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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