

CONTROL, OPERATION AND PROTECTION OF LOW VOLTAGE DC SYSTEMS

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by

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to the



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Dedicated

to

My Father

CERTIFICATE

This is to certify that the thesis entitled “**Control, Operation and Protection of Low Voltage DC Systems**” submitted by **Ms. Vibhuti Nougain**, to Indian Institute of Technology Delhi for the award of degree of **Doctor of Philosophy (PhD)** is a bona fide record of research work carried out by her under my supervision. The contents of this thesis have not been submitted to any other institute or university for the award of any degree or diploma.

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Vibhuti Nougain

Abstract

Increasing share of direct current (DC) loads in the load profile across the world with high penetration of DC generating distributed energy resources integrated to the system with advanced power electronics devices has led to a focused discussion on LVDC system. This dissertation intends to contribute towards the same discussion showcasing the advantages of the LVDC systems.

LVDC is a challenging area of multidisciplinary research with research focus on (a) system configuration (constant power loads, DC cables, etc.), (b) power flow management, (c) converter control strategies, (d) integration of renewable energy sources, (e) storage operation in LVDC systems, (f) protection philosophy and so on, as discussed below.

- 1) System modelling, capacity, etc. are the questions related to system configuration which are application dependent. Therefore, preliminary steps include the study of various structural blocks to be utilized in DC system, their implementation, and operational constraints to develop the test system.
- 2) To regulate the DC system voltages, active power is the key indicator. An integrated power management strategy is developed to maintain power equilibrium. Various system transients such as load fluctuations, intermittent power due to uncertain weather conditions, accidental islanding, are arrested by local converter control of the corresponding sources. Event triggered communication signals are exchanged with power control unit to take control decisions in case of load shedding, autonomous mode of operation of storage units, and mode transition by grid connected voltage source converter.
- 3) Operation of battery energy storage systems (BESSs) are inevitable in the system with intermittent power sources. Interfacing the BESSs and to accommodate the operational constraints of batteries, a decentralized bi-directional converter control has been developed. Secondary control loop has two integrated loops, *P-loop* and *V-loop* working simultaneously as per the feedback due to system conditions. The default mode of operation for BESSs is power regulation but due to accidental grid disconnection, there is a smooth transition to voltage regulation mode.
- 4) Apart from operation and power management of LVDC systems, protection aspect of these systems is studied in detail. The information regarding the during fault topology has been analyzed and an equivalent RLC network is developed to study fault current

characteristics. Already available dedicated protection schemes are explored and are implemented on simulation platform to identify the literature gaps.

- 5) In case of DC faults, it is important to detect, identify and isolate the faulty segment without the intervention of converter's inherent protection. In case the protection scheme is not prompt enough, the converters block themselves leading to the disconnection of the sources. This de-energizes the complete system. To avoid this, a dedicated protection scheme to detect and isolate feeder faults in LVDC systems has been developed utilizing single-ended information.

Key words: LVDC system, Power Management, Bi-directional Converter Control, Battery Storage, LVDC Protection, DC-AC Converter Control.

सार

दुनिया भर में लोड प्रोफाइल में डायरेक्ट करंट (डीसी) लोड की बढ़ती हिस्सेदारी के साथ डीसी जनरेटिंग डिस्ट्रीब्यूटेड एनर्जी रिसोर्सेज को उन्नत पावर इलेक्ट्रॉनिक्स उपकरणों के साथ सिस्टम में एकीकृत करने से एलवीडीसी सिस्टम पर एक केंद्रित चर्चा हुई है। यह शोध प्रबंध LVDC प्रणालियों के लाभों को प्रदर्शित करते हुए उसी चर्चा में योगदान देने का इरादा रखता है।

