Battery Characterisation and Management - the key to Smart Grids and the Integration of Electric Vehicles

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Partners

NSFC
国家自然科学基金委员会
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Engineering and Physical Sciences Research Council

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State Grid
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China Electric Power Research Institute

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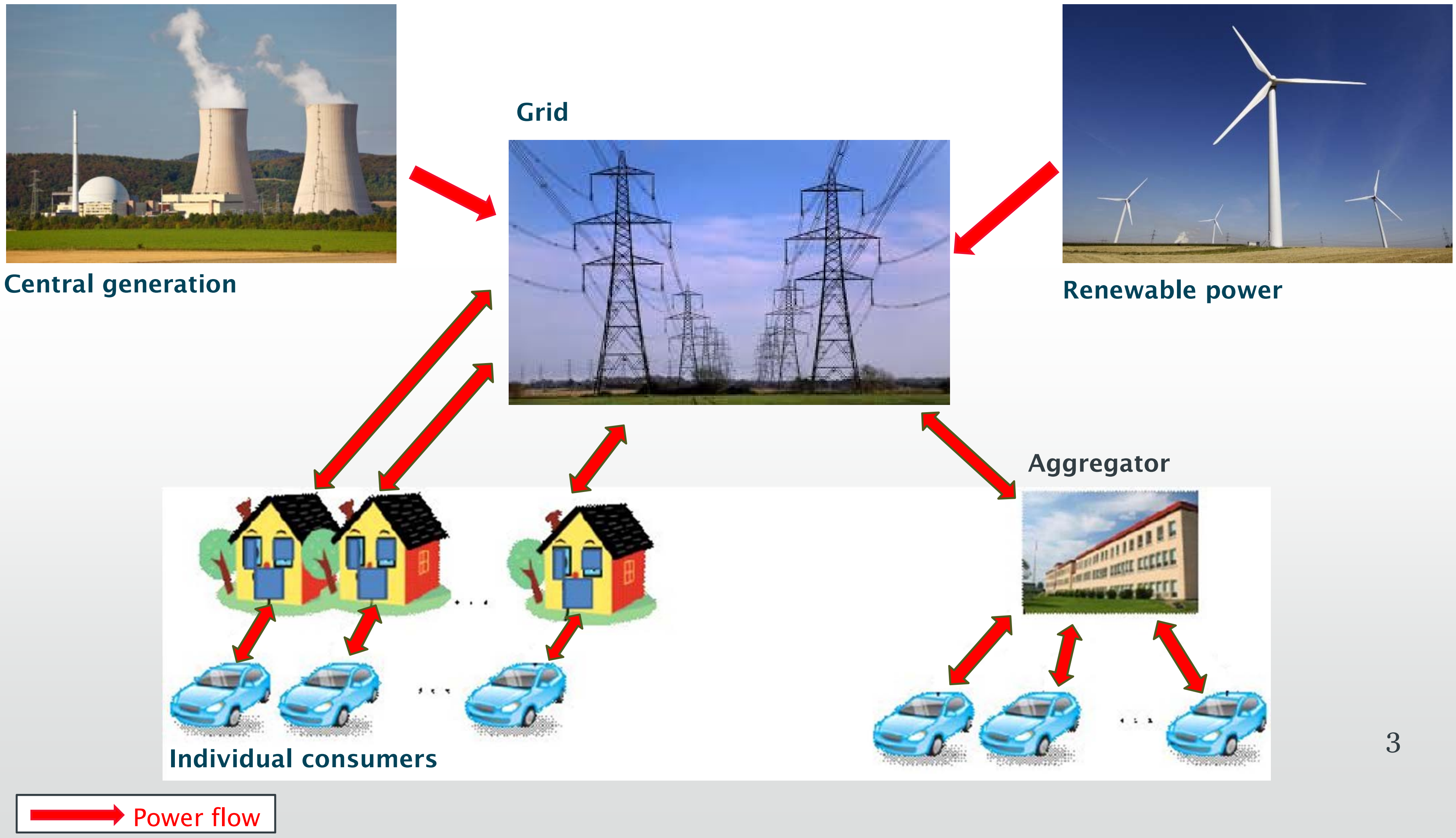
University of Southampton

The University Of Sheffield.

Overview of the project

We look at the system from the battery perspective upward



Project Aims

1) Determining the anticipated patterns of battery cycling associated with driving and V2G operation for specified grid support functions.

2) Investigating the impact of the anticipated V2G operation on battery cell, module and pack cycle life, failures and thermal behaviour. More accurate determination of battery SoC and state of health (SoH).

3) Investigating the communication and control temporal and physical information requirements from the battery management system (BMS) to the grid control system and vice versa.

4) Demonstrating V2G operation within distinct UK and Chinese environments.

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1) Determining the anticipated patterns of battery cycling associated with driving and V2G operation for specified grid support functions

Driving statistics from the UK Time of Use (TUS) survey data

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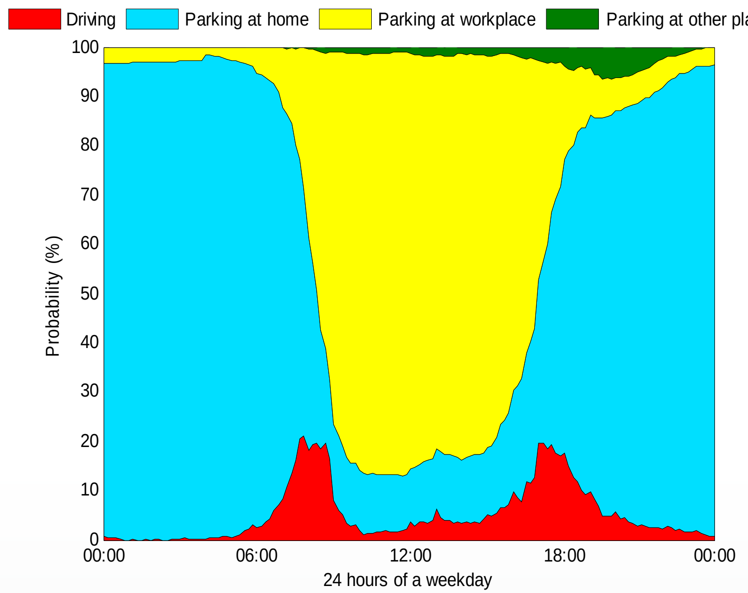


Figure 1: Vehicle state proportion during a weekday

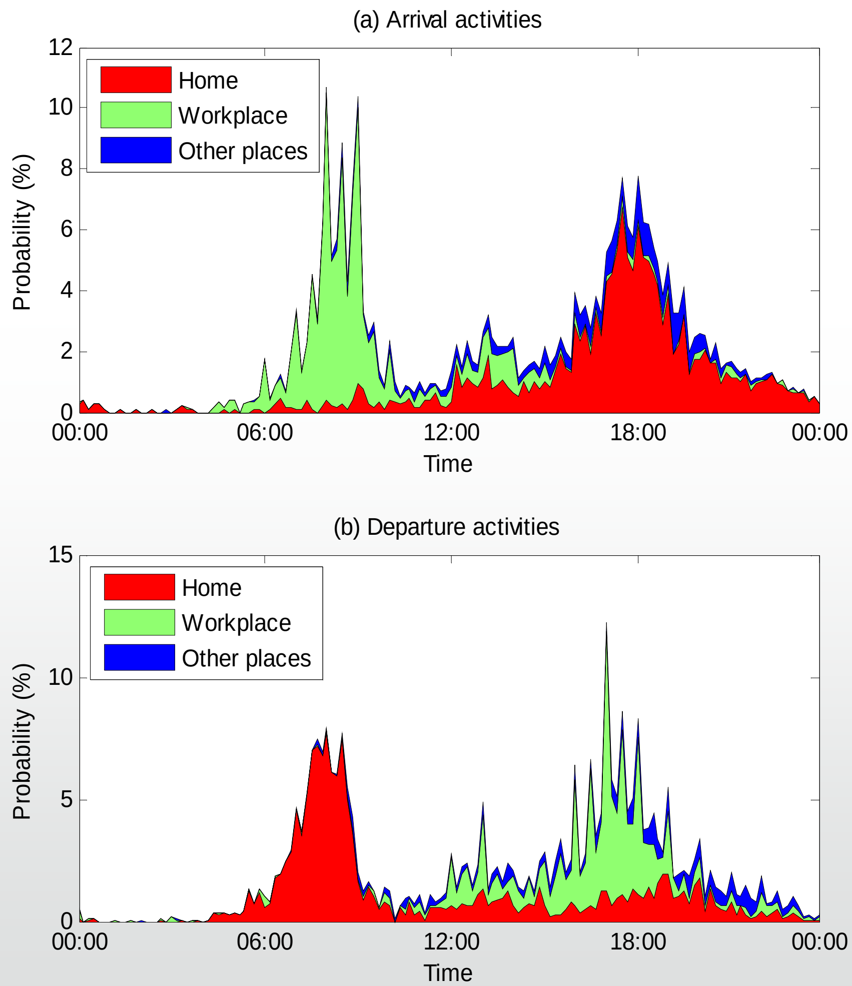


Figure 3: Probability of vehicles' arrival and departure for different locations

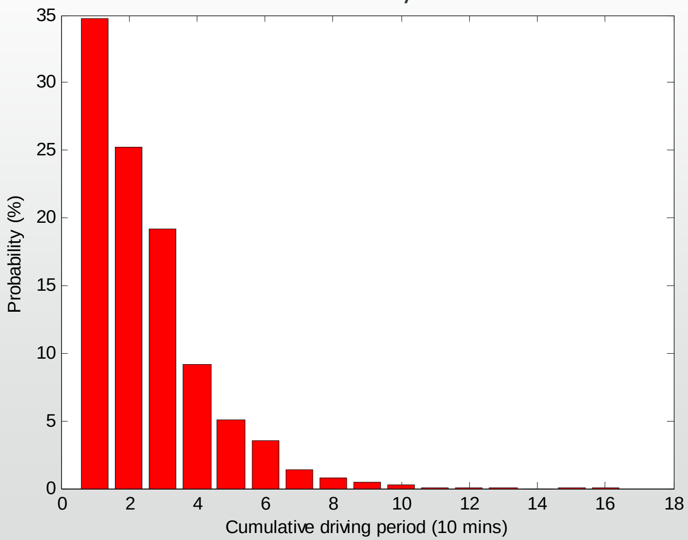
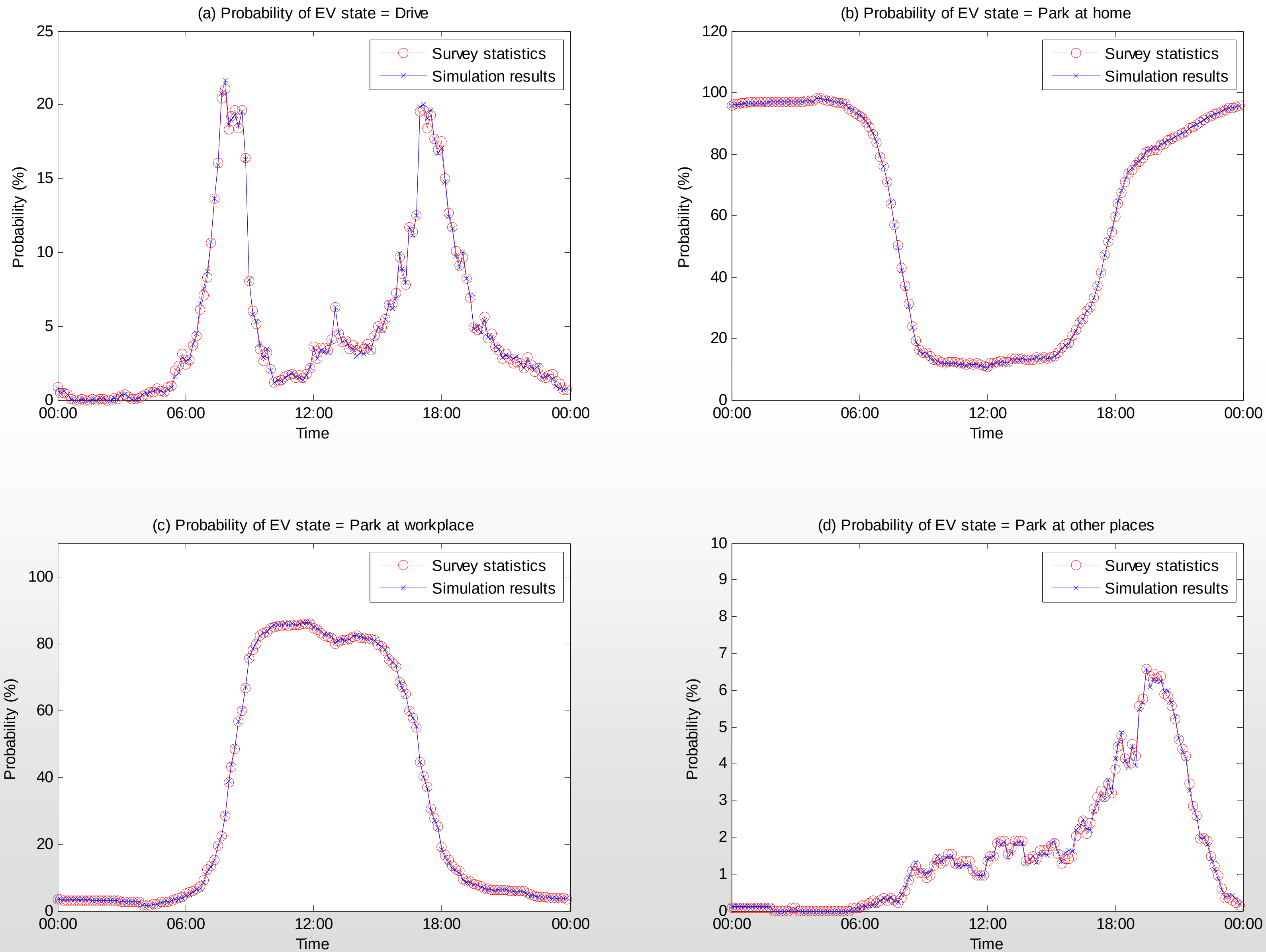


