

ANALYSIS, DESIGN AND CONTROL OF SINGLE PHASE MICROGRID

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**ANALYSIS, DESIGN AND CONTROL OF SINGLE
PHASE MICROGRID**

by

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CERTIFICATE

It is certified that the thesis entitled “**Analysis, Design And Control of Single Phase Microgrid,**” being submitted by **Mr. Tripurari Nath Gupta** 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 award of any other degree or diploma.

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Tripurari Nath Gupta

ABSTRACT

Technical advancement, continuously improving living standard and dependency on the electrical power on daily life have increased the demand of electricity exponentially. The availability of fossil fuels is limited in nature and may deplete soon. Moreover, the deteriorating environmental conditions have grabbed the attention of the world towards the nonconventional energy sources, which are freely available in nature and do not pollute the environment. The solar PV (Photovoltaic) generation system and WEGS (Wind Energy Generation System) are gaining popularity. The SPV generation systems require low maintenance and have modular structure with possibility of installation on roof tops as small generation system. The WEGS has gained great interest in recent years to improve its behaviour and response. Unlike fossil fuels, with the fact that it emits no air pollution or greenhouse gas, also its ability to generate high amount of power with no fuel consumption, the wind power is becoming much more reliable and promising to the number one source for clean energy in very near future. One of the most important aspect is MPPT (Maximum Power Point Tracking), which is important to extract maximum power at different wind speeds, which increases the efficiency of the variable speed turbine system when the rotational speed is below rated speed. The evolution of generator technology and power electronic devices, has made it available to control it at variable wind speeds, and have made it much more reliable to design large and small scale WEGS. Different types of generators are used in variable speed WEGS, some of them are DFIG (Doubly Fed Induction Generator), SCIG (Squirrel Cage Induction Generator) and PMSG (Permanent Magnet Synchronous Generator). With the advancement in power converters, the use of the direct driven PMSG has increased as a much reliable method for power generation. PMSG is characterized by its high efficiency with no need for additional power supply.

This work presents multi-objective PV-BES (Battery Energy Storage), wind-BES and PV-wind-BES microgrid systems, which address the problems related to remote places, where system is dependent on diesel generators for supporting the loads under outage of utility grid. It reduces the consumption of conventional fuels and also supplies the load continuously under outage of the utility grid or under deficit generation. Moreover, conventional energy conversion systems are shut down at loss of utility grid for protection reasons. However, presented microgrid are operated 24x7, the load is supported by BES. The same converter is operated in the grid connected mode and islanded mode, which increases the utilization of the system. This results in saving of substantial capital investment, and maintenance cost on behalf of multi-functional features. However, under islanded mode of operation, BES and renewable energy resources (RESs) must supply the load uninterruptedly. These microgrids are installed for dedicated local loads, thereby reduce the losses by avoiding the long transmission line and, therefore, reduce the overall cost. It has capability to transfer the mode of operation from grid connected to islanded and vice versa seamlessly, without disturbing the load power supply. The voltage and frequency are decided by the utility grid under grid connected mode operation. The load side voltage source converter (LSC) performs multiple objectives, such as, it supplies the harmonics current required by the loads, compensates the reactive power demand of the nonlinear loads and maintains unity power factor. Under islanded mode, the same converter operates in voltage control mode and maintains the voltage and frequency across the loads, which is supported by BES. The BES increases the reliability and utilization of the microgrid, as it absorbs the excess power in case of excess generation and discharges to maintain the load demand in case of deficit generation or utility outage.

This research work aims at the design, control and implementation of various single-phase PV-BES, wind-BES and PV-wind-BES microgrids. These microgrids are further classified

based on PV array connection (single-stage and two-stage) and the battery connection (with and without bidirectional converter) on the DC link. In two-stage PV based microgrid, the MPPT from the PV array is harvested by controlling the boost converter and second stage is LSC. However, in single-stage PV based microgrid, the bidirectional converter is utilized to extract the optimal power along with charging/discharging control of BES. The feed-forwards terms for wind and solar energies are incorporated in current control scheme for injection of active power to the grid, which also improve the dynamics of the microgrid. All the presented microgrids are simulated in MATLAB/Simulink platform. Their topology, control techniques and developed simulation models are validated on the developed laboratory prototype. The problem of utility grid outage is common issue in the rural areas. Therefore, the simple, autonomous and intelligent control techniques for microgrids, are developed such that they are capable of operating under grid connected mode and islanded mode and maintains continuous supply across the load.

