate
T_{el}	Electrolyte temperature
A_{el}	Area of electrode
η_f	Faraday's efficiency
η_c	Number of cells in series per stack
$\dot{q}_{gen}$	Internal heat generation
$\dot{q}_{loss}$	Heat loss to surrounding
$\dot{q}_{cool}$	Auxiliary cooling demand
η_e	Energy efficiency
R_t	Overall thermal resistance
C_t	Overall thermal capacity
T_a	Ambient temperature
C_w	Thermal capacity of cooling water
$T_{w,i}$	Inlet temperature of cooling water
$T_{w,o}$	Outlet temperature cooling water
U	Overall heat transfer coefficient
T_{fc}	Operating temperature of cells
$N_{cell,fc}$	Number of cells
$\dot{V}_{fc}$	Consumption rate of hydrogen
$\eta_{I,fc}$	Utilisation factor of fuel cell

I_{fc}	Current produced by fuel cell
β	Flight path in degrees