DECENTRALIZE CONTROL PARADIGMS FOR ENHANCEMENT OF POWER SYSTEM STABILITY

ABDUL SALEEM MIR

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

ABDUL SALEEM MIR

Department of Electrical Engineering

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CERTIFICATE

This is to certify that the thesis entitled **"Decentralized Control Paradigms for Enhancement of Power System Stability"** submitted by **Mr. Abdul Saleem Mir**, to Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted to any other institute or university for the award of any degree or diploma.

Prof. Nilanjan Senroy

Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi-110016, India.

Date:

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Dated: Abdul Saleem Mir

Abstract

This dissertation primarily focuses on the mitigation of instabilities in the power system via novel auxiliary stabilizers and intelligently controlled energy storage systems. Improving the stability margins in a power system allows the higher flow of power through interties which translates into a measurable economic benefit. Dynamic state estimator using local measurements acts as a precursor for the auxiliary stabilizers as they utilize unmeasurable interior states of the machine in the control law. Further, bulk integration of renewable energy requires fast-acting energy sources/sinks at the time of the disturbance. In this context, intelligently controlled fast-acting energy storage systems have been suggested to mitigate intermittency, enhance transient and frequency stability margins. Several aspects investigated in this thesis are as follows-

1) A nonlinear dynamic state estimator has been recommended to estimate the unmeasurable states of the machine using analogue measurements from the generator (terminal) bus instrument transformers. This methodology is well suited for enhancing system control, assessing dynamic security and monitoring oscillatory modes to name a few.
2) A decentralized nonlinear excitation controller utilizing terminal bus voltage and frequency measurements as exogenous inputs and machine states (estimated locally) in the robust optimal control law for significant enhancement in the dynamic and transient stability margins has been proposed.
3) Grid integrated low inertia DFIG wind energy conversion system (WECS) exhibits prolonged oscillations following a network disturbance. A computationally adaptive optimal damping controller using DFIG-WECS interior states (estimated locally) has been suggested for the mitigation. Compared to its predecessors, proposed stabilizer being robust and cost effective improves the stability significantly.
4) Performance of auxiliary stabilizers is affected by the system nonlinearities like saturation limits, dead-bands, rate constraints etc. In this context, effective use of properly controlled fast acting storage facilities like flywheel energy storage system and ultrabattery storage is suggested. Modelling and control architecture of the new storage technology namely ultrabattery and flywheel storage has been introduced and discussed for subsequent use in power system stability enhancement.
5) The application of an intelligently controlled flywheel energy storage system (FESS), to

mitigate the intermittency in wind power injection, as well as enhance the transient stability of the connected multimachine power system has been investigated. The main contributions are – *a*) enhanced use of DFIM based FESS for transient stability improvement following a network disturbance, *b*) demonstrating the intelligent controller development and its application for the flexible operation of the FESS facility, and *c*) intermittency mitigation via FESS considering actual wind speed profile.

6) The use of intelligent virtual synchronous generator and constrained LQR based ultrabattery storage has been suggested for improved frequency control.

Keywords: Adaptive control, cubature-Kalman-filter (CKF), decentralized, dynamic state estimator, damping control, DFIG, linear quadratic regulator (LQR), neural networks (NNs), optimal control, phasor measurement unit (PMU), power systems, stability.

सार

यह शोध प्रबंध मुख्य रूप से उपन्यास के माध्यम से बिजली व्यवस्था में अस्थिरताओं के शमन पर केंद्रित है सहायक स्टेबलाइजर्स और समझदारी से नियंत्रित ऊर्जा भंडारण प्रणाली। स्थिरता में सुधार एक पावर सिस्टम में मार्जिन अंतर के माध्यम से शक्ति के उच्च प्रवाह की अनुमति देता है जो अनुवाद करता है एक औसत दर्जे का आर्थिक लाभ। स्थानीय माप का उपयोग कर गतिशील राज्य आकलनकर्ता एक के रूप में कार्य करता है सहायक स्टेबलाइजर्स के लिए अग्रदूत के रूप में वे मशीन के अनम्य आंतरिक राज्यों का उपयोग करते हैं नियंत्रण कानून। इसके अलावा, अक्षय ऊर्जा के थोक एकीकरण के लिए तेजी से काम करने वाली ऊर्जा की आवश्यकता होती है गड़बड़ी के समय स्रोत / डूब इस संदर्भ में, बुद्धिमानी से तेजी से अभिनय को नियंत्रित किया ऊर्जा भंडारण प्रणालियों को आंतरायिकता को कम करने, क्षणिक को बढ़ाने और आवृत्ति स्थिरता मार्जिन। इस थीसिस में जांच किए गए कई पहलू इस प्रकार हैं–

