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Weijia Yang

Hydropower Plants and Power Systems

Dynamic Processes and Control for Stable and Efficient Operation

Doctoral Thesis accepted by
Uppsala University, Sweden

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There is no elevator to success.
You have to take stairs.

Dedicated to my parents and my love

Supervisor's Foreword

Hydropower will most likely continue to be a vital part of regulating capacity in many power systems worldwide, i.e. an important resource for balancing variations in both electricity demand and production. The unintentional variability of new renewable sources is a challenge to power systems, both due to larger amplitude in variations and due to characteristic timescales that old systems are not designed for. The ability of hydropower to adjust output power and delivering energy on a wide range of time scales is yet unparalleled.

In the changing environment represented by electrical power systems transitioning to higher penetration of intermittent renewable sources, there is a need for predictions regarding the ability of existing and planned hydropower installations to provide system services. There is also a need to determine the operational costs related to these services. The thesis provides tools and insights into both these areas, treating, e.g. response time of hydropower units with complex waterways after major frequency disturbances, frequency control contribution during normal operation and relations between the quality of frequency control work and wear and fatigue indicators relevant for hydro power owners.

The thesis shows an exceptional width in several dimensions, with modelling ranging from mechanical construction details via control systems, hydraulics and electrical phenomena, up to market conditions and incentives; with tools including mathematical analysis, numerical simulation, and on-site measurements; with results ranging from factors influencing generating equipment lifetime to electrical grid frequency quality and compliance with regulations.

During his time as a Ph.D. student, Dr. Yang first developed tools, e.g. adding turbine controller capabilities to an existing computational framework for hydraulic computations (TOPSYS), and by that greatly expanding the set of applications possible to examine. He also wrote a description of the framework, making it more available to a wider academic audience. The validity of the framework was examined by comparisons to measurements from both Chinese and Swedish power plants, and performance measures such as response time were studied. These are only a few of the building blocks obtained by Dr. Yang, that eventually permitted him to evaluate cross-couplings between power plant dynamics and power system behaviour, under the different incentive structures valid in China, Sweden and the USA. The result is a work with international relevance, to a great extent thanks to the willingness of Dr. Yang to incorporate opinions from others, such as the Swedish industrial reference group and from academic contacts obtained at his visits abroad.

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Dr. Per Norrlund

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- **Stable Operation Regarding Frequency Stability:**

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Weijia Yang, Jiandong Yang, Wencheng Guo, Per Norrlund. Response time for primary frequency control of hydroelectric generating unit, *International Journal of Electrical Power and Energy Systems*, 74(2016):16–24.
Weijia Yang, Jiandong Yang, Wencheng Guo, Per Norrlund. Frequency stability of isolated hydropower plant with surge tank under different turbine control modes, *Electric Power Components and Systems*, 43(15): 1707–1716.
Wencheng Guo, Jiandong Yang, **Weijia Yang**, Jieping Chen, Yi Teng. Regulation quality for frequency response of turbine regulating system of isolated hydroelectric power plant with surge tank. *International Journal of Electrical Power & Energy Systems*, 2015, 73: 528–538.
Wencheng Guo, Jiandong Yang, Jieping Chen, **Weijia Yang**, Yi Teng, Wei Zeng. Time response of the frequency of hydroelectric generator unit with surge tank under isolated operation based on turbine regulating modes. *Electric Power Components and Systems*, 2015, 43(20), 2341–2355.
Wei Zeng, Jiandong Yang, **Weijia Yang**. Instability analysis of pumped-storage stations at no-load conditions using a parameter-varying model. *Renewable Energy*, 90 (2016): 420–429.
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- **Stable Operation Regarding Rotor Angle Stability:**

Weijia Yang, Per Norrlund, Chi Yung Chung, Jiandong Yang, Urban Lundin. Eigen-analysis of hydraulic-mechanical-electrical coupling mechanism for small signal stability of hydropower plant, *Renewable energy,* 115 (2018): 1014–1025.
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- **Efficient Operation and Balancing Renewable Power Systems:**

Weijia Yang, Per Norrlund, Linn Saarinen, Jiandong Yang, Wencheng Guo, Wei Zeng. Wear and tear on hydro power turbines – influence from primary frequency control, *Renewable Energy*, 87(2015) 88–95.

