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Real-time coordination of distributed energy resources for frequency control in microgrids with unreliable communication

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ABSTRACT

The management of distributed energy resources (DER) via control strategies mitigates frequency fluctuations stemming from the volatility of renewable resources and fluctuating power demand. Recently, open communication networks are integrated with the traditional control strategies to overcome the ubiquity of DER system and the lack of dedicated communication infrastructures. However, open networks are exposed to communication degradation and can reduce the control performance. This work investigates the reliability of the integrated DER system and open communication networks, i.e. the cyber-physical microgrid system, with reference to the frequency control in the face of communication degradation. Adequate control strategy is provided by a discrete PID controller tuned via multi-objective particle swarm optimization. The integrated system is tested on a real-time platform with different MAC protocols and open-communication-network architectures to investigate how the communication degradation reduces the frequency control performance. Simulation results demonstrate that transmission delays and packet dropouts jeopardize the ability of the integrated system to maintain the system frequency deviation within bounds. In particular, the use of Ethernet ensures higher reliability as compared to 802.11 b/g. Moreover, the impact of interfering traffic and of the percentage of used bandwidth on the PID controller performance reduction is assessed. The optimized PID controller can compensate for communication degradation and uncertainty conditions of the microgrid, and ensures robustness against unknown network configurations.

1. Introduction

The power sector is experiencing a structural trend towards decentralization stemming from the integration of large shares of renewable energy resources (RERs) [1]. This is fostered by distributed energy resources (DERs), which require the integration of power generation means located at or near the end-user side [2,3]. However, the stochastic nature of RERs and of the load demand induces system frequency fluctuations [4,5]. An effective control strategy is needed to keep the system frequency to its nominal value by balancing power generation and demand in real time. To this aim, automatic generation control (AGC) schemes are developed for damping frequency oscillations in distributed generation systems (DGS) [5–8]. AGC is performed by computing control signals based on the system frequency and delivering balancing inputs to various energy storage systems (ESSs) to absorb (release) the surplus (deficit) power from (to) the grid [8–10]. However, the ubiquity of DERs across wide areas and the complex structure of DGS hinder the development of dedicated communication infrastructures for the DGS with massive DERs [11–14].

Recently, the AGC has been integrated with the open communication network, due to low cost, high speed, simple structure and flexible access. Data exchanges among PMUs, generators and the control center are provided by the open communication network in the form of time stamped data packets [7,13–15]. Stable AGC depends heavily on the performance of the open communication network [7–9,15–20]. Cognitive radio networks, Cellular Networks, Local Area Networks (LAN), Wide Area Networks (WAN) and Wireless Local Area Networks (WLAN) are employed as open communication infrastructures in these networked control systems [10,11,14].

However, open communication networks are exposed to various types of degradation processes, i.e. network-induced time delays [8,9,18,19], packet dropouts [20,21], failures of communication infrastructure [22], uncertain communication links [23] and cyberattacks [24]. As a result, the measurement signals (control signals) received by the control center (ESSs or generators) degrade, effective AGC cannot be carried out and the system frequency response worsens [9–13]. Studying the performance of open communication networks is critical for understanding the occurrence of time delays and packet dropouts.

