

COORDINATED CONTROL OF DC MICROGRIDS

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DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2018

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COORDINATED CONTROL OF DC MICROGRIDS

by

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Department of Electrical Engineering

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2018

I dedicate this thesis to my loving family ...

Certificate

This is to certify that the dissertation entitled "**Coordinated control of DC microgrids**", being submitted by **Mr. Subham Swaroop Sahoo** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering at Indian Institute of Technology Delhi, New Delhi.

Mr. Subham Swaroop Sahoo has worked under our supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the requisite standard. The results obtained here have not been submitted to any other University or Institute for the award of any degree.

.....

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July 2018

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my supervisor, Prof. Sukumar Mishra for playing an eminent role in garnering my Ph.D studies and accompanying research, for his immaculate patience, motivation and extensive knowledge. His guidance has helped me to strengthen my research skills and persevere the thesis with confidence. I could not have imagined having an exceptional advisor for my Ph.D study.

Besides my supervisor, I would also like to extend my thanks to the thesis committee members: Prof. Bhim Singh, Dr. Nilanjan Senroy and Dr. Ashu Verma. The valuable suggestions and timely feedback provided by them on my work came out extremely worthwhile in improving the quality of work. In particular, Prof. Bhim Singh provided provided some constructive comments on power electronics applications in microgrids, which helped me to focus and reconsider my work objectives. I would further like to thank Dr. Nilanjan Senroy and Dr. Ashu Verma for providing productive insights on my work, which helped in creating a widened perspective for my thesis. My journey wouldn't be complete without thanking Prof. B. K. Panigrahi, Dr. A. R. Abhyankar and Dr. P. R. Bijwe for thoughtful discussions on various subjects and constant motivation.

My sincere thanks to the staff and all other faculty members of IIT Delhi for assisting me in the administrative work, which provided ample time to focus on research. I would specifically extend my thanks to Dean Academics, Prof. Bhim Singh and the Head of the Department, Prof. S. D. Joshi who ensured my research work meets the right platform.

My thesis would not have been possible with the guidance and help I received from the Power Systems Simulation Lab & Smart Grid Lab. I'm grateful to seniors: Dr. Nitin Kumar, Dr. Gayathri Nair, Dr. Neelakanteshwara Battu, Dr. Somesh Bhattacharya, Dr. Satish Sharma, Deep Kiran, Snigdha Rani Behara, Dr. Pratyasha Bhui, Dr. Rahul Dubey, Dushyant Sharma, Dr. Deepak Reddy Pullaguram, Dr. Kritika Saxena, Kush Khanna, Sirin Dutta Choudhary, T. Sathiyarayanan, Dr. Ganesh Prajapat, BR Manoj, Sandeep Joshi, Abdul Saleem Mir, Ayesha Firdaus, Dr. Manas Jena, Sayari Das, Muddassir Maniyar, Rajiv Jha, Rishi Sharma, Shivraman Mudaliyar, Nilay Pandey, Abhilash Patel who have been informative and lend their experience in various aspects. I'd particularly like to offer my sincere thanks to my go-to friend in the campus, Surya Prakash, not just for helpful discussions and guidance with him on setting up the experimental prototype but imbibing motivation in my personal life which has helped me a lot in organizing myself. I would like to extend my thanks to my juniors: Shruti Ranjan, Rubi Rana, Megha Gupta, Shaziya Rasheed, Tabia Ahmad, Abhishek Nayak, Dhiman Das, Sandeep Singh, Santosh Kumari, Manas Ranjan Mishra, Aakanksha Rajput, Ashwani Arora, Bhanu Duggal, Vaibhav Nougain and all other research associates, interns for providing constant support. I will always cherish the warmth shown by them.

I cannot forget friends who have always backed me during my hard times by cheering and celebrating every accomplishments: Srikanth K, Pallav Kishore Dash, Shakti Sekhar Pati, Chinmoy Samal, Ansuman Pujari, Premanand Gour, Avash Bohidar, Stuti Mondal, Manvi Semalty and Soumya Ranjan Meher.

I would like to express gratitude to my brother, Swagat Sahoo who has always been generous with his love and encouragement.

Last but not the least, I deeply thank my source of inspiration: my parents, Nabaghana Sahoo and Minakshi Sahoo for their unconditional love and trust throughout my journey. It was their endless support that aroused positive things amidst all the disappointments and rejections I've faced in my life. Their infallible love and support has always been my strength.

Without their help, I would not have been able to complete much of what I have done and become who I am.

