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DAMPING OF SUBSYNCHRONOUS OSCILLATIONS IN POWER SYSTEMS

A thesis submitted for the M.Sc. degree in Electrical Engineering

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ABSTRACT

This thesis presents a comparative study of different controller design options for Subsynchronous Resonance (SSR) mitigation. The objective is to investigate different methodologies to mitigate the torsional oscillations due to subsynchronous resonance in a capacitor–compensated power system using modern control techniques. Controller design options presented in this thesis are: (i) Pole placement, (ii) Linear quadratic regulator (LQR)-based artificial neural network (ANN), and (iii) H_∞ control.

A proposed pole placement technique that provides a complete state feedback excitation regulator, that damps the unstable torsional modes of oscillations, is introduced. This controller design is effective in stabilizing the system at a certain compensation level. However, if the compensation level is changed, a new adjustment of the regulator gains is required.

Linear quadratic control methodology results in a complete state feedback linear optimal controller. This method minimizes a quadratic functional of the plant states and control inputs. The designed controller provides an optimal damping solution for all torsional modes simultaneously. Albeit, such regulator is to some extent robust, the regulator gains must be adjusted to new values as the compensation level changes widely. To accommodate for a wider range of variation in the compensation level, the objective function has been modified to contain not only the states and control signal, but also special state combination that provides information about load and compensation variation. Moreover, an effective

LQR-based ANN is developed in order to adaptively cope with the system compensation level and loading conditions.

H_∞ technique provides a robust output feed back regulator that results in a sub-optimal damping solution for all torsional modes. This technique minimizes the ∞-norm of the closed loop system from the disturbance input to the required output. Such controller uses a minimum number of system outputs to provide the proper damping. Computer simulation results show that all oscillating modes can be stabilized simultaneously for a wide range of capacitor compensation.

All the aforementioned techniques have been applied to the first IEEE Subsynchronous Resonance (SSR) benchmark model. Time-domain simulations show that LQR-based ANN and H_∞ regulator provide complete robustness over the suggested operating conditions (20% - 90% compensation, and 50% - 100% loading) with reasonable control signals.

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LIST OF ABBREVIATIONS

ANN	**Artificial Neural Network.**
DSCF	**Design Series Compensation Factor.**
FBM	**IEEE First Benchmark Model.**
H_∞	**H refers to the hardy space of all stable systems and ∞ refers to the system norm.**
LQR	**Linear Quadratic Regulator.**
PPR	**Pole Placement Regulator.**
SCF	**Series Compensation Factor (X_C/X_L %).**
SSR	**Subsynchronous Resonance.**

LIST OF SYMBOLS

A	state matrix
a	speed relay
B	input matrix
C	capacitance in p.u
D	damping constant
EX	exciter
F	torque fraction
f	frequency
GEN	generator
g	governor opening
HP	High Pressure turbine
IP	Intermediate Pressure turbine
I, i	current in p.u
J	objective function
K	spring constant in p.u or gain matrix
L	inductance in p.u
LPA	Low Pressure turbine A
LPB	Low Pressure turbine B
m	measured outputs
P	power in p.u. or Riccatti equation solution
Q	reactive power in p.u or state weighting matrix or Riccatti equation solution
q	state weighting elements
R, r	resistance in p.u or input weighting matrix
T	torque in p.u or time constant in sec
u	inputs
w	disturbance
X, x	reactance in p.u or system states
y	system or reference output
z	modal states
α, β	phase angles in rad
γ	performance bound or phase angle in rad
Δ	parameter change or variation
δ, θ	rotor angle displacement in rad
λ	eigenvalue

σ	damping or decrement factor (eigenvalue real part)
ψ	flux linkage in p.u
ω	speed in p.u

Superscript:

'	transpose or transient value
"	sub-transient value
T	matrix transpose

Subscript:

A	low pressure turbine A or regulator
a	phase a winding or armature winding
ad	mutual d axis
aq	mutual q axis
B	low pressure turbine B
b	phase b winding or base value
C	capacitive
CH	steam chamber
CO	crossover connection
c	phase c winding
D	damper winding in d axis
d	armature winding in d axis
E	transmission or external or exciter
e	electrical
F, f	field winding
FD	internal generator voltage
G	first damper winding in the q axis, or generator
H	high pressure turbine
I	intermediate pressure turbine
m	modal value

o	initial value or infinite bus
Q	second damper winding in the q axis
q	armature winding in q axis
R	regulator
RH	reheater
Ref or ref	reference value
SM	servomotor
SR	speed relay
T	transformer
t	generator terminal
X	exciter