

INTEGRATION AND CONTROL OF RENEWABLE ENERGY BASED RURAL MICROGRIDS

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INTEGRATION AND CONTROL OF RENEWABLE ENERGY BASED RURAL MICROGRIDS

by

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CERTIFICATE

This is to certify the thesis entitled “**Integration and Control of Renewable Energy based Rural Microgrids**”, being submitted by **Mr. Vinit Kumar Singh** to the Indian Institute of Technology, New Delhi for the award of the degree **Doctor of Philosophy** in Department of Energy Science and Engineering is a bona-fide research work carried out under my supervision and guidance. The research reports and the results presented in this thesis have not been submitted in parts or in full to any other university or Institute for the award of any degree or diploma.

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ABSTRACT

In India, around 70% of the population is residing in rural areas having villages with different population sizes and resources as per their geographical location and many of them do not have proper access to grid electric supply. Some rural areas have been electrified through grid extension but they get power for a very limited duration with a frequent power cut and load shedding. The absence of continuous electric supply became a very big hurdle in rural development as the main source of income is from agricultural and small industries for which power is essential. The non-availability of electricity also affects other facilities such as children's education, irrigation, etc. In India, many targeted schemes of rural electrification were initiated after 1989, but the targets were not achieved due to slow growth initially. However, with dedicated efforts of state/central governments, progress in rural electrification is remarkable. But still, the rural consumers in India are deprived of a proper 24x7 power supply due to the gap between demand and supply of electricity.

The utility grid has a definite power supply capacity and the addition of capacity is comparatively slower than the increase in load demand. Alternative resources have been explored to assist in increasing electric generation and one option available is to harness power from renewable energy sources (RES). Presently the power generation using RES became more attractive globally as it saves in terms of environmental pollution. However, some of these sources are intermittent and uncontrolled with low energy density/potential.

A new scheme of integrated rural microgrid electrification systems (IRMES) has been proposed in the thesis which will overcome the problem of shortage in grid supply by use of available RES in the area. A reduced but continuous power will be taken from the grid, called it limited grid, and the remaining power will be supplied by local RES. The operation of a limited grid and RES will be parallel to supply power to the area. In addition, these rural microgrids could be interconnected through AC/DC links such that power surplus in one microgrid could be transferred to a power deficit microgrid. Six configurations of IRMES have been considered depending upon the availability of RES. As some of the RES have intermittent nature, therefore adequate control is necessary for good quality supply to the consumers.

This thesis deals with the state space modelling and dynamic stability study of IRMES. For limited grid operation and interconnection with AC/DC link three parameters: frequency,

system voltage, and system voltage angle have been considered to be maintained at nominal value. Small signal models of all the IRMES have been developed using power balance equations. The power generations from RES have been considered by WECS, PVS, and biogas genset. The biogas genset has a speed governor and actuator to control power generation and the frequency can be maintained constant by using a controller to manipulate the reference set. The gensets are coupled with a synchronous generator (SG) for electric power generation and have an automatic voltage regulator (AVR) and exciter for reactive power balance and to maintain the system voltage. The WECS considered have a permanent magnet synchronous generator (PMSG) for power generation. The frequency and voltage of the generator vary with wind speed, therefore the interconnection with the system has been considered by voltage source converter (VSC). The PVS considered having interconnection with the system through power electronic converters. AC link simply consists of a cable network while DC-link consists of the rectifier, inverter with cable. The inverters used in WECS and PVS have the capability to transfer power at the desired frequency and control reactive power accordingly required by the system. A distribution network supplying power to a cluster of villages with different nature of loads has been considered.

The objective of this study is to control the grid source as a limited grid and to maintain IRMES voltage and frequency at a nominal value. Since some of the renewable energy sources are intermittent in nature, therefore to take care of their input power variations biogas genset have been considered always to be part of IRMES. To achieve the objective, a number of PI and FOPI controllers has been used in the IRMES for all the sources. The dynamic performance of the systems under consideration depends upon the value of the gains of these PI and FOPI controllers. The gains of PI and FOPI controllers have been tuned using the integral square error (ISE) method. The intelligent technique soccer competition league (SCL) algorithm has been used to determine the optimum gain settings and the dynamic performances have been compared. The studies have been conducted for real and reactive power load disturbances with and without input variations in input wind power and/or input solar power. It has been observed that the dynamic performance of the different configurations of IRMES is better with gain settings using PI and FOPI controller tuned by SCL technique as compared with ISE methods.

