ADAPTIVE CONTROL STRATEGIES FOR RESILIENT OPERATION OF GRID INTERFACED SOLAR ENERGY CONVERSION SYSTEM ENABLING POWER QUALITY IMPROVEMENT

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by

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Dedicated to

My family and all the teachers whom I came across at different stages during my life.

CERTIFICATE

It is certified that the thesis entitled "**Adaptive Control Strategies for Resilient Operation of Grid Interfaced Solar Energy Conversion System Enabling Power Quality Improvement**," being submitted by **Mr. Priyank Mukeshkumar Shah** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

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PRIYANK SHAH

ABSTRACT

The usage of fossil fuels is responsible for environmental issues such as green-house gas, acid rain and deteriorates the ozone layer, which captures the world's attention towards non-conventional green energy sources. Of different non-conventional energy sources such as solar energy, wind energy, tidal and biomass energy, the solar photovoltaic system based technology has proved a breakthrough in the field of distributed power generation due to having technological advancement, ease of installation, low maintenance, clean nature, freely available, noiseless and non-polluting nature.

The grids of developing and underdeveloped countries are generally weak, unreliable, and have a poor power quality. Therefore, integration of solar energy conversion system (SECS) to the grid is facing extra challenges, apart from usual power quality challenges. Different challenges can identified as the system operation during weak distribution grids, operation during the shunt faults in grid side network, operation during sensor malfunctioning events, system capability to provide inertia to the grid and to eliminate the grid leakage currents. This research work is aimed at addressing the aforementioned challenges, without compromising the grid power quality.

Firstly, the performance of a SECS is analyzed under weak distribution grid scenarios such as distorted grid voltages, unbalanced grid voltages, voltage sags and voltage swells. An adaptive control strategy is presented to resolve these issues and compel the distribution grid to follow the IEEE-519-2014 and IEEE-1547 grid codes. Secondly, the problem of disconnection of SECS system from the grid under grid shunt-faults, voltage flickers, power outages is addressed, by derating the solar photovoltaic (PV) operating point and supplying the deficit reactive power as per the country grid-codes to the grid to assist the grid stability. The maximum permissible active power is curtailed and the peak current rating of the voltage source converter is inherently incorporated into the control strategy to keep the operating point within a safe operating region. Thirdly, the leakage currents caused due to large parasitic capacitance formed in solar PV array, are mitigated by controlling common-mode voltage of PV coupled voltage source converter (VSC) system. The typical value of leakage current is maintained within 300 mA as per VDE-00126 standard even under the presence of nonlinear load, without compromising with the grid harmonic current limits. Thus, the life-time of the solar PV panel is increased and mal-operation of the neutral current protection scheme is avoided. Fourthly, improvement in the frequency response of renewable energy

based distribution system is contemplated, by providing virtual inertia to the system. A virtual induction generator concept is introduced to not only assist the grid by providing inertia, but also to eliminate the usage of phase locked loops during grid synchronization. Therefore, the solar PV coupled voltage source converter behaves as a virtual induction generator along with self-synchronizing capability. It is capable to operate under grid interfaced mode as well as islanded mode without control reconfiguration. The dependency on phase-locked loop and requirement of proportional-integral controller are totally waived-off. Finally, a robust solar PV system is proposed, which can withstand the malatious attacks caused in the system. As the attacker injects malicious data into the receiver, the system performance is degraded and leads to unstable operation of SECS. An adaptive control is proposed under malicious attacks in phase currents, such as false data injection, DC bias injection, replay attack and denial-of-service.

The proposed solution to the various challenges aforementioned, are implemented and tested in MATLAB/ Simulink software. These are further validated through different experiments, carried out on a developed laboratory protype using d-SPACE interface. This work is expected to provide a good acquaintance in developing multi-objective solar energy conversion systems with robust and reliable performance throughout the operation.

सार

जीवाश्म ईंधन का उपयोग ग्रीन-हाउस गैस, एसिड वर्षा जैसे पर्यावरणीय मुद्दों के लिए जिम्मेदार है और ओजोन परत को खराब करता है, जो गैर-पारंपरिक हरित ऊर्जा स्रोतों की ओर दुनिया का ध्यान आकर्षित करता है। विभिन्न गैर-पारंपरिक ऊर्जा स्रोतों जैसे कि सौर ऊर्जा, पवन ऊर्जा, ज्वार और बायोमास ऊर्जा, सौर फोटोवोल्टिक प्रणाली आधारित तकनीक ने तकनीकी प्रगति, स्थापना में आसानी, कम रखरखाव के कारण वितरित बिजली उत्पादन के क्षेत्र में एक सफलता साबित की है। स्वच्छ प्रकृति, स्वतंत्र रूप से उपलब्ध, नीरव और प्रदूषण रहित प्रकृति।

