Robust Control Techniques for Virtual Impedance Shaping to Mitigate and Share the Double Line Frequency Ripple in Microgrids

A Thesis submitted by
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in partial fulfillment of the requirements for the award of the degree of
Doctor of Philosophy

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Department of Electrical Engineering
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Declaration

I hereby declare that the work presented in this Thesis titled *Robust Control Techniques for Virtual Impedance Shaping to Mitigate and Share the Double Line Frequency Ripple in Microgrids* submitted to the Indian Institute of Technology Jodhpur in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Professor Deepak M. Fulwani. The contents of this thesis in full or in parts, have not been submitted to, and will not be submitted by me to, any other Institute or University in India or abroad for the award of any degree or diploma.

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Certificate

This is to certify that the thesis titled *Robust Control Techniques for Virtual Impedance Shaping to Mitigate and Share the Double Line Frequency Ripple in Microgrids*, submitted by *Shivam Chaturvedi (P15EE004)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under our supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. Deepak M. Fulwani
Ph.D.Thesis Supervisor

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List of Symbols

Symbol	Description
P_c	Power dc component
P_r	Power ripple component
ω	ac supply frequency
ϕ	Load power factor angle
V_m	Voltage maximum values
I_m	Current maximum values
i_L	Inductor current
v_c	Capacitor terminal voltage
d_{st}	Shoot through duty cycle
e_i	Inductor current error
e_v	Voltage error
κ	Positive constant
L	Inductance
C	Capacitance
i_{ref}	Current reference
v_{ref}	Voltage reference
τ	Low pass filter time constant
2ω	Angular frequency of second-order ripple
V_c	Steady state values of capacitor voltage
I_L	Steady state values of inductor current
D	Steady state values of duty cycle
E	Source voltage
r_L	Inductor resistance
G_{vd}	Capacitor voltage to control
G_{id}	Inductor current to control
G_{vi}	Capacitor voltage to inductor current
G_i	Inductor Current Controller
G_v	Capacitor Voltage Controller
T_{pi}	Control to inductor current transfer function
T_{pv}	Control to voltage transfer function
G_{iLio}	Inductor current to output current transfer function
G_{vcio}	Capacitor voltage to output current transfer
$\phi_m(t)$	Matched uncertainty
$\phi_u(t,x)$	Unmatched uncertainty
d_o	Nominal control law
d_{2f}	Second order oscillations in the control law
d_n	Non-linear control law
d_{pi}	Control law from PI controller
d_{neq}	Equivalent control law
H_1, H_2	Current and voltage sensor gain
Z_v	Virtual Impedance

Symbol	Description
v_{refo}	DC bus voltage reference
k_1, k_2	Current share proportions
v_{refi}	Voltage reference of i^{th} converter
G_D	Communication delay
G_{com}	PI controller for secondary control
I_i^{pu}	Per-unit loading of i^{th} converter
I_j^{pu}	Per-unit loading of j^{th} converter
V_{dcj}	The source voltage
v_{cj}	Voltage across output capacitor
i_{Lj}	Inductor current of j^{th} converter
u_{1j}	Duty cycle of j^{th} converter
$\mathcal{N}_j$	Number of electrically connected neighbors of j^{th} converter
r_{Lj}	the inductor resistance
i_{oj}	total current flowing out of j^{th} converter
ΔV_{ref}	the voltage reference variation due to ISMSC control
d_i	Dynamic droop
d_o	Constant droop
k_i, β_i, α_i, ρ_i, μ	Positive Constants
Γ_i, Q_i	SMC reaching Design parameters
$I_i^{\bar{p}u}$	Average microgrid load
I_i	The load current of i^{th} converter
I_r	Converter's current rating

List of Abbreviation

Abbreviation	Full form
ASMCOIC	Adaptive Sliding Mode Control based Output Impedance Shaping
AACC	Adaptive Active Capacitor Converter
APDC	Active Power Decoupling Scheme
APF	Active Power Filter
BMS	Battery Management System
BPFICF	Band-Pass Incorporated Inductor Current Feedback
CSI	Current Source Inverter
CPD	Combinational Power Decoupling
eqSBI	Embedded Quasi Switched Boost Inverter
FCs	Fuel Cell
ISMC	Integral Sliding Mode Control
LED	Light Emitting Diode
$Li-ion$	Lithium Ion
MPPT	Maximum Power Point Tracking/Tracker
MPP	Maximum Power Point
MOSFET	Metal-Oxide Semiconductor Field Transistor
MMCs	Modular Multilevel Converters
NF	Notch Filter
$NF-CR$	Notch Filter inserted Current Reference
$NF-LCFFS$	Notch Filter inserted Load Current Feed Forward Scheme
$Na-S$	Sodium Sulphur
$Ni-Cd$	Nickel Cadmium
NFVRLCFFS	Notch Filter Cascading Voltage Regulator Load Current Feed-Forward Scheme
PEMFC	Proton Exchange Membrane based Fuel Cell
PMU	Power Management Unit
PV	Photo Voltaic
PWM	Pulse Width Modulation
qZSIs	Quasi-Z Source Inverters
SSIs	Single Stage Inverters
SLZSI	Switched Inductor Switched Boost Inverter
SMC	Sliding Mode Control
SMPC	Sliding Mode Based Primary Control
SRCs	Second Order Ripple Currents

Abbreviation	Full form
SORI	Second Order Ripple Impedance
SMM	Sequential Magnetization Modulation
SCC	Stacked Switched Capacitor
TZSI	Trans-Z Source Inverter
THD	Total Harmonic Distortion
TMM	Time Shared Magnetization Modulation
VLA	Vented Lead Acid
VRLA	Valve Regulated Lead Acid
VAWT	Vertical Axis Wind Turbines
VRS	Virtual Resistance Scheme
VSI	Voltage Source Inverter
WT	Wind Turbines
ZVS	Zero Voltage Switching
ZSN	Z-Source Network