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Nomenclature

Acronyms

DER	Distributed Energy Resource
AGC	Automation Generation Control
RERs	Renewable Energy Resources
DGS	Distributed Generation Systems
ESS	Energy Storage Systems
LAN	Local Area Networks
WAN	Wide Area Networks
WLAN	Wireless Local Area Networks
MAC	Media Access Control
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CSMA/AMP	Carrier Sense Multiple Access with Arbitration on Message Priority
PSO	Particle Swarm Optimization
MOPSO	Multi-objective Particle Swarm Optimization
DEG	Diesel Engine Generator
WTG	Wind Turbine Generator
PV	Photovoltaic Generator
BESS	Battery Energy Storage System
FESS	Flywheel Energy Storage System
HPS	Hybrid Power System
PMU	Phasor Measurement Unit
RTU	Remote Terminal Unit
MCS	Monte Carlo Simulation
G_{WTG}, T_{WTG}	transfer function and time constant of the WTG
G_{PV}, T_{PV}	transfer function and time constant of the PV
G_{DEG}, T_{DEG}	transfer function and time constant of the DEG
P_W, P_{sol}	wind power and solar power
v_W, v_{cutin}, v_r, v_{cutout}	real-time, cut-in, rated and cut-out wind speed
$P_{r,WTG}$	rated power of the wind turbine
N_{WT}	number of wind turbines in the wind farm
η, T_r	conversion efficiency and nominal operation temperature of the PV cells
k_{pv}	maximum power temperature coefficient
T_a	ambient temperature
Φ	sun irradiance level
S	measured area of the PV array
$u(t)$	control signal sent out by the PID controller
G_{FESS}, T_{FESS}	transfer function and time constant of the FESS
G_{BESS}, T_{BESS}	transfer function and time constant of the BESS
P_{FESS}, P_{BESS}	output power of the FESS and BESS
$\overline{P}_{DEG}$, $\overline{P}_{FESS}$, $\overline{P}_{BESS}$	maximum rated output power of the DEG, FESS and BESS
G_{HPS}, M, D	transfer function, inertia constant and damping constant of the HPS
$\Delta f(t)$	power system frequency deviation
P_L	power demand
T_{pre}, T_{wait}, T_{tx}, T_{post}	preprocessing time, waiting time, time for traveling across the channel, postprocessing time
T_d	total time delay

T_s	sampling interval of the PMU
RD	generated from a discrete uniform distribution in $(0,2^{N_c}-1)$, where is the number of detected consecutive collisions
τ_{sc}, τ_{ca}	time delay in sensor-to-controller and controller-to-actuator channel
$U(s)$, $Y(s)$	transfer functions of the control signal and system output
$\gamma_k = 1$	indicates the transmission of $\Delta f(kT_s)$ at kth period is successful
t_n	time instant when the nth data packet is received by the control center
τ_{sc}^n	transmission time of packet n from the PMU to the control center
L_d	expected packet loss probability
$\gamma_n = 1$	indicates the control signal $u(t_n)$ is not dropped
t_m	time at which the mth data packet is received by the DER i
τ_{ca}^m	transmission time packet m from the control center to the DER i
T_i	period that the interference node sends traffic data to the network
UN_i	uniformly distributed random number sampled at time period T_i in the interval [0,1]
BWShare	expected ratio of network bandwidth used by the interference node
K_P, K_I, K_D	proportional, integral and derivative gain of the PID controller
N_L	filter's coefficient indicating location of pole in the derivative filter
R	system reliability
T_I	total amount of time in which the system frequency remains smaller than the maximum permissible instantaneous frequency deviation
T	the total operating time of the AGC
J	objective function for the optimization of the PID controller
η_1	indicates the relative importance of the two terms
η_2	normalizing constant to scale both terms in a uniform range
N	number of MCS samples
$\mathrm{E}[J]$	expectation of the stochastic objective function obtained from MCS
$J_1(\vec{x})$, $J_2(\vec{x})$	objective functions $(\Delta f(t))^2$ and $(\Delta u(t))^2$
NP, NI	maximum number of particles and iterations
MP	number of dimensions
x_i, v_i	current position and velocity of particle i
c_1, c_2	cognitive and social factors
r_1, r_2	random numbers drawn from a uniformly distributed interval [0,1]
$pbest$, $gbest$	local best-known position and global best-known position
mf_i, MF	linear membership function and aggregate membership function

To this aim, medium access and packet transmission must be analyzed. The media access control (MAC) layer is the lower layer of the data link layer of the Open System Interconnection model, and it is responsible for moving data packets among network interface cards across the communication channels. Several MAC protocols, e.g. CSMA/CD (Carrier Sense Multiple Access with Collision Detection, Ethernet), CSMA/AMP (Carrier Sense Multiple Access with Arbitration on Message Priority, CAN) and 802.11 b/g (WLAN), prevent the collision of packets sent from different nodes across the same channel [14,25–27].

Time delays are variable, challenging to predict, deteriorate the AGC performance and reduce the stability region [9,10]. Packet dropouts refer to lost messages, which occupy network bandwidth but cannot reach destination. They affect the operations of DERs and the reduction of frequency fluctuations, particularly in uncertain network environments. Optimal feedback AGC regulators for DERs are investigated in numerous works for perfect communication networks and the impact of transmission delays and packet dropouts on the controller cannot be captured [28]. Robust PID controllers against constant or uniformly distributed time delays [8–11] are designed to cope with perturbations of the control parameters. Yet, constant or uniformly