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Primary frequency control and dynamic grid support for vehicle-to-grid in transmission systems

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ABSTRACT

Because of vehicle-to-grid (V2G) growth, the provision of ancillary services by V2Gs is now required in the most recent network codes. A lack of primary frequency control (PFC) and dynamic grid support (DGS) in V2Gs could thus be detrimental to power system stability. This research presents a detailed V2G model with a hybrid energy storage system (HESS). The main contribution of the model is the simultaneous provision of PFC and DGS at its plug-in terminal. PFC includes both droop response (DR) and inertial response (IR). Accordingly, a frequency management system (FMS) determines the command of the V2G converter control for PFC without disturbing the scheduled charging-discharging. Simultaneously, this control enables DGS. The design of a new model for connecting V2Gs at transmission level allows the assessment of power system stability. This research study analysed the stability of an IEEE 39 bus system with 30% V2G penetration after critical contingencies. Various strategies for providing ancillary services in V2Gs (DGS and/or PFC) were compared in two scenarios defined by extreme V2G operating modes (as load or generator) at different locations. An analysis of the impact of each ancillary service as well as their interaction was performed to measure their influence on both system stability and critical operating variables of V2Gs. The results showed that system stability remained almost invariable when the V2Gs included PFC (DR + IR) and DGS.

1. Introduction

The new concept of V2G means that electric vehicles (EVs) should not only be regarded as passive assets, but also as a converter-based active generation. In general, an excessive and uncontrolled penetration of a converter-based distributed generation (DG) in power systems along with a partial replacement of traditional centralized generation reduces the available rotational inertia in power systems [1–6] and can cause a lack of DGS [2,7]. In order to ensure transient stability in power systems, the latest network codes and standards [8–13] recommend or require generating units (including those based on static converters, e.g. V2Gs) to synthetically inherit frequency support strategies from conventional generation and also provide DGS. In this context, V2Gs should receive operation references from the corresponding transmission system operator (TSO), mainly in the form of active and reactive power commands for providing different ancillary services, e.g. PFC [8,9,11–13] and DGS [8,9,11–13].

In recent years, much research has focused on the provision of PFC by EVs in electrical systems [14–40]. Recently, this provision by static a converter-based DG, though not specifically with EVs, has been a major research focus [41,42]. As a result, the impact of EVs providing PFC on the transient stability of an electrical system can be characterised by the following EV-dependent factors: (i) EV penetration level [14,21–23,25]; (ii) EV location [38]; (iii) frequency control in the EV [15–18,20–22,25,28–30,32,33–35,38]; (iv) EV battery charger topology and its charging protocol [21,23,26–28,32,33,36,38]; (v) management of the state of charge (SOC) of an EV battery [16,18,27,29,30,33,38]; (vi) EV load model [24,26,34,39,40]; (vii) EV battery parameters [31,38]; (viii) use of a fast-response HESS embedded in the EV [19,32]; (ix) EV power variation limit for PFC (and droop coefficient [21]). Moreover, there are system-dependent factors that can have an impact on resulting transient stability: (i) medium voltage (MV) and low voltage (LV) lead conductors for the EV (aggregate model of EVs at MV or high voltage [HV] level) [21,25]; (ii) level of detail for modelling the power system, i.e., simplified vs. detailed system. Furthermore, any study of this impact should clearly differentiate outcomes in non-large electrical systems (e.g. microgrids [15,17,18,41,42], small island systems [20,23,26,33,38,39], and primary distribution systems [19,25,31,32,36]) as compared to large electrical systems (e.g. transmission systems [16,21,22,24,25,27–29,30,34,35,40]). Nonlinear interactions in non-large vs. large systems [43,44] involve