Figure 2: PDF of vehicle cumulative driving period

Validation of MCMC model – EV state



Implementation of optimization target using Dynamic Optimal Power Flow

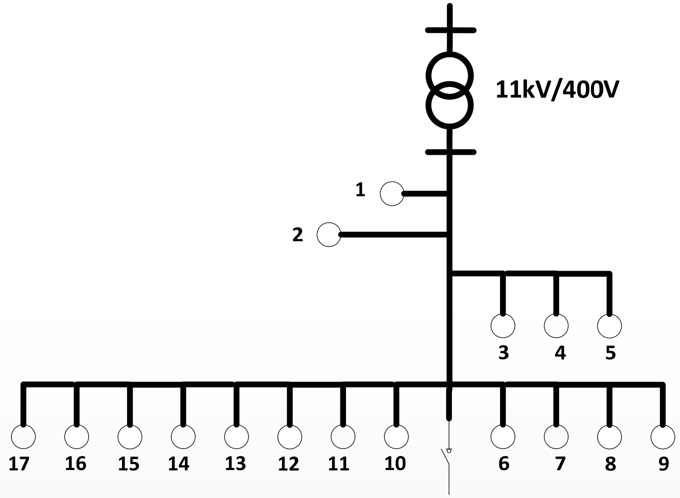


Figure 2: Single phase distribution network layout

- Matpower: static optimal power flow
- Optimization: dynamic optimal power flow

Case study — RTP signal and parameter setting

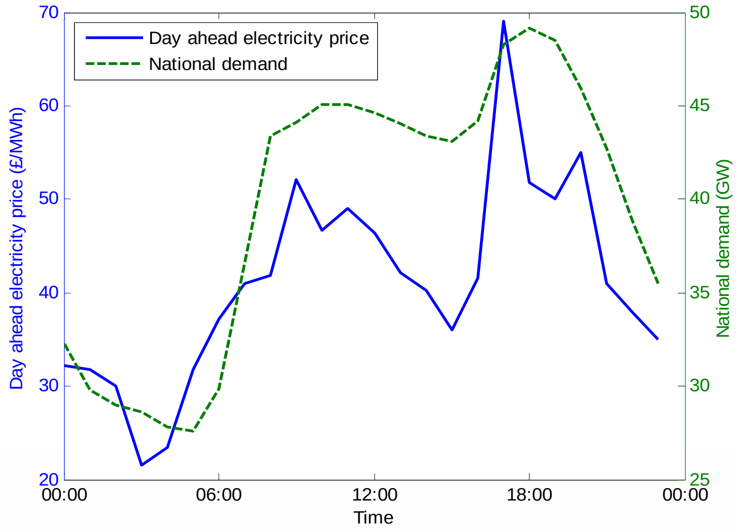
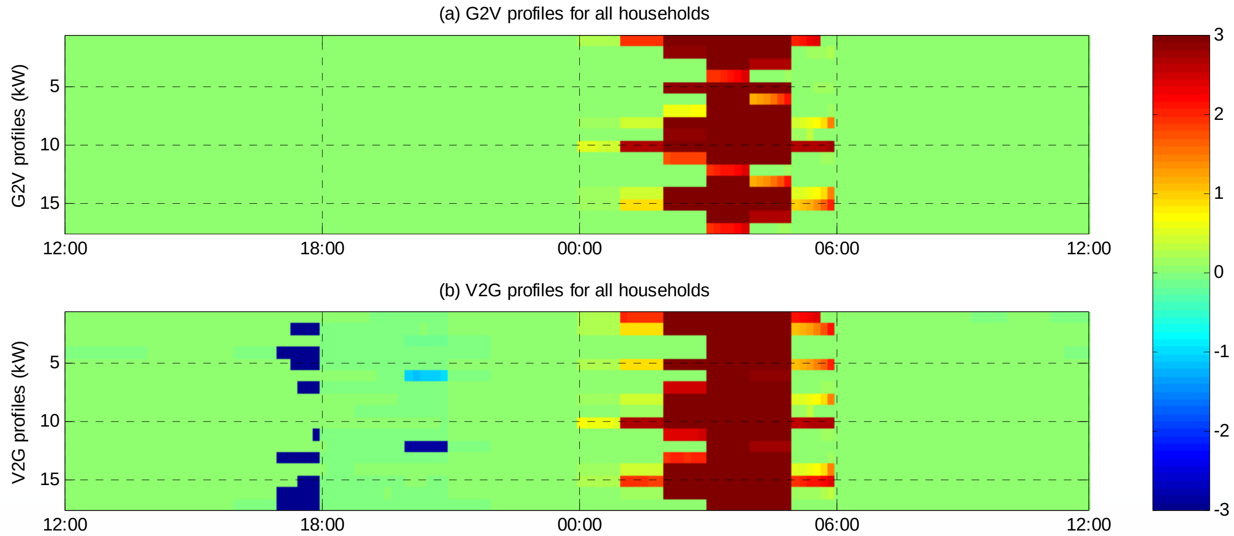


Figure 3: The UK day-ahead electricity price and associated national demand curve

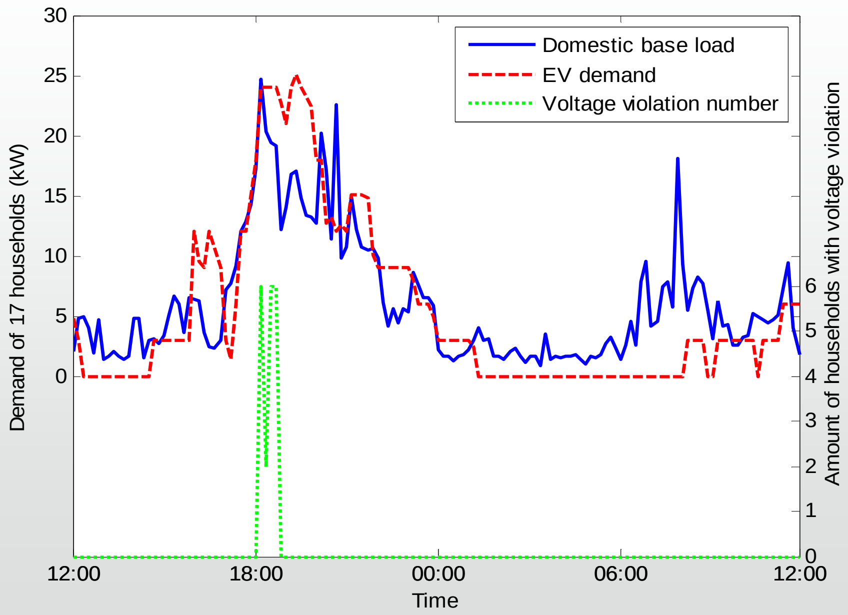
Variable	Value
Battery consumption rate due to driving	6.192kW
Batery degradation cost (C)	0.028£/kWh
	3kW
	-3kW
	0.9
	0.93
	20%
	50%
	[-0.06, +0.10] p.u.

Case study — charging/discharging profiles



EV uncontrolled charging cost:

£17.64, a 68% increase on smart G2V and V2G; a 62% increase of the pure smart G2V



Case study —aggregated EV load and domestic base load

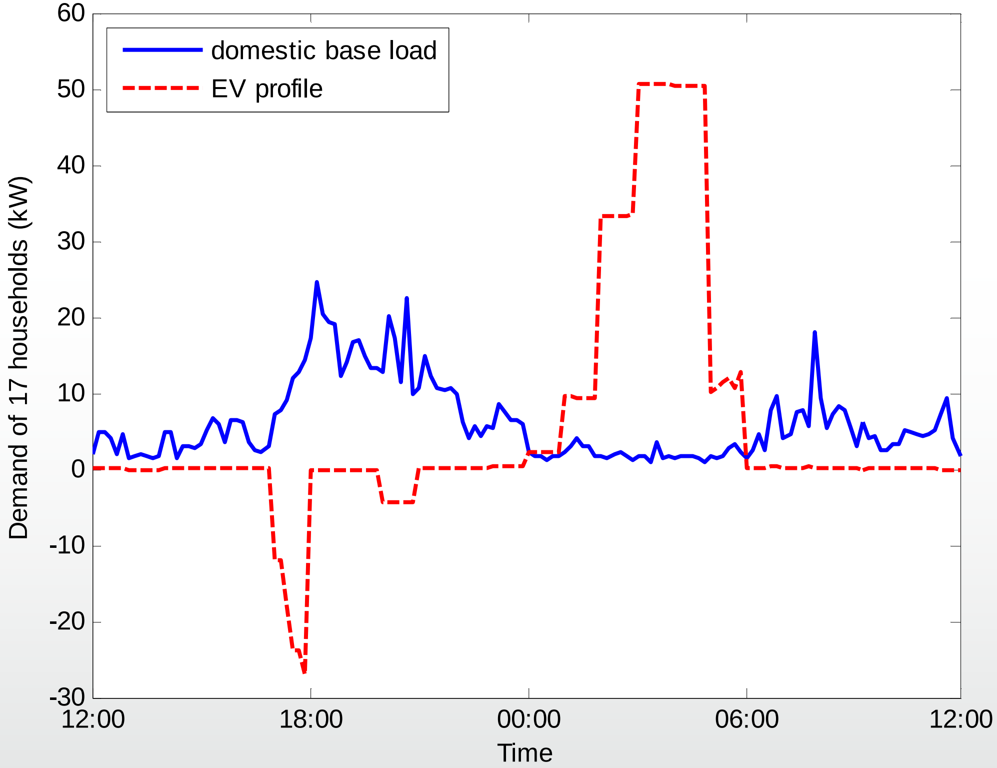


Figure 7: Aggregated load

- Network constraint satisfied
- 100% local EV penetration, low system EV penetration

