TIME-COORDINATED DISTRIBUTED CONTROL STRATEGY FOR A LOW VOLTAGE ACTIVE DISTRIBUTION NETWORK

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by

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न गुरुर अधिकं तत्वं न गुरुर अधिक तपः ।
तत्व ज्ञानात परं नास्ति तस्मै श्री गुरवे नमः ॥

----- श्री गुरु स्तोत्रम्

No theory is more than the Master, No spiritual Work is more than the Master, There is nothing beyond deep knowledge, but there is Master whom we pray.

----- Shri Guru Strotram

CERTIFICATE

This is to certify that the thesis entitled **'Time-Coodinated Distributed Control Strategy For A Low Voltage Active Distribution Network'**, being submitted by **Mr. Manas Ranjan Mishra** to **Indian Institute of Technology, Delhi** is a record of bonafide research work carried out under my supervision and I consider it worthy for consideration of the award of the degree **Doctor of Philosophy** in Electrical Engineering. The results obtained here have not been submitted to any other University or Institute for the award of any degree or diploma.

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— Manas Ranjan Mishra

Abstract

Gradual increasing installation of solar photovoltaic inverters (SPVIs) at the low voltage (LV) network causes over-voltage issues at the SPVI-connected point-of-common-couplings (PCCs) during high irradiance period. The over-voltage issue at the point-of-common-couplings (PCCs) occur due to the inherent radial nature of the distribution network, and it further degrades the Voltage regulation (VR) of the Distribution Transformer (DT). To mitigate the over-voltage in the network, IEEE 1547 recommends the constant QV-droop and PV-droop characteristics in the SPVIs. Due to the high R/X ratio of the lines, active power curtailment (APC) occurs at the SPVIs due to the PV droop. Further, unplanned and dramatically increasing trends in the single-phase converter (SPC) deployment significantly impacts on phase voltage unbalance factor (PVUF) and voltage regulation (VR) of the LV-ADS. High PVUF at the buses may lead to the tripping of SPVIs and poor voltage regulation at the DT.

This thesis focuses on developing novel control strategies for SPVIs and SPCs. A new control philosophy has been formulated in the thesis to minimize the APC issue among the SPVIs. Further, in this thesis, a novel algorithm is formulated to mitigate the over-voltage issue in SPC and SPVI-dominated LV-ADS. To address the above-mentioned issues, an irradiance driven adaptive PQV (IAPQV) droop mechanism is formulated to resolve using the distributed control approach. The IAPQV proposes irradiance driven QV-Droop and PV-Droop to improve voltage regulation in the ADS. In the latter part of the thesis, a time-coordinated leader-follower feedback-based algorithm (CLFFA) is formulated to operate the SPVIs and SPCs. CLLFA is orchestrated in a time-graded approach to reduce the PVUF and improve the VR in the LV-ADS. Both the formulations, IAPQV and CLFFA use a smart and novel cluster selection algorithm (CSA). The basic aim of CSA formulation is to optimally choose a portion of the network that requires attention a priori in terms of PVUF or VR.

Since the IAPQV and CLFFA control methodology makes use of the communication links between SPVIs and SPCs, the resiliency of the links becomes extremely important from both the perspective of utility and prosumer. Hence, to operate these power infrastructures in an efficient

and reliable manner, cooperative/distributed control is incorporated as a control solution. The communication medium is an inherent infrastructure to exhibit cooperative control in microgrids. The measurement states are communicated using the medium. Thereby, the states communicated come under the realm of the attacker. Voltage of the converters in grid-connected/islanded microgrids is one such state that may be vulnerable to cyber attack. Hence, the last part of the thesis details an event-driven resilient control strategy to detect and mitigate such attacks.
Key Words: Single-phase converter, three-phase converter, droop, adaptive, voltage regulation, voltage unbalance.

साराश

निम्न वोल्टेज (LV) नेटवर्क में सौर फोटोवोल्टिक इनवर्टर्स (SPVIs) की लगातार बढ़ती स्थापना, उच्च विकिरण अवधि के दौरान SPVI से जुड़े बिंदु-सामान्य-संयोजन (PCCs) पर ओवर-वोल्टेज समस्या उत्पन्न करती है। वितरण नेटवर्क की अंतर्निहित रेडियल प्रकृति के कारण PCCs पर ओवर-वोल्टेज समस्या होती है, जो वितरण ट्रांसफार्मर (DT) के वोल्टेज विनियमन (VR) को और भी खराब करती है। नेटवर्क में ओवर-वोल्टेज को कम करने के लिए, IEEE 1547 SPVIs में स्थिर QV-ड्रूप और PV-ड्रूप विशेषताओं की अनुशंसा करता है। उच्च R/X अनुपात के कारण PV ड्रूप की वजह से SPVIs पर सक्रिय पावर कटौती (APC) होती है। इसके अलावा, सिंगल-फेज़ कन्वर्टर (SPC) की अनियोजित और अत्यधिक बढ़ती प्रवृत्ति चरण वोल्टेज असंतुलन कारक (PVUF) और LV-ADS के वोल्टेज विनियमन (VR) पर महत्वपूर्ण प्रभाव डालती है। बसों पर उच्च PVUF SPVIs के ट्रिपिंग और DT पर खराब वोल्टेज विनियमन का कारण बन सकती है।

