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Coordinated control of smart microgrid during and after islanding operation to prevent under frequency load shedding using energy storage system

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ABSTRACT

This work presents a smart microgrid consisting of diesel, photovoltaic (PV), and battery storage plants. One of the key features of smart grid is to provide a redundant high quality power for the consumers. In islanded microgrid, the under frequency and/or voltage collapse, caused by power deficiency, can lead to power outage. The current practice is to shed the load demand until the frequency and voltage are restored. However, the redundancy in supplying power has no meaning as long as the loads are shed. The main objective of this paper is to propose a power management system (PMS) that protects the microgrid against the load shedding. PMS is able to control the microgrid in both centralized and decentralized fashions. To prevent under frequency load shedding (UFLS), this work proposes using battery energy storage system (BESS) to compensate for the power mismatch in the islanded microgrid. A method is presented to estimate the rate of change of frequency and to calculate the power deficiency. The approximated value is exploited as the set-point to dispatch BESS. PV and battery plants are supposed to share the reactive power demand proportionally and thus regulate the voltage at the load bus. This work also suggests two outer control loops, namely, frequency restoration loop (FRL) and difference angle compensator (DAC). These loops ensure microgrid smooth transition from islanded mode to grid-connected mode. The microgrid is configured to investigate the effective utilization of exiting solar PV plant connected to distribution network in Sabah Malaysia. The microgrid is implemented in PSCAD software and tested under different scenarios. The microgrid with PMS shows operational stability and improvements in comparison with the original system. The results indicate that PMS can effectively control the microgrid in all operating modes.

1. Introduction

Smart grid concept has emerged followed by integrating distributed energy resources (DERs) such as solar photovoltaic (PV), wind, and energy storage systems into the power networks [1]. Smart grid incorporates control algorithms, communication platforms, and advanced measurement techniques into a conventional power grid. In modern power systems, the demand side also contributes in generation of electricity and hence electrical power can flow in any direction from the central generation plant to load or vice versa. Another definition which comes up with smart grid is microgrid. Microgrid can be considered as a cluster of load and generation inside of smart grid [2]. Microgrid is a small scale smart grid which can be autonomous or grid-tied. Successful operation of the microgrid depends on its ability to make balance between internal sinks and sources of power.

Microgrid infrastructure generally consists of four technologic layers i.e. physical layer, network layer (data link), data management layer, and interface layer [3]. These layers together facilitate active communication and automated management between utilities and customers. A supervisory channel which controls a microgrid operation can include several agents. The supervision system which encompasses several agents is so-called "multi-agent" system (MAS) [4,5]. Agent is an intelligent entity composed by software (at data management and interface layers) and/or hardware (at physical and network layers) [6]. All information associated with a DER can be recorded in its agent. Data such as local measurements, availability of energy resources, and feedback signals for controllers are some examples brought to this end. The tasks

