CONTROLLERS FOR DISTRIBUTED ENERGY RESOURCES IN ACTIVE DISTRIBUTION NETWORKS

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DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2018

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by

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Submitted

In fulfillment of the requirements of the Degree of Doctor of Philosophy

to the

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2018

CERTIFICATE

This is to certify that the dissertation entitled ‘**Controllers for Distributed Energy Resources in Active Distribution Networks**’, being submitted by **Mr. Somesh Bhattacharya** 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. Somesh Bhattacharya has worked under my supervision and has fulfilled the requirements for the submission of this dissertation, which to my knowledge has reached the requisite standard. The results obtained in the thesis has not been submitted in part or in full to any other University or Institute for the award of any degree.

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ACKNOWLEDGEMENTS

I would like to express my immense appreciation and thanks to my supervisor, Prof. Sukumar Mishra, who has been a tremendous mentor for me. I would like to thank him for allowing me to freely broaden my horizons in the field of Power Systems and renewable energy, and constantly motivating me to explore the above mentioned fields in every possible way. Every piece of advice provided by him has been priceless and I can confidently state that his tutelage and way of thinking will help me grow further my research prospects for several years to come.

I owe my heartfelt thanks to my student research committee experts and members, Prof. P.R. Bijwe, Dr. Nilanjan Senroy and Dr. Ashu Verma who have constantly prepared me for presenting my research in the best possible way and gave vital suggestions for my research based work. I am also very thankful to the Head of the Electrical Engineering Department, Prof. S. D. Joshi, and the Dean of Academics, Prof. Bhim Singh, Indian Institute of Technology Delhi for letting me seamlessly carrying out my thesis work and making sure that no kind of administrative hurdles affect my research work at any point of time.

I take immense pleasure in thanking my friends and colleagues of Power System Simulation Laboratory who always have strived to create a very positive environment, full of energy and looking at them has always motivated me and made me stronger throughout my time spent at IIT Delhi. Personally, I would like to express my gratitude to Dr. P. C. Sekhar, Dr. Surender Reddy, Dr. Mallesham, Dr. A. Mohapatra, Dr. Zarina and Dr. Sudipta Ghosh from whom, I learnt how to effectively start my research work. I am also thankful to Dr. Satish Sharma, Deep Kiran, Deepak Reddy, Kush Khanna and Sathiyanarayanan with whom I have spent days of cheerfulness and sorrow. They have always been by my side and motivated me to bring the best in me. I am very thankful to Dr. Deepak Ramasubramanian and Puspal Hazra, who in the little time spent here ignited the spirit of my research, on which my thesis lies today.

I have no words to thank my parents, Dr. Bijoy Krishna Bhattacharya and Smt. Madhumita Bhattacharya, who have made several sacrifices to help me gain leverage during the entire period of my research. They always helped me coming out of the loop quickly whenever I felt trapped and helpless. Without their support, I would not have been able to finish my thesis work. My heartfelt thanks to my wife and my best friend, Mrs. Monideepa Paul

Bhattacharya, who patiently waited for several years before marriage and a little after marriage so that I could finish my work, and has always motivated me to work harder.

Date:

Place: New Delhi

Somesh Bhattacharya

ABSTRACT

With the growing penetration levels of Photovoltaic Generators (PVG) at both medium voltage and low voltage levels, the grid connected microgrids, which generally house such generation sources face several problems due to intermittency of the aforementioned sources. These problems vary from voltage rise and drop due to direct relation of the output voltage and the insolation, to frequency related problems, especially when such sources are working in the isolated mode. Therefore, in this thesis, control strategies have been proposed for the efficient integration of renewable sources in the microgrid, which can work seamlessly in both isolated and the grid connected modes.

In this first phase of the thesis, to overcome the problem of erroneous power sharing, a modified droop control has been proposed which can not only overcome the aforementioned problem, but also help in the mitigation of the low frequency oscillations which arise due to the direct on-line switching of the induction motor loads in a system, which is primarily fed by the static sources present in the microgrid network. The efficacy of the proposed control approach has been observed through both time domain and system wide small signal analysis, and it is seen that the proposed droop control is able to cancel out the low frequency modes, arising out of the induction motor dynamics.