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Linn Saarinen, Per Norrlund, **Weijia Yang**, Urban Lundin. Allocation of frequency control reserves and its impact on wear on a hydropower fleet, *IEEE Transactions on Power Systems* 33.1 (2018): 430–439.

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Wuhan, China Dr. Weijia Yang

Contents

Abbreviations and Symbols

0-D	Zero dimensional
1-D	One dimensional
2-D	Two dimensional
3-D	Three dimensional
AVR	Automatic voltage regulator
GV	Guide vane
GVO	Guide vane opening
HPP	Hydropower plant
OF	Opening feedback
PF	Power feedback
PFC	Primary frequency control
PI	Proportional–integral
PID	Proportional–integral–derivative
PJM	PJM interconnection LLC
PSAT	Power system analysis toolbox
PSS	Power system stabilizer
RB	Runner blade
RBA	Runner blade angle
SISO	Single input and single output
SPS	Simpowersystems
SvK	Svenska kraftnät
TSO	Transmission system operator
VRE	Variable renewable energy

Latin Symbols

a	Runner blade angle (pu)
a_w	Velocity of pressure wave (m/s)
A	Cross-sectional area of pipeline (m^2)

A_P	Cross-sectional area of turbine inlet (m^2)
A_S	Cross-sectional area of turbine outlet (m^2)
a_{tk}	Runner blade angle at time step *tk* (pu)
BL_a	Runner backlash (pu)
BL_{gv}	Guide vane backlash (pu)
B_M, B_P	Intermediate variables of method of characteristic (m^2/s)
C_M, C_P	Intermediate variables of method of characteristic (m^3/s)
b_p	Governor droop (pu)
b_{p2}	Governor droop of the rest of the units in the grid (pu)
b_{p3}	Governor droop in Model 3 (pu)
c	Pressure propagation speed in penstock (m/s)
D	Common damping coefficient (pu)
D_1	Diameter of runner (m)
D_p	Inner diameter of the pipe (m)
D_t	Equivalent hydraulic turbine damping coefficient (“the damping coefficient”) (pu)
E''_d	d-axis component of the sub-transient internal EMF (pu)
E_{fd}	Excitation emf (pu)
e_g	Coefficient of load damping (pu)
E'_q	q-axis component of the transient internal emf (pu)
E''_q	q-axis component of the sub-transient internal emf (pu)
e_{qy}, $e_{q\omega}$, e_{qh}	Partial derivative of turbine discharge with respect to guide vane opening, speed and head (pu)
e_y, e_ω, e_h	Partial derivative of turbine power output with respect to guide vane opening, speed and head (pu)
f	Frequency or turbine rotational speed (pu)
f_D	Darcy–Weisbach coefficient of friction resistance (pu)
f_0	Rated frequency of power system (50 Hz in this thesis) (Hz)
f_c	Given frequency (Hz)
f_g	Generator frequency (Hz)
f_i	Frequency of oscillation corresponding to an eigenvalue (Hz)
f_p	Frictional coefficient of penstock (pu)
f_t	Frictional coefficient of tunnel (pu)
G	Comprehensive gate opening (pu)
g	Gravitational acceleration (m/s^2)
G_1	Gain from frequency deviation to power deviation for the Kaplan unit (pu)
G_2	Gain from frequency deviation to power deviation for the lumped hydropower plant (pu)
G_F	Fitting function of the comprehensive gate opening (pu)
G_g	Transfer function describing the grid (pu)
G_P	Transfer function describing the head variation due to the discharge deviation in the penstock (pu)

