# Modelling of Distributed Time Constants in Carbon Based Supercapacitors

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EPSRC funding

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# Overview

- Goals of ELEVATE project

  *ELEctrochemical Vehicle Advanced TEchnology*
- Modelling and simulation of supercapacitors
- Application to working devices
- MatLab / SIMULINK to model non-ideal systems
- Conclusions
- Further studies / future work

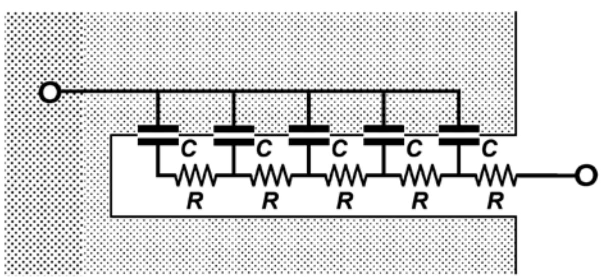
# Goals of ELEVATE Project

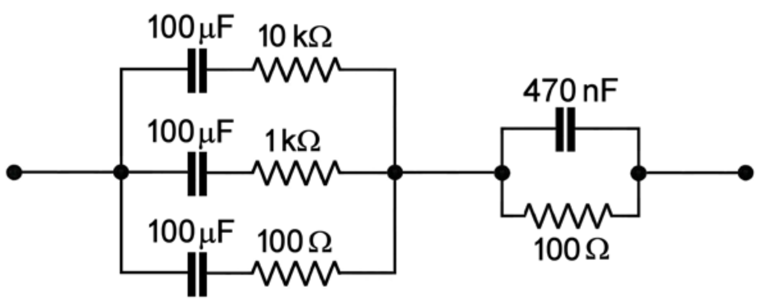
- Develop supercapacitors for use in electric vehicles based on:
  - ionic liquid electrolytes
  - porous carbon electrodes

- Develop a successful equivalent circuit model of supercapacitor performance
  - simulation and fitting
  - characterisation

# Modelling Supercapacitors

Previously modelled supercapacitor performance using simple equivalent circuit model



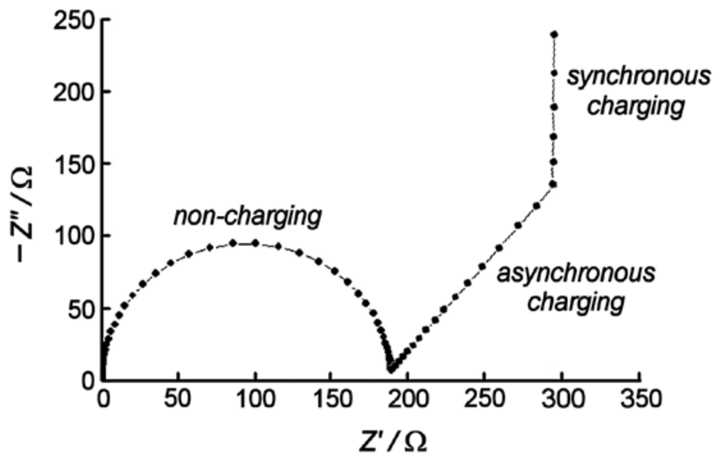



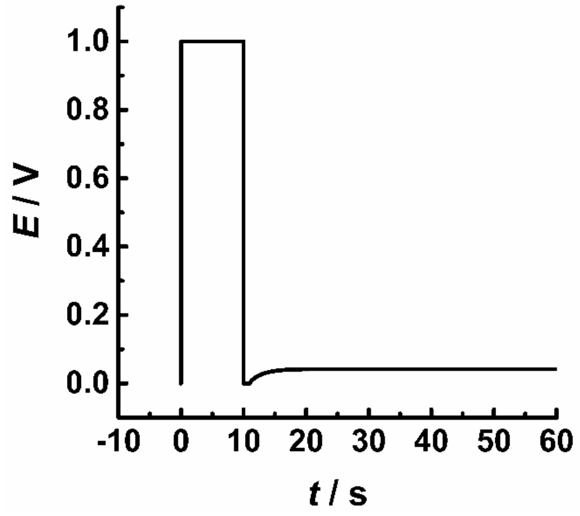

S. Fletcher, V. J. Black and I. Kirkpatrick, *A Universal equivalent circuit for carbon based supercapacitors*, J. Solid State Electrochem. 2014, 18, 1377-1387

