COORDINATED CONTROL AND STABILITY ANALYSIS OF DC MICROGRIDS

Shivraman Mudaliyar

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

Shivraman Mudaliyar

DEPARTMENT OF ELECTRICAL ENGINEERING

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Dedicated to

My parents & My wife Anshu

Certificate

This is to certify that the dissertation entitled **"Coordinated Control and Stability Analysis of DC Microgrids"** being submitted by **Shivraman Mudaliyar** to the Department of Electrical Engineering, Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is the record of the bonafide research work carried out by him under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Prof. Sukumar Mishra
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016
India

Date:

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Date: **Shivraman Mudaliyar**

Abstract

The practical implementation and control of geographically dispersed microgrids bring its own challenges and issues. One of the major issues that can impact is the issue of poor voltage regulation across different buses in the network. The rate and amount of power generation and absorption at different buses can introduce significant voltage deviations. This problem can be further aggravated if the dc lines are connected such that it forms a ring-topology. In networked dc microgrids (DCMG), the voltage is influenced by power flows and vice-versa. Since the load behaviour is also linked with voltage, the control becomes more challenging. Moreover, development of scenarios such as increasing penetration of intermittent renewable energy sources (RES) e.g., photovoltaic (PV) and uncoordinated charging and discharging patterns of plugged-in electric vehicles can further worsen the voltage regulation issue.

First, a supervisory voltage control scheme based on centralized communication is proposed for a grid-connected DCMG with ring topology. In order to study the voltage regulation problem, the loads and PV based RES are placed at different buses. With three different types of controllable sources available in the system, a suitable optimization strategy is proposed to determine the appropriate set-points. Energy storage systems (ESS) with only battery stacks are limited in operation with respect to their state of charge (SoC) status. In order to increase the availability of battery-based ESS, an energy hub (EH) concept is proposed which consists of fuel cell (FC) and an electrolyzer connected in parallel with the battery stack. The proposed combination of EH extends the range of bidirectional capability and provides more participation in the optimization process compared to the case if we consider the battery stack alone. Then, different simulation studies were conducted considering variations in PV and

load powers to verify and validate the performance of proposed supervisory voltage control. The simulation results demonstrate the effectiveness of voltage control strategy in minimizing the load voltage deviations.

Typically, the ring topology of any distribution system is created by connecting the mechanical isolators at the remote end of the feeders. Now if the ring configuration is desired by the network operator, then it can be done either by connecting the isolator in the off-load condition of the feeders or on load. If the switching is performed onload then it can generate a propagating disturbance in both the feeders even if the voltage difference is minimal. Therefore, in order to overcome this problem, this thesis proposes a power electronic converter based solution to provide seamless and flexible connection of remote ends of the dc feeders. The proposed power electronic converter is termed as soft open point (SOP) based on its capability of providing soft switching compared to the hard switching associated with isolators. The proposed SOP is then designed to connect three radial feeders at the remote end and the voltage regulation problem of the overall system is studied with and without the SOP. Steady state analysis is performed on the study system considering a 24 hours horizon with different profiles of PV and electric vehicle charging. The results show significant improvement in voltage profile of the system thereby allowing more penetration for plugged-in electric vehicles compared to the case when feeders are connected through mechanical isolator. The simulation results obtained from real-time implementation and experimental set-up also demonstrate the effectiveness of supervisory voltage control strategy in minimizing the voltage deviations at load terminals when subjected to changes in operating conditions.

Generally, stability related issues are not a major concern when the feeders of dc microgrids are connected to a relatively strong grid. However, during the autonomous operation, stability issues arising due to negative incremental resistance offered by increased penetration of constant power loads (CPL) along with voltage weak network characteristics cannot be ignored. Therefore, four of the important factors that can affect the stability of autonomous dc microgrids are investigated such as limited control bandwidth of parallel connected sources, presence of CPL, high inductance to resistance ratios and low terminal capacitances. Detailed modeling of converters and controls based on their average behavior representation is presented. In order to improve the stability under these circumstances a power oscillation damper (POD) function is also proposed which can be integrated with SOP local control strategy. Detailed analysis with regard to the selection of input signals to POD is discussed. Finally, small-signal stability analysis and time-domain simulations are presented to provide useful insights on the stability factors and validate the performance of studied system with and without the POD.