G_{PI}	Gain from GVO deviation to frequency deviation for the PI controller (pu)
G_S	Transfer function describing the head variation due to the discharge deviation in the surge tank (pu)
G_t	Transfer function describing the Francis turbine and waterway system (pu)
h	Water head (pu)
H	Water head in the pipeline (m)
h_0	Initial water head (pu)
H_0	Net head of turbine (m)
h_I	Derivative of water head with respect to time (s^{-1})
H_p	Water head at turbine inlet (m)
H_s	Water head at turbine outlet (m)
h_{y0}	Head loss of draw water tunnel (pu)
I_d, I_q	d- and q-axis component of the armature current (pu)
J	Moment of inertia ($kg \cdot m^2$)
K_1	Scaling factor in Model 1 (pu)
K_2	Scaling factor of the lumped hpp in Model 2-K-2 (pu)
K_3	Scaling factor of the lumped hpp in Model 2-K-3 (pu)
K_a	Gain of exitation system (automatic voltage regulator) (pu)
K_d	Governor parameter for the proportional term (s)
K_i	Governor parameter for the integral term (s^{-1})
K_p	Governor parameter for the derivative term (pu)
K_s	Gain of power system stabilizer (pu)
K_ω, K_{Pe}	Gain of power system stabilizer for selecting different inputs (pu)
L	Length of penstock (m)
M	System inertia (s)
M_{11}	Unit mechanical torque ($N/m^{2.5}$)
M_g	Resistance torque of generator ($N \cdot m$)
m_g	Relative resistance torque of generator (pu)
M_R	Regulation mileage (MW)
$M_{R\text{-}base}$	Base value of regulation mileage (MW)
M_t	Mechanical torque ($N \cdot m$)
m_t	Relative mechanical torque (pu)
n	Rotational speed (rpm)
n_{11}	Unit rotational speed ($m^{0.5}/s$)
n_c	Given rotational speed (rpm)
n_r	Rated rotational speed (rpm)
$P_{A,i}$, $P_{B,i}$	Absolute value of a local maximum or local minimum of speed deviation (pu)
Pay_{mile}	Amount of mileage payment (pu)
$Pay_{strength}$	Amount of strength payment (pu)
p_c	Given power (MW)
P_e, P_m	Electromagnetic active power and mechanical power (pu)
p_g	Generator power (pu)

p_l	Load (pu)
p_m	Active power (pu)
$p_{m,\ k}$	Active power at time step k (pu)
p_{m0}	Initial active power (pu)
p_{m2}	Active power of the lumped HPP (pu)
$P_{m\text{-}rated}$	Rated power of generating unit (MW)
p_r	Rated power of generating unit (MW)
P_{RMSE}	A root mean square error used for quantifying D_t (pu)
P_{step}	Increase in output power caused by a frequency step change from 50 to 49.9 Hz (MW)
q	Discharge (pu)
q_0	Initial discharge (pu)
Q_{11}	Unit discharge ($\mathrm{m}^{0.5}$/s)
Q_e, Q_g	Reactive power of generator (pu)
Q_p	Discharge of turbine inlet (m^3/s)
Q_s	Discharge of turbine outlet (m^3/s)
q_t	Discharge of turbine (pu)
q_y	Discharge of draw water tunnel (pu)
s	Complex variable in Laplace transform (s^{-1})
S_R	Regulation strength (MW/Hz)
S_{R1}, $S_{R1\text{-}pu}$	Regulation strength of the Kaplan unit (pu)
S_{R2}, $S_{R2\text{-}pu}$	Regulation strength of the lumped hydropower plant (pu)
$S_{R\text{-}base}$	Base value of regulation strength (MW/Hz)
S_{RT}	Regulation strength of all the units in the grid (pu)
t	Time (s)
T_0, T_1, T_2	Parameters of power system stabilizer (s)
T'_{d0},T''_{d0}	Open-circuit d-axis transient and sub-transient time constants (s)
$T_{del\text{-}a}$	Delay time in runner control (s)
$T_{del\text{-}gv}$	Delay time in guide vane control (s)
T_e	Time constant of water column elasticity, $T_e = L/c$ (s)
T_f	Period of frequency oscillation (s)
T_F	Surge tank time constant (s)
T_j	Mechanical time constant (s)
t_k	Number of time step (–)
t_p	Time constant in grid inverse model (s)
T''_{q0}	Open-circuit d-axis sub-transient time constants (s)
T_r	Time constant in exitation system (automatic voltage regulator) (s)
T_s	Time constant of surge (s)
T_w	Water starting time constant (s)
T_{wp}	Water starting time constant of penstock (s)
T_{wt}	Water starting time constant of tunnel (s)
T_{wy}	Water starting time constant of draw water tunnel (s)
T_y	Time constant of guide vane servo (s)
T_{ya}	Time constant of runner blade servo (s)