सार

भारत में, लगभग 70% आबादी ग्रामीण क्षेत्रों में निवास कर रही है, जहां उनकी भौगोलिक स्थिति के अनुसार विभिन्न जनसंख्या आकार और संसाधनों वाले गांव हैं और उनमें से कई के पास ग्रिड बिजली की आपूर्ति तक उचित पहुंच नहीं है। कुछ ग्रामीण क्षेत्रों को ग्रिड विस्तार के माध्यम से विद्युतीकृत किया गया है, लेकिन उन्हें बार-बार बिजली कटौती और लोड शेडिंग के साथ बहुत सीमित अवधि के लिए बिजली मिलती है। निरंतर विद्युत आपूर्ति का अभाव ग्रामीण विकास में एक बहुत बड़ी बाधा बन गया क्योंकि आय का मुख्य स्रोत कृषि और छोटे उद्योगों से है जिसके लिए बिजली आवश्यक है। बिजली की अनुपलब्धता अन्य सुविधाओं जैसे बच्चों की शिक्षा, सिंचाई आदि को भी प्रभावित करती है। भारत में, ग्रामीण विद्युतीकरण की कई लक्षित योजनाएं 1989 के बाद शुरू की गईं, लेकिन शुरुआत में धीमी वृद्धि के कारण लक्ष्य हासिल नहीं किया जा सका। हालांकि, राज्य/केंद्र सरकारों के समर्पित प्रयासों से, ग्रामीण विद्युतीकरण की प्रगति उल्लेखनीय है। लेकिन फिर भी, भारत में ग्रामीण उपभोक्ता बिजली की मांग और आपूर्ति के बीच के अंतर के कारण 24x7 बिजली की उचित आपूर्ति से वंचित हैं।

उपयोगिता ग्रिड की एक निश्चित बिजली आपूर्ति क्षमता होती है और क्षमता का जोड़ लोड मांग में वृद्धि की तुलना में तुलनात्मक रूप से धीमा होता है। विद्युत उत्पादन बढ़ाने में सहायता के लिए वैकल्पिक संसाधनों का पता लगाया गया है और उपलब्ध एक विकल्प अक्षय ऊर्जा स्रोतों (आरईएस) से बिजली का दोहन करना है। वर्तमान में आरईएस का उपयोग कर बिजली उत्पादन विश्व स्तर पर अधिक आकर्षक हो गया है क्योंकि यह पर्यावरण प्रदूषण के मामले में बचाता है। हालांकि, इनमें से कुछ स्रोत कम ऊर्जा घनत्व/क्षमता के साथ रुक-रुक कर और अनियंत्रित हैं।

थीसिस में एकीकृत ग्रामीण माइक्रोग्रिड विद्युतीकरण प्रणाली (आईआरएमईएस) की एक नई योजना प्रस्तावित की गई है जो क्षेत्र में उपलब्ध आरईएस के उपयोग से ग्रिड आपूर्ति में कमी की समस्या को दूर करेगी। ग्रिड से एक कम लेकिन निरंतर बिजली ली जाएगी, इसे सीमित ग्रिड कहा जाएगा, और शेष बिजली की आपूर्ति स्थानीय आरईएस द्वारा की जाएगी। एक सीमित ग्रिड और आरईएस का संचालन क्षेत्र में बिजली की आपूर्ति के समानांतर होगा। इसके अलावा, इन ग्रामीण माइक्रोग्रिड को एसी/डीसी लिंक के माध्यम से इस तरह जोड़ा जा सकता है कि एक माइक्रोग्रिड में बिजली अधिशेष को बिजली की कमी वाले माइक्रोग्रिड में स्थानांतरित किया जा सके। आरईएस की उपलब्धता के आधार पर आईआरएमईएस के छह विन्यासों पर विचार किया गया है। चूंकि कुछ आरईएस की प्रकृति रुक-रुक कर होती है, इसलिए उपभोक्ताओं को अच्छी गुणवत्ता की आपूर्ति के लिए पर्याप्त नियंत्रण आवश्यक है।

यह थीसिस आईआरएमईएस के राज्य अंतरिक्ष मॉडलिंग और गतिशील स्थिरता अध्ययन से संबंधित है। एसी/डीसी लिंक के साथ सीमित ग्रिड संचालन और इंटरकनेक्शन के लिए तीन पैरामीटर: आवृत्ति, सिस्टम वोल्टेज, और सिस्टम वोल्टेज कोण को नाममात्र मूल्य पर बनाए रखा गया है। सभी IRMES के छोटे सिग्नल मॉडल पावर बैलेंस समीकरणों का उपयोग करके विकसित