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Nomenclature

ΔP_{Char}	battery energy storage system active power dispatching reference in MW in charging mode
ΔP_{Dis}	battery energy storage system active power dispatching reference in MW in discharging mode
$\Delta t'$	setting time in second (s) to align V_{MG} with V_g
C_f	LC filter capacitor in milli-Farad (mF)
$D_{P,D}$	diesel generator plant active power droop coefficient
$D_{Q,B}$	battery energy storage system reactive power droop coefficient
$D_{Q,D}$	diesel generator plant reactive power droop coefficient
$D_{Q,PV}$	solar photovoltaic plant reactive power droop coefficient
I_{Ld}	battery storage system VSC direct axis output current in (kA)
I_{Lq}	battery storage system VSC quadrature axis output current in (kA)
I_{PV}	solar photovoltaic array output current in (kA)
$I_{d,ref}$	battery storage system VSC direct axis reference current in (kA)
$I_{q,ref}$	battery storage system VSC quadrature axis reference current in (kA)
K_{PF}	frequency index for active power of load model
K_{QF}	frequency index for reactive power of load model
L_f	LC filter inductor in milli-Henry (H)
M_d	direct axis modulation index
M_q	quadrature axis modulation index
P_{0L}	load rated active power in (MW)
$P_{B,ref}$	battery storage system active power reference in (MW)
P_B	battery storage system instantaneous active power output in (MW)
$P_{D,max}$	maximum active power capability of diesel generator plant in (MW)
$P_{D,min}$	minimum active power capability of diesel generator plant in (MW)
$P_{D,ref}$	diesel generator plant active power reference in (p.u.)
$P_{D,set}$	diesel generator plant active power set-point in p.u. at nominal frequency
P_{PV}	active power output of solar photovoltaic plant in (MW)
P_{in}	input power to dc link of solar photovoltaic plant in (MW)
P_{out}	output power from dc link of solar PV plant in (MW)
Q_{0L}	load rated reactive power in (MVar)
$Q_{B,ref}$	battery storage system reactive power dispatching reference in (p.u.)
$Q_{B,set}$	battery storage system reactive power set-point in p.u. at nominal voltage
Q_B	battery storage system reactive power output in (MVar)
Q_{B0}	battery storage system reactive power set-point by operator in MVar at nominal voltage
$Q_{D,max}$	maximum reactive power capability of diesel generator plant in (MVar)
$Q_{D,min}$	minimum reactive power capability of diesel generator plant in (MVar)
$Q_{D,ref}$	diesel generator plant reactive power reference in (p.u.)
$Q_{D,set}$	diesel generator plant reactive power set-point in p.u. at nominal voltage
Q_D	diesel generator plant reactive power output in (MVar)
Q_{D0}	diesel generator plant reactive power set-point by operator in MVar at nominal voltage
Q_{DMD}	reactive power load demand in (MVar)
$Q_{PV,max}$	maximum reactive power capability of solar PV plant in (MVar)
$Q_{PV,min}$	minimum reactive power capability of solar photovoltaic plant in (MVar)
$Q_{PV,ref}$	solar PV plant reactive power dispatching reference in (p.u.)
$Q_{PV,set}$	solar photovoltaic plant reactive power set-point in p.u. at nominal voltage
Q_{PV}	solar PV plant reactive power output in (MVar)
Q_{PV0}	solar photovoltaic plant reactive power set-point by operator in MVar at nominal voltage
$ROCOF_i$	rate of change of frequency estimated in *i*th iteration in (Hz/s)
R_f	LC filter resistor in series with inductor in milli-ohm (mΩ)
S_B	nominal apparent power capability of battery storage system in (MVA)
S_D	nominal apparent power capability of diesel generator plant in (MVA)
SOC_{ref}	battery bank reference state of charge in (%)
S_{PV}	nominal apparent power capability of solar PV plant in (MVA)
V_0	RMS nominal line voltage of microgrid in (kV)
V_{0L}	load nominal RMS phase voltage in (kV)
$V_{B,d}$	direct axis component of battery energy storage system phase voltage at PCC in (kV)
$V_{B,dc}$	battery energy storage system voltage at DC link in (kV)
$V_{B,q}$	quadrature axis component of battery energy storage system phase voltage at PCC in (kV)
V_B	battery energy storage system RMS line voltage at VSC terminal in (kV)
$V_{BESS,L}$	battery energy storage system RMS line voltage in (p.u.)
$V_{D,ref}$	diesel generator plant reference voltage in (p.u.)
V_D	diesel generator plant RMS line voltage at synchronous generator terminal in (p.u.)
V_L	RMS value of phase voltage at load bus in (kV)
V_{MG}	RMS value of voltage at microgrid side in (p.u.)
V_{MPPT}	reference voltage from MPPT algorithm in (kV)
$V_{PV,L}$	solar photovoltaic plant RMS line voltage in (p.u.)
$V_{PV,dc}$	solar photovoltaic plant voltage at DC link in (kV)
V_{PV}	photovoltaic array output voltage in (kV)
$V_{dc,ref}$	solar photovoltaic plant DC link reference voltage in (kV)
V_g	RMS value of voltage at grid side in (kV)
V_{gd}	grid side voltage direct axis component in (kV)
V_{max}	maximum allowed voltage in (kV)
V_{min}	minimum allowed voltage in (kV)
V_t	solar PV plant RMS output voltage at VSC terminal in (p.u.)
X_{L_f}	series output line reactance of battery storage system VSC in (Ω)
X_{PV}	series output line reactance of solar photovoltaic plant VSC in (Ω)
Z_{C_f}	LC filter shunt impedance in (Ω)
Z_f	LC filter equivalent impedance in (Ω)
Z_g	grid equivalent impedance in (Ω)
f_L	frequency of voltage phasor in Hz measured at load bus by *PLL*
f_{MG}	V_{MG} phasor frequency of rotation in (Hz)
$f_{s.w}$	VSC PWM switching frequency
f_{z1}	1st zone boundary of definition for frequency deviation during islanding
f_{z2}	2nd zone boundary of definition for frequency deviation during islanding
f_{z3}	3rd zone boundary of definition for frequency deviation during islanding
δ_{MG}	voltage phasor angle at microgrid side in radian (rad)
$\delta_{PV,PWM}$	solar photovoltaic plant SPWM reference angle in (rad)