University of Technology Sydney

Advanced Control Strategies for Vehicle to Grid Systems with Electric Vehicles as Distributed Sources

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A thesis submitted to the University of Technology Sydney

for the Degree of Doctor of Philosophy

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree as fully acknowledged with the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

Acknowledgements

First of all, I would like to express heartfelt gratitude and appreciation to my supervisor, Professor Jianguo Zhu, for his enthusiastic help, inspiration, patience, unlimited support and consistent encouragement throughout the entire research period providing the opportunity to work in this highly promising research field. I am also grateful to Associate Professor Youguang Guo, my co-supervisor, for his useful suggestions and encouragement of my attitude.

Also, I would like to thank Professor Guoxiu Wang, the external co-supervisor, from the School of Mathematical and Physical Sciences, Faculty of Science for his precious discussion and comments. His research experience on electrochemical energy storage components has made a significant contribution to the hybrid energy storage system development.

I would also like to express thanks to my research group mates, in particular Dr. Jiefeng Hu and Dr. Gang Lei of the Centre for Electrical Machines and Power Electronics, University of Technology Sydney (UTS), for their precious time, professional advice, sharing of knowledge, technical support and friendship. Their opinions and advices have provided me with great assistance in completing my PhD research work.

On a personal aspect, I would like to thank my parents for their love and support given to me during this research period. Their support is so important for me to finish my PhD study and grow up in Australia. I also would like to thank my special friends who helped me and gave me essential support during this period of study.

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List of Symbols

A	Normal distribution of arrival time
$A0, A1, A2$	Control of address signals
a	Regulation prices [$]
B	Cost upper bound [$]
$C, C_{1c}, C_{2c}, C_{3c}, C_{4c}$	Capacitor capacitance [F]
$Cap_{r,i}(k)$	Remaining battery capacity needed to be filled [F]
$c_{i,t}$	Cost of charging EV *i* at timeslot *t* ($)
D	Normal distribution of departure time
d_P d_Q	Digitized signals by two fixed-band hysteresis comparators
d_t	Energy consumption at time *t* (Wh)
E	Energy density (Wh/L)
e	Line to line AC Voltage (V)
f	Source voltage frequency (hZ)
g	Electricity prices ($)
I	Current supplied by the battery (A)
$I_l(t)$	Current value across supercapacitor (A)
I_a	Charger current (A)
I_C	Charge current across R_{1c} (A)
K_f	Infrastructure cost ($)
K_{T1}	Transformer T1 ratio
K_{T2}	Transformer T2 ratio
K_{T3}	Transformer T3 ratio
l	Base loads (W)
M	Estimated number of miles driven daily (km)
$m_{i,t}$	Aggregator’s revenue from EV *i* at timeslot *t* ($)

N	Total number of plug-in electric vehicles (PEVs)
P	Active power exchanged with the grid (W)
P_{EV}	Charging station injects active power (W)
P_{EVavg}	Average constant power requirement for all PEVs (W)
P_i	Active power flows in line i (W)
$p_{i,t}$	Charging rate of EV i at timeslot t (kW)
$\overline{P}_{i,t}$	Maximum charging rate limit of EV i at timeslot t (kW)
P_{Li}	Active load at bus i (W)
P_{ref}	Active power reference (W)
p_t	Price per energy unit at time t (\$)
Q	Reactive power exchanged with the grid (Var)
Q_{EV}	Charging station injects reactive power (Var)
Q_i	Reactive power flows in line i (Var)
Q_{Li}	Reactive load at bus i (Var)
$\mathrm{Q}_{\mathrm{ref}}$	Reactive power reference (Var)
R	Transformer delivery capacity (W)
R_0	Series resister of battery (Ω)
R_1	Parallel resister of battery (Ω)
R_{1c}, R_{2c}, R_{3c}, R_{4c}	Resister (Ω)
R_L	Leakage resister of supercapacitor (Ω)
R_S	Series resister of supercapacitor (Ω)
$r_{i,t}$	Regulation capacity of EV i at timeslot t (kW)
S_{a1}-S_{a5} S_{b1}-S_{b5}	Bidirectional switches
S_B	System rated power (W)
S_{EV}	Power supplied by the battery (W)
SOC_{end}	Terminal EV battery SOC
SOC_{init}	Initial EV battery SOC