# Modelling Supercapacitors (cont)

Model implemented in both hardware and software

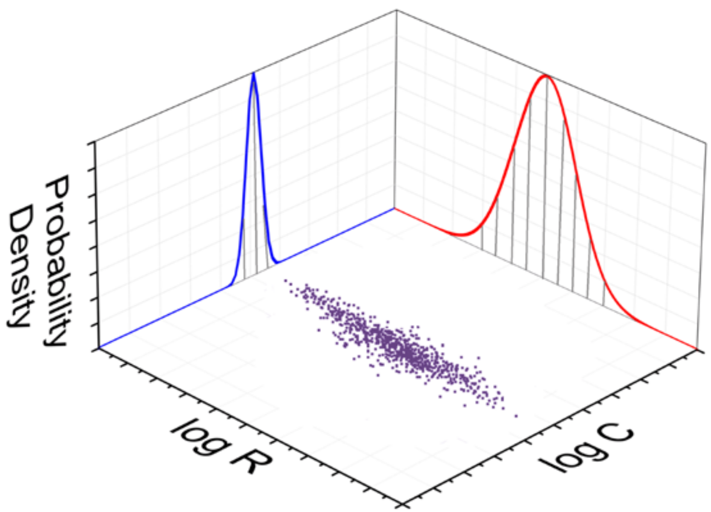
Can account for voltage decay after charging and voltage ‘rebound’ after discharging at short circuit

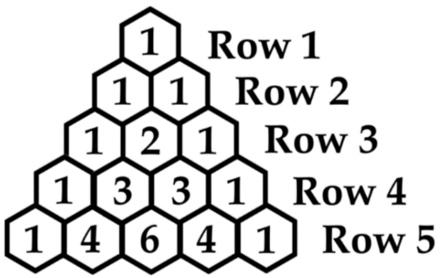


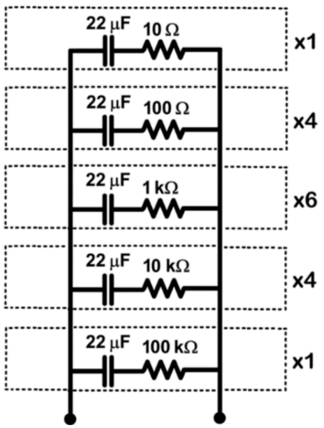



# Equivalent Circuit for Supercapacitors

Equivalent circuit consisting of parallel network of RC components



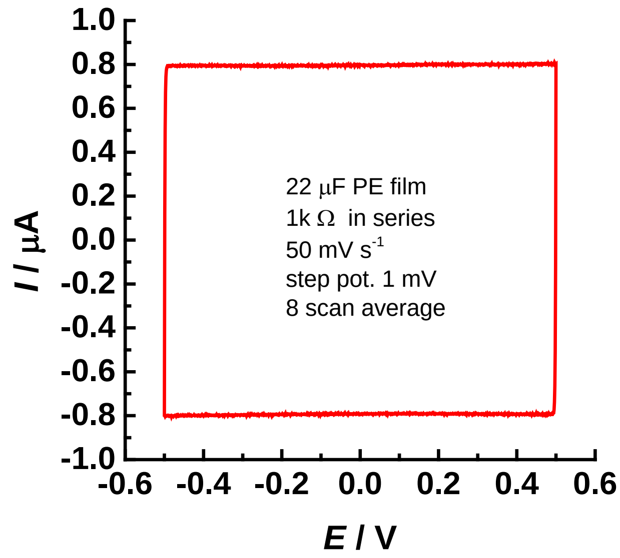



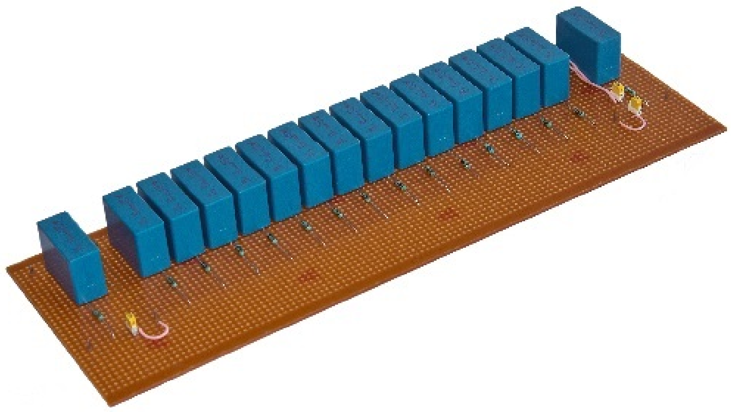




S. Fletcher, I. Kirkpatrick, R. Dring, R. Puttock, R. Thring and S. Howroyd, *The modelling of carbon-based supercapacitors: Distributions of time constants and Pascal Equivalent Circuits*, J. Power Sources, 2017, 345, 247

