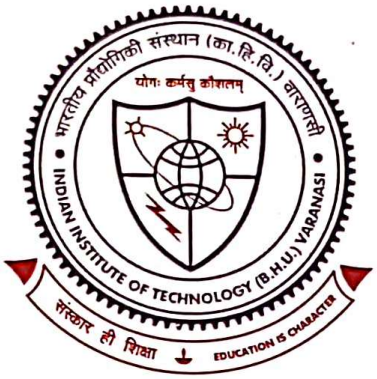
Low Frequency Oscillations Damping in Power Networks Through PSS and Robust Wide-Area Damping Controller



Thesis submitted in partial fulfillment
for the award of degree

Doctor of Philosophy

by

Rohit Kumar

DEPARTMENT OF ELECTRICAL ENGINEERING
Indian Institute of Technology
(Banaras Hindu University)
Varanasi

Roll No: 18081502

2024

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CERTIFICATE

It is certified that the work contained in the thesis titled **Low Frequency Oscillations Damping in Power Networks Through PSS and Robust Wide-Area Damping Controller** by **author** has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

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DECLARATION

I, **Rohit Kumar**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Prof. Mitresh Kumar Verma** and **Prof. Soumya R Mohanty** from January-2019 to July-2024, at the Departement of Electrical Engineering, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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It is certified that the above statement made by the student is correct to the best of my/our knowledge.

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Acknowledgment

First and foremost, I would like to express my gratitude to **Lord Vishwanath Ji** for the countless blessings, knowledge, and opportunities bestowed upon me, enabling me to complete this thesis. While my name appears on the cover of this dissertation, the success of this work is due to the support and guidance of many others. I owe my heartfelt thanks to everyone who made this thesis possible and contributed to a research experience I will cherish forever.

I extend my deepest gratitude to my supervisor, **Prof. Mitresh Kumar Verma** and co-supervisor, **Prof. Soumya R. Mohanty**, from the Department of Electrical Engineering at IIT (BHU) Varanasi, for their unwavering support, guidance, and patience throughout my research. It has been a privilege to work under their mentorship.

I also thank the Head of the Department of Electrical Engineering, IIT (BHU), Varanasi, for providing all the facilities necessary for my research work. My sincere thanks go to **Prof. S.P. Singh** and **Prof. R.K. Pandey** for their unconditional support during my research journey. I also appreciate the other faculty members of my research progress evaluation committee, **Dr. J.C. Pandey** and **Prof. Subir Das**, for their invaluable support and constant encouragement throughout the research period. I am grateful to **Dr. Avirup Maulik**, **Prof. Sandip Ghosh**, and **Dr. Subho Paul** for their support and for helping me maintain high standards in my work. I extend my heartfelt thanks to all the faculty members of the Electrical Engineering Department. I am grateful to my friend, **Dr. Shailendra Singh**, **Mr. Abhishek Singh** and **Mr. Ambuj Pandey**, who provided me with technical, moral, and emotional support during my research program.

I am also thankful to our laboratory staff, **Mr. Sanjay Bharti**, **Mr. Dharmendra Singh**, and **Mr. Vinish Singh**, for their assistance during this research. My gratitude goes to all the office staff and authorities of the Department of Electrical Engineering for their help during my stay to complete the thesis work.

A special thanks to my colleagues, including **Dr. Manohar Singh, Dr. Am Kumar Thakur, Dr. Devesh Shukla, Dr. Akhilesh Barnwal, Dr. Lokes Yadav, Dr. Vivek Kumar, Dr. Mahitosh Banafer, Mr. Udit Prasad, M Alok Kumar, Mrs. Babita Faujdar, Mr. Ankit Mishra, Mr. Ritwik Tripath** and **Mr. Kunal Singh**, for the thought-provoking discussions, support, cooperation and sincere help in many ways.