Date:

Subham Swaroop Sahoo

Abstract

This thesis mainly focuses on developing reliable and scalable coordinated control strategies for various architectures of DC microgrids. In contrast to the conventional coordination philosophy, the primary goal is to reduce the communication burden & infrastructure by employing *distributed* control philosophy using the neighboring measurements. The reliability, scalability, cost-effectiveness of distributed control is discussed in detail. Further, this concept is realized for the design of secondary controllers to achieve various objectives such as voltage regulation, load sharing, energy balancing in DC microgrids. Several aspects of the coordination philosophy for DC microgrids, investigated in this thesis are as follows:

- Design of a methodology to solve conventional constant current/constant voltage (CC/CV) charging techniques using an adaptive progressive de-rating control strategy in a seamless fashion via power curtailment from PV for CV charging of battery energy storage systems (BESSs) to ensure longevity in an autonomous single bus DC microgrid. It ensures regulated DC voltage eliminating the need of DC bus signaling mechanism, leading to various voltage levels.
- Design of non-linear proportionate charging/discharging control strategy for energy balancing of BESSs in an autonomous single bus DC microgrid. As BESSs are responsible for maintaining voltage, the impact of the performance of the proposed energy balancing strategies in presence of various sources having different dynamics such as PV & fuel cell is studied during transients.

- Design of a cooperative adaptive droop for each BESS to realize energy balancing in a multi-bus DC microgrid consisting of PV and BESSs at different buses. Additionally to ensure longevity, various modes of charging of BESSs is communicated by a binary signal depicting transition of modes using the distributed cyber topology.
- To highlight the application of plug-and-play capability of sources using distributed cyber topology in real-life practice, a generalized case of grid connected electric vehicles (EV) charging park is considered which undergoes handshaking with the aggregator to increase economic benefit. To avoid penalties, (N-1) contingency solutions usually serves the purpose, however cooperative control coordination between each charging unit in the park manages to meet the energy requirement if (N-1) contingency fails.
- Design of a cooperative finite-time dynamic framework for each source aggregated as, RESs equipped with BESSs in a single bus, to undergo average voltage regulation & proportionate current sharing within finite settling time in multi-bus DC microgrids. Further, it is supported by theoretical analysis on maximum time delay for a given cyber network that the controller can withstand to achieve stability ensuring reliable performance for time delays, different cyber topologies, link failure, converter failure etc.
- Design of an event-based aperiodic sampling of the cooperative channel instead of time-based sampling, referred to as *event-triggering* which samples only during events/disturbances, such as load changes, using an event-triggered error analyzed using a Lyapunov technique. In other words, it focuses on transmission of sensor values only during the events (disturbances such as load change) which is an energy saving approach as it reduces energy consumption required for communication channel when there's no event. A sensitive analysis of model uncertainties is also explored which manipulates the error threshold.

- Design of an attack-resilient distributed controller for DC microgrids using a cooperative vulnerability factor (CVF) methodology to detect the presence of false data as well as a balanced set of zero sum false data also termed as, *stealthy* attacks. A detailed study on modeling of such attacks using multiple sensors as well as communication links is provided to show the accuracy of the detection and corrective mechanism.
- Design of a fixed-time based dual layer cooperative secondary controller for a cluster of DC microgrids to minimize loading mismatch between each microgrid within fixed settling time during high loading conditions. On the other hand, for a significantly large network during light load conditions, the transmission line loss dominates which suggests an optimal loss minimization strategy for inter-microgrid sharing. To carry out these objectives, a fixed-time based fully distributed dual layer secondary controller is designed which alternatively handles loading mismatch mitigation and loss minimization depending on the loading conditions.
- Design of a containment control strategy for leader-follower cyber network with constrained flow of information between each source to achieve bounded voltage regulation & proportionate sharing within finite-time in a multi-bus DC microgrid. Further, reverse $I - V$ droop methodology is explored to enhance the dynamic performance of the control system by avoiding an additional compensating (voltage) loop.

Keywords: DC microgrids, Distributed control, Finite-time control, Fixed-time control, Event-triggering, Microgrid clusters, Cyber attacks, Load sharing, Energy balancing, Distributed voltage observer.

सार

यह थीसिस मुख्य रूप से डीसी माइक्रोग्रिड के विभिन्न वास्तुकला के लिए विश्वसनीय और स्केलेबल समन्वित नियंत्रण रणनीतियों को विकसित करने पर केंद्रित है। पारंपरिक समन्वय दर्शन के विपरीत, प्राथमिक लक्ष्य पड़ोसी माप का उपयोग करके वितरित नियंत्रण दर्शन को नियोजित करके संचार बोझ और बुनियादी ढांचे को कम करना है। वितरित नियंत्रण की विश्वसनीयता, मापनीयता, लागत प्रभावीता पर विस्तार से चर्चा की गई है। इसके अलावा, यह अवधारणा डीसी माइक्रोग्राइड्स में वोल्टेज विनियमन, लोड शेयरिंग, ऊर्जा संतुलन जैसे विभिन्न उद्देश्यों को प्राप्त करने के लिए माध्यमिक नियंत्रकों के डिजाइन के लिए महसूस की जाती है। डीसी माइक्रोग्रिड के लिए समन्वय दर्शन के कई पहलुओं, इस थीसिस में जांच इस प्रकार हैं:

