DESIGN AND DEVELOPMENT OF RENEWABLE ENERGY BASED MICROGRIDS WITH GRID SYNCHRONIZATION AND THEIR APPLICATIONS TO EV CHARGING INFRASTRUCTURE

PAVITRA SHUKL

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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by

PAVITRA SHUKL

Electrical Engineering Department

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CERTIFICATE

It is certified that the thesis entitled "**Design and Development of Renewable Energy Based Microgrids with Grid Synchronization and Their Applications to EV Charging Infrastructure**," being submitted by **Mrs. Pavitra Shukl** 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 her under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

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(Prof. Bhim Singh)
Electrical Engineering Department
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016, India

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ABSTRACT

This work focuses on the utilization of hybrid distributed energy resources such as solar, wind, battery and fuel cell sources based microgrids with applications to the electric vehicles (EVs) charging infrastructure. The usage of microgrids addresses the problems related to the electrification of remote areas along with the ability to synchronize with the utility grid. Thus, with the utilization of renewable energy sources and energy storage devices, the problems to feed the remote locations along with reduction in fossil-fuels consumption can be resolved. In addition, the EVs connected to the microgrids for charging purposes, act as highly flexible loads, with additional storage capacity and offers the advantages of reduction in harmful emissions, thereby, guaranteeing environmental friendly transportation.

The microgrids consisting of renewable energy sources such as solar PV array, wind turbine and fuel cell stack are utilized here, which work in synchronicity with the utility grid along with power transfer to the local loads and charging of EVs. Moreover, the microgrid reliability is dependent upon the capability to operate both in the grid connected and grid disconnected modes of operation. Therefore, the smooth transition between the modes of operation is achieved here, with the utilization of static transfer switches and appropriate switching of the voltage source converter (VSC) during different modes of operation. The VSC works as a power conditioner unit for mitigating harmonics and providing the reactive power required by the loads. Moreover, power quality problems such as poor power factor, harmonics in the grid current, neutral current etc. are also observed in the distribution network, which pollutes the grid and causes mal-operation of the appliances, increased losses and deterioration in the power factor. Therefore, the control and coordination among various sources are presented here for the integrated system, thereby, complementing the variability of each, along with multifunctional and multimode operating capabilities for the charging of EVs.

This research work aims at the design, control and implementation of various renewable energy sources based microgrids with applications to EVs charging system. The microgrids structures and control algorithms are simulated in MATLAB platform and the simulation results are verified with the test results to be in compliance with the IEEE standards. In order to deal with the power quality issues along with charging of EVs, various configurations are developed, which are classified based on the type of distribution networks i.e. number of power stages, the functionalities of the microgrids and connection of the battery storage to the DC link along with DC/ AC charging capabilities of EVs. Moreover, the three-phase microgrids are further classified into the three-phase three-wire and three-phase four-wire configurations, where the three-phase four-wire microgrids are also capable of providing neutral current compensation abilities. Therefore, the selection of the type of microgrid, depends on the requirements of the consumers. Thus, the control techniques are developed for the renewable energy sources based microgrids with satisfactory operation under the grid connected and grid outage modes of operation along with the uninterrupted power supply to the critical local loads. Moreover, the participation of EVs in the microgrids, has the potential to enhance the system resilience along with the improvement in environmental conditions. Thus, the proficiency in the charging of EVs with the off-board and on-board chargers are tested during various conditions of grid disconnection, load perturbation, varying solar insolation and changing wind speed conditions.