Finally, I am eternally grateful to my entire family for their faith, patience, en couragement, blessings, and love. I thank my father, **Mr. Ganesh Choudhary**; my mother, **Mrs. Nisha Devi**; my brother, **Mr. Rahul Kumar**; my sister-in-law, **Mrs. Tunni Kumari**; my sister, **Mrs. Priyanka Choudhary**; my brother-in-law, **Mr. Satyendra Singh**; and my niece, **Ms. Priushu**, for motivating, believing in, and strengthening me to reach new heights. A special thanks to my special family for always being there for me through all the ups and downs.

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Place: Varanasi

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Nomenclature

List of Abbreviations

IBRs	Inverter-Based Resources
RESs	Renewable Energy Sources
WTS	Wind Turbine System
PV	Photovoltaic
ESS	Energy Storage System
BESS	Battery Energy Storage System
SOC	State of Charge
SMES	Superconducting Magnetic Energy Storage System
VSG	Virtual Synchronous Generator
LFOs	Low-Frequency Oscillations
SGs	Synchronous Generators
PSS	Power System Stabilizer
WAPSS	Wide-Area Power System Stabilizer
WADC	Wide-Area Damping Controller
PMUs	Phasor Measurement Units
SDC	Supplementary Damping Controller

FACTS	Flexible AC Transmission Systems
POD	Power Oscillation Damping controller
STATCOM	Static Synchronous Compensator
GFC	Grid Forming Control
PSO	Particle Swarm Optimization
ATDC	Adaptive Time-Delay Compensator
MMPN	Multi-Machine Power Network
CDTA	Classical Damping Torque Analysis
DTI	Damping Torque Index
GMO	Geometric measurement of Observability
PF	Participation Factor
SI	Sensitivity Index
BT	Balanced Truncation
RTDS	Real Time Digital Simulator
GTSYNC	Giga-Transceiver Synchronization Card
RPS	Rest Part of Power System
VSC	Voltage Source Converter
RSC	Rotor Side Converter
GSC	Grid Side Converter
PCC	Point of Common Connection
APC	Active Power Controller
RPC	Reactive Power Controller

BC	Base case
CS1	Case-1
CS2	Case-2
CS3	Case-3
C1	Contingency-1
C2	Contingency-2
S1	Scenario-1
S2	Scenario-2
S3	Scenario-3
S4	Scenario-4
OC1	Operating Condition-1
OC2	Operating Condition-2
OC3	Operating Condition-3
DS1	Disturbance-1
DS2	Disturbance-2
DS3	Disturbance-3

List of Symbols

δ	Rotor angle
ω_s	Synchronous speed
$E_q^{'}$	q-axis transient internal voltage
E_{fd}	Field voltage
D	Damping coefficient
T_M	Mechanical input torque
H	Machine inertia constant
I_d, I_q	d-axis and q-axis stator current
$X_d, X_d^{'}$	d-axis reactance and q-axis transient reactance
$T_{do}^{'}, T_{qo}^{'}$	d-axis and q-axis transient flux decay constant
V_t	Terminal voltage
V_{ref}	Reference voltage
K_A, T_A	Gain and time constant of the exciter
m	Number of SG
B_L	Transfer function matrix from Δu_s to state variables
Δu_s	Output signal of the stabilizer
Δy_s	Stabilizer feedback signal

F_{PSS}	Forward path from the PSS controlling signal to the electro-mechanical oscillation loop of the SG
T_{PSS}	Transfer function of the PSS
D_{PSSKL}	Damping coefficient in the electromechanical oscillation loop of SG
T_{PSSKL}	Electric torque contribution from the PSS to the electro-mechanical oscillation loop of all SG
γ_L	Reconstructed function
$\angle\varphi_L$	SG critical LFO loop angle
$\angle\phi$	Compensation angle
λ_K	Critical LFO mode
p	Differential operator
ω_t	Speeds of the wind turbine
ω_r	Speeds of the Induction generator
ω_e	Speeds of the synchronous reference frame
H_t	Inertia constant of wind turbine
D_{tg}	Damping coefficients between the generator and wind turbine
D_t	Wind turbine damping coefficient
K_{tg}	Drive train shaft stiffness coefficient
D_g	Damping coefficient of the induction generator
T_g	Electromagnetic torque of the induction generator
T_m	Wind turbine mechanical torque
β	Wind turbine pitch angle
λ	Wind turbine tip speed ratio
C_p	Power coefficient of the wind turbine blade

