DESIGN, DEVELOPMENT AND CONTROL OF MULTIFUNCTIONAL GRID INTERFACED SOLAR PV SYSTEMS AND BATTERY ENERGY STORAGE BASED MICROGRIDS WITH GRID SUPPORTIVE FEATURES

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by

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CERTIFICATE

It is certified that the thesis entitled "**Design, Development and Control of Multifunctional Grid Interfaced Solar PV Systems and Battery Energy Storage Based Microgrids With Grid Supportive Features**," being submitted by **Mr. Syed Bilal Qaiser Naqvi** 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's 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.

Dated:

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Dated:

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ABSTRACT

This work aims to propose multiple solutions to address various challenges associated with integrating PV generation systems into modern low voltage distribution networks. Various configurations of grid interfaced multifunctional PV units are presented, and associated control algorithms are developed. Grid voltages in distribution network are prone to being unbalanced and distorted. An accurate phase angle of grid voltages is necessary for grid synchronized operation, otherwise stability and power quality (PQ) issues arise. In this work, multiple new filters are developed, analyzed and compared with reported filters, and provide better removal of defects in sensed grid voltages such as harmonics components, unbalance and DC offset. Using developed control mechanisms, system has a capability of grid interconnection at weak grid conditions, and continues feeding balanced, and sinusoidal currents to the grid.

Local loads present at point of common coupling (PCC) are nonlinear, which draw reactive power, neutral current, harmonics currents, and unbalanced power from grid. The system is suitably controlled by advanced control algorithms, to mitigate the impact of such loads on the grid. Conventionally, the regulation of the DC link voltage of the voltage source converter (VSC) interfacing the PV array with the PCC, is used to achieve power balance, and control grid currents. However, the dynamic performance at changing PV array power or varying local loads, is not satisfactory. The response in grid currents, to changes on the PV side and grid voltage variations, is expedited using a PV feed forward term. Similarly, an estimate of the load current is made, and used to hasten system response to load changes. In the reported methods to estimate load, a vulnerability is found, which is the poor performance in the presence of impulsive noise. In this work, the significance of local load current weight estimation is underlined, in conditions where the DC link voltage is liable to have ripples due to unbalanced VSC currents, and a mechanism is implemented to make the estimation robust against impulsive environment or sensor noise.

A single stage PV system involves direct coupling of PV array with the DC link of the grid interfaced VSC. While an intermediate stage is avoided, the control of DC link voltage is constrained to track the maximum power point (MPP) voltage of the PV array. In conventional single stage system, this causes PQ issues at conditions such as low irradiance and grid overvoltage, when the DC link voltage is less than required to properly control grid currents. A flexible mechanism for the control of DC link voltage for a single stage system is presented in this work, which rectifies the PQ issues, maintains desired modulation index of VSC, and reduces operating losses. The presented control also enables deliberate de-rating of PV array power during voltage dips to limit grid currents and mitigate overcurrent tripping issues, ensuring continued current injection to support the grid. During voltage rises, the de-rated PVA power helps prevent further deterioration of utility network conditions, by lessening or eliminating the power outflow to the grid.

The challenges faced by utilities in accommodating significant amounts of intermittent power from local distributed PV generation units are also addressed. The lack of control over the PV array power production makes it difficult to match the real time supply against demand, which causes voltage regulation problems of undervoltage (UV) and overvoltage (OV) as well. Moreover, the time of availability of PV power causes large variations between the amount of power the utility is required to supply throughout the day, causing increased reliance on peak power plants which are often diesel run. Hence, buffering energy storage is required for easing such issues, and to allow for further penetration of PV units. However, it is seen that the utilization of battery energy storage (BES) is limited in the reported PV-BES systems.