LVDC बहु-विषयक अनुसंधान का एक चुनौतीपूर्ण क्षेत्र है जिसमें (ए) सिस्टम कॉन्फिगरेशन (निरंतर बिजली भार, डीसी केबल, आदि), (बी) बिजली प्रवाह प्रबंधन, (सी) कनवर्टर नियंत्रण रणनीतियों, (डी) नवीकरणीय ऊर्जा का एकीकरण पर ध्यान केंद्रित है। स्रोत, (ई) एलवीडीसी सिस्टम में भंडारण चालन, (एफ) सुरक्षा दर्शन पर चर्चा हुई है।

1) सिस्टम मॉडलिंग, क्षमता, आदि सिस्टम कॉन्फिगरेशन से संबंधित प्रश्न हैं जो एप्लिकेशन पर निर्भर हैं। इसलिए, प्रारंभिक कदमों में डीसी प्रणाली में उपयोग किए जाने वाले विभिन्न संरचनात्मक ब्लॉकों का अध्ययन, उनका कार्यान्वयन और परीक्षण प्रणाली विकसित करने के लिए परिचालन संबंधी बाधाएं शामिल हैं।

2) डीसी सिस्टम वोल्टेज को विनियमित करने के लिए, सक्रिय शक्ति प्रमुख संकेतक है। शक्ति संतुलन बनाए रखने के लिए एक एकीकृत बिजली प्रबंधन रणनीति विकसित की गई है। लोड में उतार-चढ़ाव, अनिश्चित मौसम की स्थिति के कारण रुक-रुक कर बिजली, आकस्मिक द्वीप, जैसे विभिन्न सिस्टम ट्रांज़िएंट को संबंधित स्रोतों के स्थानीय कनवर्टर नियंत्रण द्वारा गिरफ्तार किया जाता है। लोड शेडिंग, भंडारण इकाइयों के संचालन के स्वायत्त मोड, और ग्रिड से जुड़े वोल्टेज स्रोत कनवर्टर द्वारा मोड संक्रमण के मामले में नियंत्रण निर्णय लेने के लिए घटना ट्रिगर संचार संकेतों का आदान-प्रदान बिजली नियंत्रण इकाई के साथ किया जाता है।

3) रुक-रुक कर बिजली के स्रोतों के साथ सिस्टम में बैटरी एनर्जी स्टोरेज सिस्टम (बीईएसएस) का संचालन अपरिहार्य है। बीईएसएस का इंटरफेसिंग और बैटरी की परिचालन बाधाओं को समायोजित करने के लिए, एक विकेंद्रीकृत द्वि-दिशात्मक कनवर्टर नियंत्रण विकसित किया गया है। सेकेंडरी कंट्रोल लूप में दो एकीकृत लूप होते हैं, पी-लूप और वी-लूप सिस्टम स्थितियों के कारण फीडबैक के अनुसार एक साथ काम करते हैं। बीईएसएस के लिए ऑपरेशन का डिफॉल्ट मोड पावर रेगुलेशन है लेकिन आकस्मिक ग्रिड डिस्कनेक्शन के कारण वोल्टेज रेगुलेशन मोड में आसानी से संक्रमण होता है।

4) एलवीडीसी प्रणालियों के संचालन और बिजली प्रबंधन के अलावा, इन प्रणालियों के सुरक्षा पहलू का विस्तार से अध्ययन किया जाता है। ऊर्चिंग फॉल्ट टोपोलॉजी के बारे में जानकारी का विश्लेषण किया गया है और फॉल्ट करंट विशेषताओं का अध्ययन करने के लिए एक समान आरएलसी नेटवर्क विकसित किया गया है। पहले से ही उपलब्ध समर्पित सुरक्षा योजनाओं का पता लगाया गया है और साहित्य अंतराल की पहचान करने के लिए सिमुलेशन प्लेटफॉर्म पर लागू किया गया है।