# Hardware Equivalent Circuit

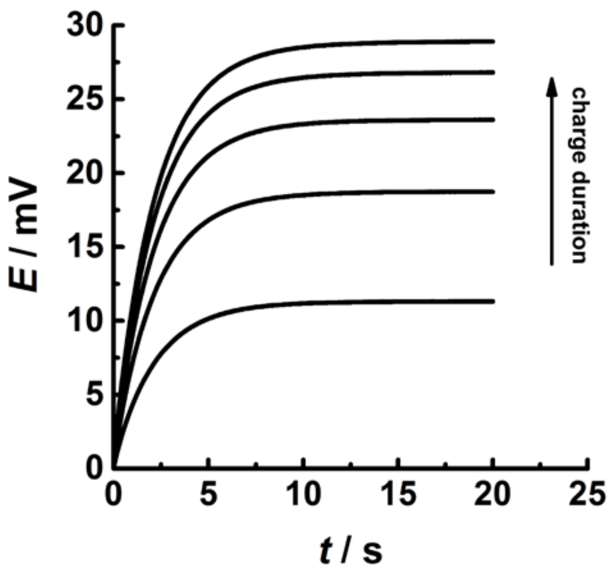
Equivalent circuit built using solid state polymer film capacitors exhibiting near ideal behaviour

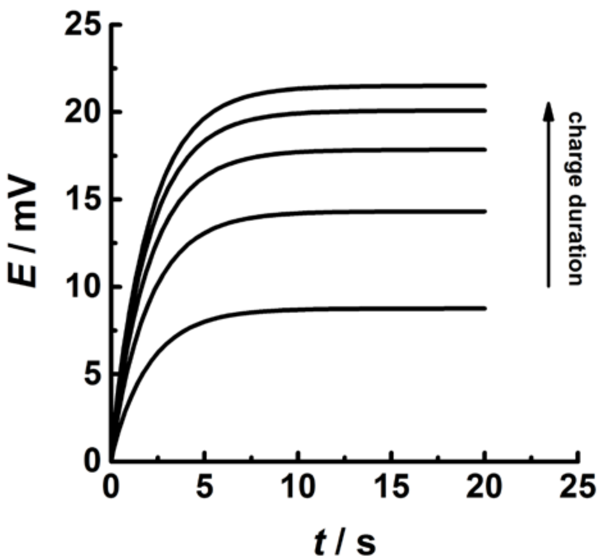


# Software Validation of Model

Hardware equivalent circuit validated in software (Matlab / SimuLink)




hardware

software

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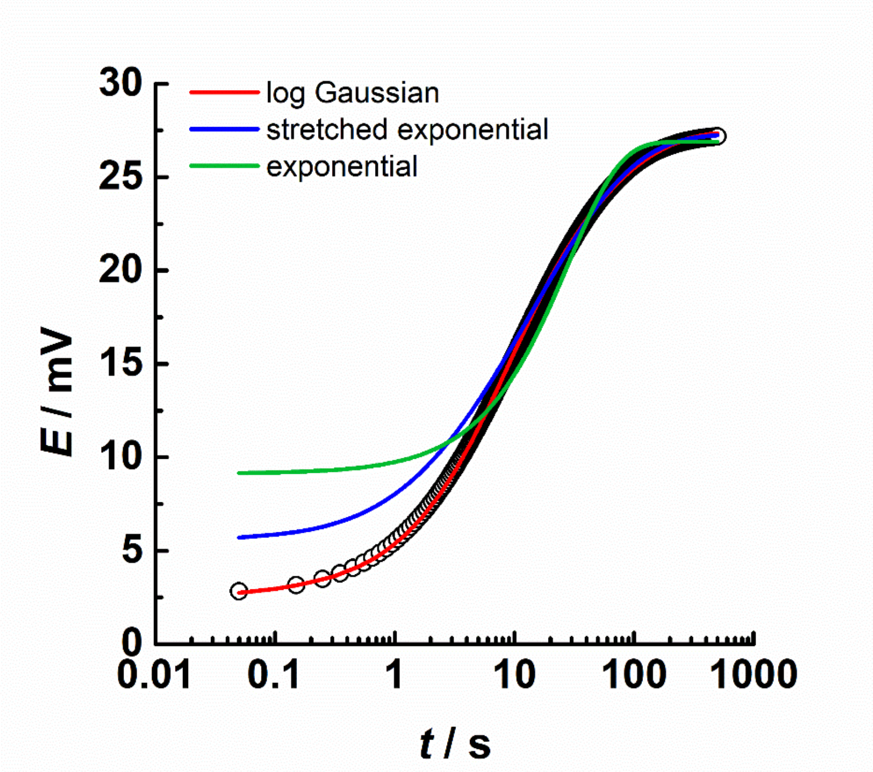
# Distributed Time Constants in Commercial Device