The developed control strategy leverages the BES to achieve several operational benefits. It eliminates grid power fluctuations caused by variations in PV array output and local load demand. The injected grid power is dynamically adjusted based on prevailing feed-in tariffs, maximizing economic benefits and contributing to demand-side power curve flattening. There is a provision to import and store power from the grid at lower rates. Unlike conventional systems, it prevents tripping during significant voltage drops, ensuring continued support to the utility even when PV power production is absent. Additionally, no de-rating of PV array is required. During overvoltage conditions, the system aids the utility by halting power export while allowing power import as needed. Furthermore, the BES health is preserved by transitioning to a recovery mode upon detecting over-charge or over-discharge conditions.

Proposed solutions are developed for three phase three wire and three phase four wire system configurations, with two stage and single stage implementations. The system and associated developed control strategies are modelled and simulated using MATLAB SIMULINK platform and evaluated using tests performed on a developed hardware prototype at various challenging use cases. The PQ compliance with IEEE 519 and IEEE 1547 standards is verified.

सार

यह शोध कार्य आधुनिक लो वोल्टेज डिस्ट्रीब्यूशन नेटवर्क में फोटावोल्टिक (PV) जनरेशन सिस्टम्स के एकीकरण से जुड़ी विभिन्न चुनौतियों के समाधान हेतु कई विकल्प प्रस्तुत करता है। ग्रिड-इंटरफेस्ड मल्टीफंक्शनल PV यूनिट्स के विभिन्न कॉन्फ़िगरेशन प्रस्तुत किए गए हैं, और उनके लिए उपयुक्त कंट्रोल एल्गोरिद्म विकसित किए गए हैं। डिस्ट्रीब्यूशन नेटवर्क में ग्रिड वोल्टेज सामान्यतः असंतुलित और विकृत होते हैं। ग्रिड-सिंक्रोनाइज़्ड ऑपरेशन के लिए वोल्टेज का सटीक फेज एंगल आवश्यक होता है, अन्यथा स्टेबिलिटी और पावर क्वालिटी (PQ) की समस्याएं उत्पन्न होती हैं। इस कार्य में कई नए फिल्टर्स विकसित किए गए हैं, जिनका विश्लेषण और तुलना पूर्ववर्ती रिपोर्टेड फिल्टर्स से की गई है, और ये सेंस किए गए ग्रिड वोल्टेज से हार्मोनिक्स, अनबैलेंस, और DC ऑफ़सेट जैसी खराबियों को अधिक प्रभावी ढंग से हटाते हैं। विकसित नियंत्रण विधियों की सहायता से यह सिस्टम वीक ग्रिड कंडीशन्स में भी ग्रिड इंटरकनेक्शन करने में सक्षम है, और संतुलित, साइनसॉइडल करंट्स ग्रिड को देता रहता है।

पॉइंट ऑफ कॉमन कपलिंग (PCC) पर मौजूद लोकल लोड्स सामान्यतः नॉन-लिनियर होते हैं, जो ग्रिड से रिएक्टिव पावर, न्यूट्रल करंट, हार्मोनिक करंट्स और अनबैलेंस्ड पावर लेते हैं। इस प्रभाव को कम करने के लिए सिस्टम को उन्नत कंट्रोल एल्गोरिद्म द्वारा नियंत्रित किया गया है। परंपरागत रूप से, PV ऐरे और PCC के बीच इंटरफेसिंग वोल्टेज सोर्स कन्वर्टर (VSC) के DC लिंक वोल्टेज को नियंत्रित करके पावर बैलेंसिंग और ग्रिड करंट कंट्रोल प्राप्त किया जाता है। हालांकि, PV पावर में बदलाव या लोकल लोड वेरिएशन के समय सिस्टम की डायनामिक परफॉर्मेंस संतोषजनक नहीं रहती। इस शोध में, PV फीड फॉरवर्ड टर्म और लोड करंट का इस्टीमेशन जोड़कर ग्रिड करंट की प्रतिक्रिया को तेज किया गया है। पहले से रिपोर्टेड लोड इस्टीमेशन मेथड्स में इम्पल्सिव नॉइज़ की उपस्थिति में परफॉर्मेंस खराब पाई गई है। इस कार्य में, ऐसी स्थितियों में जहाँ DC लिंक वोल्टेज में रिपल्स उत्पन्न होते हैं, एक मजबूत और नॉइज़-रोबस्ट इस्टीमेशन मेथड प्रस्तावित की गई है।