- बैटरी एनर्जी स्टोरेज सिस्टम (बीईएस) के सीवी चार्जिंग के लिए पीवी से बिजली कटौती के माध्यम से एक निर्बाध फैशन में एक अनुकूल प्रगतिशील डी-रेटिंग नियंत्रण रणनीति का उपयोग कर पारंपरिक निरंतर वर्तमान / निरंतर वोल्टेज (सीसी / सीवी) चार्जिंग तकनीकों का उपयोग करने के लिए एक पद्धति का डिजाइन एक स्वायत्त एकल बस डीसी में दीर्घायु। यह डीसी माइक्रोग्रिड बस सिग्नलिंग तंत्र की आवश्यकता को खत्म करने वाले विनियमित डीसी वोल्टेज को सुनिश्चित करता है, जिससे विभिन्न वोल्टेज स्तर होते हैं।
- एक स्वायत्त एकल बस डीसी माइक्रोग्रिड में बीईएस के ऊर्जा संतुलन के लिए गैर रेखीय आनुपातिक चार्जिंग / निर्वहन नियंत्रण रणनीति का डिजाइन। चूंकि बीईएस वोल्टेज को बनाए रखने के लिए ज़िम्मेदार हैं, पीवी और ईंधन सेल जैसे विभिन्न गतिशीलता वाले विभिन्न स्रोतों की उपस्थिति में प्रस्तावित ऊर्जा संतुलन रणनीतियों के प्रदर्शन का प्रभाव ट्रांजिस्टर के दौरान अध्ययन किया जाता है।
- प्रत्येक बस के लिए एक सहकारी अनुकूल डूप का डिजाइन एक बहु-बस डीसी माइक्रोग्रिड में ऊर्जा संतुलन को समझने के लिए अलग-अलग बसों में पीवी और बीईएस से युक्त है। इसके अतिरिक्त दीर्घायु सुनिश्चित करने के लिए, बीईएस के चार्जिंग के विभिन्न तरीकों को एक बाइनरी सिग्नल द्वारा वितरित किया जाता है जो वितरित साइबर टोपोलॉजी का उपयोग करके मोड के संक्रमण को दर्शाता है।
- वास्तविक जीवन अभ्यास में वितरित साइबर टोपोलॉजी का उपयोग करके स्रोतों की प्लग-एंड-प्ले क्षमता के अनुप्रयोग को हाइलाइट करने के लिए, ग्रिड से जुड़े इलेक्ट्रिक वाहन (ईवी) चार्जिंग पार्क के सामान्यीकृत मामले को माना जाता है, जो आर्थिक लाभ बढ़ाने के लिए एग्रीगेटर के साथ हैंडशेकिंग से गुजरता है। जुर्माना से बचने के लिए, (एन -1) आकस्मिक समाधान आम तौर पर उद्देश्य को पूरा करते हैं, हालांकि पार्क में प्रत्येक चार्जिंग इकाई के बीच सहकारी नियंत्रण समन्वय ऊर्जा आवश्यकता को पूरा करने के लिए प्रबंधन करता है यदि (एन -1) आकस्मिकता विफल हो जाती है।
- प्रत्येक स्रोत के लिए एक सहकारी परिमित समय गतिशील ढांचे का डिजाइन, एक ही बस में बीईएस से लैस आरईएस, औसत वोल्टेज विनियमन से गुजरने के लिए और बहु-बस डीसी माइक्रोग्रिड्स में सीमित निपटारे समय के भीतर आनुपातिक वर्तमान साझाकरण के लिए। इसके अलावा, यह किसी दिए गए साइबर नेटवर्क के लिए अधिकतम समय देरी पर सैद्धांतिक विश्लेषण द्वारा समर्थित है कि नियंत्रक समय देरी, विभिन्न साइबर टोपोलॉजीज, लिंक विफलता, कनवर्टर विफलता इत्यादि के लिए विश्वसनीय प्रदर्शन सुनिश्चित करने के लिए स्थिरता प्राप्त करने का सामना कर सकता है।
- टाइम-आधारित नमूनाकरण के बजाय सहकारी चैनल के इवेंट-आधारित एपिरियोडिक नमूनाकरण का डिजाइन, जिसे इवेंट-ट्रिगरिंग के रूप में जाना जाता है, जो केवल इवेंट्स के दौरान नमूने होते हैं, जैसे लोड परिवर्तन, एक इवेंट-ट्रिगर त्रुटि का उपयोग करके लाइफुनोव तकनीक का उपयोग करके विश्लेषण किया

