

**ADVANCED CONTROL AND POWER MANAGEMENT  
OF DISTRIBUTED ENERGY RESOURCES IN AN  
AUTONOMOUS MICROGRID**

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by

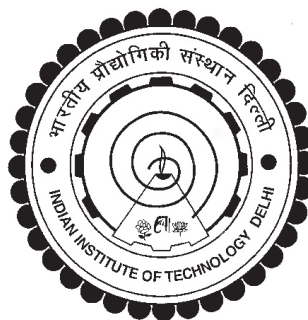
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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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*I dedicate this thesis to my wife Prachi, daughter Pranshi, and to my loving parents . . .*

## Certificate

This is to certify that the dissertation entitled '**Advanced Control and Power management of Distributed Energy Resources in an Autonomous Microgrid**', being submitted by **Mr. Rishi Kant Sharma** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering at Indian Institute of Technology Delhi, New Delhi.

**Mr. Rishi Kant Sharma** has worked under my supervision and has fulfilled the requirements for the submission of this dissertation, which to my knowledge has reached the requisite standard. The results obtained here have not been submitted to any other University or Institute for the award of any degree.

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**Date:**

**Rishi Kant Sharma**

## **Abstract**

The thesis works pertain to the development of efficient and reliable power management schemes, optimal load dispatch based control, and robust stabilization of multiple voltage source inverter (VSI) interfaced distributed energy resources (DERs) operating in a standalone AC/DC system or a networked autonomous microgrid (MG).

Initially, a dynamic power management scheme (PMS) is developed for a standalone AC/DC system constituting of photovoltaic (PV) system, PEM fuel cell, and hybrid energy storage (HES) comprising battery energy storage (BES) and supercapacitor (SC) pack. The developed PMS uses a moving average filter (MAF) such that the generated current references to the DC-DC converters of PV, PEM fuel cell, BES, and SC are based on their different dynamic response characteristics. The PMS ensured stable operation of hybrid standalone AC/DC system even when the HES was subjected to the maximum and minimum state of charge (SoC) limits. Moreover, a MAF was augmented with inverse dc droop method and SoC adaptive droop control for decentralized proportional power-sharing among geographically distributed multiple PVs and multiple BESs, fuel cell, and SC.

Further, the maximum penetration of PV systems in diesel generator (DG) based power system is limited in the range of 40% to 60%. When the PV capacity becomes comparable to DG capacity, the system suffers from stability and synchronization issues. A dc integration technique employing a dc droop-based hierarchical control was developed for the PV-BES-DG system integrated at a common dc bus to overcome these issues. Moreover, an optimal regulator-based secondary control is developed to ensure optimal load sharing among DG and BES while safeguarding BES life. Further, a PMS is designed to ensure the standalone

system's reliable operation during source and load power imbalances and operation under the critical SoC limit condition of BES.

For the standalone operation of DERs interfaced to VSI, the VSI operates in grid forming mode to maintain a constant voltage and constant frequency (CVCF) across the load terminals. Under unbalanced and nonlinear loading, the output voltage waveform's power quality deteriorates, leading to increased voltage unbalance factor (VUF) and total harmonic distortion (THD). A multivariable nonlinear disturbance observer was developed to observe the SRF components of load current containing  $2^{nd}$  and  $6k$  harmonic components. The observed SRF load currents were feed-forwarded to the outer voltage control loop, which minimizes the effect of load current as the grid forming VSI supplies reactive power current components for harmonic compensation.

The autonomous microgrid (MG) with multiple voltage source inverters (VSI) is operated in droop mode to share the load proportionally. These VSI controllers require higher droop constants if the feeder lines connecting the VSI to the microgrid have a low X/R ratio. The higher droop gains and large loading conditions in the microgrid may exhibit instability with the low-frequency power modes (LFPM). A systematic multivariable plant model of the MG using dynamic phasor modeling of power flow transfer functions is developed to analyze the LFPM. Further, a robust supplementary multivariable controller is developed to stabilize the developed plant model, damp LFPM, and improve transient power-sharing performance of VSIs without affecting their steady-state power-sharing. This stabilizer is developed based on Glover-McFarlane  $H_\infty$  loop shaping robust stabilization technique with additional pole placement constraints formulated in linear matrix inequality framework.