सारांश

यह काम हाइब्रिड वितरित ऊर्जा संसाधनों जैसे सौर, पवन, बैटरी और ईंधन सेल स्रोतों पर आधारित माइक्रोग्रिड के उपयोग पर केंद्रित है, जिसमें इलेक्ट्रिक वाहनों) ईवी (चार्जिंग बुनियादी ढांचे के अनुप्रयोग हैं। माइक्रोग्रिड का उपयोग उपयोगिता ग्रिड के साथ तालमेल बिठाने की क्षमता के साथ-साथ दूरस्थ क्षेत्रों के विद्युतीकरण से संबंधित समस्याओं का समाधान करता है। इस प्रकार, अक्षय ऊर्जा स्रोतों और ऊर्जा भंडारण उपकरणों के उपयोग से, जीवाश्म-ईंधन की खपत में कमी के साथ-साथ दूरस्थ स्थानों को खिलाने की समस्याओं का समाधान किया जा सकता है। इसके अलावा, चार्जिंग उद्देश्यों के लिए माइक्रोग्रिड से जुड़े ईवी, अतिरिक्त भंडारण क्षमता के साथ अत्यधिक लचीले भार के रूप में कार्य करते हैं और हानिकारक उत्सर्जन में कमी के लाभ प्रदान करते हैं, जिससे पर्यावरण के अनुकूल परिवहन की गारंटी मिलती है। सौर पीवी सरणी, पवन टरबाइन और ईंधन सेल स्टैक जैसे नवीकरणीय ऊर्जा स्रोतों से युक्त माइक्रोग्रिड का उपयोग यहां किया जाता है, जो स्थानीय भार में बिजली हस्तांतरण और ईवी की चार्जिंग के साथ-साथ उपयोगिता ग्रिड के साथ तालमेल में काम करते हैं। इसके अलावा, माइक्रोग्रिड विश्वसनीयता ग्रिड से जुड़े और ग्रिड डिस्कनेक्टेड मोड दोनों में संचालित करने की क्षमता पर निर्भर है। इसलिए, संचालन के विभिन्न तरीकों के दौरान स्थिर हस्तांतरण स्विच और वोल्टेज स्रोत कनवर्टर)वीएससी (के उपयुक्त स्विचिंग के उपयोग के साथ, संचालन के तरीकों के बीच सुचारू संक्रमण यहां प्राप्त किया जाता है। वीएससी हार्मोनिक्स को कम करने और भार के लिए आवश्यक प्रतिक्रियाशील शक्ति प्रदान करने के लिए एक पावर कंडीशनर इकाई के रूप में काम करता है। इसके अलावा, बिजली की गुणवत्ता की समस्याएं जैसे कि खराब पावर फैक्टर, ग्रिड करंट में हार्मोनिक्स, न्यूट्रल करंट आदि भी वितरण नेटवर्क में देखे जाते हैं, जो ग्रिड को प्रदूषित करते हैं और उपकरणों के खराब संचालन का कारण बनते हैं, नुकसान में वृद्धि और पावर फैक्टर में गिरावट का कारण बनते हैं। . इसलिए, एकीकृत प्रणाली के लिए विभिन्न स्रोतों के बीच नियंत्रण और समन्वय यहां प्रस्तुत किया गया है, जिससे ईवीएस की चार्जिंग