The second phase of the thesis discusses about the seamless control strategy for mode transition. The proposed droop control in the first phase of the thesis is modified further in order to attain two objectives, i.e. transfer of the controls of the PVG from the constant dispatch mode to the frequency and voltage control mode, and vice versa, and also provide better damping to the oscillatory behavior of the powers in the microgrid network, operating in the isolated mode, after a fault has occurred. The dynamic stability analysis has been performed at the VSI level to obtain the best set of the control parameters.

The integration of PVG with other sources such as a battery energy storage has been considered in the third phase of the thesis. In this work, a power management approach has been proposed, based on the modified droop control at the AC side of the network, and a power- voltage based droop control for the current sharing within the batteries, when they operate in parallel. It is observed in this work that when the PVG-BESS based microgrid enters the isolated mode, the

adaptive droop control for the PVG has the capability to make the PVG work in both MPPT and the load following mode, based on the magnitude of the droop coefficients. It is also observed that when the PVG operates in the de-rated condition, in tandem with the BESS, a better frequency control is achieved in the isolated mode of operation.

An inertial control for the static DERs operating in the grid connected hybrid AC-DC microgrid has been proposed in the fourth phase of the thesis, and it is observed that upon the application of the proposed inertial control, the PVG or the DC microgrid can contribute in the inertial response, whenever there is a grid exigency. For the DGs to assist in the inertial control, whenever a microgrid is considered where the inverter dominance is higher, the inputs to the governor and the AVR is modified so as to mimic a P-Q-*f* and P-Q-*v* droop control, in order to share powers in accord with the control coefficients, along with the DCM-VSI and the PVG.

सार

दोनों मध्यम वोल्टेज और कम वोल्टेज स्तरों पर फोटोवोल्टिक जेनरेटर (पीवीजी) के बढ़ते प्रवेश स्तर के साथ, ग्रिड से जुड़े माइक्रोग्रिड्स, जो आम तौर पर उपरोक्त स्रोतों की अंतःक्रिया के कारण ऐसी पीढ़ी के स्रोतों को घर में कई समस्याओं का सामना करते हैं। आउटपुट वोल्टेज और विद्रोह के प्रत्यक्ष संबंध के कारण वोल्टेज वृद्धि और गिरावट से ये समस्याएं अलग-अलग होती हैं, विशेष रूप से जब ऐसे स्रोत पृथक मोड में काम कर रहे होते हैं। इसलिए, इस थीसिस में, माइक्रोग्रिड में नवीकरणीय स्रोतों के कुशल एकीकरण के लिए नियंत्रण रणनीतियों का प्रस्ताव दिया गया है, जो अलग-अलग और ग्रिड-जुड़े मोड दोनों में निर्बाध रूप से काम कर सकते हैं।

थीसिस के इस पहले चरण में, गलत बिजली साझा करने की समस्या को दूर करने के लिए, एक संशोधित ड्रूप नियंत्रण प्रस्तावित किया गया है जो न केवल उपरोक्त समस्या को दूर कर सकता है, बल्कि प्रत्यक्ष आवृत्ति के कारण उत्पन्न होने वाली निम्न आवृत्ति उत्सर्जन की कमी में भी मदद करता है एक प्रणाली में प्रेरण मोटर भार की ऑन-लाइन स्विचिंग, जिसे मुख्य रूप से माइक्रोग्रिड नेटवर्क में मौजूद स्थिर स्रोतों द्वारा वितरित किया जाता है। प्रस्तावित नियंत्रण दृष्टिकोण की प्रभावकारिता दोनों समय डोमेन और सिस्टम-व्यापी छोटे सिग्नल विश्लेषण के माध्यम से देखी गई है, और यह देखा जाता है कि प्रस्तावित ड्रूप नियंत्रण प्रेरण मोटर गतिशीलता से उत्पन्न होने वाले निम्न आवृत्ति मोड को रद्द करने में सक्षम है।

