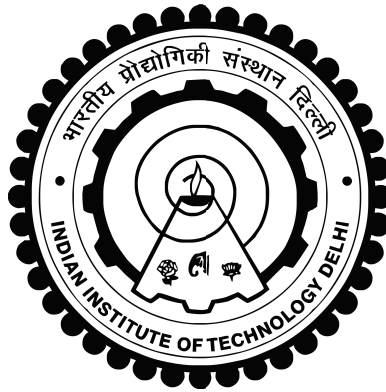


**CONTROL AND IMPLEMENTATION OF SOLAR PV-DG BASED
MICROGRIDS IN GRID-CONNECTED AND ISLANDED MODES**

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HAUZ KHAS, NEW DELHI-110016, INDIA
JANUARY 2023**

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by

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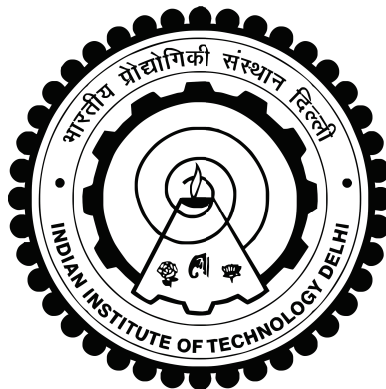
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DOCTOR OF PHILOSOPHY

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JANUARY 2023

DEDICATED TO MY MOTHER
MRS. CHANDRA PRABHA SHARMA

CERTIFICATE

This is to certify that the thesis entitled, “**CONTROL AND IMPLEMENTATION OF SOLAR PV-DG BASED MICROGRIDS IN GRID-CONNECTED AND ISLANDED MODES**” being submitted by **Mrs. Shatakshi** for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by her in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mrs. Shatakshi has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained herein, have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

The advent of distributed power generation using various renewable and non renewable sources has given rise to the concept of microgrids. Using solar photovoltaic (PV) array, wind mills, diesel generators (DG), hydro plants etc, have enabled power production at utility as well as residential and community levels. Though the initial microgrids started as AC microgrids, consisting of AC generators and loads, however, the majority of distributed energy sources and upcoming loads are DC, the trend is shifting towards DC microgrids, and hybrid AC-DC microgrids. The remote areas and mountain villages where grid is not accessible, can now create their own microgrid and operate it in standalone mode (SAM). The same distributed power generation plant can be synchronized with the grid as and when available, and operate in grid-connected mode (GCM). Thus, the convenience of having electricity supply has increased for remote, hilly, as well as utility fed communities. However, the reliability, safety, security, and quality of power need to be maintained, which need prior planning, design and complex control schemes. Additionally, the multimode operation of the microgrid is desired for it to smoothly transfer between SAM and GCM, without disturbing the system. The islanding & synchronization with grid are regulated as per IEEE standard 1547.

DGs have been used conventionally as main power source in the villages devoid of grid power, and as back up power source in residential communities and industries. Combining DG with solar PV array would help in saving fuel as well as environment, along with maintaining the reliability of power. In order to reduce the rating of DG, and store excess PV array power whenever available, BES becomes an important part of the microgrid. However, presence of multiple sources not only add to complexity, but also call for intelligent power management control schemes in order to coordinate between different sources under various scenarios. The control schemes need to

be resilient to variations in load and solar PV array power, and also regulate the charging and discharging of battery within permissible limits. Additionally, the control should be robust to be applied to a variety of loads.

In today's world, the loads in residential as well industrial communities comprise of power electronics based devices such as laptop chargers, mobile chargers, welding machines, variable speed drives, etc., apart from the lighting load. The nonlinear nature of the loads causes non sinusoidal current to be drawn from the source. Drawing nonlinear current from grid leads to nonlinearity in the voltage at point of connection (POC), thus, deteriorating the power quality factor. The total harmonic distortion (THD) in the grid current is regulated as per IEEE-519 standard, and must be kept below 5%. In the absence of grid, DG is used as auxiliary generator, and the manufacturers of DG advise to use it with linear loads only, as drawing nonlinear current from the DG leads to reduction in its loadability. Thus, the THD of DG current is also regulated to be below 5% to maximize the loading. Moreover, the fuel efficiency of DG is effected by the percentage loading also. At low loading, typically below 40% of the rated, the inefficient burning of fuel causes emission of soot, thick smoke, and toxic gases. Thus, the DG is operated within its fuel economy zone (FEZ), and with linear DG currents.

This research work aims at developing multiobjective control schemes for coordinated control of solar PV array power, BS power, and DG power for power management, along with maintaining the power quality at source end within given limits. The work discusses design, control, and implementation of a number of plausible system architectures which are opted for deployment in AC, DC, and AC-DC microgrids. The challenges associated with each system configuration are identified and addressed through design and control.

