SMART GRID STATE ESTIMATION AND ITS APPLICATIONS TO GRID STABILIZATION

by

MD MASUD RANA

UNIVERSITY OF TECHNOLOGY SYDNEY

AN ABSTRACT OF A DISSERTATION

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Dedicated to UTS students and staffs.

Abstract

The smart grid is expected to modernize the current electricity grid by commencing a new set of technologies and services that can make the electricity networks more secure, automated, cooperative and sustainable. The smart grid can integrate multiple distributed energy resources (DERs) into the main grid. The need for DERs is expected to become more important in the future smart grid due to the global warming and energy problems. Basically, the smart grid can spread the intelligence of the energy distribution and control system from the central unit to long-distance remote areas, thus enabling accurate state estimation and wide-area real-time monitoring of these intermittent energy sources. Reliable state estimation is a key technique to fulfil the control requirement and hence is an enabler for the automation of power grids. Driven by these motivations, this research explores the problem of state estimation and stabilization taking disturbances, cyber attacks and packet losses into consideration for the smart grid.

The first contribution of this dissertation is to develop a least square based Kalman filter (KF) algorithm for state estimation, and an optimal feedback control framework for stabilizing the microgrid states. To begin with, the environment-friendly renewable microgrid incorporating multiple DERs is modelled to obtain discrete-time state-space linear equations where sensors are deployed to obtain system state information. The proposed smart grid communication system provides an opportunity to address the state regulation challenge by offering two-way communication links for microgrid information collection, estimation and stabilization. Interestingly, the developed least square based centralised KF algorithm is able to estimate the system states properly even at the beginning of the dynamic process, and the proposed H_2 based optimal feedback controller is able to stabilize the microgrid states in a fairly short time.

Unfortunately, the smart grid is susceptible to malicious cyber attacks, which can create

serious technical, economic, social and control problems in power network operations. In contrast to the traditional cyber attack minimization techniques, this study proposes a recursive systematic convolutional (RSC) code and KF based method in the context of smart grids. The proposed RSC code is used to add redundancy in the microgrid states, and the log maximum a-posterior is used to recover the state information which is affected by random noises and cyber attacks. Once the estimated states are obtained, a semidefinite programming (SDP) based optimal feedback controller is proposed to regulate the system states. Test results show that the proposed approach can accurately mitigate the cyber attacks and properly estimate as well as regulate the system states.

The other significant contribution of this dissertation is to develop an adaptive-then-combine distributed dynamic approach for monitoring the grid under lossy communication links between wind turbines and the energy management system. Based on the mean squared error principle, an adaptive approach is proposed to estimate the local state information. The global estimation is designed by combining local estimation results with weighting factors, which are calculated by minimizing the estimation error covariances based on SDP. Afterwards, the convergence analysis indicates that the estimation error is gradually decreased, so the estimated state converges to the actual state. The efficacy of the developed approach is verified using the wind turbine and IEEE 6-bus distribution system.

Furthermore, the distribution power sub-systems are usually interconnected to each other, so this research investigates the interconnected optimal filtering problem for distributed dynamic state estimation considering packet losses. The optimal local and neighbouring gains are computed to reach a consensus estimation after exchanging their information with the neighbouring estimators. Then the convergence of the developed algorithm is theoretically proved. Afterwards, a distributed controller is designed based on the SDP approach. Simulation results demonstrate the accuracy of the developed approaches.

The penultimate contribution of this dissertation is to develop a distributed state estimation algorithm for interconnected power systems that only needs a consensus step. After modelling the interconnected synchronous generators, the optimal gain is determined to obtain a distributed state estimation. The consensus of the developed approach is proved based on the Lyapunov theory. From the circuit and system point of view, the proposed framework is useful for designing a practical energy management system as it has less computational complexity and provides accurate estimation results.

The distributed state estimation algorithm is further modified by considering different observation matrices with both local and consensus steps. The optimal local gain is computed after minimizing the mean squared error between the true and estimated states. The consensus gain is determined by a convex optimization process with a given local gain. Moreover, the convergence of the proposed scheme is analysed after stacking all the estimation error dynamics. The efficacy of the developed approach is demonstrated using the environment-friendly renewable microgrid and IEEE 30-bus power system.

Overall, the findings, theoretical development and analysis of this research represent a comprehensive source of information for smart grid state estimation and stabilization schemes, and will shed light on green smart energy management systems and monitoring centre design in future smart grid implementations. It is worth pointing out that the aforementioned contributions are very important in the smart grid community as communication impairments have a significant impact on grid stability and the distributed strategies can reduce communication burden and offer a sparse communication network.