R	Wind turbine rotor radius
ρ	Air density
V_w	Wind speed
P_m	Wind turbine mechanical power
ω_b	Base angular velocity
ω	Rotational speed of the arbitrary reference frame
x_m	Magnetizing reactance of the induction generator
$x_{rr}^{'}$	Rotor reactance of the induction generator
$r_r^{'}$	Rotor resistance of the induction generator
r_s	Stator resistance of the induction generator
ψ_s, & $\psi_r^{'}$	Stator and rotor fluxes of the induction generator
V_s, & $V_r^{'}$	Stator,and rotor voltages of the induction generator
P_{sref}, & Q_{sref}	Active and reactive power reference of RSC in WTS
P_s, & Q_s	Active and reactive power of WTS
u_p, & u_q	Damping control signal of the WADC
K_{pr1}, & K_{ir1}	Proportional and integral gain coefficients of the PI controller of the RSC outer control loop for active power control loop
K_{pr3}, & K_{ir3}	Proportional and integral gain coefficients of the PI controller of the RSC outer control loop for reactive power control loop
I_{drref}, & I_{qrref}	dq-axis reference current generation for RSC
I_{dr}, & I_{qr}	dq-axis rotor current of RSC
K_{pr2}, & K_{ir2}	Proportional and integral gain coefficients of the PI controller of the RSC inner control loop for active current control loop
K_{pr4}, & K_{ir4}	Proportional and integral gain coefficients of the PI controller of the RSC inner control loop for reactive current control loop

V_{dr}, & V_{qr}	dq-axis RSC voltages
V_{dc}	DC-link voltage
V_{dcref}	Reference voltage of voltage control loop of GSC
Q_{gref} & Q_g	Reactive power reference and reactive power of GSC in WTS
K_{pg1}, & K_{ig1}	Proportional and integral gain coefficients of the PI controller of the GSC outer control loop for voltage control loop
K_{pg3}, & K_{ig3}	Proportional and integral gain coefficients of the PI controller of the GSC outer control loop for reactive power control loop
I_{dgref}, & I_{qgref}	dq-axis reference current generation for GSC
I_{dg}, & I_{qg}	dq-axis current of GSC
K_{pg2}, & K_{ig2}	Proportional and integral gain coefficients of the PI controller of the GSC inner control loop for voltage current control loop
K_{pg4}, & K_{ig4}	Proportional and integral gain coefficients of the PI controller of the GSC inner control loop for reactive current control loop
Δ	Small deviation
x, u & y	Power system state, input, and output vectors
A, B, C, & D	Power system system, input, output, and feed-forward matrices
m, n, & o	Power system state, input, and output variables
T_d	Delay time
λ_i	LFO mode
$gm_{oj}\,(i)$	GMO of i^{th} oscillation mode
φ_i	Right eigenvector of i^{th} oscillation mode
$\|\ \|$, & $\|\ \|$	Euclidean norm and modulus
P_L	Real power flow through transmission line
w	External input

K	Transfer function of the controller
T	Transfer function for generalized plant
z	Regulated variables
v	Measure output
M_{zw}	Closed-loop transfer function from w to z
V_1	Battery pack terminal voltage
I_L	Inductor current
I_{dc}	DC-link current
V_b	Battery cell voltage
R_b	Battery internal resistance
α_1	Bidirectional converter duty cycle
C_1, C_2, & L	Converter capictance and inductance
V_{sd},& V_{sq}	dq - axis grid voltage or PCC voltage of VSC
V_{cd},& V_{cq}	dq- reference frame voltages of VSC
m_d,& m_q	Modulation index of VSC in dq reference frame
V_s,V_c,& I_c	Grid voltage, VSC voltage, and VSC current
L_V,& R_V	Aggregated inductance and resistance of the VSC, transformer, and filter
C_V	Filter capicatance
V_{cd},& V_{cq}	Pulse width modulation control signal for VSC
I_{cd},& I_{cq}	dq - axis current of VSC
I_{cdref},& I_{cqref}	dq - axis reference current generation for inner current control loop of VSC