ABSTRACT

विभिन्न नवीकरणीय और गैर पारंपरिक स्रोतों का उपयोग करके वितरित बिजली उत्पादन के आगमन ने माइक्रोग्रिड की अवधारणा को जन्म दिया है। सौर फोटोवोल्टिक (PV) सरणी, पवन मिलों, डीजल जनरेटर (डीजी), हाइड्रो प्लांट आदि का उपयोग करके उपयोगिता के साथ-साथ आवासीय या सामुदायिक स्तर पर बिजली उत्पादन को सक्षम किया है। हालांकि प्रारंभिक माइक्रोग्रिड एसी माइक्रोग्रिड के रूप में शुरू हुए, जिसमें एसी जनरेटर और लोड शामिल थे, हालांकि, वितरित ऊर्जा स्रोतों और आने वाले भारों में से अधिकांश DC हैं, प्रवृत्ति DC माइक्रोग्रिड और हाइब्रिड AC-DC माइक्रोग्रिड की ओर बढ़ रही है। दूरदराज के इलाके और पहाड़ी गांव जहां ग्रिड तक पहुंच नहीं है, अब अपना खुद का माइक्रोग्रिड बना सकते हैं और इसे स्टैंडअलोन मोड में संचालित कर सकते हैं। उसी वितरित बिजली उत्पादन संयंत्र को जब भी उपलब्ध हो, ग्रिड के साथ सिंक्रनाइज़ किया जा सकता है, और ग्रिड कनेक्टेड मोड में काम कर सकता है। इस प्रकार, दूरस्थ, पहाड़ी, और समुदायों के लिए बिजली आपूर्ति की सुविधा में वृद्धि हुई है। हालांकि, बिजली की विश्वसनीयता, सुरक्षा, और गुणवत्ता को बनाए रखने की जरूरत है, जिसके लिए पूर्व योजना, डिजाइन और जटिल नियंत्रण योजनाओं की आवश्यकता होती है। इसके अतिरिक्त, माइक्रोग्रिड का मल्टीमोड संचालन वांछित है ताकि सिस्टम को परेशान किए बिना एसएएम और जीसीएम के बीच आसानी से स्थानांतरित किया जा सके। IEEE मानक 1547 के अनुसार मुख्य ग्रिड के साथ द्वीपीकरण और तुल्यकालन को विनियमित किया जाता है।

डीजी का उपयोग पारंपरिक रूप से ग्रिड पावर से रहित गांवों में मुख्य बिजली स्रोत के रूप में और आवासीय समुदायों और उद्योगों में बैक अप पावर स्रोत के रूप में किया जाता रहा है। डीजी को सोलर पीवी एरे के साथ मिलाने से बिजली की विश्वसनीयता बनाए रखने के साथ-साथ ईंधन के साथ-साथ पर्यावरण को बचाने में मदद मिलेगी। डीजी की रेटिंग को कम करने के लिए, और जब भी उपलब्ध हो, अतिरिक्त PV शक्ति को स्टोर करने के लिए, बीएस माइक्रोग्रिड का एक महत्वपूर्ण हिस्सा बन जाता है। हालांकि, कई स्रोतों की उपस्थिति न केवल जटिलता को जोड़ती है, बल्कि विभिन्न परिदृश्यों के तहत विभिन्न स्रोतों के बीच समन्वय के लिए बुद्धिमान बिजली प्रबंधन नियंत्रण योजनाओं की भी आवश्यकता होती है। नियंत्रण योजनाओं को भार और सौर पीवी सरणी शक्ति में भिन्नता के लिए लचीला होना चाहिए, और अनुमेय सीमा के भीतर बैटरी की चार्जिंग और डिस्चार्जिंग को भी विनियमित करना चाहिए। इसके अतिरिक्त, विभिन्न भारों पर लागू होने के लिए नियंत्रण मजबूत होना चाहिए।

आज की दुनिया में, आवासीय और साथ ही औद्योगिक समुदायों में लोड में लाइटिंग लोड के अलावा बिजली इलेक्ट्रॉनिक्स आधारित डिवाइस जैसे लैपटॉप चार्जर, मोबाइल चार्जर, वेल्लिंग मशीन, वेरिएबल स्पीड ड्राइव आदि शामिल हैं। भार की अरेखीय प्रकृति के कारण स्रोत से गैर-साइनसॉइडल धारा खींची जाती है। ग्रिड से नॉनलाइनियर करंट खींचने से PCC पर वोल्टेज में गैर-