के लिए बहुआयामी और मल्टीमोड ऑपरेटिंग क्षमताओं के साथ-साथ प्रत्येक की परिवर्तनशीलता का पूरक है। इस शोध कार्य का उद्देश्य ईवीएस चार्जिंग सिस्टम के अनुप्रयोगों के साथ विभिन्न अक्षय ऊर्जा स्रोतों पर आधारित माइक्रोग्रिड का डिजाइन, नियंत्रण और कार्यान्वयन करना है। माइक्रोग्रिड संरचनाएं और नियंत्रण एल्गोरिदम MATLAB प्लेटफॉर्म में सिम्युलेटेड हैं और सिमुलेशन परिणाम IEEE मानकों के अनुपालन में परीक्षण परिणामों के साथ सत्यापित किए जाते हैं। ईवी की चार्जिंग के साथ-साथ बिजली की गुणवत्ता के मुद्दों से निपटने के लिए, विभिन्न विन्यास विकसित किए जाते हैं, जिन्हें वितरण नेटवर्क के प्रकार के आधार पर वर्गीकृत किया जाता है, जैसे कि बिजली के चरणों की संख्या, माइक्रोग्रिड की कार्यक्षमता और डीसी से बैटरी भंडारण का कनेक्शन। ईवीएस की डीसी/एसी चार्जिंग क्षमताओं के साथ लिंक। इसके अलावा, तीन-चरण माइक्रोग्रिड को आगे तीन-चरण तीन-तार और तीन-चरण चार-तार कॉन्फ़िगरेशन में वर्गीकृत किया जाता है, जहां तीन-चरण चार-तार माइक्रोग्रिड भी तटस्थ वर्तमान मुआवजा क्षमता प्रदान करने में सक्षम हैं। इसलिए, माइक्रोग्रिड के प्रकार का चयन उपभोक्ताओं की आवश्यकताओं पर निर्भर करता है। इस प्रकार, महत्वपूर्ण स्थानीय भार के लिए निर्बाध बिजली आपूर्ति के साथ-साथ ग्रिड से जुड़े और ग्रिड आउटेज मोड के संचालन के तहत संतोषजनक संचालन के साथ अक्षय ऊर्जा स्रोतों पर आधारित माइक्रोग्रिड के लिए नियंत्रण तकनीक विकसित की जाती है। इसके अलावा, माइक्रोग्रिड में इलेक्ट्रिक वाहनों की भागीदारी में पर्यावरणीय परिस्थितियों में सुधार के साथ-साथ सिस्टम के लचीलेपन को बढ़ाने की क्षमता है। इस प्रकार, ऑफ-बोर्ड और ऑन-बोर्ड चार्जर्स के साथ इलेक्ट्रिक वाहनों को चार्ज करने में दक्षता का परीक्षण ग्रिड डिस्कनेक्शन, लोड गड़बड़ी, अलग-अलग सौर सूर्यातप और बदलती हवा की गति की स्थितियों की विभिन्न स्थितियों के दौरान किया जाता है।

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LIST OF ABBREVIATIONS

DERs	Distributed Energy Sources
PV	Photovoltaic
EV	Electric Vehicles
FC	Fuel Cells
WT	Wind Turbines
DG	Distributed Generation
STSs	Static Transfer Switches
PLLs	Phase Locked Loops
LMF	Least Mean Fourth
LMS	Lean Mean Square
GI	Generalized Integrators
PCC	Point Of Common Coupling
MPP	Maximum Power Point
P&O	Perturb And Observe
FCVs	Fuel Cell Vehicles
EVCS	EV Charging Systems
DC	Direct Current
AC	Alternating Current
RESs	Renewable Energy Sources
PQ	Power Quality
VSC	Voltage Source Converter
INC	Incremental Conductance
UPF	Unity Power Factor
S&H	Sample/Hold Logic
ZCD	Zero Crossing Detector
PR	Proportional Resonant
ADCs	Analog To Digital Converters
FPGA	Field Programmable Gate Array
DIO	Digital Inputs And Outputs
DSO	Digital Storage Oscilloscope
CLBs	Configurable Logic Blocks
ADC	Analog To Digital Conversion
THD	Total Harmonic Distortion
IGBTs	Insulated Gate Bipolar Transistors
LTI-EPLL	Linear Time Invariant Enhanced Phase Locked Loop
VDFs	Variable Digital Filters
PI	Proportional Integral
BES	Battery Energy Storage
SOC	State Of Charge
PEM	Proton Exchange Membrane
PMSG	Permanent Magnet Synchronous Generator
WGC	Wind Power Generating Converter