सार

तकनीकी प्रगति, जीवन स्तर में निरंतर सुधार और दैनिक जीवन की विद्युत शक्ति पर निर्भरता में तेजी से विद्युत की मांग में वृद्धि हुई है। जीवाश्म ईंधन की उपलब्धता प्रकृति में सीमित है और जल्द ही समाप्त हो सकती है। इसके अलावा, बिगड़ती पर्यावरणीय स्थितियों ने गैर-पारंपरिक ऊर्जा स्रोतों की ओर दुनिया का ध्यान खींचा है जो प्रकृति में स्वतंत्र रूप से उपलब्ध हैं और पर्यावरण को प्रदूषित नहीं करते हैं। सौर पीवी (फोटोवोल्टिक) उत्पादन प्रणाली और पवन ऊर्जा उत्पादन प्रणाली लोकप्रियता प्राप्त कर रहे हैं। एसपीवी उत्पादन प्रणाली को कम रखरखाव की आवश्यकता होती है और इसकी मॉड्यूलर संरचना, इसमें छोटे उत्पादन प्रणाली के रूप में छत के शीर्ष पर स्थापना की संभावना प्रदान करती है। डबल्यूईजीएस ने हाल के वर्षों में अपनी व्यवहार और प्रतिक्रिया में बदलाव की संभावना के कारण बहुत रुचि प्राप्त की है। जीवाश्म ईंधन के विपरीत, इस तथ्य के साथ कि यह कोई वायु प्रदूषण या ग्रीनहाउस गैस का उत्सर्जन नहीं करता है, बिना ईंधन की खपत के साथ उच्च मात्रा में बिजली उत्पन्न करने की क्षमता भी है, पवन ऊर्जा बहुत अधिक विश्वसनीय होती जा रही है और निकट भविष्य में स्वच्छ ऊर्जा के लिए नंबर एक स्रोत का वादा करती है। सबसे महत्वपूर्ण पहलू में से एक एमपीपीटी (अधिकतम पावर प्वाइंट ट्रैकिंग) है जो विभिन्न हवा की गति पर अधिकतम शक्ति निकालने के लिए महत्वपूर्ण है, जब घूर्णी गति अधिकतम गति से नीचे होती है तब यह परिवर्तनीय गति टरबाइन प्रणाली की दक्षता बढ़ाता है। जनरेटर तकनीक और पावर इलेक्ट्रॉनिक उपकरणों का विकास इसे परिवर्तनीय हवा की गति पर नियंत्रण करने के क्षमता प्रदान करता है, और बड़े और छोटे पैमाने के डबल्यूईजीएस को डिजाइन करने के लिए इसे और अधिक विश्वसनीय बनाता है। विभिन्न प्रकार के जनरेटर का उपयोग 'परिवर्तनीय गति डबल्यूईजीएस' में किया जाता है, उनमें से कुछ डीएफआइजी (डबली फेड इंडकशन जेनरेटर), एससीआइजी (स्विचरेल केज इंडकशन जेनरेटर) और पीएमएसजी (परमानेंट मैग्नेट सिंक्रोनस जेनरेटर) हैं। पावर इलेक्ट्रॉनिक्स कन्वर्टर्स में उन्नति के साथ, डायरेक्ट पावर्ड पीएमएसजी का उपयोग बिजली उत्पादन के लिए एक अधिक विश्वसनीय विधि के रूप में बढ़ा है। उच्च दक्षता पीएमएसजी की विशेषता है, जिसको संचालन के लिए अतिरिक्त बिजली की आपूर्ति की आवश्यकता नहीं होती है। यह कार्य बहु-उद्देश्य पीवी-बीईएस (बैटरी एनर्जी स्टोरेज), विंड-बीईएस और हाइब्रिड पीवी-विंड-बीईएस माइक्रोग्रिड सिस्टम प्रस्तुत करता है, जो दूरस्थ स्थानों से संबंधित समस्याओं को संबोधित करता है, जहां सिस्टम उपयोगिता ग्रिड के उपलब्ध न होने पर लोड का समर्थन करने के लिए डीजल जनरेटर पर निर्भर है। यह पारंपरिक ईंधन की खपत को कम करता है और उपयोगिता ग्रिड के उपलब्ध न होने पर या कम उत्पादन की स्थिति में भी लोड की आपूर्ति निरंतर करता है। इसके अलावा, पारंपरिक ऊर्जा रूपांतरण प्रणाली सुरक्षा कारणों से उपयोगिता ग्रिड के उपलब्ध न होने पर बंद कर दी जाती हैं। हालांकि, प्रस्तुत माइक्रोग्रिड