1) एक ग़ैर-गतिशील गतिशील राज्य आकलनकर्ता को अचूक का अनुमान लगाने की सिफारिश की गई है जनरेटर (टर्मिनल) बस से एनालॉग माप का उपयोग करते हुए मशीन की स्थिति उपकरण ट्रांसफार्मर। यह पद्धति प्रणाली नियंत्रण को बढ़ाने के लिए अच्छी तरह से अनुकूल है, गतिशील सुरक्षा का आकलन और कुछ नाम करने के लिए दोलन मोड की निगरानी करना।

2) टर्मिनल बस वोल्टेज और आवृत्ति का उपयोग एक विकेन्द्रीकृत अरेखीय उत्तेजना नियंत्रक बहिर्जात आदानों और मशीन राज्यों के रूप में माप (स्थानीय रूप से अनुमानित) मजबूत में गतिशील और क्षणिक स्थिरता में महत्वपूर्ण वृद्धि के लिए इष्टतम नियंत्रण कानून मार्जिन प्रस्तावित किया गया है।

3) ग्रिड एकीकृत कम जड़ता डीएफआईजी पवन ऊर्जा रूपांतरण प्रणाली (डब्ल्यूईसीएस) प्रदर्शित करता है एक नेटवर्क गड़बड़ी के बाद लंबे समय तक दोलनों। एक कम्प्यूटेशनल रूप से अनुकूली डीएफआईजी-डब्ल्यूईसीएस आंतरिक राज्यों (स्थानीय रूप से अनुमानित) का उपयोग करके इष्टतम भिगोना नियंत्रक रहा है शमन के लिए सुझाव दिया। अपने पूर्ववर्तियों की तुलना में, प्रस्तावित स्टेबलाइजर मजबूत हो रहा है और प्रभावी लागत स्थिरता में काफी सुधार करती है।

4) सहायक स्टेबलाइजर्स का प्रदर्शन संतृप्ति जैसी प्रणाली की गैर-प्रभावितताओं से प्रभावित होता है सीमाएं, डेड-बैंड, दर की कमी आदि। इस संदर्भ में, ठीक से नियंत्रित का प्रभावी उपयोग फ्लाईव्हील ऊर्जा भंडारण प्रणाली और पराबैंगनी भंडारण की तरह तेजी से अभिनय भंडारण की सुविधा है सुझाव दिया। नई भंडारण

प्रौद्योगिकी की मॉडलिंग और नियंत्रण वास्तुकला पराबैंगनी और चक्का भंडारण शुरू किया गया है और बाद के उपयोग के लिए चर्चा की गई है बिजली प्रणाली की स्थिरता में वृद्धि।

5) एक बुद्धिमानी से नियंत्रित चक्का ऊर्जा भंडारण प्रणाली (एफईएसएस) का अनुप्रयोग पवन ऊर्जा इंजेक्शन में आंतरायिकता को कम करें, साथ ही क्षणिक स्थिरता को बढ़ाएं कनेक्टेड मल्टीमाचिन पावर सिस्टम की जांच की गई है। मुख्य योगदान कर रहे हैं - क) क्षणिक स्थिरता में सुधार के लिए डीएफआईएम आधारित एफईएसएस का एक बढ़ाया उपयोग निम्नलिखित एक नेटवर्क गड़बड़ी, ख) बुद्धिमान नियंत्रक विकास और उसके प्रदर्शन एफईएसएस सुविधा के लचीले संचालन के लिए आवेदन, और सी) आंतरायिक शमन वास्तविक पवन गति प्रोफ़ाइल पर विचार करते हुए एफईएसएस के माध्यम से।

6) बुद्धिमान आभासी तुल्यकालिक जनरेटर और विवश एलक्यूआर आधारित पराबैंगनी का उपयोग भंडारण में सुधार आवृत्ति नियंत्रण के लिए सुझाव दिया गया है।