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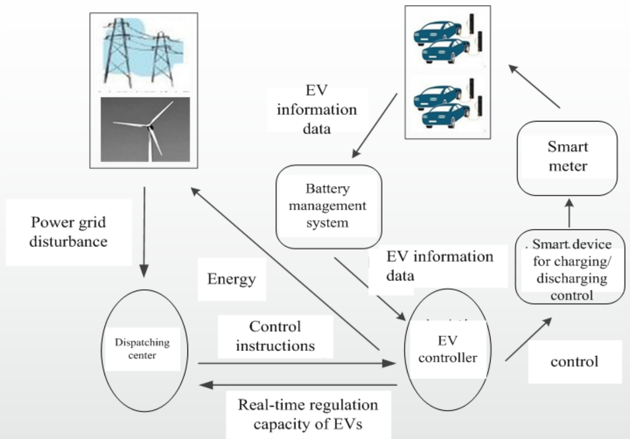
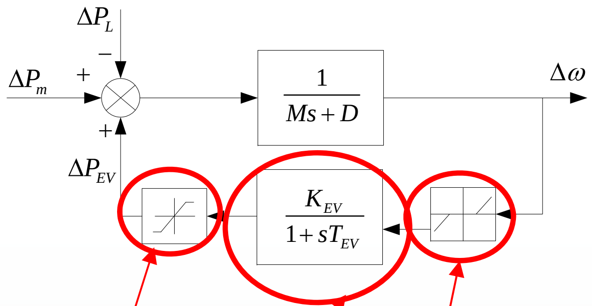
CEPRI-Nanjing work: Frequency regulation with large scale EVs

- Static characteristic frequency model of EV controller

> ➢ Both load and power
> ➢ Take the controller as an equivalent power to take part in frequency regulation



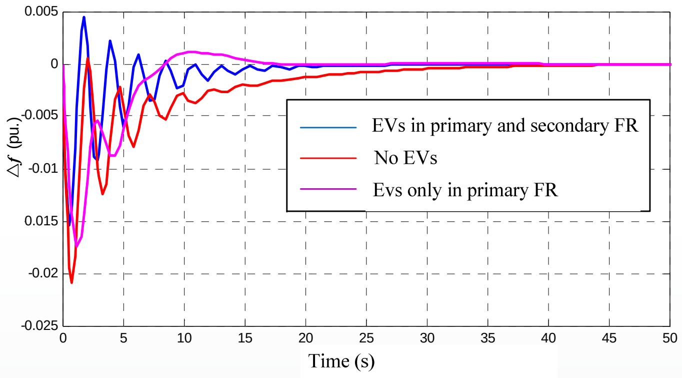


$$\Delta P_m + \Delta P_{EV} - \Delta P_L = (Ms + D)\Delta\omega$$

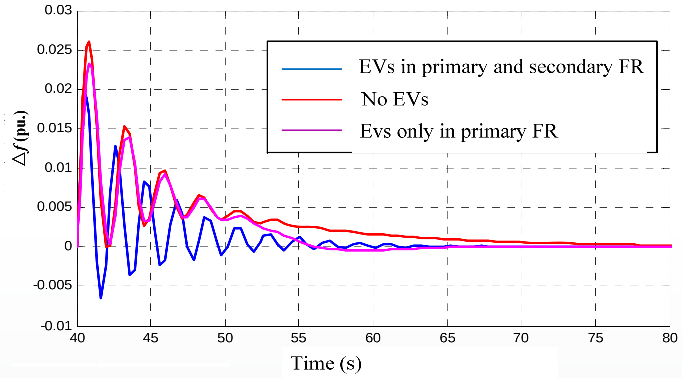
$$\Delta P_{EV} = \frac{K_{EV}}{1 + sT_{EV}}\Delta\omega$$

- To guarantee the battery life
- To consider the adjustment capacity of EVs
- Use the real-time adjustment capacity estimation considering the charging and discharging

Frequency regulation with large scale EVs – case study



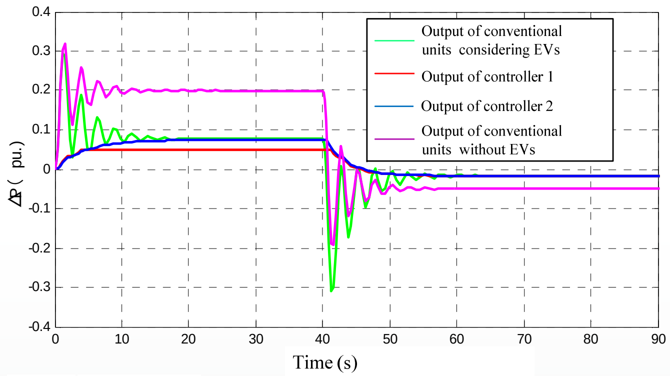
The change of frequency with the load increasing



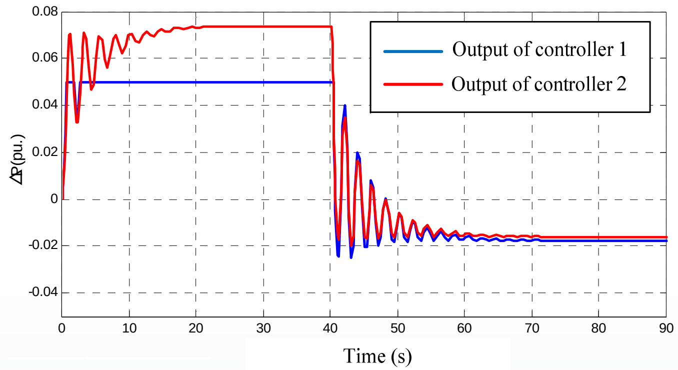
The change of frequency with the load decreasing

- EVs participate in frequency regulation can effectively reduce the system frequency deviation, reduce the adjustment time and improve the power quality.
- Compared with the participation in primary and secondary frequency regulation, system with EVs only in primary frequency regulation can recover the frequency faster. However, the overshoot of frequency deviation increased.

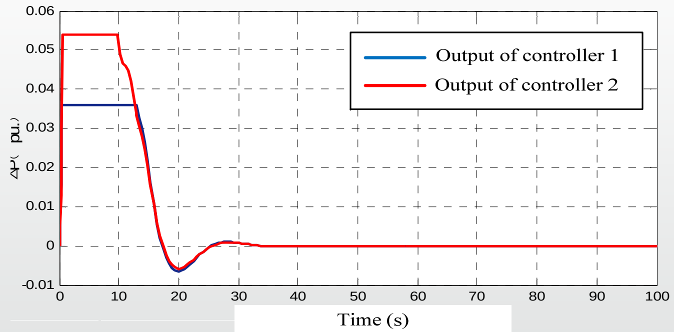
Frequency regulation with large scale EVs – case study



Output of EVs and conventional units



Output of controllers with participation in secondary FR



Output of controllers with participation in primary FR

- When the EVs only participate in primary frequency regulation, EVs can only soften the disturbance. The adjustment capacity will go to zero with the recovery of system frequency.

Main window

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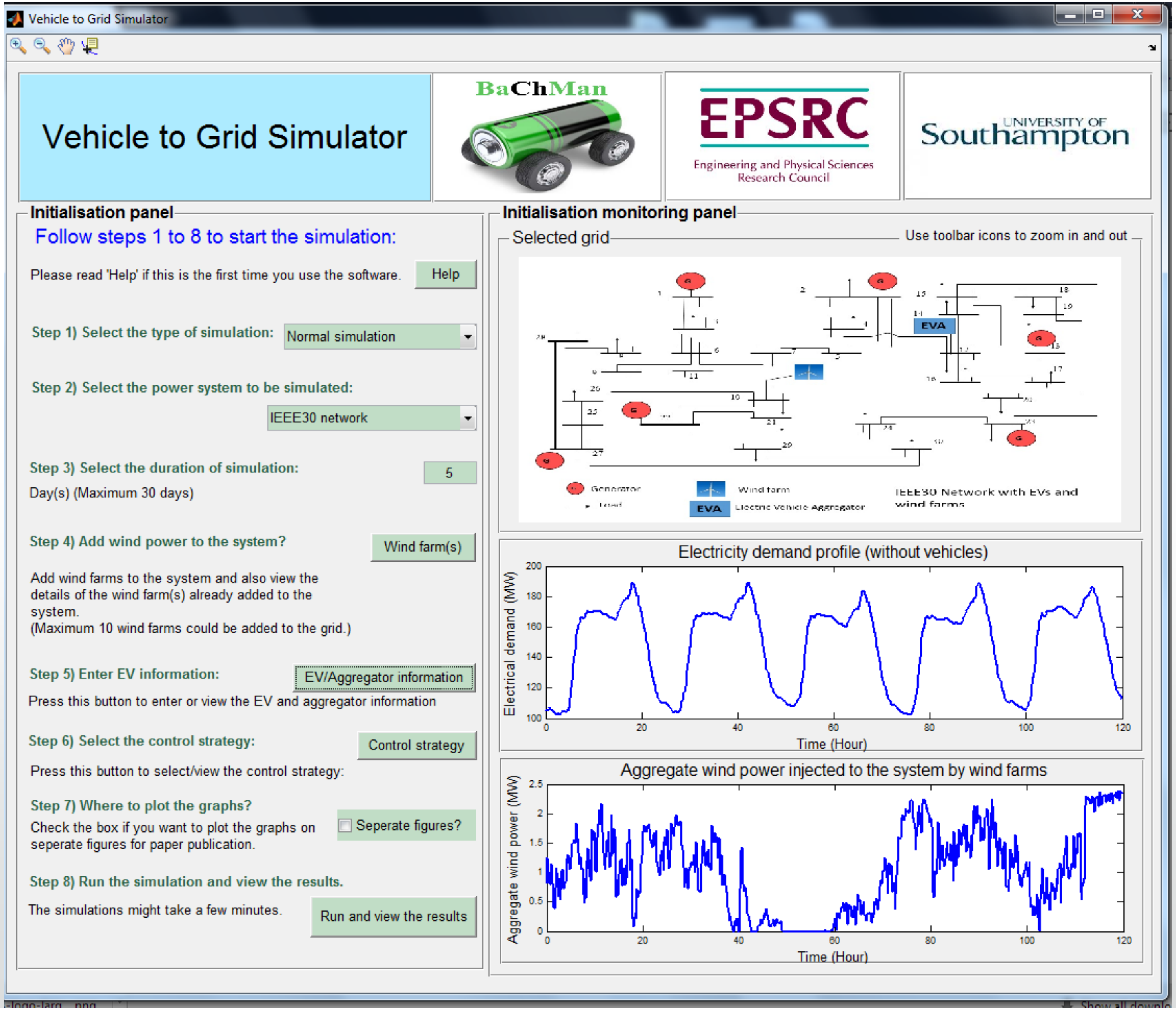
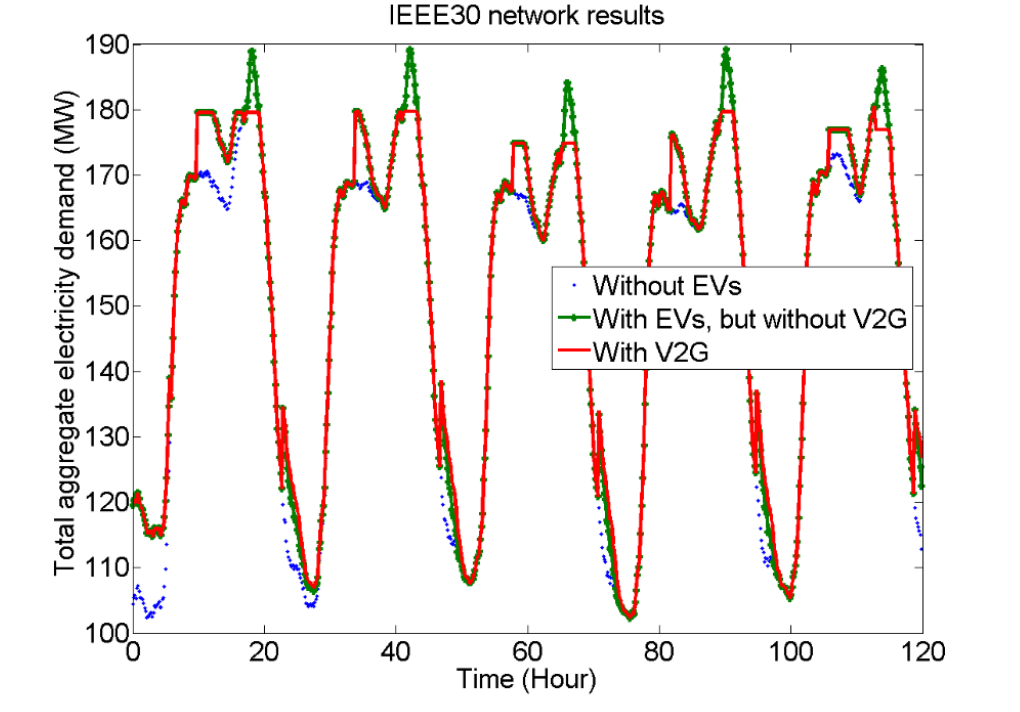