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Nomenclature

Abbreviations

BCMS	bidirectional charging management system
DG	distributed generation
CC	constant current
CV	constant voltage
DGS	dynamic grid support
DR	droop response
EV	electric vehicles
FMS	frequency management system
FRTC	fault-ride through capability
HESS	hybrid energy storage system
IR	inertial response
LCL	inductor-capacitor-inductor
LV, MV, HV	low voltage, medium voltage, high voltage
PFC	primary frequency control
PI	proportional-integral
PLL	phase-locked loop
SC	supercapacitor
SOC	state of charge
TSO	transmission system operator
TS-LV2GU	load and V2G unit at transmission-scale
V2G	vehicle-to-grid
V2GC	V2G charger

Variables

C	capacitor
f	frequency
$G_{\#i}$	conventional generating unit $\#i$ connected to the transmission bus $\#i$
H	inertia constant
i	current
K	adaptive gain
L	inductor
LRC_{DR} (LRC_{IR})	limit rate of the change in active power due to DR (IR)
m	exponential coefficient
p	active power
$p_{\dots\text{-}cmd}$	active power command of …
$p_{PFC\text{-}V2G\text{-}\max/\min}$	maximum/minimum limit of power variation of V2G for PFC
P	base capacity of power
q	reactive power
R	droop coefficient
SOC	state of charge
S_{wi}	ith switch
T	temperature
T_D	time constant associated with frequency derivate measurement accuracy
T_{HF1}	time constant associated with high-pass filter *1*
T_{LF1} (T_{LF2})	time constant associated with low-pass filter *1* (*2*)
T_P	time constant associated with frequency measurement accuracy
$TS\text{-}LV2GU_{\#i}$	TS-LV2GU $\#i$ connected to the transmission bus $\#i$
u	voltage
$V2G_{Bi\#j}$	V2G connected to the Bith,$\#j$ bus

Symbols

α	exponent coefficient
γ_{V2G}	penetration level of V2G into the grid
ζ	damping ratio
ς	overshoot ratio
Δf	frequency deviation
Δf_{RI}	frequency response insensitivity
Δf_{SS}	steady-state frequency deviation
Δp	change in active power
$\Delta p_{\dots\text{-}cmd}$	active power command of …
μ	rate of power variation of the V2G for PFC normalized by the nominal charging power
$\rho_{SOC_{bat_i},SOC_{bat_j}}$	ijth correlation coefficient for SOCs of ith and jth batteries

Indices: Subscripts

av	average
bat	battery
cmd	command
$d\text{-}axis$	at d axis
DC	at DC-link
$DC\text{-}AC$	to refer to DC-AC converter
DR	droop response
f	at AC LCL filter
g	grid
$HESS$	hybrid energy storage system
IR	inertial response
L	inductor
lo	lower
max	maximum
min	minimum
n	at nominal condition
PFC	primary frequency control
$q\text{-}axis$	at q axis
ref	at reference condition
sc	supercapacitor
scd	at scheduled condition
up	upper
$V2G$	vehicle-to-grid

Indices: Superscripts

$*$	measured value
$+$	to refer to the aggregated approach when providing DGS
$\odot$	to refer to commands under adaptive control
c	at charging condition
d	at discharging condition

different impacts. Therefore, the impact of the models/controls for PFC provision by EVs in non-large electrical systems cannot be extrapolated to transmission systems.

Frequency control in EVs includes simple approaches based on the sudden disconnection of EVs [21,35], a constant droop control [17,25,33–35], or an enhanced approach based on an adaptive droop control [27,29,30,33,38]. This control may also include a participation factor in the PFC that would facilitate the incorporation of various EV characteristics such as battery SOC management [16,22,25,27,29,30,38] and/or battery charging protocol [38].

Associated EV battery charger topology and charging protocols are the following: (i) a unidirectional EV charger [16,28,33,40]; (ii) a bidirectional EV charger with a charging protocol [45] limited to constant current (CC) charging [17,18,23,26,32,38].

In the literature, EV load models are based on a simplified exponential load model (exponent α [40]) which may not be accurate: (i)