K_{pp}, & K_{ip}	Gain coefficients of the PI controller in the outer active control loop of the VSC
K_{pq}, & K_{iq}	Gain coefficients of the PI controller in the outer reactive control loop of the VSC
$K_{pi_{cd}}$, & $K_{ii_{cd}}$	Gain coefficients of the PI controller in the inner active current control loop of the VSC
$K_{pi_{cq}}$, & $K_{ii_{cq}}$	Gain coefficients of the PI controller in the inner reactive current control loop of the VSC
$G(s)$	Transfer funcition of system
R_i	Residue index
N_i^T, & M_i	Left and the right eigenvector matrices related to the eigenvalue λ_i
M_p	Consequence of the choice
ρ	Set of each candidate's installation positions, feedback signals, and control loops
γ_0	Steady-state operating condition
γ_p	Operating condition
$\Phi(\gamma)$	Collection of various operating conditions
V_1, & V_2	Voltage drops across $R_1 \mid\mid C_1$ and $R_2 \mid\mid C_2$
R_{in}	Charge transfer resistance
V_{oc}	Open circuit voltage
V_b	Terminal voltage of the battery cell
I_b	Battery cell current
$S(s)$	Sensitivity function
$K(s)S(s)$	Complementary sensitivity functions
G_{dp}	Transfer function for the open-loop plant model of the system
I_{ds},& I_{qs}	Point of coupling current in d-q axis

x_{pll},& θ_{pll}	PLL state variables
x_{p1},& x_{q1}	Power control loop states of VSC
x_{p2},& x_{q2}	Current control loop states of VSC
d	Disturbance signal
$W_1(s)$,& $W_2(s)$	Shaping filter (low pass and high pass filter)
$W_{2h}(s)$	Small constant or high pass filter
x_k	Damping controller state vector
A_k, B_k, C_k,& D_k	Damping controller system state, input, output, and feed-forward matrices
r	Reference signal for damping controller
X	Real symmetric matrix
R_1, S_1, M_1,& N_1	Sub-matrices of X
ζ_{min}	Minimal damping ratio
θ	Conic sector angle
θ_r	Reference angle
V^*	Voltage magnitude of virtual AVR for VSG
V_s	Voltage magnitude of PCC
ω_{VSG}, & ω_o	VSG angular frequency and grid angular frequency
D_q	Droop coefficient of the Q–V loop
K_q, & V^*	Reactive power adjustment coefficient, and output voltage of the virtual excitation loop
x_1, & x_2	Voltage control loop state variables of IBR
K_{ivd}, & K_{ivq}	Integral gain coefficient of the voltage control loop of VSG control in the dq reference frame

K_{pvd}, & K_{pvq}	Proportional gain coefficient of voltage control loop in the dq reference frame
x_3, & x_4	Current control loop state variables of IBR
x_{VSG}&,u_{VSG}	state vector, and input vector for the state model of IBR controlled through the VSG technique
y_{VSG}	Output vector for the state model of IBR controlled through the VSG technique
A_{VSG},&B_{VSG}	System and input matrices coefficient of state model of IBR controlled through the VSG technique
V_{VSG},&D_{VSG}	Output and feed-forward matrices coefficient of state model of IBR controlled through the VSG technique
$P_p(s)$	Power system model that includes the parameters perturbation of the proportional gain coefficient of the voltage control loop of IBRs
$G_p(s)$	Power system model without the IBRs control loop perturbations
$\Delta(s)$	Perturbation block
Z_2,& Z_∞	Output channel of H_2/H_∞ damping controller
H_2,& H_∞	H_2,& H_∞ are performance channel of H_2/H_∞ damping controller
D_r	Pole placement region
A_∞,& A_2	Weight of the H_∞ and H_2 performance channel
$\|M_{wz_2}(s)\|_2$	H_2 norm
$\|M_{wz_\infty}\|_\infty$	H_∞ norm