सिंगल स्टेज PV सिस्टम में PV ऐरे को सीधे ग्रिड-इंटरफेस्ड VSC के DC लिंक से जोड़ा जाता है। इसमें कोई मध्यवर्ती चरण नहीं होता, और DC लिंक वोल्टेज को मैक्सिमम पावर पॉइंट (MPP) वोल्टेज के साथ ट्रैक करना होता है। परंपरागत सिंगल स्टेज सिस्टम्स में, लो इर्रैडिएंस और ग्रिड ओवरवोल्टेज जैसी स्थितियों में DC लिंक वोल्टेज पर्याप्त नहीं होता जिससे PQ इश्यूज़ आते हैं। इस कार्य में एक फ्लेक्सिबल DC लिंक वोल्टेज कंट्रोल मेकैनिज़्म प्रस्तावित की गई है जो PQ समस्याओं को सुलझाती है, VSC के डिज़ायर्ड

मॉड्यूलेशन इंडेक्स को बनाए रखती है और ऑपरेटिंग लॉसेज़ को घटाती है। यह कंट्रोल सिस्टम वोल्टेज डिप्स के समय जानबूझकर PV पावर डी-रेट कर सकता है ताकि ओवरकरंट ट्रिपिंग से बचा जा सके, और ग्रिड को निरंतर सपोर्ट मिलता रहे। वोल्टेज राइज़ के दौरान, डी-रेटेड PV पावर यूटिलिटी नेटवर्क कंडीशन को खराब होने से बचाने में सहायक होती है।

डिस्ट्रिब्यूटेड PV जनरेशन यूनिट्स से मिलने वाली अस्थिर शक्ति के कारण यूटिलिटीज को कई समस्याओं का सामना करना पड़ता है। PV ऐरे आउटपुट पर नियंत्रण का अभाव रियल टाइम डिमांड के साथ मिलान करना कठिन बनाता है, जिससे अंडरवोल्टेज (UV) और ओवरवोल्टेज (OV) जैसी समस्याएं आती हैं। साथ ही, PV पावर की उपलब्धता का समय यूटिलिटी के पूरे दिन की पावर डिलीवरी प्रोफाइल को प्रभावित करता है, जिससे पीक पावर प्लांट्स (अक्सर डीज़ल आधारित) पर निर्भरता बढ़ती है। इस स्थिति में एनर्जी स्टोरेज की आवश्यकता होती है ताकि PV की फर्दर पेनेट्रेशन संभव हो सके। हालांकि रिपोर्टेड PV-बैटरी एनर्जी स्टोरेज (BES) सिस्टम्स में BES का उपयोग सीमित रहा है।

इस कार्य में विकसित कंट्रोल स्ट्रैटेजी BES के जरिए कई ऑपरेशनल बेनिफिट्स प्राप्त करती है। यह PV आउटपुट और लोड डिमांड में उतार-चढ़ाव से उत्पन्न ग्रिड पावर फ्लक्चुएशन को समाप्त करती है। फीड-इन टैरिफ्स के अनुसार ग्रिड पावर का डायनामिक एडजस्टमेंट किया जाता है, जिससे आर्थिक लाभ होता है और डिमांड साइड पावर कर्व को फ्लैट किया जाता है। कम दर पर ग्रिड से पावर इम्पोर्ट करके स्टोर करना भी संभव होता है। यह प्रणाली अंडरवोल्टेज के समय भी ट्रिप नहीं करती, और तब भी यूटिलिटी सपोर्ट जारी रखती है जब PV पावर उपलब्ध नहीं होती। साथ ही, इसमें PV पावर को डी-रेट करने की आवश्यकता नहीं होती। ओवरवोल्टेज की स्थिति में, यह ग्रिड को पावर एक्सपोर्ट रोक देती है लेकिन ज़रूरत पड़ने पर पावर इम्पोर्ट की अनुमति देती है। इसके अलावा, BES की सेहत को बनाए रखने के लिए ओवरचार्ज या ओवर-डिस्चार्ज की स्थिति में यह रिकवरी मोड में चली जाती है।