थीसिस का दूसरा चरण मोड संक्रमण के लिए निर्बाध नियंत्रण रणनीति पर चर्चा करता है। थीसिस के पहले चरण में प्रस्तावित ड्रूप नियंत्रण को दो उद्देश्यों को प्राप्त करने के लिए आगे संशोधित किया जाता है, यानि निरंतर प्रेषण मोड से आवृत्ति और वोल्टेज नियंत्रण मोड से पीवीजी के नियंत्रण का हस्तांतरण, और इसके विपरीत, और बेहतर प्रदान करता है माइक्रोग्रिड नेटवर्क में शक्तियों के कंपन व्यवहार के लिए भिगोना, अलग मोड में परिचालन, एक गलती के बाद हुआ है। नियंत्रण पैरामीटर का सबसे अच्छा सेट प्राप्त करने के लिए गतिशील स्थिरता विश्लेषण वी एस आई स्तर पर किया गया है।

थिसिस के तीसरे चरण में बैटरी ऊर्जा भंडारण जैसे अन्य स्रोतों के साथ पीवीजी का एकीकरण माना गया है। इस काम में, नेटवर्क के एसी पक्ष में संशोधित ड्रूप नियंत्रण के आधार पर एक पावर प्रबंधन दृष्टिकोण प्रस्तावित किया गया है, और बैटरी के भीतर वर्तमान साझाकरण के लिए एक पावर-वोल्टेज आधारित ड्रूप नियंत्रण, जब वे समानांतर में काम करते हैं। यह इस काम में देखा जाता है कि जब पीवीजी-बीईएस आधारित माइक्रोग्रिड पृथक मोड में प्रवेश करता है, तो पीवीजी के लिए अनुकूली ड्रूप नियंत्रण में पीपीजी

दोनों एमपीपीटी में काम करने की क्षमता होती है और ड्रूप की परिमाण के आधार पर लोड निम्न मोड गुणांक। यह भी देखा गया है कि जब पीवीजी डी-रेटेड स्थिति में काम करता है, तो बीईएस के साथ मिलकर, संचालन के अलग-अलग तरीके में बेहतर आवृत्ति नियंत्रण प्राप्त होता है।

ग्रिड से जुड़े हाइब्रिड एसी-डीसी माइक्रोग्रिड में चल रहे स्थिर डीईआर के लिए एक जड़ नियंत्रण थासिस के चौथे चरण में प्रस्तावित किया गया है, और यह देखा गया है कि प्रस्तावित जड़ नियंत्रण के आवेदन पर, पीवीजी या डीसी माइक्रोग्रिड कर सकते हैं जब भी ग्रिड आवृत्ति होती है, तो जड़ में प्रतिक्रिया में योगदान मिलता है। डीजी को जड़ नियंत्रण में सहायता करने के लिए, जब भी एक माइक्रोग्रिड माना जाता है जहां इन्वर्टर प्रभुत्व अधिक होता है, तो गवर्नर और एवीआर को इनपुट संशोधित किया जाता है ताकि पीक्यूएफ और पीक्यूवी ड्रूप नियंत्रण की नकल करने के लिए, शक्तियों को साझा करने के लिए नियंत्रण गुणांक के साथ, डीसीएम-वीएसआई और पीवीजी के साथ।

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
A-h	Ampere Hour
AVR	Automatic voltage regulator
BESS	Battery Energy Storage System
CERTS	Consortium for Electric Reliability Technology Solutions
CPL	Constant Power Loads
DC	Direct Current
DG	Diesel Generator
DOF	Degree of Freedom
DSO	Distribution System Operator
EV	Electric Vehicles
IM	Induction Motor
IPP	Independent Power Producer
LB	Low Bandwidth
LV	Low Voltage
MGCC	Microgrid Centralized Controller
MMS	Microgrid Management System
PCC	Point of Common Coupling
PLL	Phase Locked Loop
PI	Proportional- Integral
PVG	Photovoltaic Generator
P-*f*	Active Power- frequency