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Statement of Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Md Masud Rana
Faculty of Engineering and Information Technology
University of Technology Sydney, Australia.

List of Publications

1. M. M. Rana, L. Li and S. W. Su, ”State estimation over unreliable communication networks with an application to smart grids,” *IEEE Transactions on Green Communications and Networking, vol. 1, no. 11, pp. 89-96, March 2017.*

2. M. M. Rana, L. Li and S. W. Su, ”Controlling the renewable microgrid using semidefinite programming technique,” *International Journal of Electrical Power and Energy Systems*, vol. 84, pp. 225-231, January 2017.

3. M. M. Rana, L. Li and S. W. Su, ”An adaptive-then-combine dynamic state estimation considering renewable generations in smart grids,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 12, pp. 3954-3961, December 2016.

4. M. M. Rana, L. Li and S. W. Su, ”Microgrid state estimation and control using Kalman filter and semidefinite programming technique,” *International Energy Journal*, Thailand, vol. 2, pp. 47-56, June 2016.

5. M. M. Rana, L. Li and S. W. Su, ”Cyber attack protection and control of microgrids,” *IEEE/CAA Journal of Automatica Sinica (Acceptance notified on the 25th May, 2016, Appear in 2017).*

6. M. M. Rana and L. Li, ”Renewable microgrid state estimation using the internet of things communication network,” *ICACT Transactions on Advanced Communications Technology*, South Korea, vol. 5, no. 2, pp. 823-829, May 2016.

7. M. M. Rana, L. Li and S. W. Su, ”Distributed state estimation using RSC coded smart grid communications,” *IEEE Access: Special Section on Smart Grids: A Hub of Interdisciplinary Research* , vol. 3, pp. 1340-1349, August 2015.

8. M. M. Rana and L. Li, ”An overview of distributed microgrid state estimation and control for smart grids,” *Sensors*, Switzerland, vol. 15, no. 2, pp. 4302-4325, February 2015.

9. M. M. Rana and L. Li, ”Microgrid state estimation and control for smart grid and Internet of Things communication network,” *Electronics Letters*, vol. 51, no. 2, pp. 149-151, January 2015.

10. M. M. Rana, L. Li and S. W. Su, ”Microgrid state estimation using the IoT with 5G technology,” *Internet of Things (IoT) in 5G Mobile Technologies. Springer International Publishing*, Germany, Chapter 9, pp. 175-195, June 2015.

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12. M. M. Rana, L. Li and S. W. Su, ”Distributed dynamic state estimation considering renewable generation and packet losses,” *Proc. of the 14th International Conference on Control, Automation, Robotics and Vision*, Thailand, November 2016.

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14. M. M. Rana, L. Li and S. W. Su, ”Cyber attack protection and control in microgrids using channel code and semidefinite programming,” *Proc. of the IEEE Power and Energy Society General Meeting*, USA, July 2016.

15. M. M. Rana, L. Li and S. W. Su, ”Distributed condition monitoring of renewable microgrids using adaptive-then-combine algorithm,” *Proc. of the IEEE Power and Energy Society General Meeting*, USA, July 2016.

16. M. M. Rana, L. Li and S. W. Su, ”Kalman filter based microgrid state estimation and control using the IoT with 5G networks,” *Proc. of the IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Australia, November 2015.

17. M. M. Rana, L. Li and S. W. Su, ”Kalman filter based distributed state estimation with communication systems,” *Proc. of the IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Australia, November 2015.

18. M. M. Rana, L. Li and S. W. Su, ”Distributed microgrid state estimation using smart grid communications,” *Proc. of the IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Australia, November 2015.

19. M. M. Rana and L. Li, ”Distributed generation monitoring of smart grid using accuracy dependent Kalman filter with communication systems,” *Proc. of the 12th International Conference on Information Technology-New Generations*, USA, April 2015.

20. M. M. Rana and L. Li, ”Kalman filter based microgrid state estimation using the internet of things communication network,” *Proc. of the 12th International Conference on Information Technology-New Generations*, USA, April 2015.

21. M. M. Rana and L. Li, ”Controlling the distributed energy resources using smart grid communications,” *Proc. of the 12th International Conference on Information Technology-New Generations*, USA, April 2015.

Awards and Scholarships

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- Publications Award 2015 from the Faculty of Engineering and Information Technology, UTS, Australia.
- The UTS President's Scholarship (UTSP) during PhD study from the UTS, Australia.
- International Research Scholarship during PhD study from the UTS, Australia.