Further, a polytopic uncertain model of droop control DGs is obtained to include the uncertainties in DG loading and the  $X/R$  value of the line. A robust decentralized auxiliary controller based on pole-placement constraints is developed for the obtained uncertain polytopic plant model to improve the damping of low-frequency modes, enhance stability margin, and improve DGs' transient power-sharing performance of MG.

## सार

यह थीसिस विश्वसनीय बिजली प्रबंधन योजनाओं के विकास, इष्टतम लोड प्रेषण-आधारित नियंत्रण के विकास पर केंद्रित है। थीसिस एक स्टैंडअलोन एसी / डीसी सिस्टम या एक नेटवर्क स्वायत्त माइक्रोग्रिड में संचालित कई वोल्टेज स्रोत इन्वर्टर इंटरफेस वितरित ऊर्जा संसाधनों के मजबूत स्थिरीकरण के विकास पर भी चर्चा करता है।

प्रारंभ में, एक फोटोवोल्टिक प्रणाली, पीईएम ईंधन सेल, और बैटरी ऊर्जा भंडारण और सुपरकेपेसिटर पैक युक्त हाइब्रिड ऊर्जा भंडारण का गठन करने वाले स्टैंडअलोन एसी / डीसी सिस्टम के लिए एक गतिशील बिजली प्रबंधन योजना विकसित की गई है। विकसित बिजली प्रबंधन योजना एक चलती औसत फिल्टर का उपयोग करती है जैसे कि एक फोटोवोल्टिक प्रणाली, पीईएम ईंधन सेल, बैटरी ऊर्जा भंडारण और सुपरकेपेसिटर के डीसी-डीसी कन्वर्टर के लिए उत्पन्न वर्तमान संदर्भ उनकी विभिन्न गतिशील प्रतिक्रिया विशेषताओं पर आधारित होते हैं। बिजली प्रबंधन योजना ने हाइब्रिड स्टैंडअलोन एसी/डीसी सिस्टम के स्थिर संचालन को सुनिश्चित किया, भले ही हाइब्रिड ऊर्जा भंडारण अधिकतम और न्यूनतम चार्ज सीमा के अधीन था।

इसके अलावा, डीजल जनरेटर आधारित बिजली प्रणालियों में फोटोवोल्टिक प्रणालियों की अधिकतम पैठ 40% से 60% की सीमा में सीमित है। जब फोटोवोल्टिक प्रणाली की क्षमता डीजल जनरेटर क्षमता के बराबर हो जाती है, तो सिस्टम स्थिरता और सिंक्रनाइज़ेशन मुद्दों से ग्रस्त होता है। इन मुद्दों को दूर करने के लिए एक डीसी ड्रूप-आधारित पदानुक्रमित नियंत्रण को नियोजित करने वाली एक डीसी एकीकरण तकनीक को फोटोवोल्टिक प्रणाली, बैटरी ऊर्जा भंडारण और एक सामान्य डीसी बस में एकीकृत डीजल जनरेटर प्रणाली के लिए विकसित किया गया था। इसके अलावा, बैटरी ऊर्जा भंडारण जीवन की सुरक्षा करते हुए डीजल जनरेटर और बैटरी ऊर्जा भंडारण के बीच इष्टतम लोड साझाकरण सुनिश्चित करने के लिए एक इष्टतम नियामक आधारित माध्यमिक नियंत्रण विकसित किया गया है। इसके अलावा, बिजली प्रबंधन योजना को बैटरी ऊर्जा भंडारण की चार्ज सीमा की महत्वपूर्ण स्थिति के तहत स्रोत और लोड बिजली असंतुलन और संचालन के दौरान स्टैंडअलोन सिस्टम के विश्वसनीय संचालन को सुनिश्चित करने के लिए डिज़ाइन किया गया है।