24x7 संचालित हैं, और लोड बीईएस द्वारा समर्थित है। वही कनवर्टर ग्रिड कनेक्टेड मोड और आइलैंडेड मोड में संचालित होता है, जो सिस्टम के उपयोग को बढ़ाता है। बहु-कार्यात्मक सुविधाओं की वजह से पूंजी निवेश और रखरखाव लागत में पर्याप्त बचत होती है। हालाँकि, आइलैंडेड मोड ऑपरेशन के तहत, बीईएस और अक्षय ऊर्जा संसाधनों को निर्बाध रूप से लोड की आपूर्ति करनी चाहिए। ये माइक्रोग्रिड स्थानीय लोड के लिए स्थापित किए जाते हैं, जिससे लंबी ट्रांसमिशन लाइन की आवश्यकता समाप्त हो जाती है जिसकी वजह से लागत मूल्य में कमी आ जाती है। यह लोड की आपूर्ति को निर्बाध रखते हुए, आइलैंडेड मोड से ग्रिड कनेक्टेड मोड अथवा इसके विपरीत बिना किसी बढ़ा के स्थानांतरित करने की क्षमता रखता है। ग्रिड कनेक्टेड मोड ऑपरेशन के तहत उपयोगिता ग्रिड द्वारा वोल्टेज और आवृत्ति निर्धारित की जाती है। लोड कनेक्टेड वोल्टेज सोर्स कन्वर्टर (एलसीवीएससी) कई उद्देश्यों को पूरा करता है, जैसे कि, यह लोड द्वारा आवश्यक हार्मोनिक करंट की आपूर्ति करता है, नानलिनियर लोड की रिएक्टिव पावर की मांग की भरपाई करता है और यूनिटी पावर फैक्टर को बनाए रखता है। आइलैंडेड मोड के तहत, वही कनवर्टर वोल्टेज नियंत्रण मोड में काम करता है और लोड पर वोल्टेज और आवृत्ति को बनाए रखता है, जो बीईएस द्वारा समर्थित है। बीईएस माइक्रोग्रिड की विश्वसनीयता और उपयोग को बढ़ाता है, क्योंकि यह ज्यादा उत्पादन की स्थिति में अतिरिक्त बिजली को अवशोषित करता है और कम उत्पादन या उपयोगिता ग्रिड के उबलबुध न होने की स्थिति में लोड की मांग को बनाए रखने के लिए आवश्यक ऊर्जा प्रदान करता है।

इस शोध कार्य का उद्देश्य विभिन्न एकलबीईएस-चरण पीवी-, विंड-विंड-बीईएस और पीवी-बीईएस माइक्रोग्रिड्स के डिजाइन, नियंत्रण और कार्यान्वयन है। डीसी लिंक पर पीवी एरे कनेक्शन (सिंगल-स्टेज और टू-स्टेज) और बैटरी कनेक्शन (द्विदिश कनवर्टर के साथ और बिना) के आधार पर इन माइक्रोग्रिड को वर्गीकृत किया जाता है। दो-चरण पीवी आधारित माइक्रोग्रिड में, पीवी एरे से अधिकतम पावर बूस्ट कनवर्टर को नियंत्रित करके प्राप्त जाता है और इसमें दूसरा चरण एलसीवीएससी है। हालाँकि, एकल-चरण पीवी आधारित माइक्रोग्रिड में, बीईएस के चार्जिंग / डिस्चार्जिंग नियंत्रण के साथ-साथ इष्टतम बिजली निकालने के लिए द्विदिशीय कनवर्टर का उपयोग किया जाता है। पवन और सौर ऊर्जा के लिए फीड-फॉरवर्ड टर्म का उपयोग ग्रिड को एक्टिव पावर की आपूर्ति के लिए करंट नियंत्रण स्कीम में शामिल किया गया है, जो माइक्रोग्रिड की गतिशीलता में भी सुधार करता है। सभी प्रस्तुत किए गए माइक्रोग्रिड मैटलैब/सिमुलिक प्लेटफॉर्म में सिम्युलेटेड हैं। उनकी टोपोलॉजी, नियंत्रण तकनीक और विकसित सिमुलेशन मॉडल विकसित प्रयोगशाला प्रोटोटाइप पर मान्य हैं। ग्रामीण इलाकों में यूटिलिटी ग्रिड आउटेज की समस्या आम है। इसलिए, माइक्रोग्रिड के लिए सरल, स्वायत्त और इंटेलिजेंट नियंत्रण तकनीकों को इस तरह विकसित किया जाता है कि ये आइलैंडेड मोड और ग्रिड कनेक्टेड मोड के तहत काम करने में सक्षम हैं और साथ ही लोड की आपूर्ति को निर्बाध रखते हैं।