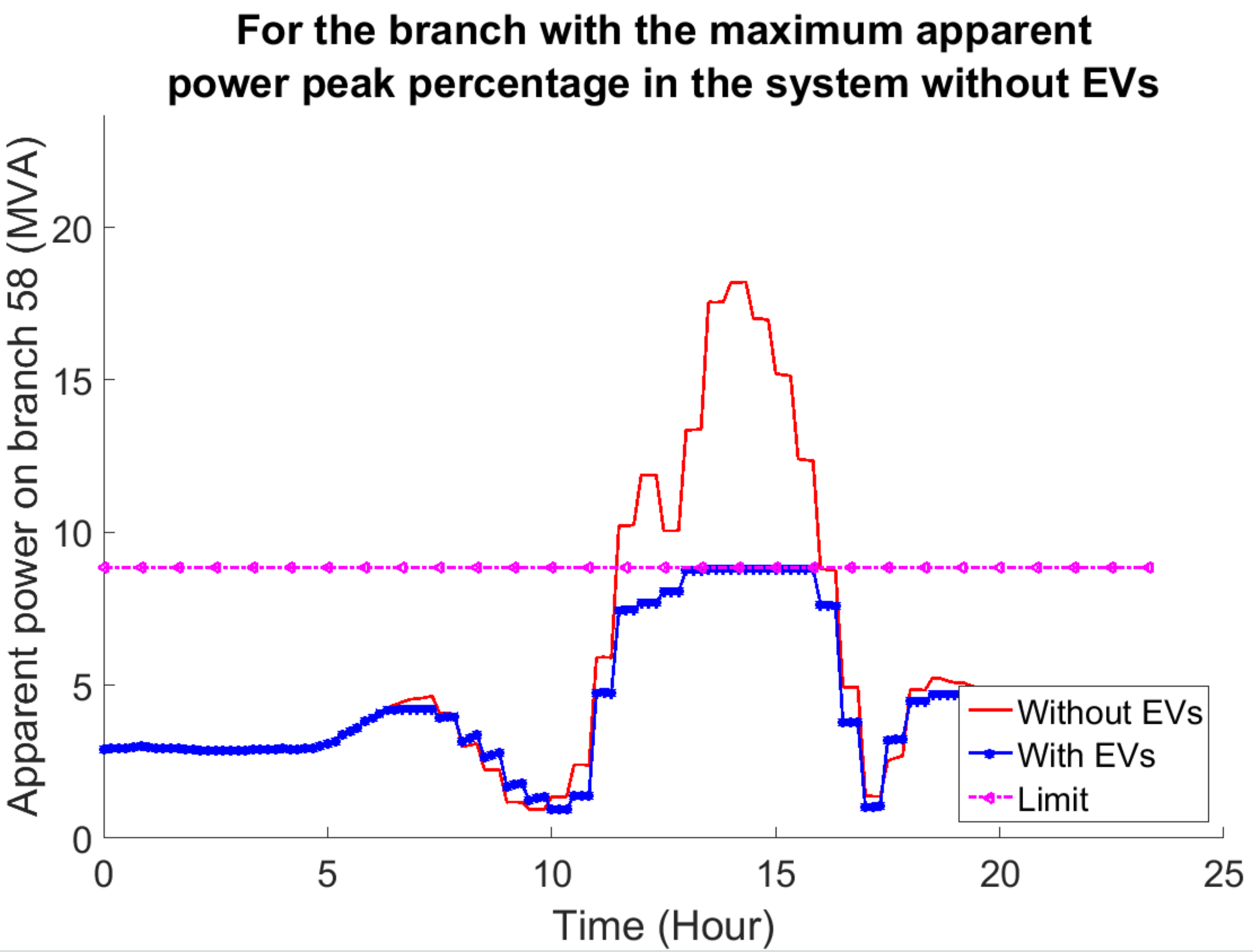
Simulation results (For load levelling strategy)



The total peak electricity demand in the system is decreased by 3% in 'With V2G' scenario in comparison to the 'Without EV' scenario.

In addition to shaving the peak of the demand, the applied control strategy has been able to fill the valley of the demand curve with electric vehicle loads in both 'With V2G' and 'Without V2G' scenarios.

Simulation results
For the scenario with solar farms and car parks with optimisation



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2) **Investigating the impact of the anticipated V2G operation on battery cell, module and pack cycle life, failures and thermal behaviour. More accurate determination of battery SoC and state of health (SoH).**

1.2 Pulse Discharging of LIB

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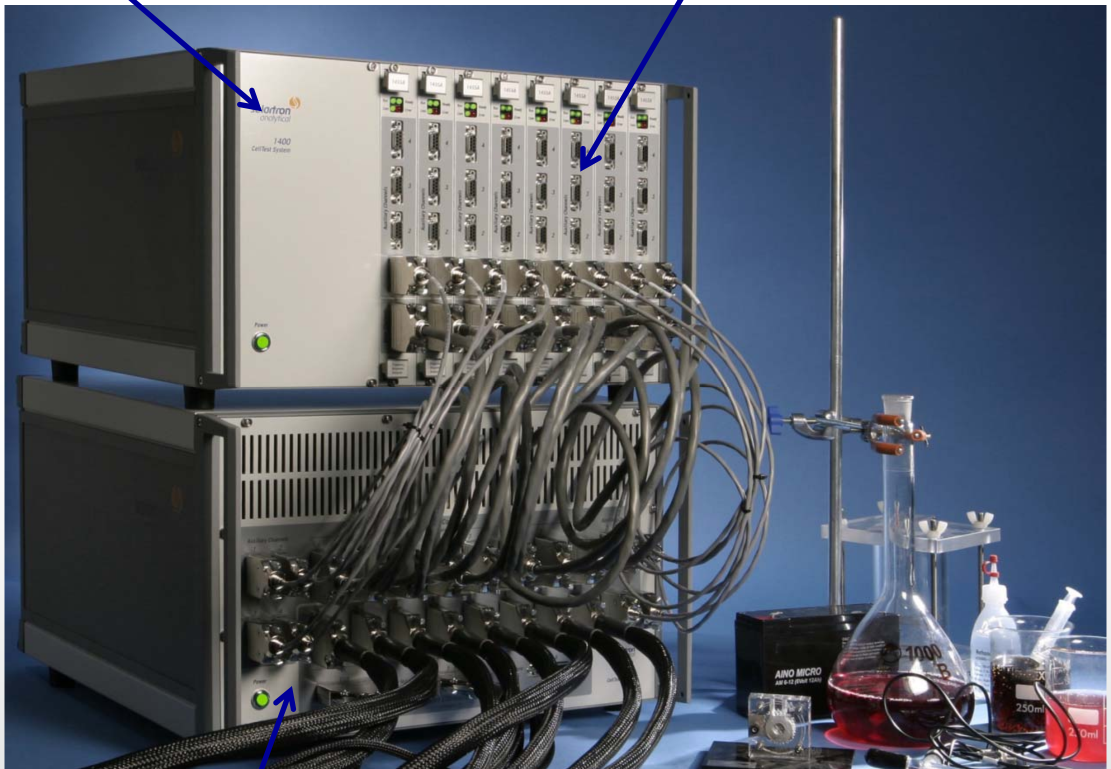
1400 mother module

1455 EIS module



1470E Potentiostat/ Galvanostat

Booster

.7 1470-1455 Solartron test platform with Booster of 20A

1.2 Pulse Discharging of LIB

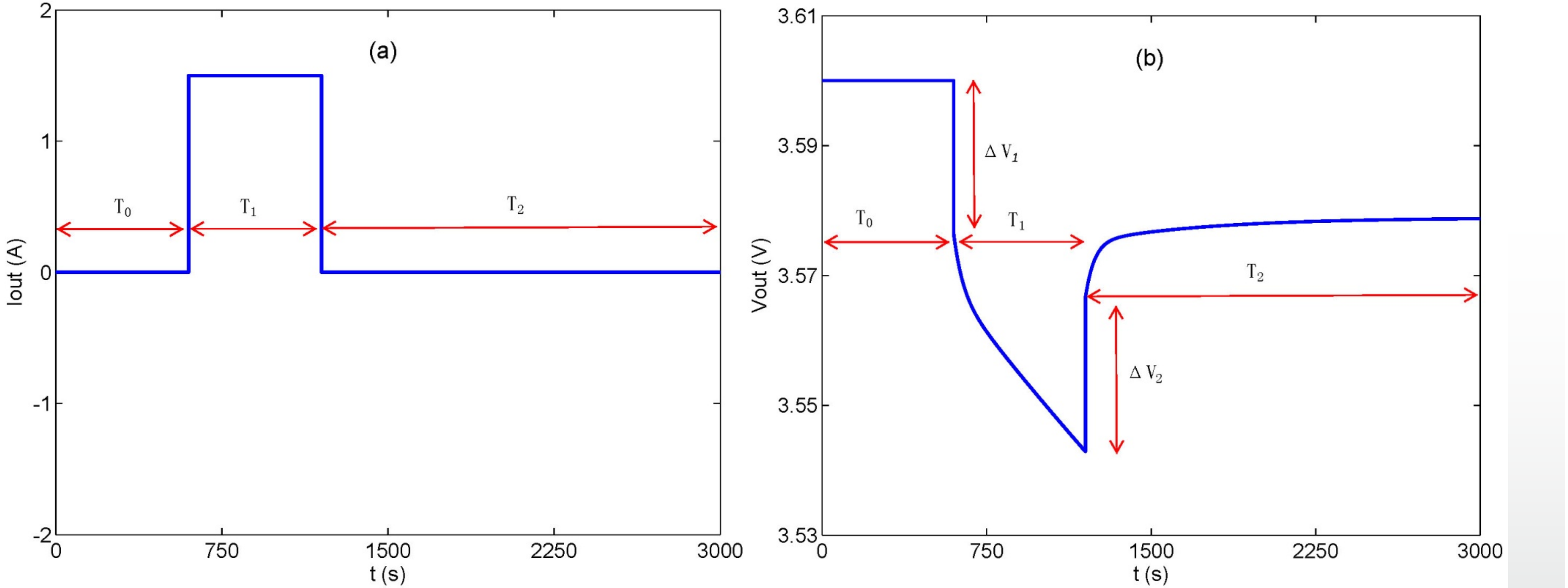
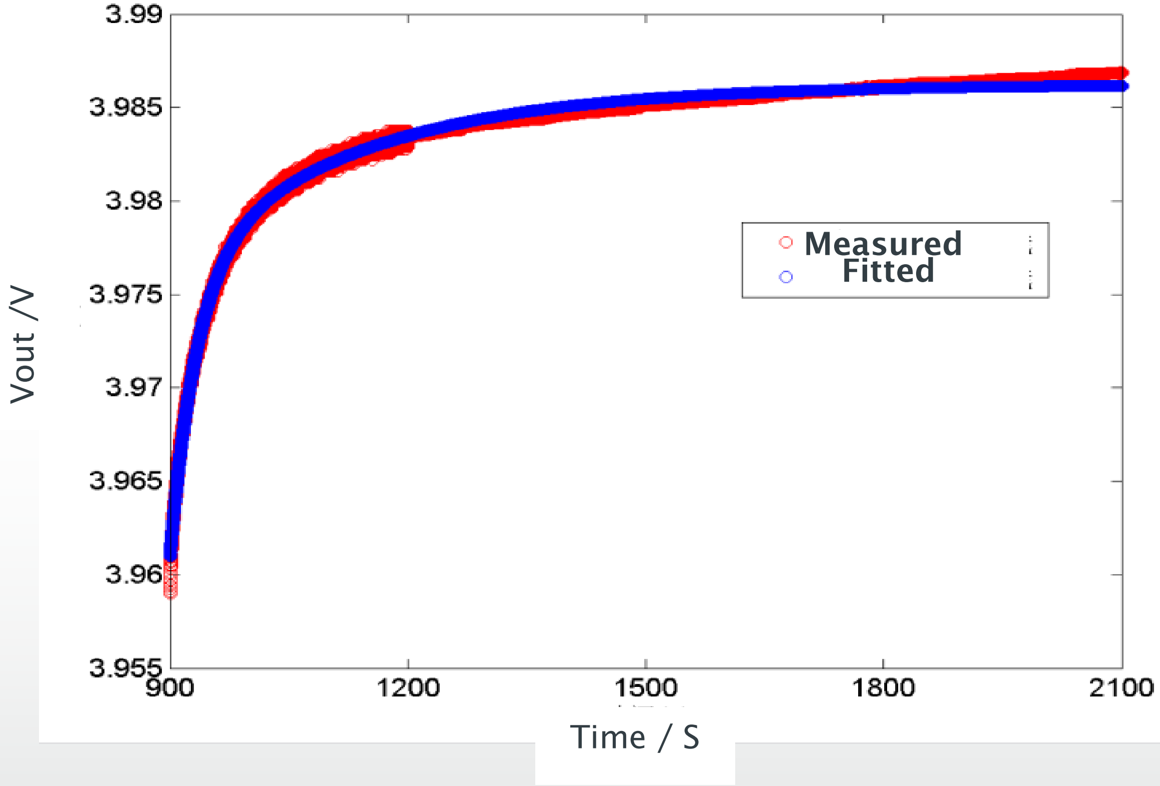
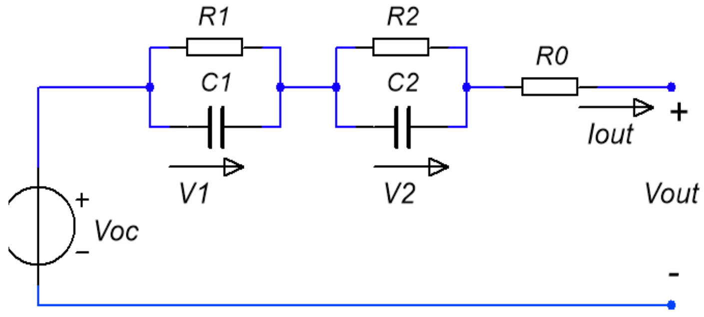