When microgrids belong to the same utility, sharing of power and resources through interconnected lines increases reliability and security of power supply and further provides economic benefits to the utility. However, if the microgrids are owned by different utilities then it would be desirable that each individual microgrid is responsible to manage its own load at steady state. One way to ensure that is to regulate the power flow through the lines connecting the boundary buses of these microgrids at a predefined and mutually agreed schedule. This way it can be ensured that the steady state impact of load or any voltage changes in one microgrids won't affect the generation cost in other microgrid. To this end, a unifying hierarchical control scheme based on distributed communication is proposed where the tie-line power flow control based on a pinning control strategy is unified with the distributed optimization and average voltage regulation control loops. The distributed optimization utilizes economic dispatch to minimize the operating costs of the dispersed generation, while the average voltage control regulates the microgrid's average voltage at its nominal value. With the application of this approach, the responsibility of tie-line regulation is distributed in an economic manner without degrading the voltage quality in the system. At first the proposed philosophy is tested on a two microgrid system connected through tie-line. Real-time simulation and experimental platforms are employed to demonstrate the implementation and efficacy of proposed distributed tie-line control. Then the proposed control is extended for three-microgrid systems connected through three tie lines.

सार

भौगोलिक रूप से फैले हुए माइक्रोग्रिड का व्यावहारिक कार्यान्वयन और नियंत्रण की अपनी चुनौतियाँ और मुद्दे है। प्रमुख मुद्दों में से एक जो प्रभावित कर सकता है वह है नेटवर्क में विभिन्न बसों में खराब वोल्टता विनियमन की समस्या। बिजली उत्पादन और अवशोषण की दर और राशि विभिन्न बसों में महत्वपूर्ण वोल्टता विचलन पेश कर सकता है। अगर दिष्ट- धारा (डी.सी) लाइन को इस तरह से जोड़ा जाए कि यह एक गोल-टोपोलॉजी बन जाये तो यह समस्या और बढ़ सकती है। डी.सी माइक्रोग्रिड में वोल्टता से शक्ति-प्रवाह प्रभावित होती है और शक्ति-प्रवाह से वोल्टता । चूंकि लोड व्यवहार भी वोल्टता से जुड़ा हुआ है, इसलिए नियंत्रण अधिक चुनौती पूर्ण हो जाता है।

सबसे पहले, केंद्रीकृत संचार पर आधारित एक पर्यवेक्षी वोल्टता नियंत्रण योजना गोल-टोपोलॉजी के साथ ग्रिड से जुड़े डीसी माइक्रोग्रिड के लिए प्रस्तावित है। वोल्टता विनियमन समस्या का अध्ययन करने के लिए, लोड और प्रकाश वोल्टीय (पी.वी) तंत्र को अलग-अलग बसों में रखे गए हैं। सिस्टम में उपलब्ध तीन अलग-अलग प्रकार के नियंत्रणीय स्रोत रखे गए हैं। इसलिए उनके उपयुक्त सेट-पॉइंट निर्धारित करने के लिए, एक उपयुक्त अनुकूलन रणनीति प्रस्तावित है। प्रभार की सीमित अवस्था के कारण, केवल बैटरी स्टैक के साथ ऊर्जा भंडारण प्रणालियों (ई.एस.एस) का संचालन प्रतिबंधित होता है। बैटरी आधारित ई.एस.एस की उपलब्धता बढ़ाने के लिए, एक ऊर्जा हब (ई.एच) अवधारणा प्रस्तावित है। प्रस्तावित ई.एच में ईंधन सेल (एफ.सी) और एक इलेक्ट्रोलाइज़र, बैटरी स्टैक के साथ समानांतर में जुड़ा है। प्रस्तावित संयोजन ई.एच में द्विदिश क्षमता की सीमा का विस्तार करता है और अनुकूलन प्रक्रिया में अधिक भागीदारी प्रदान करता है। फिर, प्रस्तावित पर्यवेक्षी वोल्टता नियंत्रण के प्रदर्शन को सत्यापित करने और मान्य करने के लिए पी.वी और लोड शक्तियों में भिन्नता पर विचार करते हुए विभिन्न सिमुलेशन अध्ययन किए गए।

यह शोध डी.सी फीडरों के दूरस्थ सिरों को निर्बाध और लचीला संबंध प्रदान के लिए एक पावर इलेक्ट्रॉनिक कनवर्टर आधारित समाधान प्रस्तावित करता है। सॉफ्ट स्विचिंग प्रदान करने की क्षमता के कारण,

प्रस्तावित पावर इलेक्ट्रॉनिक कन्वर्टर को इस शोध में सॉफ्ट ओपन पॉइंट (एस.ओ.पी) कहा गया है। समग्र प्रणाली में वोल्टता विनियमन समस्या का अध्ययन एस.ओ.पी के साथ और उसके बिना गया है।

आम तौर पर, स्थिरता संबंधी मुद्दे एक प्रमुख चिंता का विषय नहीं होते हैं जब डी.सी. माइक्रोग्रिड के फीडर अपेक्षाकृत मजबूत ग्रिड से जुड़े होते हैं। हालांकि, स्वायत्तता संचालन के दौरान, स्थिरता के मुद्दों को नजरअंदाज नहीं किया जा सकता है, क्यों कि नेटवर्क की कमजोर वोल्टता विशेषताएं और निरंतर बिजली भार उसकी स्थिरता को प्रभाव करता है। कन्वर्टर्स और नियंत्रणों के औसत व्यवहार प्रतिनिधित्व के आधार पर विस्तृत मॉडलिंग प्रस्तुत किया गया है। इन परिस्थितियों में स्थिरता में सुधार के लिए एक पावर ऑसीलेशन डैम्पर (पी.ओ.डी) फलन भी प्रस्तावित है जिसे एस.ओ.पी स्थानीय नियंत्रण रणनीति के साथ एकीकृत किया गया है।