किए गए हैं। RES से बिजली उत्पादन को WECS, PVS और बायोगैस जेनसेट द्वारा माना गया है। बायोगैस जेनसेट में बिजली उत्पादन को नियंत्रित करने के लिए एक स्पीड गवर्नर और एक्चुएटर है और संदर्भ सेट में हेरफेर करने के लिए एक नियंत्रक का उपयोग करके आवृत्ति को स्थिर रखा जा सकता है। जेनसेट विद्युत ऊर्जा उत्पादन के लिए एक तुल्यकालिक जनरेटर (एसजी) के साथ युग्मित होते हैं और प्रतिक्रियाशील शक्ति संतुलन के लिए और सिस्टम वोल्टेज को बनाए रखने के लिए एक स्वचालित वोल्टेज नियामक (एवीआर) और उत्तेजक होते हैं। माना जाता है कि WECS में बिजली उत्पादन के लिए एक स्थायी चुंबक तुल्यकालिक जनरेटर (PMSG) है। जनरेटर की आवृत्ति और वोल्टेज हवा की गति के साथ बदलती रहती है, इसलिए वोल्टेज स्रोत कनवर्टर (वीएससी) द्वारा सिस्टम के साथ इंटरकनेक्शन पर विचार किया गया है। पीवीएस ने पावर इलेक्ट्रॉनिक कन्वर्टर्स के माध्यम से सिस्टम के साथ इंटरकनेक्शन होने पर विचार किया। एसी लिंक में केवल एक केबल नेटवर्क होता है जबकि डीसी-लिंक में रेक्टिफायर, केबल के साथ इन्वर्टर होता है। WECS और PVS में उपयोग किए जाने वाले इनवर्टर में वांछित आवृत्ति पर बिजली स्थानांतरित करने और सिस्टम द्वारा आवश्यक प्रतिक्रियाशील शक्ति को नियंत्रित करने की क्षमता होती है। विभिन्न प्रकार के भार वाले गांवों के समूह को बिजली की आपूर्ति करने वाले वितरण नेटवर्क पर विचार किया गया है।

इस अध्ययन का उद्देश्य सीमित ग्रिड के रूप में ग्रिड स्रोत को नियंत्रित करना और नाममात्र मूल्य पर आईआरएमईएस वोल्टेज और आवृत्ति को बनाए रखना है। चूंकि कुछ नवीकरणीय ऊर्जा स्रोत प्रकृति में रुक-रुक कर होते हैं, इसलिए उनकी इनपुट शक्ति विविधताओं का ध्यान रखने के लिए बायोगैस जेनसेट को हमेशा IRMES का हिस्सा माना जाता है। उद्देश्य को प्राप्त करने के लिए, सभी स्रोतों के लिए IRMES में कई PI और FOPi नियंत्रकों का उपयोग किया गया है। विचाराधीन प्रणालियों का गतिशील प्रदर्शन इन पीआई और एफओपीआई नियंत्रकों के लाभ के मूल्य पर निर्भर करता है। इंटीग्रल स्क्रायर एरर (ISE) पद्धति का उपयोग करके PI और FOPi नियंत्रकों के लाभ को ठ्यून किया गया है। इष्टतम लाभ सेटिंग्स निर्धारित करने के लिए बुद्धिमान तकनीक सॉकर प्रतियोगिता लीग (एससीएल) एल्गोरिदम का उपयोग किया गया है और गतिशील प्रदर्शन की तुलना की गई है। इनपुट पवन ऊर्जा और/या इनपुट सौर ऊर्जा में इनपुट विविधताओं के साथ और बिना वास्तविक और प्रतिक्रियाशील पावर लोड गड़बड़ी के लिए अध्ययन आयोजित किए गए हैं। यह देखा गया है कि आईएसई विधियों की तुलना में एससीएल तकनीक द्वारा ठ्यून किए गए पीआई और एफओपीआई नियंत्रक का उपयोग करके लाभ सेटिंग्स के साथ आईआरएमईएस के विभिन्न विन्यासों का गतिशील प्रदर्शन बेहतर है।

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NOMENCLATURE

The general abbreviations/symbols used in the thesis are listed below. Some other abbreviations/symbols, not indicated in the list, have been defined locally where they are used in this thesis.