Preface

Power system networks are interconnected, nonlinear, and extremely complex systems susceptible to various events that might cause Low-Frequency Oscillations (LFOs), which may affect the system's stability. These LFOs, which occur at a frequency lower than 2 Hz, are frequently caused by events such as line failures, abrupt load changes, and generator output power variations. The LFOs must be damped out as quickly as possible to make the system stable and dependable because they are harmful. Consequently, reducing power oscillations through Power Oscillation Damping (POD) controller and installing Power System Stabilizers (PSSs) on Synchronous Generators (SGs) are two conventional methods for damping LFOs in multi-machine power systems. PSSs are designed to enhance system stability by providing additional damping to generator rotor oscillations through modulation of the excitation system. However, PSSs primarily utilize local signals, which limits their effectiveness in damping inter-area oscillation modes due to a lack of global observability.

To address the limitations of PSSs in damping inter-area oscillations, a robust Wide-Area Damping Controller (WADC) is introduced. WADCs use wide-area measurements, such as Phasor Measurement Unit (PMU) data, to provide a broader view of the system's dynamic behaviour. By using these wide-area signals, WADC can effectively dampen inter-area oscillations, enhancing the overall stability of the interconnected power system. This approach ensures sufficient damping across the network, mitigating the adverse effects of LFOs and maintaining system reliability.

WADC can be designed using robust control strategies, such as H_∞, mixed sensitivity H_∞, and H_2/H_∞ control, to effectively handle uncertainties and varying system conditions. These controllers are designed to provide sufficient damping even when system parameters change or when faced with model inaccuracies. Various actuators, including wind energy conversion systems, solar photovoltaic systems, energy storage systems, and

virtual synchronous generators, are utilized in WADC designs to mitigate system inter-area oscillations and enhance the system's dynamic performance. A brief literature survey on low-frequency oscillations under Renewable Energy Sources (RESs) and Inverter Based Resources (IBRs) integration, various control strategies to damp these oscillations, motivation befind work carried out in this thesis based on research gap, and formulated research objectives are presented in first Chapter.

The second Chapter of the thesis presents the Damping Torque Index (DTI) for determining the optimal installation location of PSS in a multi-machine power network. The selection criteria for the PSS location are based on the maximum magnitude of the DTI under normal operating conditions, ensuring that the PSS is placed where it can provide the most effective damping. The parameters of the PSS are adjusted using the phase compensation methodology to optimize its performance. Additionally, a reduced-order model-based WADC is designed and installed at the synchronous generator, where the optimal PSS is located. This approach aims to enhance the damping of LFOs in the system, thereby improving overall system stability and performance.

The increased penetration of RESs into power systems significantly impacts the damping of LFOs. RESs, such as Wind Turbine Systems (WTS), inherently differ from traditional synchronous generators in their contribution to system inertia and damping characteristics. The intermittent and variable nature of RESs often reduces system inertia, which can exacerbate LFOs and pose stability challenges. This decrease in inertia diminishes the natural damping usually provided by synchronous machines, making the power system more susceptible to oscillatory instability.

The third Chapter of the thesis investigates the impact of inter-area oscillation damping in power systems under low system inertia conditions caused by a high penetration of WTS operating in sub-synchronous, normal, and super-synchronous scenarios. This work examines the effects of replacing a synchronous generator with a WTS of the same MVA capacity on system dynamics, mainly focusing on the emergence of new critical modes of inter-area oscillations that can affect system stability. It explores the dynamic interactions between WTS and SGs and their impact on inter-area oscillations. This work proposed a reduced-order model-based double-channel WADC for WTS to address these challenges, utilizing an H_∞ control scheme. This WADC is designed to damp prominent oscillation modes effectively and mitigate the adverse effects of reduced

system inertia. The real-time feasibility of the proposed double-channel H_∞ WADC is validated using the Real-Time Digital Simulator (RTDS) platform.