SOC_{max}	Maximum storage capacity (Ah)
SOC_t	SOC level for at time t
T	Total number of timeslots
$T_{r,i}(k)$	Remaining time for charging the *ith* vehicle at time step k
Ts	Sample time
U_B	System rated voltage (V)
$U^*(t)$	Voltage value of supercapacitor (V)
V	Voltage of voltage source (V)
$V_1 \sim V_5$, $V_6 \sim V_{11}$	Terminal voltage (V)
V_a	Grid voltage (V)
V_b	Voltage present voltage (V)
V_b*	Reference battery voltage (V)
$V_{b,nom}$	Voltage nominal value (V)
V_{dc}	DC bus voltage (V)
V_E	Terminal voltage of capacitor C_{1c} (V)
V_i	Voltage of bus i (V)
V_{oc}	Open-circuit voltage (V)
V_s	Terminal voltage for supercapacitor before charge (V)
ΔV_0	Jump of terminal voltage across capacitor (V)
X	Line reactance between the converter and the utility node (Ω)
$x_{i,t}$	SOC of EV i at time t
z_t	Location of the EV at time t
Δ	Angle between E and V
λ_t	V2G parameter for at time t
η_c	Charging efficiency
η_d	Discharging efficiency
ψ_e	Energy-related battery degradation cost ($/kWh)

ψ_p	Power-related battery degradation cost ($/kWh^2)
ϕ	Net charging amount (kWh)
φ_t	Charge parameter for at time *t* (kWh)
Φ_i	Charging schedule for a given charging task *i*
$\overline{\varphi}$	Maximum charging amount per time slot (kWh)
$\psi_e\varphi_t$	Line term reflecting the degradation from energy throughput
$\psi_p\varphi_t^2$	Quadratic term reflecting power-related degradation

List of Abbreviations

ACE	Area Control Error
AFAP	As Fast as Possible Charging
AGC	Automatic Generation Control
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
C-DCSP	Cost Dynamic Charging Scheduling Problem
CNT	Carbon NanoTube
CVT	Continuously Variable Transmission
DER	Distributed Energy Resource
DOD	Depth of Discharge
DPC	Direct Power Control
DSO	Distribution System Operator
DTC	Direct Torque Control
EIS	Electrochemical Impedance Spectroscopy
EMI	Electromagnetic Interference
EMTDC	Electromagnetic Transient and DC
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Energy Service Provider
EV	Electrical Vehicle
FACTS	Flexible AC Transmission System
FCV	Fuel Cell Vehicle
GV	Grid-able Vehicle
G2V	Grid to Vehicle
HEV	Hybrid Electrical Vehicle
HVDC	High Voltage Direct Current
ICE	Internal Combustions Engine

IGBT	Insulated-gate Bipolar Transistor
IGCT	Integrated-ate Commutated Thyristor
ISO	Independent System Operator
LP	Linear Programming
MPC	Model Predictive Control
NEC	National Electrical Code
NERC	National Electric Reliability Council
OCV	Open Circuit Voltage
PEM	Proton Exchange Membrane
PEV	Plug-in Electric Vehicle
PFCV	Plug-in Fuel Cell Vehicle
PHEV	Plug-in Hybrid Electrical Vehicle
PI	Proportional-integral
PLC	Power Line Communication
PSO	Particle Swarm Optimization
PSCAD	Power System Computer Aided Design
PV	Photovoltaic
PWM	Pulse Width Modulation
R-DCSP	Revenue Dynamic Charging Scheduling Problem
RES	Renewable Energy Resources
R-SCSP	Revenue Static Charging Scheduling Problem
SCs	Supercapacitors
SDPC	Switching Table-based Direct Power Control
SGSS	Smart Grid Stabilization System
SMPS	Switched Mode Power Supply
SOC	State of Charge
STATCOM	Static Compensator
SVM	Space Vector Modulator
V2B	Vehicle to Building
VFC	Voltage to Frequency Converters

V2G	Vehicle to Grid
V2I	Vehicle to Infrastructure
VOC	Voltage Oriented Control
VSI	Voltage Source Inverter
V2X	Vehicle to any Load
WSCC	Western System Coordinating Council

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ABSTRACT

This thesis focuses on the control and implementation of the vehicle to grid (V2G) system in a smart grid. Important issues like structure, principle, performance, and control of energy storage systems for electrical vehicles and power systems are discussed.