कई वोल्टेज स्रोत इनवर्टर के साथ स्वायत्त माइक्रोग्रिड लोड को आनुपातिक रूप से साझा करने के लिए ड्रॉप मोड में संचालित होता है। इन वोल्टेज स्रोत इनवर्टर नियंत्रकों को उच्च ड्रूप स्थिरांक की आवश्यकता होती है यदि इनवर्टर को माइक्रोग्रिड से जोड़ने वाली फीडर लाइनों में कम एक्स/आर अनुपात होता है। माइक्रोग्रिड में उच्च ड्रॉप लाभ और बड़ी लोडिंग स्थितियां कम आवृत्ति पावर मोड के साथ अस्थिरता प्रदर्शित कर सकती हैं। कम आवृत्ति पावर मोड का विश्लेषण करने के लिए पावर फ्लो ट्रांसफर फंक्शंस के गतिशील चरण मॉडलिंग का उपयोग करके माइक्रोग्रिड का एक व्यवस्थित बहुपरिवर्तनीय संयंत्र मॉडल विकसित किया गया है। इसके अलावा, विकसित प्लांट मॉडल को स्थिर करने, कम आवृत्ति वाले पावर मोड को नम करने और वोल्टेज स्रोत इनवर्टर के क्षणिक पावर-शेयरिंग प्रदर्शन को उनके स्थिर-राज्य पावर-शेयरिंग को प्रभावित किए बिना बेहतर बनाने के लिए एक मजबूत पूरक बहु-परिवर्तनीय नियंत्रक विकसित किया गया है। इस स्टेबलाइजर को ग्लोवर-मैकफर्लेन लूप पर आधारित मजबूत स्थिरीकरण तकनीक के आधार पर विकसित किया गया है, जिसमें रैखिक मैट्रिक्स असमानता ढांचे में अतिरिक्त पोल प्लेसमेंट बाधाओं को तैयार किया गया है।

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# Nomenclature

## Chapter 1 to Chapter 4

$\frac{\omega_c}{\omega_c+s}$	low pass filter transfer function
$\hat{i}_{oi}^{dq}$	observed output current of VSI in SRF
$\lambda_{BES}$	marginal cost of BES
$\lambda_{DG}$	marginal cost of DG
$\omega_{gc}$	Gain-crossover frequency of voltage control loop of VSI
$\phi^m$	phase margin of voltage control loop of VSI
$\rho_{h2}$	$H_2$ partial pressure
$C_{bi}$	Capacity (Ahr) of $i^{th}$ BES
$C_{dc}$	dc bus capacitance
$C_f$	Three-phase VSI filter capacitance
$C_{sc}$	Supercapacitor capacitance
$d_{BES}$	duty ratio of BES-BDC
$D_{bi}^{charge}$	BES droop constant in charge mode
$D_{bi}^{discharg}$	BES droop constant in discharge mode

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$D_b$	Duty ratio of BES BDC
$d_{droop}$	Duty ratio of DC-DC converter in droop mode
$D_{fc}$	Duty ratio of FC boost converter
$D_{fc}^r$	dc droop constant of FC BC converter
$D_{SC}$	Duty ratio of SC BDC converter
$D_{SC}^r$	dc droop constant of SC BDC converter
$F_{BES}$	fuel cost function for the BES
$F_{DG}$	Quadratic fuel cost function of DG
$f_{sw}$	Switching frequency of VSI
$i_{pv}^{out}$	PV BC output current
$i_{BES}$	BES-BDC input filter current
$I_{bes}^{max}$	Maximum/rated value of BES current
$I_{bes}^{min}$	Minimum value of BES current
$i_{BES}^{ref}$	BES-BDC filter current reference
$I_{bo}$	BES BDC output current
$i_{dc}^{avg}$	Average current component of $i_{dc}^{ref}$
$i_{dc}^{ref}$	total output dc current from PI dc bus voltage controller
$i_{dc}^T$	Transient current component of $i_{dc}^{ref}$
$i_{dgo}$	output current of the single-phase VSC-DG unit
$i_{dgo}^{max}$	maximum output current of the single-phase VSC-DG unit