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LIST OF ABBREVIATIONS

RES	Renewable Energy Sources
PV	Photo Voltaic
BES	Battery Energy Storage
MPPT	Maximum Power Point Tracking
P & O	Perturb and Observe
InC	Incremental Conductance
DC	Direct Current
AC	Alternating Current
CCP	Common Coupling Point
DSTATCOM	Distribution Static Compensator
IGBT	Insulated Gate Bipolar Transistor
PQ	Power Quality
VSC	Voltage Source Converter
WT	Wind Turbine
PMSG	Permanent Magnet Synchronous Generator
PLL	Phase Locked Loop
STS	Static Transfer Switch
DSP	Digital Signal Processor
ADC	Analog to Digital Converter
PI	Proportional Integrator
FF	Feed Forward
LTI-EPLL	Linear Time Invariant-Enhanced Phase Locked Loop
WEGS	Wind Energy Generation System
VC	Vector Control
IM	Islanded Mode
GCM	Grid Connected Mode
PCC	Point of Common Coupling

TF	Transfer Function
SOGI	Second Order Generalized Integrator
S&H	Sample and Hold

LIST OF SYMBOLS

P_{PV}	PV array power
I_{PV}	PV array current
V_{PV}	PV array voltage
V_{mp}	MPP voltage
I_{mp}	MPP current
P_{mp}	MPP power
V_{oc}	Open circuit PV voltage
I_{sc}	Short circuit PV current
V_{PV}^*	PV array voltage
V_w	Wind speed
ω_m	Generator rotor speed
T_e	Electromagnetic torque
i_{ga}, i_{gb}, i_{gc}	PMSG current
$i_{ga}^*, i_{gb}^*, i_{gc}^*$	PMSG reference currents
ω_{est}	Estimated rotor speed
ω_{ref}	Reference rotor speed
V_{dc}	DC link voltage
V_{de}	DC link voltage error
V_{dc}^*	Reference DC link voltage
L_b	Boost inductance
L_{bb}	Buck-boost inductance
C_{dc}	DC link capacitor
V_{bat} and I_{bat}	BES voltage and BES current
L_i	Interfacing inductor
R_f and C_f	Ripple filter resistance and inductance
i_s	Grid current
i_{s_ref}	Reference grid current

v_s	Grid voltage
v_L	Load voltage
i_L	Load current
u_v and u_q	Inphase and quadrature unit templates
$v_{s\alpha}$ and $v_{s\beta}$	Orthogonal voltages
v_L^*	Reference load voltage
i_{VSC}	VSC current
f_s and f_L	Grid and load frequency component
Θ_s and Θ_L	Grid and load voltage angles
M	Modulation index
A	Over loading factor
V_{sp}	Estimated amplitude of the grid voltage
G_{PV}	Weight of PV component
G_w	Weight of wind component
G_{Loss}	Weight of converter loss component
G_L	Weight of load
f_{sw}	Switching frequency
P_w	Wind power
$i_{L\alpha}$ and $i_{L\beta}$	Orthogonal component of load current
ω_0	Power frequency
I_d and I_q	d-axis and q-axis component of PMSG current
k_1	Gain of the DSSI filter
k_i, k_{i1}, k_{i2} and k_p, k_{p1}, k_{p2}	Integral and proportional gain of PI controllers
D	Duty ratio of the buck-boost converter
P	Air density
A	Swept area
c_p	Turbine powercoefficient
R_t and T_t	Turbine radius and turbine output torque

ω_t	Turbine angular speed
c_T	Torque coefficient
Λ	Tip speed ratio
β	Turbine blade pitch angle
a_1, a_2, a_3, a_4, a_5	Turbine coefficient
V_a, I_a, R_a and L_a	DC motor armature voltage, current and resistance and inductance
$R_f, L_f, V_f, I_f,$ and ϕ_f	DC motor field circuit resistance, inductance, voltage, current and field flux
$J, T_g,$ and T_{loss}	Total inertia, generator torque and torque due to losses in DC motor
B and T_0	Viscous torque and friction torque
n_g	Gear ratio
k_e	EMF constant
I_r	Solar irradiance
Ξ	Damping ratio