Fig. Pulse Discharging for Li-Ion Battery

1.4 Identification Results





Results demonstrate pulse current method is an effective way to detract circuit parameters.

$R_0(\Omega)$	$R_1(\Omega)$	$C_1(F)$	$R_2(\Omega)$	$C_2(F)$	$\tau_1(s)$	$\tau_2(s)$
0.0153	0.0050	6779.090	0.0028	78859.594	33.895	220.807

2.5 Identification Results When Trest=600s

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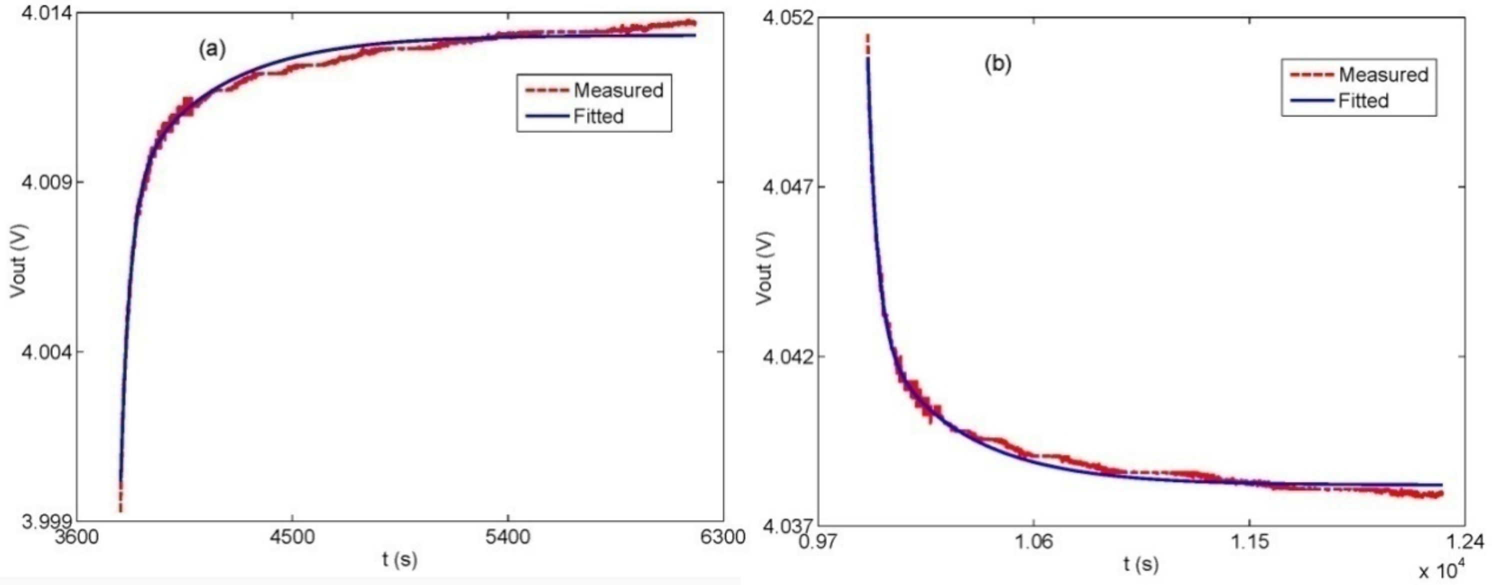

Fig. Fitted and Measured Values of terminal open circuit voltage for 15Ah-NCM LIB. (a) after discharging ;(b) after charging.

Table 4. Identification results for LIB after discharging and charging

Parameter	R_0 (Ω)	R_1 (Ω)	C_1 (F)	R_2 (Ω)	C_2 (F)
Discharge	0.0158	0.0057	7045	0.0038	97881
Charge	0.0160	0.0054	7345	0.0037	98753

3.3 Test Results for 15Ah LIB: (2)

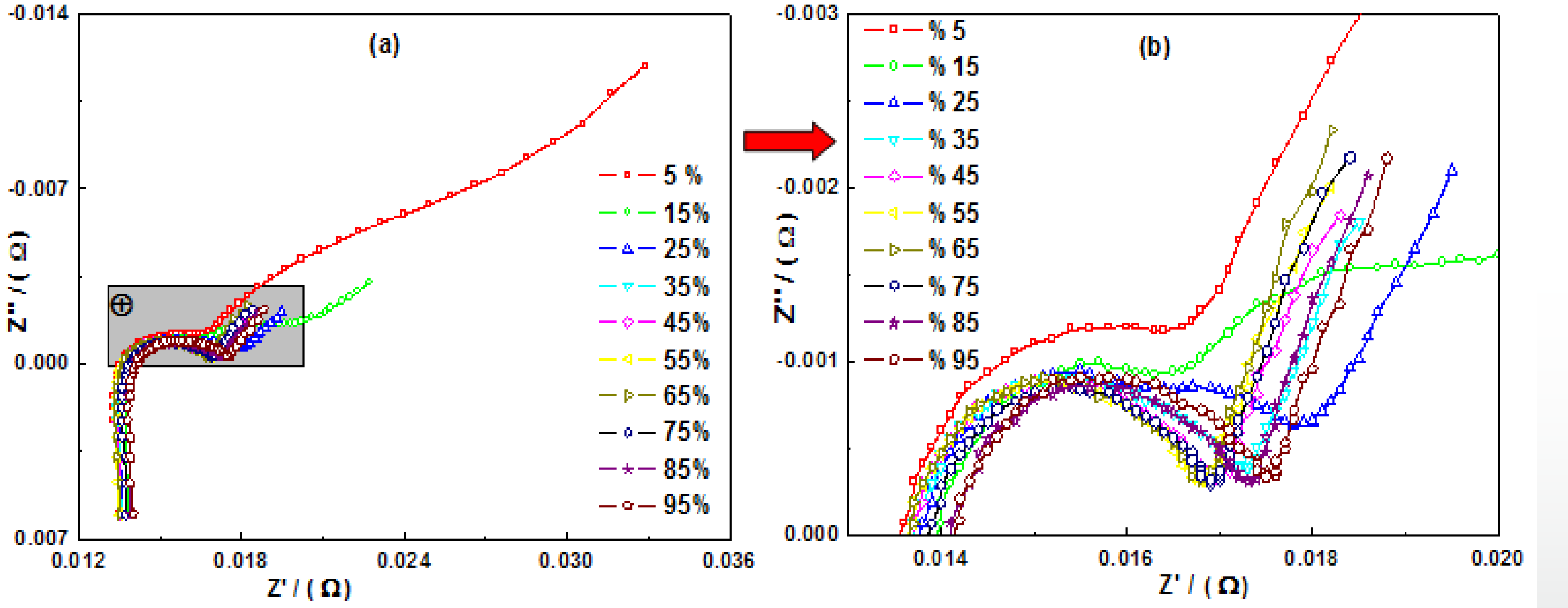

Fig. Impedance spectra under different SoCs. (a) Complete spectra from 0.01~10KHz; (b) The enlarged spectra in box.

3.4 Fractional Impedance Spectra Diagnosis: (4) f1 & f2 & ft Analysis

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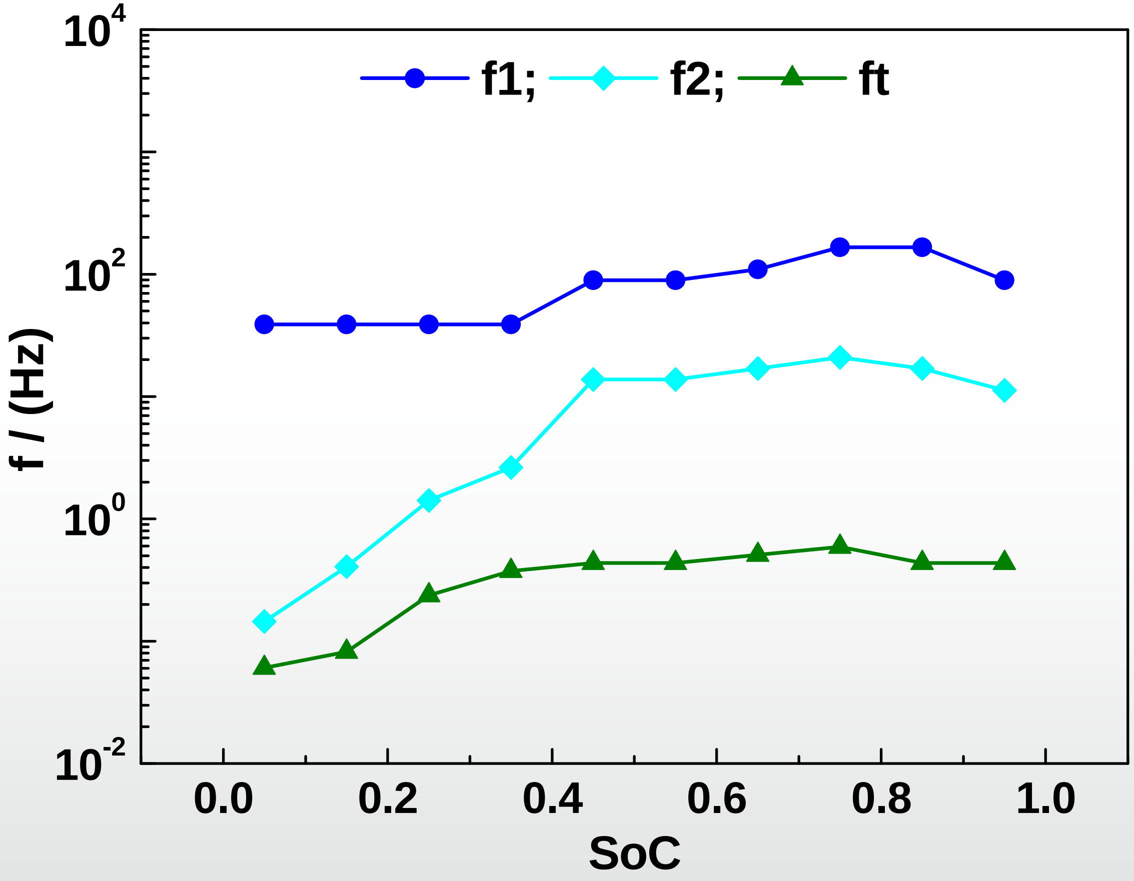

Figure. Characteristic frequencies for commercial LIB under SoCs from 5% to 95%.