विकासशील और अविकसित देशों के ग्रिड आम तौर पर कमजोर, अविश्वसनीय और खराब बिजली की गुणवत्ता वाले होते हैं। इसलिए, ग्रिड को सौर ऊर्जा रूपांतरण प्रणाली (एसईसीएस) के एकीकरण से सामान्य बिजली की गुणवत्ता की चुनौतियों के अलावा, अतिरिक्त चुनौतियों का सामना करना पड़ रहा है। अलग-अलग चुनौतियों को कमजोर वितरण ग्रिड के दौरान सिस्टम ऑपरेशन, ग्रिड साइड नेटवर्क में शंट दोष के दौरान ऑपरेशन, सेंसर में खराबी की घटनाओं के दौरान संचालन, ग्रिड में जड़ता प्रदान करने के लिए सिस्टम क्षमता और ग्रिड रिसाव धाराओं को खत्म करने के लिए पहचाना जा सकता है। यह शोध कार्य ग्रिड बिजली की गुणवत्ता से समझौता किए बिना, उपरोक्त चुनौतियों को संबोधित करने के उद्देश्य से है।

सबसे पहले, एसईसीएस के प्रदर्शन का विश्लेषण कमजोर वितरण ग्रिड परिदृश्यों जैसे कि विकृत ग्रिड वोल्टेज, असंतुलित ग्रिड वोल्टेज, वोल्टेज सैग और वोल्टेज स्वेल के तहत किया जाता है। इन मुद्दों को हल करने और आईईईई-519-2014 और आईईईई-1547 ग्रिड कोड का पालन करने के लिए वितरण ग्रिड को मजबूर करने के लिए एक अनुकूली नियंत्रण रणनीति प्रस्तुत की जाती है। दूसरे, ग्रिड शंट-फॉल्ट, वोल्टेज फ़्लिकर, पावर आउटेज के तहत ग्रिड से सिस्टम के डिस्कनेक्शन की समस्या, सौर फोटोवोल्टिक संचालन बिंदु को बंद करके और देश ग्रिड-कोड के अनुसार घाटे प्रतिक्रियाशील की आपूर्ति करके। ग्रिड ग्रिड स्थिरता की सहायता के लिए। अधिकतम अनुमेय सक्रिय शक्ति पर अंकुश लगाया जाता है और वोल्टेज स्रोत कनवर्टर की चरम वर्तमान रेटिंग को एक सुरक्षित ऑपरेटिंग क्षेत्र के भीतर ऑपरेटिंग बिंदु रखने के लिए नियंत्रण रणनीति में स्वाभाविक रूप से शामिल किया जाता है। तीसरी बात, सौर पीवी सरणी में बने बड़े परजीवी समाई के कारण रिसाव की धाराएं, पीवी युग्मित वोल्टेज स्रोत कनवर्टर प्रणाली के सामान्य-मोड वोल्टेज को नियंत्रित करके कम कर दी जाती हैं। लीकेज करंट का विशिष्ट मूल्य ग्रिड हार्मोनिक वर्तमान सीमाओं के साथ समझौता किए बिना, नॉनलाइन

लोड की उपस्थिति के तहत विदीई-00126 मानक के अनुसार 300 एमए के भीतर बनाए रखा जाता है। इस प्रकार, सौर पीवी पैनल का जीवन-काल बढ़ा दिया जाता है और तटस्थ वर्तमान सुरक्षा योजना के संचालन से बचा जाता है। चौथा, नवीकरणीय ऊर्जा आधारित वितरण प्रणाली की आवृत्ति प्रतिक्रिया में सुधार प्रणाली को आभासी जड़ता प्रदान करने पर विचार किया गया है। एक आभासी इंडक्शन जनरेटर अवधारणा को केवल जड़ता प्रदान करके ग्रिड की सहायता करने के लिए नहीं, बल्कि ग्रिड सिंक्रोनाइज़ेशन के दौरान चरण बंद लूप के उपयोग को समाप्त करने के लिए पेश किया जाता है। इसलिए, सौर पीवी युग्मित वोल्टेज स्रोत कनवर्टर आत्म-सिंक्रनाइज़िंग क्षमता के साथ एक आभासी प्रेरण जनरेटर के रूप में व्यवहार करता है। यह नियंत्रण पुनर्संरचना के बिना ग्रिड इंटरफ़ेड मोड के साथ-साथ द्वीप मोड के तहत संचालित करने में सक्षम है। चरण-बंद लूप पर निर्भरता और आनुपातिक-अभिन्न नियंत्रक की आवश्यकता पूरी तरह से छूट दी गई है। अंत में, एक मजबूत सौर पीवी प्रणाली प्रस्तावित है, जो सिस्टम में होने वाले घातक हमलों का सामना कर सकती है। जैसा कि हमलावर दुर्भावनापूर्ण डेटा को रिसीवर में इंजेक्ट करता है, सिस्टम प्रदर्शन को नीचा दिखाया जाता है और के अस्थिर संचालन की ओर जाता है। चरण धाराओं में दुर्भावनापूर्ण हमलों के तहत एक अनुकूली नियंत्रण प्रस्तावित है, जैसे कि झूठे डेटा इंजेक्शन, डीसी पूर्वाग्रह इंजेक्शन, रिप्ले हमले और इनकार-की-सेवा। उपर्युक्त विभिन्न चुनौतियों का प्रस्तावित समाधान MATLAB/Simulink सॉफ़्टवेयर में लागू और परीक्षण किया गया है। डी-स्पेस इंटरफेस का उपयोग करके एक विकसित प्रयोगशाला प्रोटोटाइप पर किए गए इन प्रयोगों को अलग-अलग प्रयोगों के माध्यम से मान्य किया गया है। यह कार्य पूरे ऑपरेशन के दौरान मजबूत और विश्वसनीय प्रदर्शन के साथ बहु-उद्देश्य सौर ऊर्जा रूपांतरण प्रणाली विकसित करने में एक अच्छा परिचित प्रदान करने की उम्मीद है।

