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Model predictive load–frequency control taking into account imbalance uncertainty

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ABSTRACT

Nonlinear model predictive control (NMPC) is investigated for load frequency control (LFC) of an interconnected power system which is exposed to increasing wind power penetration. The robustified NMPC (RNMPC) proposed here uses knowledge of the estimated worst-case deviation in wind-power production to make the NMPC more robust. The NMPC is based on a simplified system model that is updated using state- and parameter estimation by Kalman filters, and it takes into account limitations on among others tie-line power flow. Tests on a proxy of the Nordic power system show that the RNMPC is able to fulfill system constraints under worst-case deviations in wind-power production, where the nominal NMPC is not.

1. Introduction

Power systems around the world have been through great development during the last two decades. First with the liberalization of the power markets in the 1990s, and second with the increasing amount of renewable energy resources, distributed generation, and increasing energy need seen around the world. These are all elements which cause challenges for the operation of power systems, and especially with regard to load frequency control (LFC).

LFC is a term applied to describe the continuous operation of keeping the frequency of a power system stable. The frequency of a power system is connected to the balancing of produced and consumed power in the way that if there is a surplus of produced power the frequency will rise, and if there is a lack of produced power the frequency will fall. It is very important that this power balance is maintained, if not the generators could lose synchronism, and the power system would collapse. Traditionally, LFC has a hierarchical structure with primary, secondary, and tertiary control,[1] see Fig. 1. Primary control is continuous, automatic control placed locally at the generators. It is often based on proportional control, and it instantaneously covers the power imbalance between produced and consumed power. It does not, however, ensure that the frequency is restored to its set point. For this, secondary control is needed. Secondary control is a slower, centralized, and automatic controller which releases primary control. It is often referred to as automatic generator control (AGC), and this term will be applied in the following. Tertiary control is an even slower, centralized controller, which again releases the AGC. This is manually operated by the transmission system operator (TSO). In the Nordic network, consisting of Norway, Sweden, Finland, and the eastern parts of Denmark, hydro generators are the main provider for primary control, while other generating units such as thermal and nuclear power generators as well as some

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Abbreviation: AGC, automatic generator control; CMPC, centralized model predictive control; CPM, control performance measure; DMPC, distributed model predictive control; EKF, extended Kalman filter; FCR, frequency containment reserves; FRR, frequency restoration reserves; HVDC, high voltage direct current; LFC, load frequency control; MPC, model predictive control; NERC, North American electric reliability corporation; NLP, nonlinear program; NMPC, nonlinear model predictive control; NNMPC, nominal nonlinear model predictive control; OCP, optimal control problem; PM, prediction model; PMU, phasor measurement unit; PRM, plant replacement model; RNMPC, robustified nonlinear model predictive control; RR, replacement reserves; TSO, transmission system operator

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[1] Also known as frequency containment reserves (FCR), frequency restoration reserves (FRR), and replacement reserves (RR).