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$i_{dq}$	dq component filter current of DG VSC
$I_{fco}$	Fuel cell BC output current
$I_{fc}$	Fuel cell current
$I_{fc}^{max}$	Maximum/rated value of Fuel cell current
$I_{fc}^{min}$	Minimum value of Fuel cell current
$I_{fc}^{ref}$	Fuel cell reference current
$i_l^{dq*}$	VSI filter inductor current reference in SRF
$i_l^{dq}$	VSI filter inductor current in SRF
$i_o^{dq}$	VSI output current in SRF
$I_{pvo}$	PV BC output current
$I_{pv}$	PV module current
$I_{SCo}$	SC BDC output current
$I_{SC}$	Supercapacitor pack current
$I_{SC}^{ref}$	Supercapacitor pack reference current
$K_{fc}$	Voltage transformation ratio of FC boost converter
$K_{or}$	optimal regulator gain
$K_{p1}, K_{i1}$	Proportional and integral gain of voltage controller of VSC-DG unit
$K_{p2}, K_{i2}$	Proportional and integral gain of d axis current controller of VSC-DG unit
$K_{p3}, K_{i3}$	Proportional and integral gain of voltage controller of BES-BDC unit
$K_{p4}, K_{i4}$	Proportional and integral gain of current controller of BES-BDC unit

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$L_{BES}$	BES-BDC filter inductance
$L_{bes}$	inductance of BES BDC filter
$L_{DG}$	Single phase VSC diesel generator filter inductance
$L_{fc}$	inductance of FC boost converter filter
$L_f$	Three-phase VSI filter inductance
$L_{pv}$	inductance of PV boost converter filter
$L_{SC}$	inductance of SC BDC filter
$m_{dq}$	Modulation index of VSI in SRF
$m_{dq}$	dq component of modulation index of single-phase VSC
$P_{ac}$	Three-phase ac load power
$P_{dgmin}$	DG-VSC minimum current
$P_{DG}$	Single phase VSC diesel generator power
$P_L$	Total load power of system
$P_{pv}$	PV module power
$q_{h_2}^{in}$	$H_2$ input flow ( $Kmols^{-1}$ )
$q_{h_2}^{out}$	$H_2$ output flow ( $Kmols^{-1}$ )
$q_{h_2}^{ref}$	Fuel cell $H_2$ reference
$q_{h_2}^r$	$H_2$ flow that reacts ( $Kmols^{-1}$ )
$r_{BES}$	BES-BDC filter resistance
$R_c$	dc line/cable resistance

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$R_{di}$	dc droop constant of $i^{th}$ DC source
$R_d$	$V_{dc} - I_{dc}$ droop gain
$R_{fc}$	resistance of FC boost converter filter
$R_f$	Three-phase VSI filter resistance
$R_{load}$	DC load resistance
$SoC_{BH}$	Higher limit of State of charge of BES
$SoC_{BL}$	Lower limit of State of charge of BES
$V_{BES}$	BES voltage
$V_{cell}$	Fuel cell voltage
$V_{dc}$	DC bus voltage
$V_{dc}^{ref}$	DC bus voltage reference
$V_{fco}$	Fuel cell BC terminal output voltage
$V_{fc}$	Fuel cell terminal voltage
$V_{gdq}$	dq component output voltage of auto-transformer connected to DG
$v_i^{dq}$	Reference Voltage for PWM switching of VSI in SRF
$V_{mp}$	PV module voltage at MPPT
$V_{oi}^*$	output voltage reference of $i^{th}$ DC source
$v_o^{dq}$	Voltage across VSI filter capacitance in SRF
$V_{pvo}^{ref}$	PV BC output terminal voltage reference
$V_{pv}$	PV module voltage

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$V_{SCH}$	Higher limit of Supercapacitor pack voltage
$V_{SCL}$	Lower limit of Supercapacitor pack voltage
$V_{SCo}$	SC BDC output voltage
$V_{SC}$	Supercapacitor pack voltage
DG	Diesel Generator