कीवर्ड: अनुकूली नियंत्रण, क्यूरेचर-कलमन-फ़िल्टर (सीकेएफ), विकेन्द्रीकृत, गतिशील राज्य अनुमानक, भिगोना नियंत्रण, डीएफआईजी, रैखिक द्विघात नियामक (एलक्यूआर), तंत्रिका नेटवर्क (एनएन), इष्टतम नियंत्रण, चरण मापक इकाई (पीएमयू), पावर सिस्टम, स्थिरता ।

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LIST OF ABBREVIATIONS AND SYMBOLS

DDSE	Decentralized Dynamic State Estimation
ADM	Adaptive Detection Methodology
CT	Current Transformer or Continuous time
PT/VT	Potential/Voltage Transformer
AC	Actor-Critic
NETS-NYPS	New England Test System (NETS)- New-York Power System (NYPS)
WECC	Western Electricity Coordinating Council
NN	Neural Networks
ARE	Algebraic-Riccati-equation
HJB	Hamilton–Jacobi–Bellman
FA	Function Approximation
PIA	Policy Iteration Algorithm
NAOC	Nonlinear Adaptive Optimal Controller
DFIG	Doubly Fed Induction Generator based Wind Turbine system
WECS	Wind Energy Conversion System
DAE	Differential-Algebraic-Equations
ODE	Ordinary-Differential-Equations
PMSG	Permanent Magnet Synchronous Generator
FRC	Full Rated Converter
RSC	Rotor Side Converter
GSC	Grid Side Converter
MPPT	Maximum Power Point Tracking
LQR	Linear Quadratic Regulator
PSS	Power System Stabilizer
UKF	Unscented Kalman Filter
CKF	Cubature Kalman Filter
PCS	Power Conditioning System
FAST	Fatigue, Aerodynamic, Structural and Turbulence simulator
NREL	National Renewable Energy Laboratory, Department of Energy, U.S.
PMU	Phasor Measurement Unit

WSCC	Western System Coordinating Council
ω_B, ω	Base elec. speed (*rad/s*), machine speed in *p.u.*
H, f_{V}	Machine inertia (*s*), stator voltage (V) freq. in *p.u.*
$\mathrm{P_e}$, $\mathrm{I_e}$	Electrical power and stator current resp.
δ, θ	Rotor angle and stator voltage phase angle in *rad.*
V_r^*, E_{fd}	AVR reference voltage, field excitation voltage
V_r, V_s	AVR filter voltage and PSS output resp.
V_a	AVR regulator voltage
e_d', e_q'	Transient *d* and *q* axis emfs in *p.u.*
ψ_d, ψ_q	Subtransient damper coil *d* and *q* axis emfs in *p.u.*
$p_{i=1\ldots3}$	PSS states, f_{I} =frequency of the stator current.
v_q, v_d	*q* and *d* axis stator voltages ($\mathrm{V}_t = v_d + jv_q$) in *p.u.*
i_q, i_d	*q* and *d* axis stator currents ($\mathrm{I}_e = i_d + ji_q$) in *p.u.*
$\boldsymbol{x}$, $\boldsymbol{u}$	State and pseudo-input (or input) vectors respectively
$\boldsymbol{y}$, n_x	Measurement vector, State vector dimension.
$a(t)$	Instantaneous CT/PT measurement
$\boldsymbol{s}$, $\boldsymbol{q}$	Column vectors of process and pseudo-input noises resp.
$\boldsymbol{r}$	Column vector of noise in $\boldsymbol{y}$
$\mathcal{P}_x$, $\mathcal{P}_y$	State and measurement covariance matrices resp.
$\mathcal{P}_{xy}$	Cross-correlation covariance matrix
$\mathcal{P}_{xq}$	Cross-covariance matrix of $\boldsymbol{x}$ and $\boldsymbol{q}$
$\mathcal{P}_\xi$	$= [\mathcal{P}_x\ \mathcal{P}_{xq}^{\mathrm{T}}\ ;\ \mathcal{P}_{xq}\ \mathcal{P}_q]$
Q_ξ	Constant additive process noise covariance matrix
R_y	Constant measurement noise covariance matrix
$\mathrm{T_s}$	Sampling time in seconds
H_t	Turbine inertia constant
H_g	DFIG inertia constant
ω_t	Turbine angular speed
ω_r	DFIG angular speed
θ_{tw}	Shaft twist angle