रैखिकता होती है, इस प्रकार, बिजली की गुणवत्ता कारक बिगड़ती है। ग्रिड करंट में THD IEEE-519 मानक के अनुसार विनियमित है, और इसे 5% से नीचे रखा जाना चाहिए। ग्रिड के अभाव में, डीजी का उपयोग सहायक जनरेटर के रूप में किया जाता है। डीजी के निर्माता इसे केवल लीनियर लोड के साथ उपयोग करने की सलाह देते हैं, क्योंकि डीजी से नॉनलाइनियर करंट खींचने से इसकी लोडेबिलिटी में कमी आती है। इस प्रकार, लोडिंग को अधिकतम करने के लिए DG करंट का THD भी 5% से नीचे होने के लिए विनियमित है। इसके अलावा, डीजी की ईंधन दक्षता प्रतिशत लोडिंग से भी प्रभावित होती है। कम लोडिंग पर, आमतौर पर रेटेड के 40% से कम, ईंधन के अकुशल जलने से कालिख, गाढ़ा धुआं और जहरीली गैसों का उत्सर्जन होता है। इस प्रकार, डीजी अपने FEZ के भीतर और रैखिक डीजी धाराओं के साथ संचालित होता है। इस शोध कार्य का उद्देश्य दी गई सीमा के भीतर स्रोत के अंत में बिजली की गुणवत्ता बनाए रखने के साथ-साथ सौर पीवी सरणी शक्ति, बीएस पावर, और बिजली प्रबंधन के लिए डीजी पावर के समन्वित नियंत्रण के लिए बहुउद्देश्यीय नियंत्रण योजनाएं विकसित करना है। कार्य कई प्रशंसनीय सिस्टम आर्किटेक्चर के डिजाइन, नियंत्रण और कार्यान्वयन पर चर्चा करता है जिन्हें एसी, डीसी और एसी-डीसी माइक्रोग्रिड में परिनियोजन के लिए चुना जाता है। प्रत्येक सिस्टम कॉन्फिगरेशन से जुड़ी चुनौतियों को डिजाइन और नियंत्रण के माध्यम से पहचाना और संबोधित किया जाता है।

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LIST OF ABBREVIATIONS

PV	Photovoltaic
SEIG	Self Excited Induction Generator
AC	Alternating Current
DC	Direct Current
LVDC	Low Voltage Direct Current
MVDC	Medium Voltage Direct Current
DG	Diesel Generator
FEZ	Fuel Economy Zone
NDZ	Non Detection Zone
IM	Islanded Mode
SAM	Standalone Mode
GCM	Grid Connected Mode
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
IEEE	Institute of Electrical and Electronics Engineers
INC	Incremental Conductance
P&O	Perturb and Observe
PCC	Point of Common Coupling
STS	Static Transfer Switch
PES	Power Electronic Switch
PI	Proportional Integral
SOGI	Second Order Generalized Integrator
POC	Point of Connection
PLL	Phase Locked Loop
FLL	Frequency Locked Loop
EPLL	Enhanced Phase Locked Loop
S/H	Sample and Hold
THD	Total Harmonic Distortion

VSC	Voltage Source Converter
ZCD	Zero Crossing Detection
UPF	Unity Power Factor
IGBT	Insulated Gate Bipolar Transistor
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
PWM	Pulse Width Modulator
RC	Resistor-Capacitor
CC/CV	Constant Current/Constant Voltage
DSO	Digital Storage Oscilloscope
SOC	State of Charge
IG	Induction Generator
IM	Induction Machine
ILC	Interlinking Converter
BBC	Bidirectional Buck-boost Converter
BES	Battery Energy Storage
NL-VFFRLS	Non Linear Variable Forgetting Factor Recursive Least Square
APLM	Affine Projection Like M-estimate
NRMN	Normalized Robust Mixed Norm
ANFIS-MN	Adaptive Neuro Fuzzy Inference System Based Mixed Norm
VFD	Variable Frequency Drive
PCS	Power Converter System
ROCOF	Rate of Change of Frequency
NDZ	Non Detection Zone
BDDC	Bidirectional DC- DC Converter
D-STATCOM	Distributed Static Compensator

LIST OF SYMBOLS

C_{dc}	DC-link capacitor (F)
V_{dc}	DC-link voltage (V)
v_s	Single phase instantaneous grid voltage (V)
i_s	Single phase instantaneous grid current (A)
R_f	Ripple filter resistance (Ω)
C_f	Ripple filter capacitor (F)
R_{fg}	Ripple filter resistance, grid side (Ω)
C_{fg}	Ripple filter capacitor, grid side (F)
C_b	Storage battery capacitor (F)
I_b	BES current (A)
SOC_0	BES initial SOC (%)
V_{PV}	PV array voltage (V)
I_{PV}	PV array current (A)
V_{oc}	PV array open circuit voltage (V)
ω	Angular frequency of grid (rad/s)
k	Safety factor
P_b	Storage battery active power (kW)
P_{PV}	PV array power (kW)
L_f	Interfacing inductor (H)
L_b	Boost Converter inductor (H)
L_{bbc}	Buck-Boost Converter inductor (H)
V_t	Amplitude of PCC voltage
v_{sa}, v_{sb}, v_{sc}	Three phase instantaneous source voltage (V)
i_{sa}, i_{sb} and i_{sc}	Three phase instantaneous source current (A)
i_{vsca}, i_{vscb} and i_{vscc}	Three phase instantaneous VSC current (A)
u_{pa}, u_{pb}, u_{pc}	unit templates in phase with voltage
u_{qa}, u_{qb}, u_{qc}	unit templates in quadrature with voltage
STS_g, X_g	STS switch & STS switch signal for synchronization
f_{comp}	Frequency compensation for synchronization (Hz)
f_{base}	Base frequency of grid (Hz)
θ_g	Phase of grid voltage (degree)
θ_s	Phase of synchronizing converter voltage (degree)