V	Average flow velocity of pipeline section (m/s)
V_1	Signal between washout and phase compensation block in power system stabilizer (pu)
V_g	Voltage at the generator terminal (pu)
$V_{gd,}$ V_{gq}	d- and q-axis component of the voltage at the generator terminal (pu)
V_{PSS}	Output signal of power system stabilizer (pu)
V_s	Infinite bus voltage (pu)
$V_{sd,}$ V_{sq}	d- and q-axis component of the infinite bus voltage (pu)
x	Position (m)
X_d, X'_d, X''_d	d-axis synchronous, transient and sub-transient reactance of generator (pu)
$X''_{d\Sigma}$, $X''_{q\Sigma}$	$X''_{d\Sigma} = X''_d + X_s$; $X''_{q\Sigma} = X''_q + X_s$ (pu)
x_f	Relative value of speed (frequency) deviation, $x_f = (f_g - f_c)/f_c$ (pu)
X_q, X''_q	q-axis synchronous and sub-transient reactance of generator (pu)
X_s	Total reactance of transmission line (between generator and infinite bus) (pu)
y	Guide vane opening (pu)
y_c	Given value of guide vane opening (pu)
$Y_{GV,\ dist}$	Movement distance of guide vane (pu)
y_{PI}	Guide vane opening signal between PI terms and servo (pu)
y_{PID}	Guide vane opening signal after PID terms (pu)
$Y_{RB,\ dist}$	Movement distance of runner blade (pu)
y_{servo}	Guide vane opening signal after the servo (pu)
z	Relative change value of water level in surge tank (pu)

Greek Symbols

α, α_p	Elasticity coefficient of penstock (pu)
α_{HP}	Correlation coefficient of kinetic energy at turbine inlet (m^{-2})
α_{HS}	Correlation coefficient of kinetic energy at turbine outlet (m^{-2})
δ	Power (or rotor) angle (rad)
Δ	Stands for a deviation from a steady-state value (–)
Δf	Frequency deviation from set-point value (pu)
Δh	Water head deviation from initial value (pu)
ΔH	$\Delta H = \left(\frac{\alpha_{HP}}{2gA_P^2} - \frac{\alpha_{HS}}{2gA_S^2}\right)Q_P^2$ (m)
Δh_p	Water head deviation from initial value due to hydraulic dynamics in penstock (pu)
Δh_s	Water head deviation from initial value due to hydraulic dynamics in surge tank (pu)
Δn	Speed deviation (pu)
Δq	Discharge deviation from initial value (pu)
Δt	Time step in simulation (s)

Δy	Guide vane opening deviation from set-point value (pu)
ΔZ	Absolute change value of water level in surge tank (m)
$\Delta \eta$	Efficiency change (pu)
η	Turbine efficiency (pu)
η_I	Interpolation function of the turbine efficiency (pu)
η_{Sj}	Average value of the instantaneous efficiency during the operation period under a specific strategy (S_j) (pu)
η_{st}	On-cam steady-state efficiency (pu)
θ	Angle between the axis of pipeline and horizontal plane [rad)
ξ	Damping ratio of an oscillation (–)
φ	Power factor angle at the generator terminal (rad)
ω	Angular velocity of the generator (pu)
ω_0	Synchronous angular velocity in electrical radians (equals to $2\pi f_0$) (rad/s)

Note that the symbols in subsection 2.1.3 of mathematical variables for theory introduction are explained within the text, and they are not listed here