AC	Alternating current
AVR	Automatic voltage regulator
BG	Biogas generator set
DC	Direct current
DG	Diesel generator set
HPS	Hybrid Power System
IG	Induction generator
IRMES	Integrated rural microgrid electrification systems
LFC	Load frequency control
LSC	Load side converter
MSC	Machine side converter
PMSG	Permanent magnet synchronous generator
PVS	Photo voltaic system
RES	Renewable energy sources
SG	Synchronous generator
VSC	Voltage source converter
WECS	Wind energy conversion system
WT	Wind turbine
K_{AB}	Voltage regulator gain constant
K_{EB}	Exciter gain constant
K_{FB}	Stabilizing circuit gain constant
K_R	VAR regulator amplifier gain
K_{EB}	Exciter gain constant
T_{EB}	Exciter time constant
K_{FB}	Stabilizer gain constant
T_{FB}	Stabilizer time constant
T'_{d0B}	Direct axis open circuit transient time constant

T'_{dB}	Average dead time of zero crossings in a 3 phase system
$P_W, P_{BG}, P_{PV}, P_G, P_L$	Active power output of wind, biogas, PV, grid, and load demand respectively.
$Q_W, Q_{BG}, Q_{PV}, Q_G, Q_L$	Reactive power output of wind, biogas, PV, grid, and load demand respectively.
P_{acs} and P_{acr}	Sending end and receiving end active power of AC link
Q_{acs} and Q_{acr}	Sending end and receiving end reactive power of AC link
P_{dcr} and P_{dci}	DC power at rectifier end and DC power at inverter end
Q_{dcr} and Q_{dci}	Reactive power absorbed by rectifier and inverter
$\Delta P_W, \Delta P_{BG}, \Delta P_{PV}, \Delta P_G, \Delta P_T, \Delta P_{acs}, \Delta P_{acr}$ and ΔP_L	Change in active power of wind, biogas, PV, grid, total power, sending end AC link, receiving end AC link and load respectively.
$\Delta Q_W, \Delta Q_{BG}, \Delta Q_{PV}, \Delta Q_G, \Delta Q_T, \Delta Q_{acs}, \Delta Q_{acr}$ and ΔQ_L	Change in reactive power of wind, biogas, PV, grid, total power, sending end AC link, receiving end AC link and load respectively.
ΔP_{dcr} and ΔP_{dci}	Change in DC power at rectifier end and inverter end.
ΔQ_{dcr} and ΔQ_{dci}	Change in reactive power absorbed by rectifier and inverter.
$f, \Delta f$	Frequency and change in frequency of the system
$\theta, \Delta \theta$	Angle of grid voltage and change in voltage angle
$P_{IW}, \Delta P_{IW}$	Wind input power and change in wind input power
$E \angle 0^\circ$	Input voltage (on grid side) of the grid feeder transformer
$E_{fdB}, \Delta E_{fdB}$	Exciter voltage of biogas generator and change in it
$\Delta E'_{qB}$	Change in the internal armature e.m.f. proportional to the change in the direct axis field flux under transient condition
ΔE_{qB}	Change in the internal armature e.m.f. proportional to the change in the direct axis field flux under steady state condition
$V \angle \theta$	Voltage of the common bus of microgrid
$V, \Delta V$	System voltage and small change in system voltage
$V_{AB}, \Delta V_{AB}$	Amplifier output voltage of biogas generator exciter and change in it
δ_{in}	The angle of the inverter voltage (V_{in}) with respect to the system voltage (V)

$V_{inPV}, \Delta V_{inPV}$	Voltage of the inverter used for PV system and change in it
$\delta_{inPV}, \Delta \delta_{inPV}$	Voltage angle of the inverter used for PV system and change in it
$V_{inW}, \Delta V_{inW}$	Inverter voltage and change in inverter voltage of WECS
$\delta_{inW}, \Delta \delta_{inW}$	Angle and change in angle of inverter voltage of WECS
ΔV_{ref}	Change in reference voltage
$P_{inPV}, \Delta P_{inPV}$	Input solar power on the PV system and change in it.
$P_{inW}, \Delta P_{inW}$	Input wind power on the WT and change in it
I_{aB}, I_{dB}, I_{qB}	Armature current of biogas generator and its d and q-axis components
I_G, I'_G	Grid supply current, before and after the disturbance applied
X_{dB}	Direct axis synchronous reactance of the alternator
X'_{dB}	Direct axis transient reactance
X_{TPV}	Reactance of the coupling transformer of the converter
X_{TW}	Reactance of the coupling transformer of the converter used for WECS
X_G	Reactance of the feeder line and the transformer of the grid
$Z \angle \Psi$	Impedance and impedance angle of AC link
I_L	Current through AC link
$V_{acs}, \Delta V_{acs}$	Voltage at sending end of AC link and change in it
$V_{acr}, \Delta V_{acr}$	Voltage at receiving end of AC link and change in it
R_{dc}	Resistance of DC link
$V_{dcr}, \Delta V_{dcr}$	Voltage at rectifier end of DC link and change in it
$V_{dci}, \Delta V_{dci}$	Voltage at inverter end of DC link and change in it
α and γ	Firing angle of rectifier and inverter
I_L	Current through AC link
I_{dc}	Current through DC link