The application of Energy Storage Systems (ESSs) in power systems is pivotal for enhancing the damping of inter-area oscillations, which is essential for maintaining grid stability amidst the increasing integration of renewable energy sources. ESS provides rapid and precise control over active and reactive power, helping to stabilize grid frequency and dampen oscillations, particularly in regions prone to variability due to renewables. The strategic deployment of ESS in the grid allows operators to quickly mitigate frequency deviations by injecting or absorbing power, thus preserving system inertia and damping characteristics that might be compromised by integrating renewable energy sources.

Furthermore, ESS can operate independently or in conjunction with other stabilization technologies, such as PSS and WADC, to ensure optimal damping without compromising overall grid reliability. In addition to damping oscillations, ESS provides critical ancillary services, including frequency regulation, voltage support, and load balancing, which are essential for maintaining stability in environments with high renewable energy penetration. These capabilities make ESS a crucial component in modern power systems, enhancing flexibility and resilience in managing the dynamic challenges posed by renewable energy integration.

Mitigating inter-area LFOs is crucial for maintaining power system stability. These oscillations are closely tied to power oscillations, and adequate power modulation through the Battery Energy Storage System (BESS) can help preserve stability. The fourth Chapter of this thesis proposes a strategy for selecting the optimal location for BESS placement based on the maximum of all minimal residue indices under varying system loading conditions. This method determines the best location for the BESS, the appropriate feedback signal, and the suitable damping control loop (i.e., active or reactive power control) for implementing a supplementary damping controller. A reduced-order model-based fixed-structure H_∞ scheme-based WADC is proposed to enhance the damping performance for system LFOs. The robust damping performance of the designed controller is validated on the RTDS under different contingencies, including varying system operating scenarios, uncertainties associated with fixed and variable communication delays in the feedback signal, nonlinearities in the damping control loop, and the integration of renewable sources such as solar photovoltaic (PV) systems.

The fifth Chapter of this thesis examines the impact of multiple BESSs on inter-area oscillations in the power system under varying loading conditions to study the impact of dynamic interaction between the BESS control modes and synchronous generators, along with BESS control parameters, on the damping of prominent inter-area oscillations. Further, WADC based on an H_∞ mixed sensitivity scheme is proposed for BESS. This controller, designed using the Linear Matrix Inequality (LMI) framework, aims to mitigate prominent inter-area oscillations. The sensitivity to variations in BESS control parameters is used to determine optimal location for supplementary damping controller. The RTDS platform is used to assess the real-time effectiveness of the proposed WADC, with simulation results demonstrating that the controller significantly reduces several inter-area oscillation modes.

In RES-based generation, IBR is used to supply power to the grid. However, the increasing integration of RES-based generation in modern power systems reduces grid inertia and damping performance because IBR lacks inherent rotating inertia. This issue is especially significant when RES are integrated into the grid through IBR, given their high voltage levels and large power capacities. Conventional grid-following controls for IBR do not provide inertia support, which can lead to stability problems and pronounced oscillations from minor disturbances, potentially compromising frequency stability. The Virtual Synchronous Generator (VSG) control technique addresses this issue by emulating the inertia of synchronous generators, thereby improving grid stability and reducing these challenges.

The sixth Chapter of this thesis presents the impact of IBRs controlled through the VSG technique on power system LFOs. It investigates how dynamic interactions between the power network and the active and reactive power loops of IBRs, with varying parameters such as inertia constant (H), damping coefficient (D_p), and voltage gain coefficient (k_q), influence LFO damping. Further, the Supplementary Damping Controller (SDC) scheme for IBRs is proposed to enhance system LFOs damping and mitigate the power oscillations of IBRs. This SDC comprises a multi-stage mixed H_2/H_∞ decentralized damping controller linked with the IBR's active control loop and the PSS linked with the reactive control loop of the IBR. The robustness of the proposed SDC is validated using RTDS simulations under various operating conditions, including load changes, network topology adjustments, and the integration of renewable sources. The simulation results

demonstrate that the proposed SDC effectively mitigates both system LFOs and power oscillations in IBRs. Finally, the seventh Chapter concludes the thesis by summarizing key findings and suggesting directions for future research.