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Nomenclature

Latin Letters

A_t	Factor that accounts for different per-unit bases in turbine and governor, SINTEF model
$\bar{A}_t$	Factor that accounts for different per-unit bases in aggregated turbine and governor, prediction model
c	Valve opening in hydro turbine, SINTEF model
c_r	Valve opening set point in hydro turbine, SINTEF model
c_{r0}	Valve opening hourly set-point in hydro turbine, SINTEF model
$\bar{c}_{ss}$	Valve opening steady-state in aggregated hydro turbine, prediction model
$\Delta\bar{c}$	Valve opening in aggregated hydro turbine, prediction model
$\Delta\bar{c}_r$	Valve opening set point in aggregated hydro turbine, prediction model
D_g	Generator damping coefficient, SINTEF model
D_t	Hydro turbine damping coefficient, SINTEF model
E	Internal voltage of generator, SINTEF model
f_n	Nominal frequency, prediction model
$\Delta\bar{f}$	Deviation from nominal frequency, prediction model
H	Rotor inertia of generator, SINTEF model
$\bar{H}$	Rotor inertia of aggregated generator, prediction model
I_g	Current delivered from generator, SINTEF model
I_L	Current from network load, SINTEF model
I_{sys}	Current from other nodes in the network, SINTEF model
I_l	Load current representing real load power, SINTEF model
$\mathrm{m}_{\mathrm{base}}$	Base rating of generator, SINTEF model
P_m	Mechanical turbine power output, SINTEF model
P_e	Electrical generator power output, SINTEF model
$\Delta\bar{P}_D$	Total change in load power and uncontrollable production, prediction model
$\Delta\bar{P}_{tie}$	Change in total power flow on tie-lines, prediction model
q	Flowrate in penstock of hydro turbine, SINTEF model
q_{nl}	No-load flow in hydro turbine, SINTEF model
$\bar{q}_{ss}$	Hydro turbine water flow rate steady-state, prediction model
$\Delta\bar{q}$	Flowrate in penstock of aggregated hydro turbine, prediction model
$\mathbf{Q}$	NMPC tuning matrix
$\mathbf{R}$	NMPC tuning matrix
r	Transient droop coefficient in hydro governor, SINTEF model
$\bar{r}$	Transient droop coefficient in aggregated hydro governor, SINTEF model
s_{base}	Network base rating, SINTEF model
T	Prediction horizon in NMPC
T_g	Time constant in hydro governor servo motor, SINTEF model
$\bar{T}_g$	Time constant in aggregated hydro governor servo motor, prediction model
$\bar{T}_{ij}$	Synchronizing torque coefficient between area i and j, prediction model
T_p	Time constant in hydro governor servo motor, SINTEF model
T_r	Time constant in hydro governor transient droop, SINTEF model
$\bar{T}_r$	Time constant in aggregated hydro governor transient droop, prediction model
T_w	Water starting time in hydro turbine, SINTEF model
$\bar{T}_w$	Water starting time in aggregated hydro turbine, prediction model
$\mathbf{u}$	Input vector, SINTEF model
$\bar{\mathbf{u}}$	Input vector, prediction model
$\bar{\mathbf{u}}_0$	Hourly set-point value of input vector, prediction model
$\lvert U \rvert$	Nodal voltage absolute value, SINTEF model
$\mathbf{w}$	Disturbance vector, SINTEF model
$\bar{\mathbf{w}}$	Disturbance vector, prediction model
$\mathbf{x}$	Dynamic state vector, SINTEF model
$\bar{\mathbf{x}}$	Dynamic state vector, prediction model
$\mathbf{y}$	Measurement vector, SINTEF model
$\mathbf{Y}_c$	Network admittance matrix, SINTEF model
$\mathbf{z}$	Algebraic state vector, SINTEF model

Greek Letters

α	Generator participation factor, SINTEF model
δ	Rotor angle of generator, SINTEF model
θ	Nodal voltage angle, SINTEF model
ξ_1	Valve opening of pilot servo motor in hydro turbine governor, SINTEF model
ξ_2	Integral of controller part in hydro turbine governor, SINTEF model
$\bar{\xi}_2$	Integral of controller part in aggregated hydro turbine governor, prediction model
ξ_3	Valve opening of main servomotor in hydro governor, SINTEF model
$\bar{\xi}_3$	Valve opening of main servomotor in aggregated hydro governor, prediction model
ρ	Constant droop coefficient in hydro governor, SINTEF model
$\bar{\rho}$	Constant droop coefficient in aggregated hydro governor, prediction model
$\Delta\omega$	Rotor angular velocity of generator, SINTEF model
ω_n	Nominal rotor-speed of generator, SINTEF model

controllable loads participate in tertiary control (Statnett, 2012). AGC was first implemented here in 2012/2013, and it is assumed that hydro generators will be the main provider for this as well.

In the Nordic Network, the TSOs aim at keeping the frequency between 49.9 and 50.1 Hz. This has proven to be increasingly difficult, and as seen from Fig. 2, the number of frequency incidents (minutes spent outside 49.9 and 50.1 Hz) has increased concurrently with installed wind power capacity over the last decade. It is confirmed by Statnett, the Norwegian TSO, that the increasing amount of intermittent energy resources is part of the reason for the decreasing control performance, along with a heavier loaded network and an increasing amount of bottlenecks, which at times excludes some of the resources from participating in LFC (Statnett, 2012).

There have been many suggestions to how LFC can be improved to better cope with these challenges. In Short, Infield, and Freris (2007) and Fabozzi, Thornhill, and Pal (2013) loads are included in LFC, while Suvire, Molina, and Mercado (2012) concentrate on effective energy storage, and Chang-Chien, Lin, and Yin (2011) suggest how wind generators can participate in LFC. Others concentrate on new control methods for LFC, such as including primary control in local decentralized generators (Marinovici, Lian,