Contents

List of Figures

List of Tables

List of Acronyms

3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AC	Alternating Current
AVR	Automatic Voltage Regulator
AWGN	Additive White Gaussian Noise
BP	Belief Propagation
BPSK	Binary Phase Shift Keying
CC	Convolutional Coding
DC	Direct Current
DER	Distributed Energy Resource
DSE	Dynamic State Estimation
DKF	Distributed Kalman Filter
EMS	Energy Management System
EKF	Extended Kalman Filter
GPS	Global Positioning System
ICT	Information and Communication Technology
IED	Intelligent Electronic Device
LAN	Local Area Network
LDPC	Low Density Parity Check
LMMSE	Linear Minimum Mean Square Error
LMS	Least Mean Squares
Log-MAP	Log-maximum a-posteriori
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator

LS	Least Square
EKF	Extended Kalman Filter
FAN	Field Area Network
IAN	Industrial Area Network
IID	Independent, Identically Distributed
KF	Kalman Filter
KCL	Kirchhoff's Current Law
KVL	Kirchhoff's Voltage Law
LLR	Log-Likelihood Ratio
LMI	Linear Matrix Inquality
LTE	Long Term Evolution
MAC	Multiple Access Channel
MASE	Multi-Area State Estimation
MAP	Maximum a-Posteriori Probability
MCSE	Modified Coordinated State Estimation
MPC	Model Predictive Control
NAN	Neighborhood Area Network
NBP	Nonparametric Belief Propagation
NLMS	Normalized Least Mean Square
PCC	Point of Common Coupling
PDF	Probability Distribution Function
PID	Proportional Integral Derivative
PF	Particle Filter
PLC	Power Line Communications
PMU	Phasor Measurement Units
RFID	Radio-Frequency Identification
RL	Resistor inductor
RLC	Resistor inductor Capacitor
RSC	Recursive Systematic Convolutional
SCADA	Supervisory Control and Data Acquisition
SDP	Semidefinite Programming
SE	State Estimation
SG	Smart Grid
SNR	Signal-to-Noise Ratio

RTU	Remote Terminal Unit
UKF	Unscented Kalman Filter
VSC	Voltage Source Converter
WAN	Wireless Area Network
WiFi	Wireless Fidelity
WLS	Weighted Least Square
WiMAX	Worldwide Interoperability for Microwave Access
WSN	Wireless Sensor Networks

List of Symbols

θ	Azimuth angle
$\otimes$	Kronecker product
Δ	Deviation
Δi_{dj}	Current deviation of DER_j
Δi_{tj}	Current deviation of transmission line
Δi_{lj}	Current deviation of load
Δv_j	PCC bus voltage deviation
Δt	Sampling period
δ	Rotor angle
ω	Rotor speed
λ	Packet arrival rate
$\mathbf{a}$	Cyber attack
$\mathbf{A}$	System state matrix
$\mathbf{b}$	Sequence of bits
$\mathbf{B}$	System input matrix
$\mathbf{C}$	Observation matrix
C_j	Capacitance
$diag(\cdot)$	Diagonal matrix
D	Damping coefficient
$\mathbf{e}$	Estimation error
E'	Transient voltage
$E(\cdot)$	Expectation operator
f_o	Frequency
$\mathbf{F}$	State feedback gain
i	Current

$\mathbf{I}$	Identity matrix
J	Moment of inertia
k	Time step
$\mathbf{K}$	Kalman gain
$\mathbf{L}_r$	Received sequence length
$\mathbf{L}$	Neighbouring gain
L_{dj}	Inductance of VSC_j filter
L_{tj}	Inductance of transmission line
L_{lj}	Inductance of load
M_s	Number of states in the trellis
$\mathbf{n}$	Process noise
P_a	Turbine output power
$\mathbf{P}^-$	Predicted error covariance matrix
$\mathbf{P}$	Updated error covariance matrix
$\mathbf{Q}$	Process noise covariance matrix
$\mathbf{Q}_z$	Positive definite matrix
$\mathbf{r}$	Received sequence
$\mathbf{R}$	Measurement noise covariance matrix
R_{dj}	Resistance of VSC_j filter
R_{tj}	Resistance of transmission line
R_{lj}	Resistance of load
$\mathbf{s}$	Transmitted sequence
$tr(\cdot)$	Trace operator
T'_{doi}	Open-circuit transient time constant
T	Torque
v_{pi}	i-th DER input voltage
v_i	i-th PCC voltage
$\mathbf{w}$	Measurement noise
$\mathbf{x}$	Actual system states
$\hat{\mathbf{x}}$	Estimated system states
$\mathbf{y}$	Measurements
$\mathbf{y}_{rd}$	Dequantized and demodulated output bit sequence
$\mathbf{Y}$	Admittance matrix