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Battery Thermal Modelling

Electro-chemistry model

- Chemical reactions in the cell

Thermal model

- Convective and conductive heat transfer in the cell

Capacity fade model

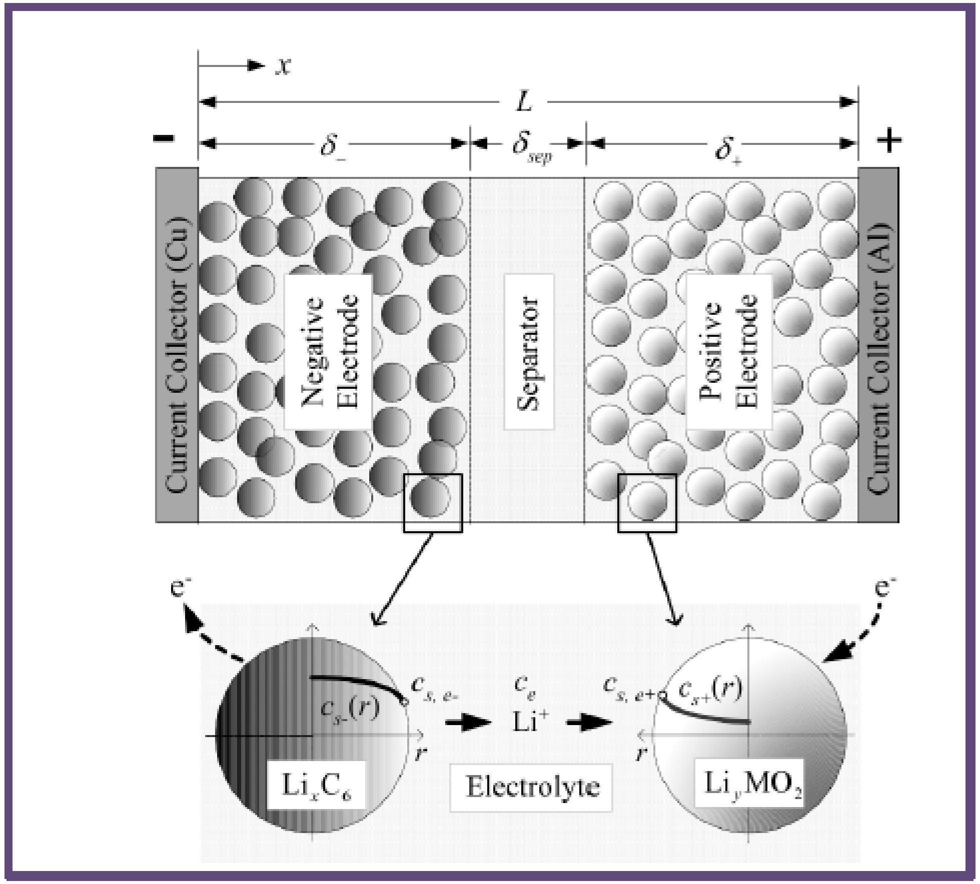
- Solid Electrolyte Interface (SEI) layer growth during charging

Variable porosity model

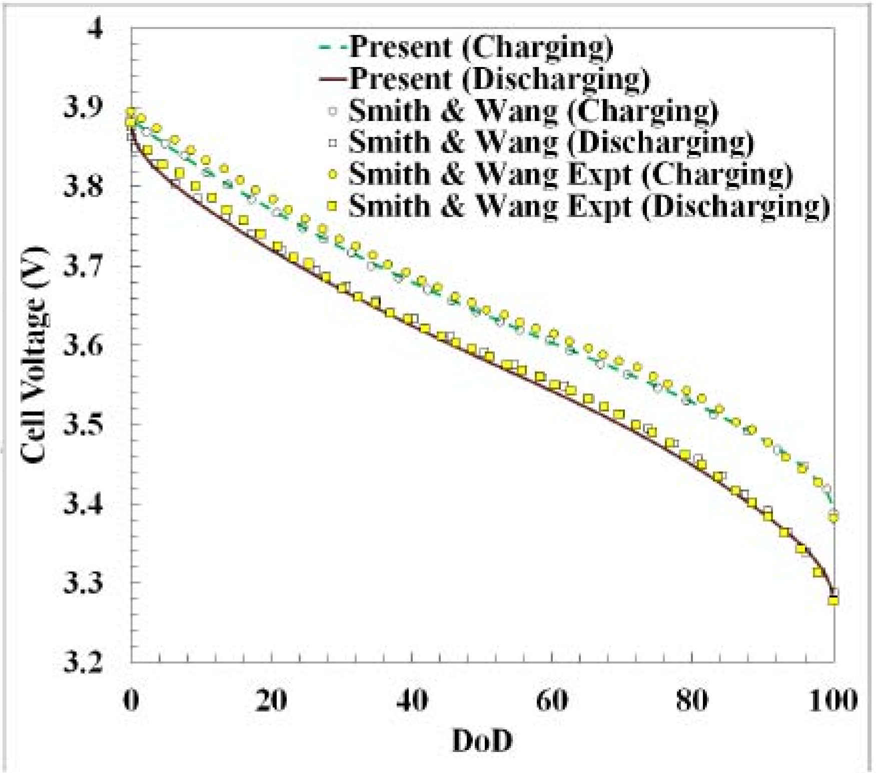
- The porosity change is directly linked to partial molar concentration

Pseudo Two Dimensional (P2D) Model

- Positive and negative electrodes consist of porous spherical particles and electrolyte.
- Solve solid phase equation at each node in positive and negative electrode giving 2D spacial dependency. i.e. Cs = f (x; r; t), Cs,e represents the surface concentration of each spherical particle.



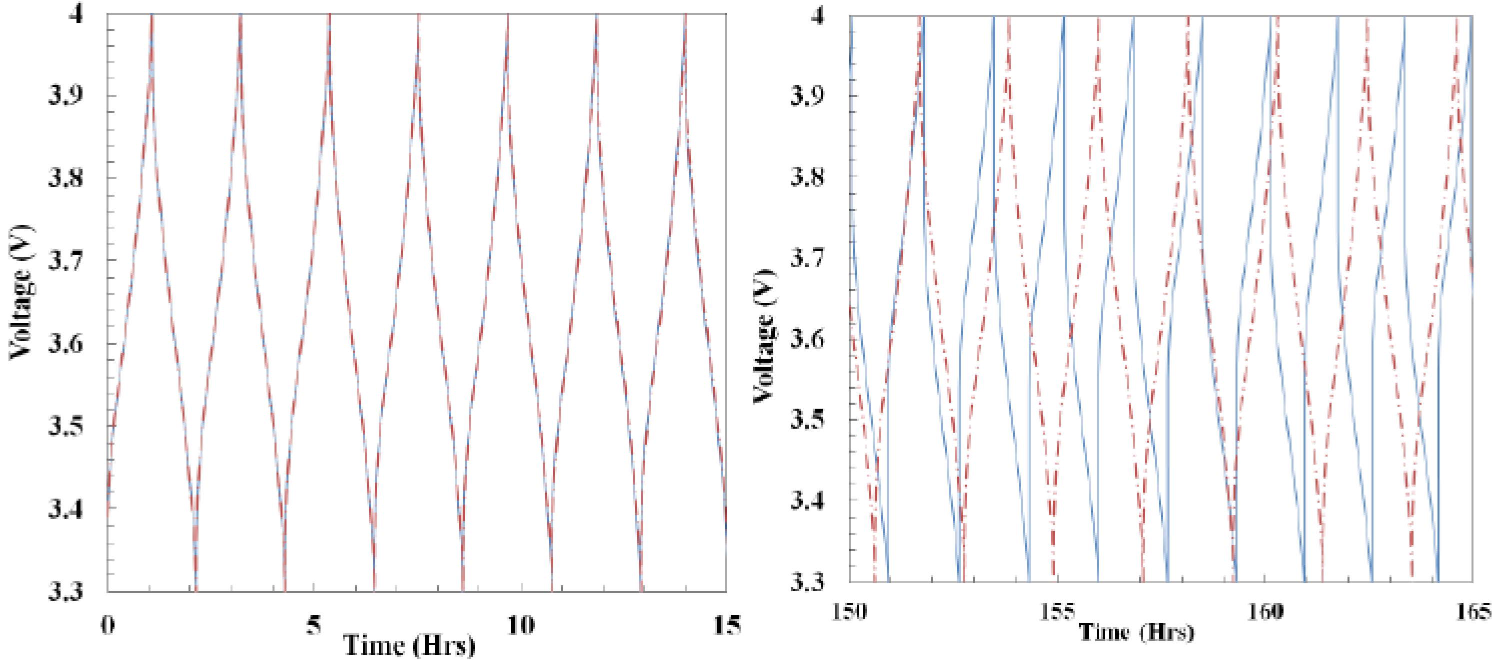
Validation study1 : 1C charging & discharging



- Runs are taken with $i_{os} = 0$ (i.e. no capacity fading effect) for a 6Ah battery [1] at 1C (6A) constant current charging and discharging.
- Sign convention: Positive current discharges the battery.
- The result shows an excellent agreement with Smith & Wang (2006) [1] for charge-discharge characteristics.

[1]Smith & Wang, Power and thermal characterisation of Li-ion battery pack for hybrid electric vehicles, JPS, 2006.

Capacity fade cyclic charging & discharging



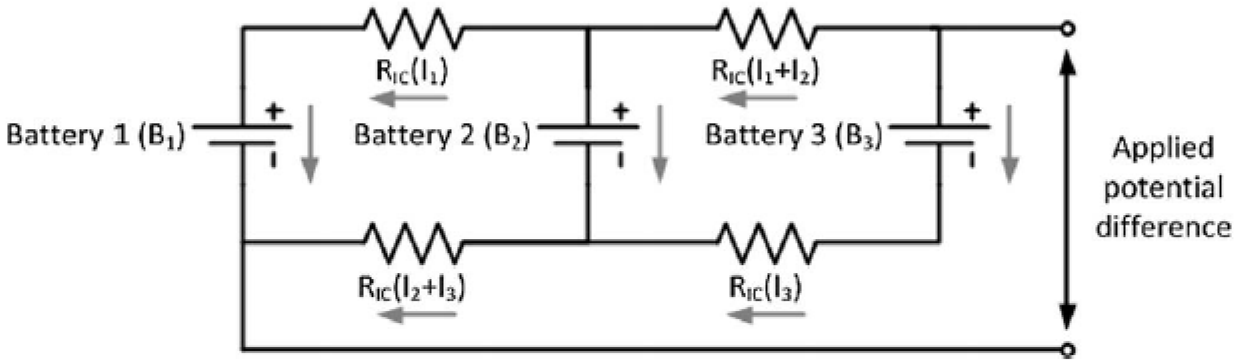
First 15hrs of operation

After 150hrs of operation

- The model was set to run under normal cycling conditions with constant current charging & discharging between 4.0V and 3.3V.
- The voltage proles are distorted after few cycles of battery operation due to build up of internal resistance.