P-Q	Constant Active Power- Reactive Power
P-*v*	Power- voltage
P-Q-*f*	Active Power- Reactive Power- frequency
P-Q-*v*	Active Power- Reactive Power- voltage
P-Q-*f*-D	Active Power- Reactive Power- frequency- Derivative
P-Q-*v*-D	Active Power- Reactive Power- voltage- Derivative
RL	Resistance- Inductance
V2G	Vehicle to Grid
V2MG	Vehicle to microgrid
v-*f*	Voltage- frequency
T-S	Takagi Sugeno

NOMENCLATURE

Symbols	Names
ω	Frequency
ω^{ref}	Reference frequency
ω_{nom}	Nominal frequency
ω_{pll}	Frequency of the PLL
ω_c	Cut off frequency of the first order filter
δ	Angle
δ^{ref}	Reference Angle
δ_{pll}	Angle measured by the PLL.
δ_{pcc}	Angle at the PCC.
R_p	Active power droop coefficient
R_v	Reactive power droop coefficient
R_{pd}	Derivative droop coefficient for active power
R_{vd}	Derivative droop coefficient for reactive power
M_c	Battery droop control coefficient while charging
M_d	Battery droop control coefficient while discharging
K_{pv}	Proportional gain of AC voltage controller
K_{iv}	Integral gain of the AC voltage controller

K_{pc}	Proportional gain of the AC current controller
K_{ic}	Integral gain of the AC voltage controller
K_{pvdc}	Proportional gain for the DC link voltage control
K_{ivdc}	Integral gain for the DC link voltage control
M_e	Inertial control gain
D_e	Damping control gain
K_{p_pdc}	Proportional gain for inner power controller (DC side)
K_{p_idc}	Integral gain for inner power controller (DC side)
K_{v_pdc}	Proportional gain for the voltage controller (DC side)
K_{v_idc}	Integral gain for the voltage controller (DC side)
K_{p_sync}	Proportional gain for the synchronization controller
K_{i_sync}	Integral gain for the synchronization controller
FF	Feedforward term
R_f	Filter resistance (AC)
L_f	Filter Inductance (AC)
C_f	Filter Capacitance (AC)
R_c	Coupling resistance

L_c	Coupling inductance
V_{od}	d axis output voltage of VSI
V_{oq}	q axis output voltage of VSI
I_{id}	d axis current of inverter
I_{iq}	q axis current of inverter
V_{id}	d axis voltage of inverter
V_{iq}	q axis voltage of inverter
V_{pd}	d-axis PCC voltage
V_{pq}	q-axis PCC voltage
V_{dc}	DC link voltage
V_{dc_in}	Battery voltage or the input voltage to the DC-DC converter
V_{dc_o}	Output voltage of the DC-DC converter
P	Active power
P_{batt}	Battery power
P_{dc}	DC power
P_{BESS}	Equivalent power for the battery energy storage system
Q	Reactive power
P^{ref}	Reference active power (AC side)
P_b^{ref}	Battery power reference
Q^{ref}	Reference reactive power
P_{dg}^{ref}	DG reference active power
Q_{dg}^{ref}	DG reference reactive power
V_{dc}^{ref}	DC link reference voltage

V_{od}^{ref}	Reference output voltage for the VSI (d axis)
V_{oq}^{ref}	Reference output voltage for the VSI (q axis)
V_{id}^{ref}	Reference input voltage for the VSI (d axis)
V_{iq}^{ref}	Reference input voltage for the VSI (q axis)
K_a	AVR gain
T_a	AVR time constant
K_e	Exciter gain
T_e	Exciter time constant
K_f	Damper gain
T_f	Damper time constant
T_{do}'	Generator time constant
R_{sync}	Synchronization virtual resistance
L_{sync}	Synchronization virtual inductance