इस शोध में विभिन्न संस्थाओं से संबंधित स्वायत्त माइक्रोग्रिड का भी अध्ययन किया गया है। यह वांछनीय होगा कि प्रत्येक व्यक्तिगत माइक्रोग्रिड स्थिर अवस्था में अपने स्वयं के भार का प्रबंधन करने के लिए स्वयं जिम्मेदार हो। यह सुनिश्चित करने का एक तरीका है कि पावर के प्रवाह को इन माइक्रोग्रिड की सीमा बसों को जोड़ने वाली लाइनों में पूर्वनिर्धारित और पारस्परिक रूप से सहमत अनुसूची के अनुसार नियंत्रित किया जाए। इस तरह यह सुनिश्चित किया जा सकता है कि एक माइक्रोग्रिड में लोड या किसी भी वोल्टता परिवर्तन का स्थिर स्थिति प्रभाव अन्य माइक्रोग्रिड में उत्पादन लागत को प्रभावित नहीं करेगा। इसके लिए, वितरित संचार पर आधारित एक एकीकृत पदानुक्रमित नियंत्रण योजना प्रस्तावित है। यहां, टाई-लाइन पावर प्रवाह नियंत्रण, वितरित अनुकूलन और औसत वोल्टता विनियमन नियंत्रण लूप के साथ एकीकृत है। इस दृष्टिकोण के आवेदन के साथ, टाई-लाइन विनियमन की जिम्मेदारी को बिना सिस्टम में वोल्टता की गुणवत्ता में गिरावट के आर्थिक तरीके से वितरित कर सकते हैं।

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Abbreviations

MG	Microgrid
DCMG	Direct current microgrid
LVDC	Low voltage direct current
DSO	Distribution system operator
PV	Photovoltaic
CEI	Customer end interface
FC	Fuel cell
RES	Renewable energy sources
POL	Point of load
PEV	Plugged-in-electric vehicle
SoC	State of Charge
ESS	Energy storage system
DG	Distributed generation
DER	Distributed energy resources
BESS	Battery energy storage system
EH	Energy Hub
SOP	Soft open point
CPL	Constant power load
POD	Power oscillation damper
PEMFC	Proton exchange membrane fuel cell
CC	Central controller

TCP/IP	Transmission control protocol/Internet protocol
INC	Incremental conductance
EMS	Energy Management system
RTU	Remote terminal unit
VSI	Voltage source inverter
PWM	Pulse width modulation
BDC	Bidirectional converter
BC	Boost converter
AVR	Average voltage regulator
ER	Economic regulator
EQ	Equalizer
VSC	Voltage source converter
MPPT	Maximum power point tracking
B2B	Back to Back
VWDCMG	Voltage weak dc microgrid

List of Symbols

Symbols

A_{eq}	resistance matrix
A_{sys}	system matrix
B_{eq}	input column vector
f	objective function
C_4^a	filter capacitance of Conv-1 SOP
d^{stab}	output of POD
d_A	duty ratio of Conv-1 SOP
I_{dc}	DC current flowing through the line
I_{ac}	AC current flowing through the line
I_{pv}	output current of the PV panel
I_{pv}^a	output current of the PV system connected in feeder A
I_{sop}^a	output current of Conv-1 SOP
I_{sop}^b	output current of Conv-3 SOP
I_{sop}^c	output current of Conv-2 SOP
I_{bess}^a	output current of battery bank connected in feeder A
I_{bess}^b	output current of battery bank connected in feeder B
I_{bess}^c	output current of battery bank connected in feeder C
I_{43}^a	line current flowing from bus 4a to bus 3a of feeder a
NL	no. of loads
$OPMode$	operating mode of the SOP
P_{ext}	DC power input to the dc-link
P_{dc}	DC power output of the dc-link

Symbols

P_{loss}	power loss in the VSC
P_t	real power input to the LC filter
P_s	real power output of the LC filter
P^{stab}	input power to the POD
Q_s	reactive power output of the LC filter
R_d	droop coefficient
R_{eq}	Resistance matrix
$\mathbb{R}$	set of real numbers
SoC_{min}	minimum state of charge
SoC_{max}	maximum state of charge
w_c	filter cutoff frequency in rad/s
V_{DC}	DC voltage
V_{dc}	dc-link voltage
V_{ac}	AC voltage
α_1	weight of the objective function
α_2	weight of the objective function