जाता है। दूसरे शब्दों में, यह केवल घटनाओं (लोड परिवर्तन जैसे डिस्टर्बेंसेस) के दौरान सेंसर मूल्यों के संचरण पर केंद्रित है जो ऊर्जा बचत दृष्टिकोण हैं क्योंकि इससे कोई घटना नहीं होने पर संचार चैनल के लिए आवश्यक ऊर्जा खपत कम हो जाती है। मॉडल अनिश्चितताओं का एक संवेदनशील विश्लेषण भी खोजा गया है जो त्रुटि दहलीज में हेरफेर करता है।

- झूठी डेटा की उपस्थिति का पता लगाने के साथ-साथ शून्य राशि झूठे डेटा के संतुलित सेट को भी चुपके हमलों के रूप में संबोधित करने के लिए एक सहकारी भेद्यता कारक (सीवीएफ) पद्धति का उपयोग करके डीसी माइक्रोग्राइड्स के लिए एक हमले-लचीला वितरित नियंत्रक का डिज़ाइन भी कहा जाता है। पहचान और सुधारात्मक तंत्र की सटीकता दिखाने के लिए कई सेंसर के साथ-साथ संचार लिंक का उपयोग करके ऐसे हमलों के मॉडलिंग पर विस्तृत अध्ययन प्रदान किया जाता है।
- डीसी माइक्रोग्राइड्स के क्लस्टर के लिए एक निश्चित समय आधारित दोहरी परत सहकारी माध्यमिक नियंत्रक का डिज़ाइन, प्रत्येक माइक्रोग्रिड के बीच लोडिंग विसंगति को कम करने के लिए उच्च लोडिंग स्थितियों के दौरान निश्चित निपटारे समय के भीतर। दूसरी तरफ, हल्के लोड की स्थिति के दौरान काफी बड़े नेटवर्क के लिए, ट्रांसमिशन लाइन हानि पर हावी है जो इंटर-माइक्रोग्रिड शेयरिंग के लिए इष्टतम हानि न्यूनीकरण रणनीति का सुझाव देता है। इन उद्देश्यों को पूरा करने के लिए, एक निश्चित समय आधारित पूरी तरह वितरित दोहरी परत माध्यमिक नियंत्रक डिज़ाइन किया गया है जो लोडिंग स्थितियों के आधार पर वैकल्पिक रूप से मिस्चैच शमन और हानि न्यूनीकरण को लोड करता है।
- बहु-बस डीसी माइक्रोग्रिड में सीमित समय के भीतर बाध्य वोल्टेज विनियमन और आनुपातिक साझा करने के लिए प्रत्येक स्रोत के बीच जानकारी के बाध्य प्रवाह के साथ नेता-अनुयायी साइबर नेटवर्क के लिए एक नियंत्रण नियंत्रण रणनीति का डिज़ाइन। इसके अलावा, अतिरिक्त क्षतिपूर्ति (वोल्टेज) पाश से बचकर नियंत्रण प्रणाली के गतिशील प्रदर्शन को बढ़ाने के लिए डी-वू डूप पद्धति को उलट दिया गया है।

कीवर्ड: डीसी माइक्रोग्रिड, वितरित नियंत्रण, परिमित समय नियंत्रण, फिक्स्ड-टाइम नियंत्रण, इवेंट-ट्रिगरिंग, माइक्रोग्रिड क्लस्टर, साइबर हमले, लोड शेयरिंग, ऊर्जा संतुलन, वितरित वोल्टेज पर्यवेक्षक।

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Nomenclature

Acronyms / Abbreviations

AC	Alternating Current
AETC	Adaptive Event-Triggered Communication
AI	Analog Input
AI	Analog Output
AO	Analog Output
BESS	Battery Energy Storage System
BMS	Battery Management System
CC	Constant Current
CS	Charging Station
CV	Constant Voltage
CVF	Cooperative Vulnerability Factor
DO	Digital Output
DoS	Denial of Service

EV	Electric Vehicles
FDIA	False Data Injection Attacks
MIMO	Multi-Input Multi-Output
MPPT	Maximum Power Point Tracking
MRAC	Model Reference Adaptive Control
MVMO	Mean Variance Mapping Optimization
PCS	Power Converter System
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
SoC	State of Charge
SOFC	Solid Oxide Fuel Cell
VD	Voltage Droop
VSC	Voltage Source Converter
ZOH	Zero Order Hold