5) डीसी दोषों के मामले में, कनवर्टर की अंतर्निहित सुरक्षा के हस्तक्षेप के बिना दोषपूर्ण खंड का पता लगाना, पहचानना और अलग करना महत्वपूर्ण है। यदि सुरक्षा योजना पर्याप्त रूप से त्वरित नहीं है, तो कन्वर्टर्स स्वयं को ब्लॉक कर देते हैं जिससे स्रोतों का वियोग हो जाता है। यह पूरे सिस्टम को डी-एनर्जेट करता है। इससे बचने के लिए, एलवीडीसी सिस्टम में फीडर दोषों का पता लगाने और उन्हें अलग करने के लिए एक समर्पित सुरक्षा योजना विकसित की गई है, जिसमें सिंगल-एंडेड जानकारी का उपयोग किया गया है।

कीवर्ड: एलवीडीसी सिस्टम, पावर मैनेजमेंट, द्वि-दिशात्मक कनवर्टर कंट्रोल, बैटरी स्टोरेज, एलवीडीसी प्रोटेक्शन, डीसी-एसी कन्वर्टर कंट्रोल।

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LIST OF ABBREVIATIONS AND SYMBOLS

LV, MV, HV DC	Low Voltage, Medium Voltage, High Voltage DC
SELV	Safety Extra Low Voltage
DER	Distributed Energy Resource
RES	Renewable Energy Source
CG	Conventional Grid
GIC	Grid Interfaced Converter
DG	Distributed Generation
PV	Photovoltaic
BESS	Battery Energy Storage System
LC	Local Controller
EMS	Energy Management System
SOC	State of Charge
VSC	Voltage Source Converter
IGBT	Insulated Gate Bipolar Transistor
PCU	Power Control Unit
IPMS	Integrated Power Management Scheme
IDA	Islanding Detection Algorithm
MPPT	Maximum Power Point Tracking
LFM	Load Following Mode
PRM/PCM	Power Regulation Mode/Power Control Mode
VRM/VCM	Voltage Regulation Mode/Voltage Control Mode
CCM	Constant Charging Mode
CDM	Constant Discharging Mode
ACK, RQST, DBLK	Acknowledge, Request, Deblock Signal
PI	Proportional plus Integral
USB	Universal Serial Bus
CPL	Constant Power Load
HIL	Hardware-in-the-loop
CHIL	Controller Hardware-in-the-loop
LBC	Low Bandwidth Communication
PWM	Pulse Width Modulated
PHF	Power Harmonic Filter

RTDS	Real-time Digital Simulator
NREL	National Renewable Energy Laboratory, Department of Energy, U.S.
EPRI	Energy Power Research Institute
TERI	The Energy Research Institute
IEC	International Electrotechnical Commission
BIS	Bureau of Indian Standards
LUT	Lappeenranta-Lahti University of Technology
CB	Circuit Breaker
SSCB	Solid State CB
HCB	Hybrid CB
EMCB	Electromechanical CB
IED	Intelligent Electronic Device
MOV	Metal Oxide Varistor
PODV	Principle of Directionality Violation
POTV	Principle of Threshold Violation
XLPE	Cross linked Polyethylene
SNR	Signal to Noise Ratio
THD	Total Harmonic Distortion
FFT	Fast Fourier Transform
SOGI	Second Order Generalized Integrator
R_l, L_l	Line resistance, inductance
V_{MPP}, I_{MPP}	Maximum Power Point Voltage, Current
V_{PV}	Terminal Voltage of PV
V_{OC}	Open Circuit Voltage of PV
V_{bat}	Nominal Voltage of BESS
$P_{bat(LCBMS)}^*$	Reference power of BESS set by LCBMS
$P_{bat(PCU)}^*$	Reference power of BESS set by PCU
R_f	Fault Resistance
r_{ij}	Resistance monitored by IED_{ij}
$\hat{r}_{ij}$	Estimated value of r_{ij}
ξ	Damping Ratio
i_i	Current through inductor
i_o	Load Current

v_o	Load-end Voltage
u_i	Terminal Voltage of VSC
r_f, L_f	Filter resistance, inductance
R_o, L_o	Load resistance, inductance
“*”	Reference value of the respective variable
<i>Subscript dq</i>	Respective variable in dq frame of reference