### Chapter 5 to Chapter 6

$\omega_i^n$	Nominal value of frequency of DG
$H_{ij}^{sh}(s)$	Shaped plant TF of MG using Glover-McFarlane loop shaping method
$H_i^{cl}(s)$	Closed loop current controller TF of DG
$H_i^{vc}(s)$	PI controller transfer function for the voltage control loop of DG
$i_{idq}$	output/load current of VSI in SRF
$i_{ldq}$	filter current of VSI in SRF
$k_{di}$	derivative droop gain Q-V of DG
$k_{pi}$	P-f droop gain of DG
$k_{qi}$	Q-V droop gain of DG
$p_i, q_i$	Active and reactive power of $i^{th}$ DG
$p_i, q_i$	Measured active and reactive power of $i^{th}$ DG
$P_i^{avg}, Q_i^{avg}$	Filtered/average active and reactive power of $i^{th}$ DG
$v_{idq}$	output voltage across filter capacitance of VSI in SRF
$v_{id}^n$	Nominal value of output voltage across filter capacitance of DG in SRF

$Z_{ij} = R_{ij} + j\bar{\omega}L_{ij}$  Equivalent impedance between the DG at bus  $i$  and load at bus  $j$

$Z_{ij}^c$  Feeder impedance between bus  $i$  and bus  $j$

### Overall

$\omega_n$  Nominal value of angular frequency of DG

$H_I^{\omega_I^* \rightarrow P_I}(s)$  Transfer function matrix of MG with active power of DGs as output and frequency deviation as input

$H_{T_i}^{\omega_I^* \rightarrow P_T}(s)$  TFM from  $\Delta\omega_I^*$  to transient active power deviations

$i_{L_i}^{dq}$  RL load current of  $i^{th}$  DG in SRF

$i_{oi}^{dq}$  Output current of  $i^{th}$  DG in SRF

$i_{T_{ij}}^{dq}$  Line current from  $i^{th}$  DG to  $j^{th}$  DG in SRF

$K_D(s)$  Robust decentralized controller transfer function

$R_{L_i}, L_{L_i}$  Resistance and inductance of RL load of  $i^{th}$  DG

$R_{T_{ij}}, L_{T_{ij}}$  Resistance and inductance of network /line connecting  $i^{th}$  and  $j^{th}$  DG

$v_{oi}^{dq}$  Output voltage across DG filter capacitor of  $i^{th}$  DG in SRF

### Acronyms / Abbreviations

BC Boost converter

BDC Bi-directional DC-DC converter

BES Battery energy storage

CVCF Constant Voltage constant frequency

DER distributed energy resource

DGs distributed generators

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DMS	Distribution management system
DPM	Dynamic phasor modeling
DRD	Disturbance relative degree
DSO	Distribution system operator
FC	Fuel cell
GPS	Global positioning system
HES	Hybrid energy storage
LFM	Low frequency modes
LFO	Low frequency oscillations
LMI	Linear matrix inequality
LPF	Low pass filter
LV	Low voltage
MAF	Moving average filter
MC	Microsource controller
MG	Microgrid
MGCC	Microgrid central controller
MPPT	Maximum power point tracking
MV	Medium voltage
NDOBC	Nonlinear disturbance observer based control
NLCF	Normalized left coprime factors

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PCC	point of common coupling
PEM	Proton exchange membrane
PI	Proportional Integral
PMA	Power management algorithm
PMS	Power management scheme
PMU	Phasor measurement unit
PSS	Power system stabilizer
PV	Photo-voltaic
RHP	Right half plane
RPP	Robust pole placement
SC	Supercapacitor
SoC	State of charge
SRF	Synchronous reference frame
SV	Singular values
TF	Transfer function
TFM	Transfer function matrix
THD	Total harmonic distortion
VCO	Voltage controlled oscillator
VSC	Voltage source converter
VSI	Voltage source inverter
VUF	Voltage unbalance factor