Challenges of multi-cell modelling

- Dynamic load imbalances due to the resistance of cell interconnectors for parallel strips in large battery packs.
- Inhomogeneous heat generation within a battery pack.
- Acceleration of capacity and power fade of the hotter cells.
- Due to the temperature dependency of the side reactions for the SEI layer growth (Ramadass et al., 2004).
- Schematic of a 3P1S battery pack configuration (Wu et al., 2013)



▪2.LIB thermal simulation

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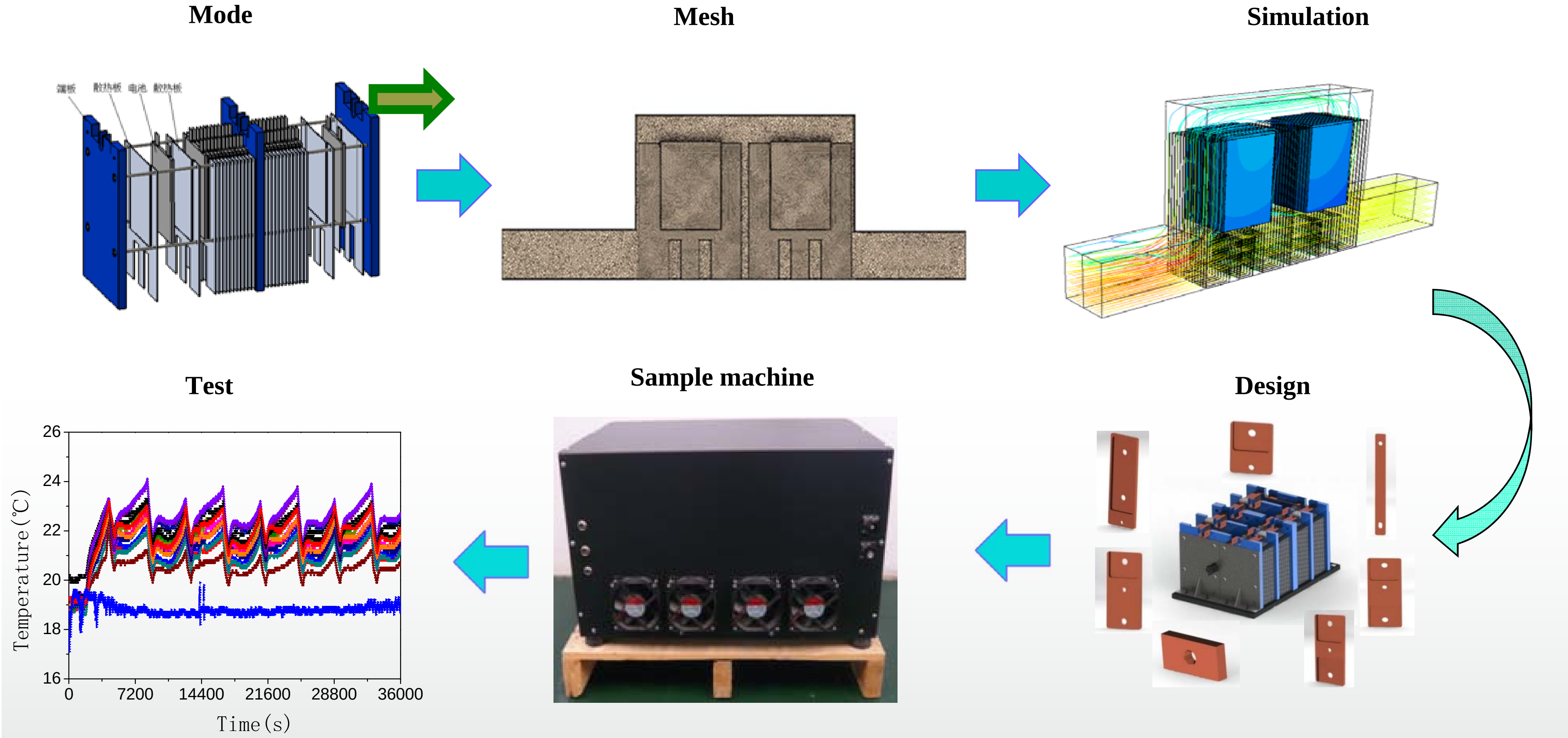


LIB thermal simulation process diagram

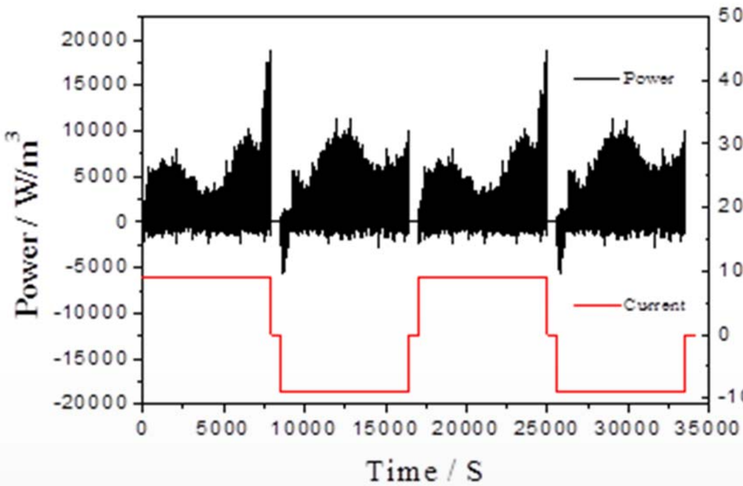
2.LIB thermal simulation

LIB thermal parameters measurements

- THT ARC-----Specific heat measurement

- Hot Disk TPS-500S---- Thermal conductivity measurement

LIB real-time calorific value



Specific heat (Cp)/ $J\cdot K^{-1}\cdot g^{-1}$	Thermal conductivity (K) / $W\cdot MK^{-1}$
1.033	1.399

▪2.LIB thermal simulation

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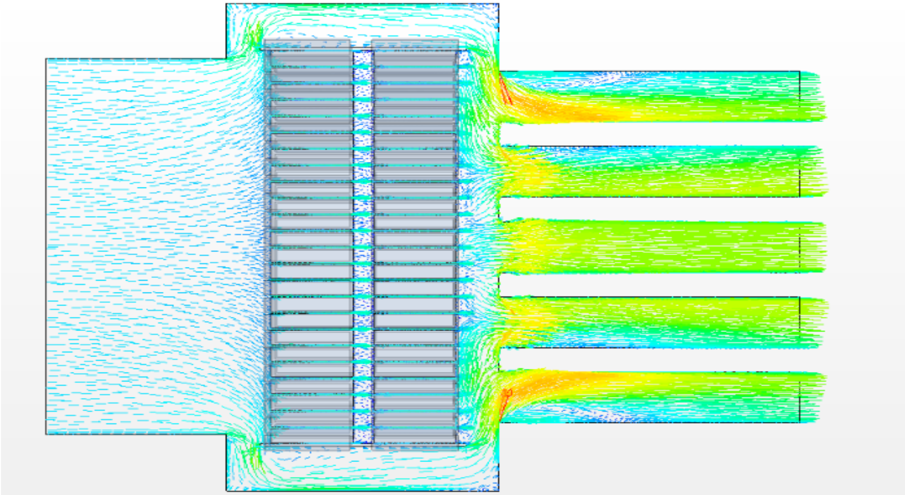
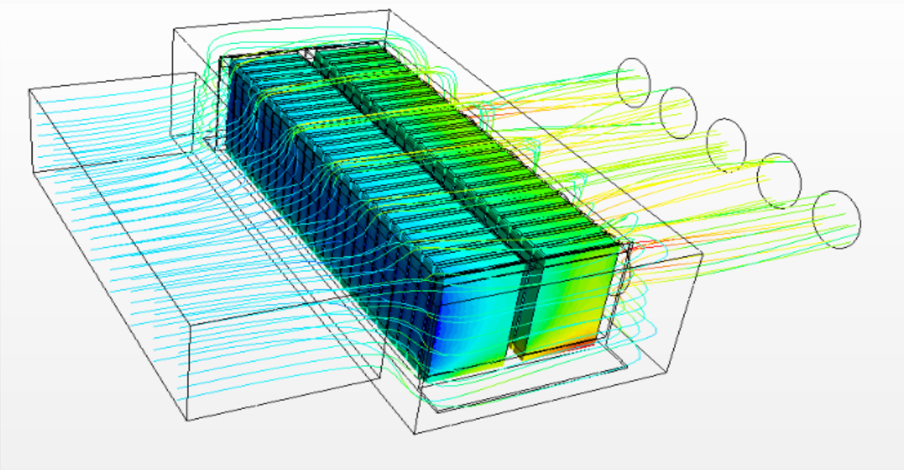
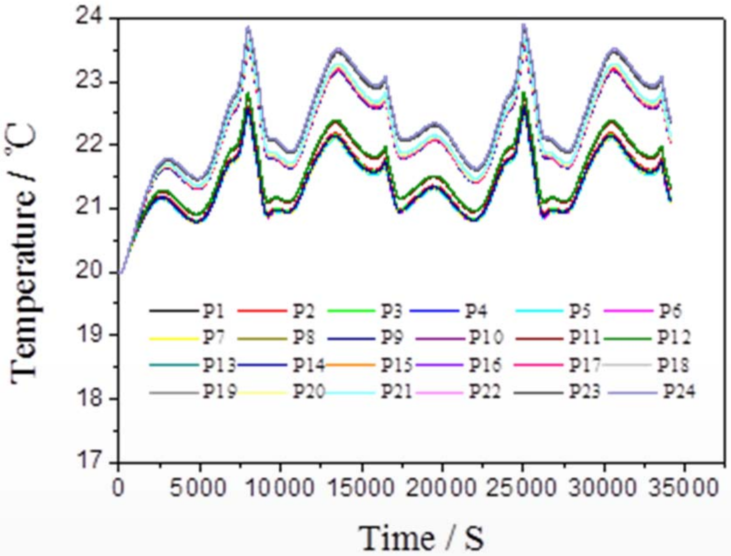


LIB group flow field and temperature field



LIB simulation temperature



During 0.5C charge/discharge, the battery pack's maximum temperature was 23.9 ℃ with a field temperature difference of 0.8 ℃ ~ 1.5 ℃.

Next step is to make prototype and do verification test.

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3) Investigating the communication and control temporal and physical information requirements from the battery management system (BMS) to the grid control system and vice versa.

II. Research focus:
Frequency support from PEVs

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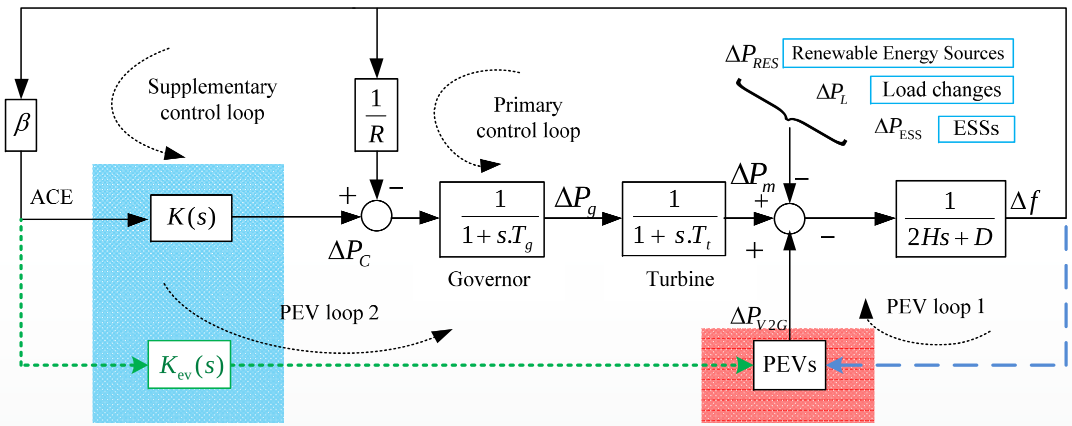
Background

a. Intermittent RESs introduce power imbalance;

b. The ESSs with big capacity require huge cost;

c. Many controllable loads, including EVs, are included.

How controllable loads (PEVs) contribute to power balance



Issue 1	Issue 2
How to model PEVs for frequency control: Charge/discharge power = F(frequency deviation)	How to design LFC scheme for systems with PEVs: Control loop characteristic + performance-based design condition + gains tuning algorithm

1. Frequency regulation of isolated grid with RES, ESS, PEVs

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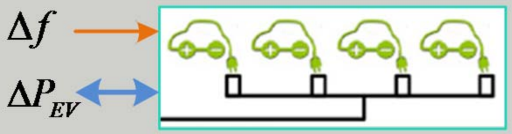
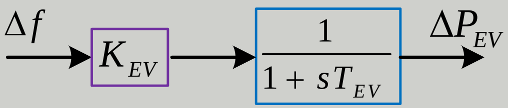
Problem and objective

For an isolated grid with RES, ESS, PEVs, design a PID-based LFC scheme with robustness against to communication delays, load changes, intermittent wind/PV power inputs etc.