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PV	Photovoltaic
PQ	Power Quality
GHGs	Green House Gases
SECS	Solar Energy Conversion System
MPPT	Maximum Power Point Tracking
PID	Proportional Integral Derivative
VIG	Virtual Induction Generator
VSC	Voltage Source Converter
CSC	Current Source Converter
SECS	Solar Energy Conversion System
H7	H-Bridge 7 Switches
H8	H-Bridge 8 Switches
JNNSM	Jawaharlal Nehru National Solar Mission
AD	Accelerated Depreciation
GBI	Generation Based Incentives
RPO	Renewable Purchase Obligations
RECs	Renewable Energy Certificates
MPC	Model Predictive Controller
ILST	Improved Linear Sinusoidal Tracer
LMF	Least Mean Fourth
SOGI-FLL	Second Order Generalized Integrator With Frequency Locked
SRF	Synchronous Reference Frame
SOGI	Second Order Generalized Integrator
HERIC	Highly Efficient And Reliable Inverter Concept
PSS	Power System Stabilizer
KLD	Kullback-Leibler Distance
MILP	Mixed Integer Linear Programming
GAN	Generative Adversarial Network
IGBT	Insulated Gate Bi-Polar Transistor
ZCD	Zero Crossing Detector

DAC	Digital To Analog
DRAM	Dynamic Random Access Memory
SPG	Solar Power Generation
R.M.S	Root Mean Square
SPVA	Solar Photovoltaic Array
NNP	Ne Nominal Point
LVRT	Low Voltage Ride Through
CCP	Common Coupling Point
CM	Common Mode
DM	Differential Mode
PLL	Phase Locked Loop
LMI	Linear Matrix Inequality
DSP	Digital Signal Processor

LIST OF SYMBOLS

V_{DC}	DC bus voltage of voltage source converter
C_{DC}	DC bus capacitance of voltage source converter
a	Over loading factor
P_{pv}	Solar power generation
f_{sw}	Switching frequency
v_{sabc}	Line voltage of the grid
i_{sabc}	Three phase grid currents
i_{Labc}	Three phase line currents
i_{vsc}	Three phase currents of the voltage source converter
D	Duty ratio
I_{pa}	Magnitude of fundamental load component
I_{loss}	Loss component
I_{pvff}	Solar photovoltaic feed-forward component
I_{load}	Load component
I_{net}	Total amplitude of reference grid currents
$i_{ref\text{-}abc}$	Three phase reference grid currents
L	Interfacing inductor of voltage source converter
$L_{vsc\text{-}n}$	Interfacing inductor of fourth leg of voltage source converter
V_{pv}	Solar PV array voltage
I_{pv}	Solar PV array current
V_t	Terminal voltage of common coupling point
u_{pabc}	In-phase unit templates
u_{qabc}	Quadrature unit templates
Γ	Gain of frequency locked loop
k_{DC}	Gain if DC control loop of generalized integrator
ω	System frequency
v_{pabc}	Positive sequence of phase voltages
P_s	Active power in the grid
Q_s	Reactive power in the grid
P_{vig}	Active power of virtual induction generator

Q_{vig}	Reactive power of virtual induction generator
i_{vim}	Three phase currents of virtual induction generator
$i_{1\alpha\beta}$	Fundamental component of load component
P_{neg}	Negative sequence power
P_{zero}	Zero sequence power
I_{leak}	Leakage current
C_{pv}	Parasitic capacitance
S_{enable}	Enabling signal
S	Apparent power of voltage source converter
P_{max}	Maximum permissible active power
V_{CM}	Common mode voltage
V_{ABCN}	Three phase pole voltage
θ_{oab}	Phase shift of virtual induction generator
θ_{gab}	Phase shift of grid
T_e	Electrical torque of virtual induction generator
$\Delta\omega_r$	Fluctuation in rotor speed of virtual induction generator
ω_v	Slip speed of virtual induction generator
S_{gain}	Synchronization gain
f_d	Attack signal in direct axis
$\hat{f}_d$	Estimated Attack signal in direct axis
f_q	Attack signal in quadrature axis
$\hat{f}_q$	Estimated Attack signal in quadrature axis
m_{abc}	Modulation signals
i_{dq}^{inj}	Processed current component in direct and quadrature axis
i_{grid}^{sensed}	Received data of grid currents