यह शोध SPVIs और SPCs के लिए नवीन नियंत्रण रणनीतियों के विकास पर केंद्रित है। इस शोध में SPVIs के बीच APC समस्या को कम करने के लिए एक नया नियंत्रण दृष्टिकोण तैयार किया गया है। इसके अतिरिक्त, SPC और SPVI-प्रधान LV-ADS में ओवर-वोल्टेज समस्या को कम करने के लिए एक नया एल्गोरिद्म तैयार किया गया है। उपरोक्त मुद्दों को हल करने के लिए, एक विकिरण-निर्देशित अनुकूली PQV (IAPQV) ड्रूप तंत्र तैयार किया गया है, जो वितरित नियंत्रण दृष्टिकोण का उपयोग करता है। IAPQV वोल्टेज विनियमन में सुधार के लिए ADS में विकिरण-निर्देशित QV-ड्रूप और PV-ड्रूप का प्रस्ताव करता है। शोध के बाद के भाग में, SPVIs और SPCs के संचालन के लिए एक समन्वित नेता-अनुयायी प्रतिक्रिया-आधारित एल्गोरिद्म (CLFFA) तैयार किया गया है। CLFFA को समय-क्रमबद्ध तरीके से PVUF को कम करने और LV-ADS में VR में सुधार करने के लिए व्यवस्थित किया गया है। दोनों IAPQV और CLFFA स्मार्ट और नवीन क्लस्टर चयन एल्गोरिद्म (CSA) का उपयोग करते हैं। CSA का मुख्य उद्देश्य PVUF या VR के संदर्भ में नेटवर्क के उस हिस्से को चुनना है, जिसमें पहले से ध्यान देने की आवश्यकता है।

चूंकि IAPQV और CLFFA नियंत्रण पद्धतियां SPVIs और SPCs के बीच संचार लिंक का उपयोग करती हैं, इसलिए इन लिंक की लचीलापन उपयोगिता और उपभोक्ता दोनों के दृष्टिकोण से अत्यधिक महत्वपूर्ण हो जाती है। इसलिए, इन ऊर्जा संरचनाओं को कुशल और विश्वसनीय तरीके से संचालित करने के लिए सहकारी/वितरित नियंत्रण को एक समाधान के रूप में शामिल किया गया है। माइक्रोग्रिड में सहकारी नियंत्रण प्रदर्शित करने के लिए संचार माध्यम एक अंतर्निहित संरचना है। माप राज्यों को इस माध्यम का उपयोग करके संचारित किया जाता है, जिससे वे हमलावरों के लिए संवेदनशील बन जाते हैं। माइक्रोग्रिड में कन्वर्टर्स के वोल्टेज ऐसे राज्य हैं जो साइबर हमले के प्रति कमजोर हो सकते हैं। इसलिए, शोध के अंतिम भाग में, इस प्रकार के हमलों का पता लगाने और उन्हें कम करने के लिए एक इवेंट-आधारित लचीली नियंत्रण रणनीति का विवरण दिया गया है।

मुख्य शब्द: सिंगल-फेज़ कन्वर्टर, थ्री-फेज़ कन्वर्टर, ड्रूप, अनुकूली, वोल्टेज विनियमन, वोल्टेज असंतुलन।

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Nomenclature

Acronyms/Abbreviations

APC Active Power Curtailment

CLFFA Coordinated Leader-Follower Feedback-Based Algorithm

CLFFA Coordinated Leader-Follower Feedback-based Algorithm

CSA Cluster Selection Algorithm

DA Data Aggregator

DB Dead Band

DT Distribution Transformer

HESS Hybrid Energy Storage System

IAPQV Irradiance Adaptive PQV Droop

LV-ADS Low Voltage Active Distribution System

LVUF Local Voltage Unbalance Factor

NREL National Renewable Energy Laboratory

OLTC On-Load Tap Changer

PCC Point-of-Common-Coupling

PV Active Power Droop (Volt-Watt)

PVUF Phase Voltage Unbalance Factor

QV Reactive Power Droop (Volt-Var)

R/X Resistance to Reactance Ratio

RMS Root Mean Square

RPS Reactive Power Support

SCB Switched Capacitor Bank

SM Smart Meter

SPC Single-Phase Converter

SPVI Solar Photovoltaic Inverter

TBP Two-Bit Priority

TPC Three-Phase Converter

UFQ Unutilized Reactive Power Ratio

VR Voltage Regulation