LIST OF SYMBOLS

i_{La}, i_{Lb}, i_{Lc}	Load currents
I_{pv}	PV current
i_{sa}, i_{sb}, i_{sc}	Grid currents
v_{sab}, v_{sbc}	Grid line voltages
v_{sa}, $v_{sb,}$ v_{sc}	Grid phase voltages
i_{VSCa}, i_{VSCb}, i_{VSCc}	VSC currents
V_{dc}	DC link voltage
$C_{f,}$ R_f	Ripple filter
V_{pv}	PV voltage
L_b	Boost inductor
S_b	Switching pulses of Boost inductor
$i_{Lfa,}$ i_{Lfb} i_{Lfc}	Fundamental of load currents
$u_{qa,}$ u_{qb} u_{qc}	Quadrature-phase unit templates
$u_{pa,}$ u_{pb} u_{pc}	In-phase unit templates
V_{dc}^{*}	Reference DC link voltage
$h_{0,}$ $\alpha_{1,}$ $h_{1,}$ $\alpha_{2,}$ k_1	Gains of Adaptive Digital Filter
$I_{fpa,}$ I_{fpb} I_{fpc}	Load active power components
I_{loss}	DC loss component
I_{pLavg}	Load active power
I_{pnet}	Grid active power
V_{dce}	Voltage error
i^{*}_{sa}, i^{*}_{sb}, i^{*}_{sc}	Reference Grid currents
V_t	Terminal voltage
Ppv	Solar PV power
θ_g, θ_L	Grid voltage angle and load voltage angle
i^{*}_{La}, i^{*}_{Lb}, i^{*}_{Lc}	Reference Load currents
v^{*}_{La}, v^{*}_{Lb}, v^{*}_{Lc}	Reference Load volatges
ω_L	Load frequency
ω_e	Frequency error
θ_e	Phase error
θ_m	Modified load voltage angle
σ_1, γ_1, β	Gains of Subband Adaptive Filter
w_{pv}	PV Feed-forward term
f_g	Grid frequency
V_{ref}	Amplitude of load voltage
$T_a(s)$, $T_b(s)$, $T_c(s)$	Transfer function of PR controllers
$G_{insolation}$	Solar insolation level
C_{dc}	DC link capacitance
$i_{sn,}$ i_{Ln}, i_{VSCn}	Neutral currents of grid, load and VSC
L_n	Neutral leg interfacing inductor
L_f	Interfacing inductor
μ, k_1, k_2, k_3	Gains of adaptive transversal filter with leaky integrator
k_1, k_2	Gains of recursive transversal filter
$\omega_{c\alpha}$	cut-off frequency
f_{center}	Centre frequency
V_{batt}, I_{batt}, P_{batt}	Battery voltage, battery current and battery power
L_{bb}	Bidirectional buck-boost converter

σ_1, σ_2, k	Gains of digital decimation filter
w_{batt}	Battery feed-forward term
β_1, β_2	Gains of variable fractional delay filter
I_{batt}^*	Reference battery current
I_{battr}	Battery current error
γ_1, γ_2	Gains of fractional Lagrange filter
$D(m)$	Duty cycle of bidirectional converter
a, γ	Gains of combined IIR and FIR filter
k, β_1, β_2	Gains of suboptimal filter
I_{ev}, P_{ev}, V_{ev}	EVs current, power and voltage
$I_{pv1}, P_{pv1}, V_{pv1}$	PV_1 array current, power and voltage
$I_{pv2}, P_{pv2}, V_{pv2}$	PV_2 array current, power and voltage
$i_{VSCa1}, i_{VSCb1}, i_{VSCc1}$	VSC currents of $unit_1$
$i_{VSCa2}, i_{VSCb2}, i_{VSCc2}$	VSC currents of $unit_2$
$i_{La1}, i_{Lb1}, i_{Lc1}$	Load currents of $unit_1$
$i_{La2}, i_{Lb2}, i_{Lc2}$	Load currents of $unit_2$
k_1, k_2, k_3	Gains of variable digital filter
I_{fc}, P_{fc}, V_{fc}	Fuel cell current, power and voltage
E_n	Nerst voltage of fuel cell
$i_{gena}, i_{genb}, i_{genc}$	PMSG stator generator currents
T_e	Electromagnetic torque
$h_0, h_1, \alpha_1, \alpha_2$	Gains of warped digital filter
$i_{VSCa3}, i_{VSCb3}, i_{VSCc3}$	VSC currents of $unit_3$
$i_{La3}, i_{Lb3}, i_{Lc3}$	Load currents of $unit_3$
γ	Gain of Biquad filter