प्रस्तावित समाधान थ्री-फेज थ्री-वायर और थ्री-फेज फोर-वायर कॉन्फ़िगरेशन के लिए, सिंगल स्टेज और टू-स्टेज इम्प्लीमेंटेशन के रूप में विकसित किए गए हैं। सिस्टम और संबंधित कंट्रोल विधियों का मॉडलिंग और सिमुलेशन MATLAB SIMULINK प्लेटफॉर्म पर किया गया है, और विकसित हार्डवेयर प्रोटोटाइप पर विभिन्न कठिन परिस्थितियों में परीक्षण द्वारा मूल्यांकन किया गया है। परिणामों की IEEE 519 और IEEE 1547 मानकों के अनुरूपता के संदर्भ में पुष्टि की गई है।

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LIST OF ABBREVIATIONS

ADC	Analog to digital converter
BDC	Bi-directional DC-DC converter
BES	Battery energy storage system
BPF	Band pass filter
CCF	Complex coefficient filter
CSOGI	Cascaded second order generalized integrator
CVF	Cascaded voltage filter
DAC	Digital to Analog converter
DSO	Digital storage oscilloscope
DSOGI	Dual second order generalized integrator
DSTATCOM	Distribution static compensator
EFGI	Enhanced filtering generalized integrator
ESOGI-APF	Enhanced SOGI all-pass filter
FiT	Feed-in tariff
FiT-MF	Feed-in tariff multiplying factor
FLL	Frequency locked loop
FRT	Fault ride through
GI	Generalized integrator
GIVF	Generalized integrator voltage filter
GVP	Grid voltage processing
INC	Incremental conductance
IGBT	Insulated gate bipolar transistor
LAF	Lorentzian adaptive filter
LMS	Least mean square
LPF	Low-pass filter
MDNLMS	Modified distributed NLMS
MPP	Maximum power point
MSOSF	Modified second order sequence filter
MSOGI-DCR	Multiple SOGI with DC offset rejection
MSTOGI	Mixed second and third order generalized integrator
NLMS	Normalized least mean square

NSOGI-FLL	Normalized SOGI-frequency locked loop
NTPG	Novel two-phase generator
OV	Overvoltage
PCC	Point of common coupling
PI	Proportional integral
PLL	Phase-locked loop
PQ	Power quality
PQA	Power quality analyzer
PSI	Pure sinusoidal integrator
PVA	Photovoltaic array
PVFF	PV feed forward
RES	Renewable energy sources
RPM	Regulated power mode
SCR	Short-circuit ratio
SECS	Solar energy conversion system
SF	Sequence filter
SRF	Synchronous reference frame
SOC	State of charge
SOGI	Second order generalized integrator
SOGI-WIF	SOGI with in-loop filter
SOGI-WPF	SOGI with prefilter
SOSF	Second order sequence filter
SRF	Synchronous reference frame
TF	Transfer function
THD	Total harmonics distortion
TLS	Total least squares
TOGI	Third-order generalized integrator
UV	Undervoltage
VPM	Variable power mode
VSC	Voltage source converter
VSS-NLMS	Variable step-size NLMS
ZCD	Zero crossing detector