In recent decades, due to rapid consumption of the earth's oil resources, air pollution and global warming (a result of the "greenhouse effect"), the development of electrical vehicles (EVs), hybrid electrical vehicles (HEVs) and plug-in electric vehicles (PEVs) are attracting more and more attentions. In order to provide regulation services and spinning reserves (to meet sudden demands for power), V2G services have a promising prospective future for grid support. It has been proposed that in the future development, such use of V2G could buffer and support effectively the penetration of renewable sources in power systems. This PhD thesis project aims to develop novel and competitive control strategies for V2G services implementation for EVs in smart electrical car parks or Smartparks.

Through a comprehensive literature review of the current EV development and energy storage systems used for EVs, several energy storage technologies are compared and a hybrid energy storage system consisting of batteries and supercapacitors is proposed. This system combines effectively the advantages of high energy density of battery banks and high power density of supercapacitor banks. Supercapacitor and battery cells are tested in the laboratory using different charging and discharging procedures. Different supercapacitor and battery models are compared, discussed, and verified using the experimental data. For the energy storage system package, a cell voltage balance circuit is developed for the supercapacitor module. The principle of this circuit is also applicable to the battery module. The proposed balancing method is simple and reliable, and presents good performance for voltage balancing to prolong the lifetime of the energy storage system.

The essential technology of V2G is based on the bidirectional power flow control of the charger. Besides charging the EV batteries, it can utilize the stored energy to feed electricity back to the power grid when there is a need. Three-phase AC/DC converters have been extensively used in industrial applications and also the V2G chargers. The power converters used for the V2G services are required to operate more efficiently and effectively to maintain high power quality and dynamic stability. Then the AC/DC converter used for the bidirectional V2G charger is developed and modelled. For the control aspect of AC/DC converter, a new control approach using a model predictive control (MPC) scheme is developed for V2G applications. With the advanced control strategy, the EVs in Smartparks can exchange both active and reactive power with the grid flexibly. The MPC algorithm presents excellent steady-state and dynamic performance.

When a very large number of EVs are aggregated in Smartparks, the charging and discharging power should be a significant viable contributor to the power grid. New challenges will be introduced into the power system planning and operation. While discharging, the V2G power brings more potential benefits to enhance the power quality and system reliability. Using V2G services, EVs can provide many grid services, such as regulation and spinning reserve, load levelling, serving as external storage for renewable sources. An effective approach to deal with the negligibly small impact of a single EV is to group a large number of EVs. An aggregator is a new player whose role is to collect the EVs by attracting and retaining them so as to result in a MW capacity that can beneficially impact the grid. From the aggregator' decision, the EVs are determined by the optimal deployment. The aggregator can act as a very effective resource by helping the operator to supply both capacity and energy services to the grid. By supplying active power and reactive power from EVs, the aggregation may be used for frequency and voltage regulation to control frequency and voltage fluctuations that are caused by supply–demand imbalances. Different case studies of EVs' support to grid are carried out; the results show that V2G services can stabilize the frequency and voltage variations and have control flexibilities to fulfil system reliability and power quality requirements.

The main attractiveness of V2G to consumers is that it can produce income to the vehicle owner to maximize car use. On the other hand, the utility companies can use EVs to stabilize the frequency in the power system and improve the utility operation. It also makes the utility companies more efficient with less loss because the energy is generated locally. From this point of view, V2G is a source of revenue in both electricity and transportation system, and it can help the environment reduce pollution and global warming. Various data of V2G systems have been collected for economic analysis, such as EV battery capacities, charging time, and grid electricity price and load demands. Then for the economic issues related to V2G services, optimal charging based on different objectives is presented. Dumbing charging, maximization of the average state of charge (SOC), maximum revenue and minimum cost are compared. Economic issues are a very special aspect of the V2G technology and how a large profit from V2G services can be produced is the main point of attraction to vehicle owners.

Significant conclusions based on the research findings are drawn, and possible future works for further development including commercialisation of the V2G technology are proposed.