ω_B	Base electrical speed
$P_{t_{pu}}$	Turbine power
T_s	Shaft torque
T_e	Generator electrical torque
T_t	Turbine torque
c_d	Shaft damping coefficient
k_s	Stiffness of the shaft
V_w	Wind speed
$\mathrm{V_{DC}}$	DC link voltage
$\mathbf{V}_s$	DFIG Stator terminal voltage
$\mathbf{V}_b$	Infinite bus voltage
x_T	Transmission line reactance
x_C	Grid side converter transformer reactance
P_e	Generator active power
Q_e	Generator reactive power
θ_{tw}	Angular position of the turbine shaft
v_{qs}, v_{ds}, v_{qr} *and* v_{dr}	DFIG *q-axis* and *d-axis* stator and rotor voltages, respectively
i_{qs}, i_{ds}, i_{qr} *and* i_{dr}	DFIG *q-axis* and *d-axis* stator and rotor currents, respectively
"^"	Estimated value of the respective variable
Superscript/Subscript	pu = Per unit value of the respective variable
Superscript/Subscript	ref/REF = Reference value of the respective variable
Superscript/Subscript	$k = k^{th}$ instant of time.
Subscript	$p = p^{th}$ machine.
$(.)_p$	Subscript: continuous variable of p^{th} machine.
$(.)_{p0}$	Subscript: steady state value of continuous variable
$(\tilde{.}) = (.) - (.)_0$;	Variable transformation
ω_B, ω	Base elec. speed (rad/s), machine speed in p.u.
H, f	Machine inertia (s), stator voltage (V) freq. in p.u.
τ_E, τ_M	Electrical and mechanical torques in p.u. resp.
τ_E0, τ_M0	Steady state electrical and mechanical torques

δ, θ	Rotor angle and stator voltage phase angle in rad.
α,$\tilde{\tau}_m$,$\tilde{\tau}_e$	$\alpha = \delta - \theta$ and $\tilde{\tau}_m = \tau_{\mathrm{M}} - \tau_{\mathrm{M0}}$; $\tilde{\tau}_e = \tau_{\mathrm{E}} - \tau_{\mathrm{E0}}$
V_r^*, E_{fd}	AVR reference voltage, field excitation voltage
e'_d, e'_q	Transient d and q axis emfs in p.u.
ψ_d, ψ_q	Subtransient damper coil d and q axis emfs in p.u.
V_r, V_{ss}	AVR filter voltage, controller output reference
v_q, v_d	q and d axis stator voltages ($\mathrm{V}_t = v_d + jv_q$) in p.u.
i_q, i_d	q and d axis stator currents (I= $i_d + ji_q$) in p.u.
τ'_{q0}, τ'_{d0}	q and d axis transient time-constants (s)
τ''_{q0}, τ''_{d0}	q and d axis subtransient time-constants (s)
k_{D}, τ_r	Damping coefficient and AVR filter time constant
$\boldsymbol{x}, \boldsymbol{u}$	State vector and control input respectively
$\boldsymbol{y}, \boldsymbol{v}$	Output and exogenous input vectors respectively
n_x, n_u	State and control vector dimensions respectively
W_1^*, φ	Ideal critic NN weight and NN activation function
$\widehat{\mathrm{W}}_2, \widehat{\mathrm{W}}_1$	Estimated weight vectors of actor and critic NNs.
δ_v, N_n	Function approximation error and no. of neurons
x''_q, x''_d	Subtransient q and d axis reactances
x'_q, x'_d	Transient q and d axis reactances
x_q, x_d	Synchronous q and d axis reactances
x_l, r_a	Armature leakage reactance and resistance resp.
k'_1	$= (x''_q - x_l)(x_q - x'_q)/(x'_q - x_l)$
k'_2	$= (x'_q - x''_q)(x_q - x'_q)/(x'_q - x_l)^2$
k'_3	$= (x''_d - x_l)(x_d - x'_d)/(x'_d - x_l)$
k'_4	$= (x'_d - x''_d)(x_d - x'_d)/(x'_d - x_l)^2$
k_1	$= k'_1/(x_q - x'_q)$, $k_2 = (x'_q - x''_q)/(x'_q - x_l)$
k_3	$= k'_3/(x_d - x'_d)$, $k_4 = (x'_d - x''_d)/(x'_d - x_l)$
$\mathcal{Z}_a^2$	$= (x_l^2 + r_a^2)$
Tria (.)	General traingularization algorithm