LIST OF SYMBOLS

C_{dc}	DC link capacitance of the VSC
C_f	Ripple filter capacitance
D	Duty ratio for BDC
D_b	Duty ratio for boost converter
e_a	Error term in load weight estimation
e_{h1}	Error term in voltage filtering
FiT	Feed-in tariff
$FiT\text{-}MF$	Feed-in tariff multiplying factor
f_{swb}	Boost converter switching frequency
i^*_{ga}, i^*_{gb}, i^*_{gc}, i^*_{gn}	Reference waveforms for i_{ga}, i_{gb}, i_{gc}, i_{gn}
I_b	BES current
I_b^*	Reference BES current produced via PI controller
I_{bchr}, I_{bdis}	Currents for BES SOC recovery
I_{bref}	Final reference value of BES current
I_{dc}	Output of PI controller to maintain V_{dc} in VPM
i_{ga}, i_{gb}, i_{gc}, i_{gn}	Three phase grid currents and neutral current
i_{ih1}	In-phase fundamental frequency component of load currents
i_{La}, i_{Lb}, i_{Lc}, i_{Ln}	Three phase local load currents and load neutral current
I_{Lw}	Average value of load current weights
I_{pa}, I_{pb}, I_{pc}	Amplitudes of fundamental active load currents, and their average value
I_{pr}	Final reference weight of grid currents
I_{PV}	PV array current
I_{pvf}	PV feed-forward expression
I_{rpm}	Calculated reference weight of grid currents (For RPM operation)
I_{rpmf}	Final selected weight of grid currents (For RPM operation)
I_{sc}	PVA short circuit current
I_{vpm}	Reference weight of grid currents (for VPM)
i_{vsca}, i_{vscb}, i_{vscc}, i_{vscn}	Three phase VSC currents and VSC neutral current

L_b	Inductor for boost converter
L_{dc}	Inductor used in BDC
L_f	VSC interfacing inductor
m_i	VSC modulation index
P_g	Grid power
P_g	BES power
P_L	Local load power
P_{min}	Minimum PV array power threshold for transition between MPP tracking and flexible V_{dc} control
P_n	Nominal grid power
P_{PV}	PV array power
P_{PVR}	Rated PVA power
P_{set}	Defined grid power
R_f	Ripple filter resistance
SOC_b	BES state of charge
SOC_{bmax}	Upper limit for BES state of charge
SOC_{bmin}	Lower limit for BES state of charge
V^*_{dc}	Reference DC link voltage
V_{av}	Average amplitude of grid voltages
V_{avmax}	Upper limit of V_{av} for transition to flexible V_{dc} control
V_{avmin}	Lower limit of V_{av} for transition to flexible V_{dc} control
V_{avUV}, V_{avOV}	Lower and upper limits of V_{av} for I_{rpmf} selection
V_{dc}	DC link voltage
v_{ga}, v_{gb}, v_{gc}	Grid phase voltages
v_{gab}, v_{gbc}	Grid line voltages
v_{gaf}, v_{gbf}, v_{gcf}	Processed grid voltages
$v_{g\alpha}$, $v_{g\beta}$	Grid voltages in α-β domain
$v_{g\alpha f}$, $v_{g\beta f}$	Processed grid voltages in α-β domain
v_i, v_{dc}	Input signal for voltage filter and its DC offset
v_{ihn}, v_{qhn}	In-phase and quadrature voltage outputs of voltage filter for n^{th} harmonic component
V_{MPP}	PV array maximum power point voltage
V_{oc}	PV array open circuit voltage

v_{pa}, v_{pb}, v_{pc}	In-phase unit templates
V_{PV}	PV array voltage
v_{qa}, v_{qb}, v_{qc}	Quadrature phase unit templates
β	Constant used in calculation of V^*_{dc}
$\Delta\omega$	Frequency update term (rad/s)
ε	Constant added to prevent division by zero in DNLMS
λ	LAF constant which selects sensitivity level to impulsive noise
μ	Learning rate for load weight estimation technique
ρ	Gain used in frequency locked loop
ω	Grid voltage frequency (rad/s)