V2G model of PEVs



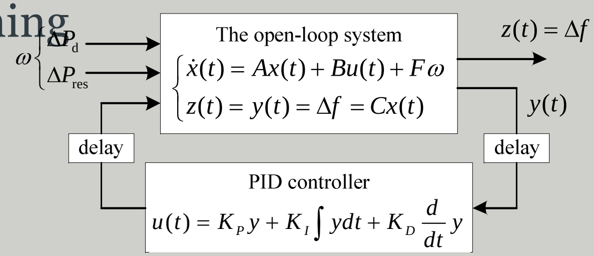
a. First-order transfer function [1-3]



b. Constant V2G gain: K_{ev}

LFC design method

a. H_∞ robust index design condition
b. Linear matrix inequality (LMI) based gain tuning



Find PID gain via solving LMI
For delay bound, h → minimise

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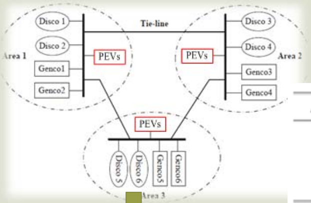
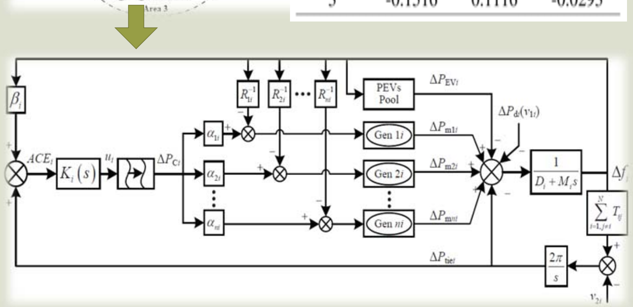
2. Robust LFC design for multi-area power systems with PEVs

Results

Three-area LFC

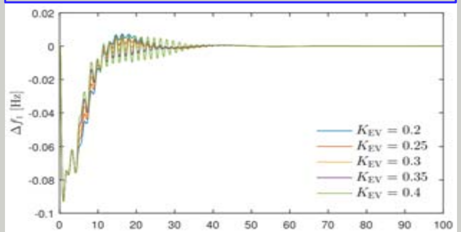


Areas	K_P	K_I	K_D
1	-0.1499	0.1519	-0.0328
2	-0.0825	0.1399	-0.0087
3	-0.1516	0.1116	-0.0293

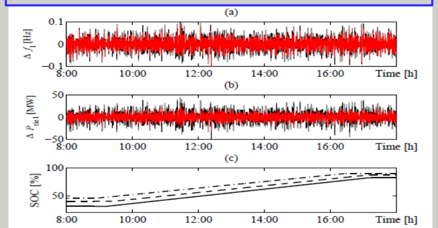


Robust to delays, load changes, uncertain of Kev

- Step change; constant delay



- Random change; random delay



Indices	K_{EV} 0.2	0.3	0.4	Without PEVs
ISE	0.101	0.091	0.085	0.155
ITAE	12.333	9.416	10.450	27.920
IAE	1.857	1.649	1.643	2.985

Δf (Hz)	Percentage (%) With PEV	W/O PEV
$0.00 \sim 0.02$	75.32	59.41
$0.02 \sim 0.03$	16.70	16.55
$0.03 \sim 0.05$	7.98	17.84

Output

1. Hua Fan, Lin Jiang, Chuan-Ke Zhang, Chengxiong Mao. Frequency regulation of multi-area power systems with plug-in electric vehicles considering communication delays. *IET GTD*, provisionally accept

University Update - Sheffield

- Work is still ongoing on the testing of cells for the BMS, cells are on test at various temperatures on Maccor cell test facilities and temperature controlled environments.

- BMS development is underway for the BMS system which is to be incorporated into the bi-directional converter interface, looks likely to be incorporated into the FPGA controller for the V2G interface.

- Construction of hardware for a Si / SiC based V2G converter has been completed, and comparisons between technologies are underway. Minor design changes will then be carried out as required based on the outcomes of tests.

- Identification of a number of Li based possibilities for the V2G project is continuing, SoC and SoH modelling has begun, together with testing of the battery on typical current cycles, and possible dynamic charge acceptance (DCA) testing for regenerative braking as seen in the vehicle.

University Update - Sheffield

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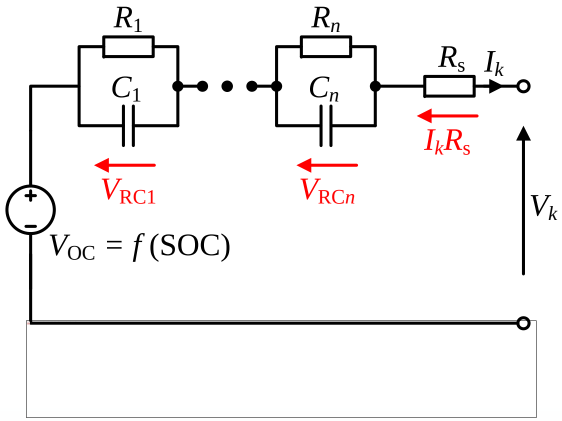
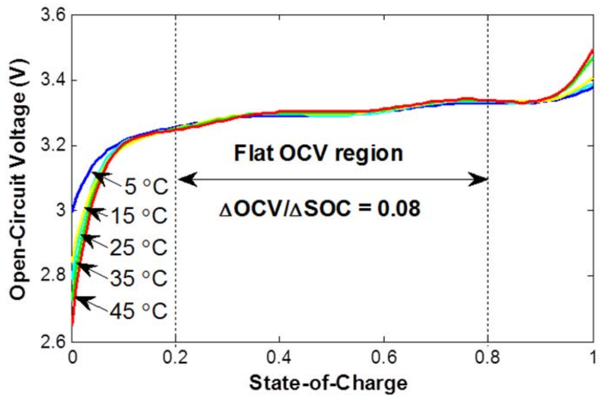
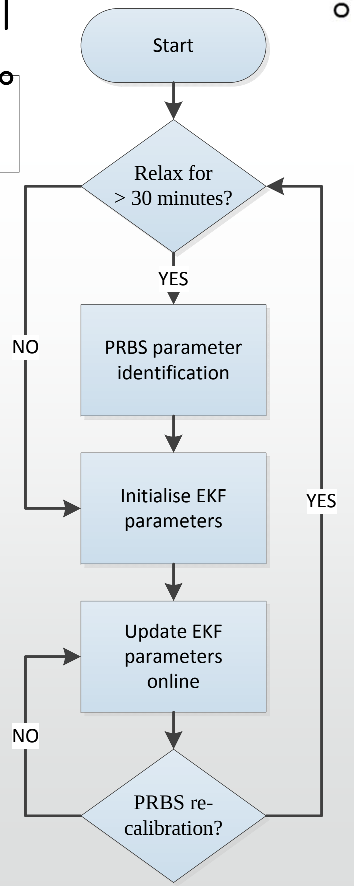
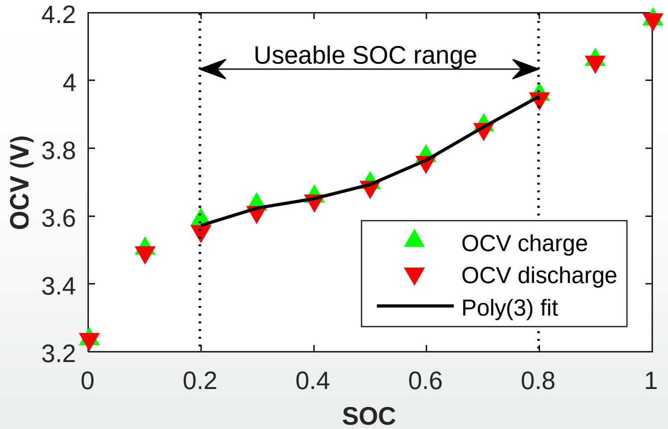
Task 1:



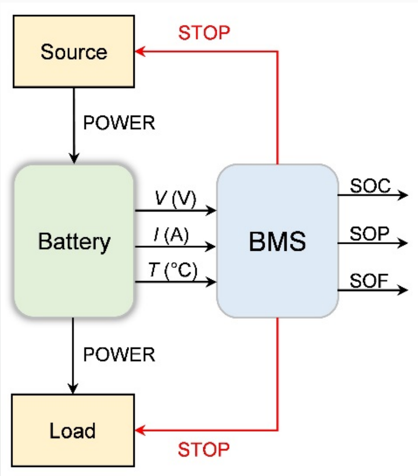


Open-circuit-voltage as a function of state-of-charge for $LiFePO_4$





OCV-SOC relationship for charge and discharge, showing 3rd order polynomial curve-fit over the useable range of 20 to 80%



BMS System operation

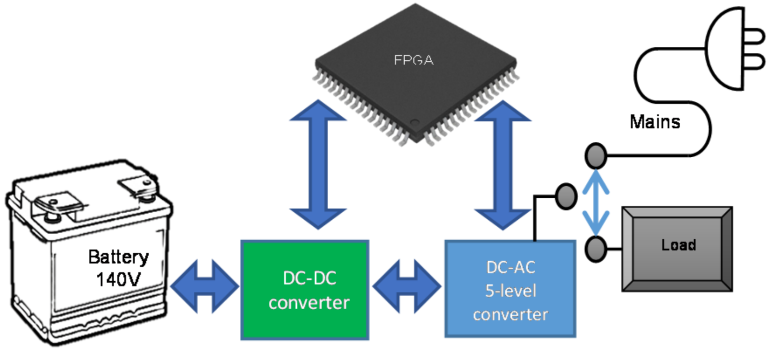
Block diagram illustrating the proposed hybrid battery parameter identification concept

University Update - Sheffield

University of Southampton

Task 2:

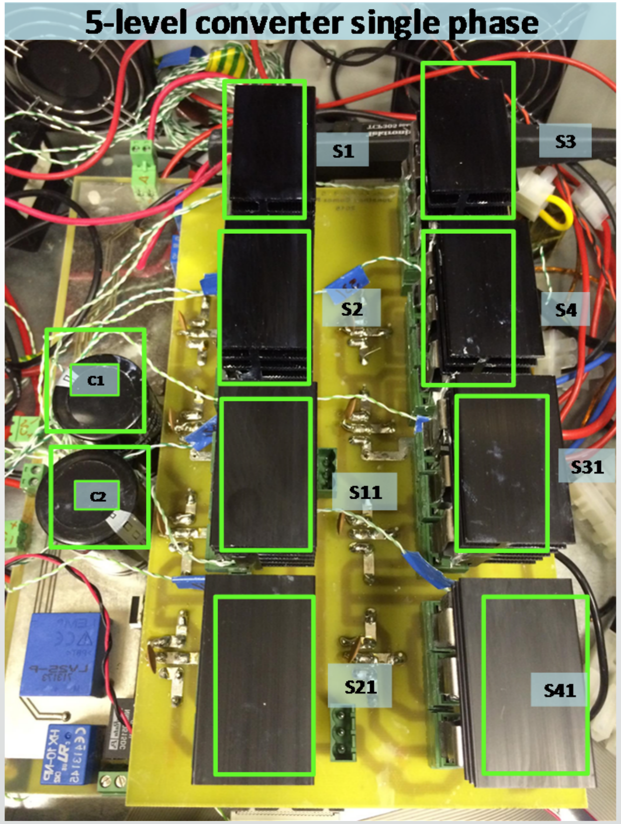
- Bi-directional DC-DC converter for battery interface coupled to 5-level converter for mains interface
- Comparisons of Si and SiC devices in a 5-level interface for loss comparisons.
- Characterisation of battery chemistries for SoH / SoC modelling for BMS system



Outline of Interface

Name	MOSFET	Manufacturer	V_{DS} (V)	I_{DS} (A)	$R_{DS(on)}$ (mΩ)
Si N95	Si	ST	950	10	680
Si FDP	Si	Fairchild	100	164	4.5
SiC 040	SiC	CREE	1200	60	40
SiC 280	SiC	CREE	1200	10	280

Table 2: Switching devices for performance evaluation in 5-level single phase converter



5-level converter hardware for comparison of switching device technologies

4) Demonstrating V2G operation within distinct UK and Chinese environments.

This activity is still under consideration

Conclusions

- Successful UK/China collaboration
- Addressing critical impact on the battery of V2G operation
- Studying grid support issues offered by V2G
- Considering how to demonstrate these!

Thank you for your attention

Any questions?