Voltage rebound from commercial NEC 10 mF device exhibits non-exponential behaviour corresponding to log Gaussian model

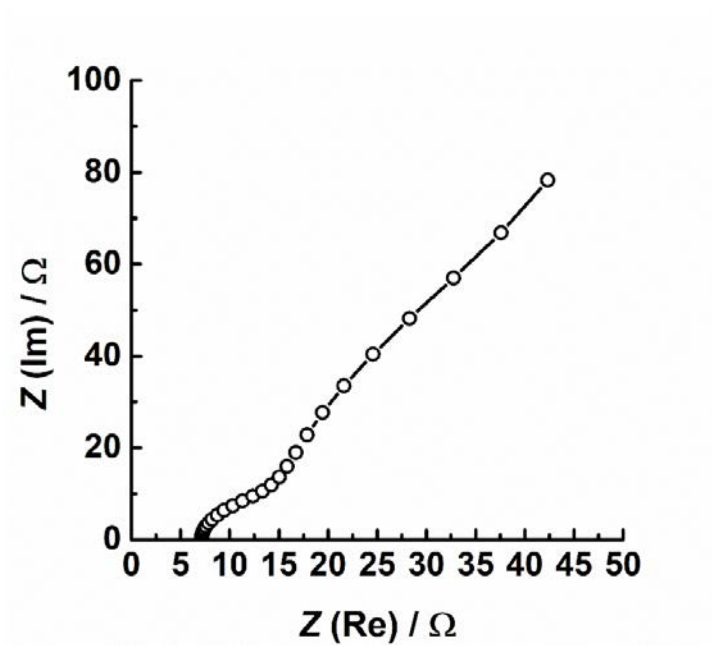


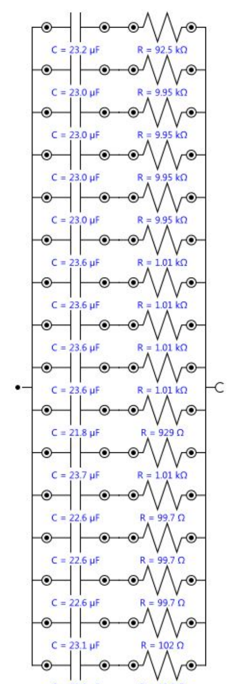

OCP after:

charge 1 V for 2 s
short circuit for 2 s

# A.C. Impedance of Equivalent Circuit

A.C. impedance of equivalent circuit and fitting performed with floating parameters (no bias)

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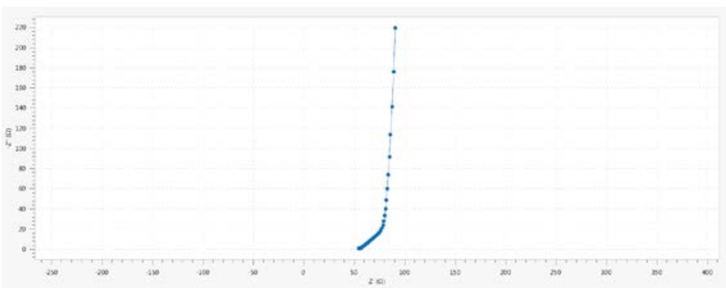
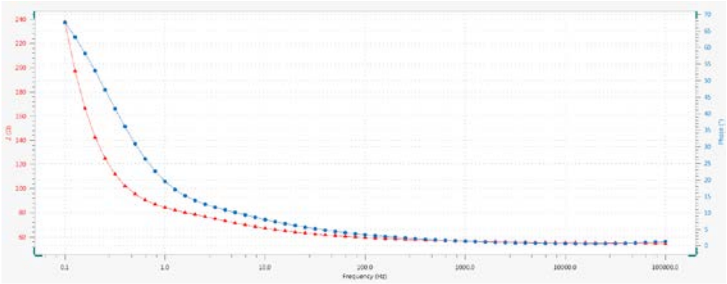
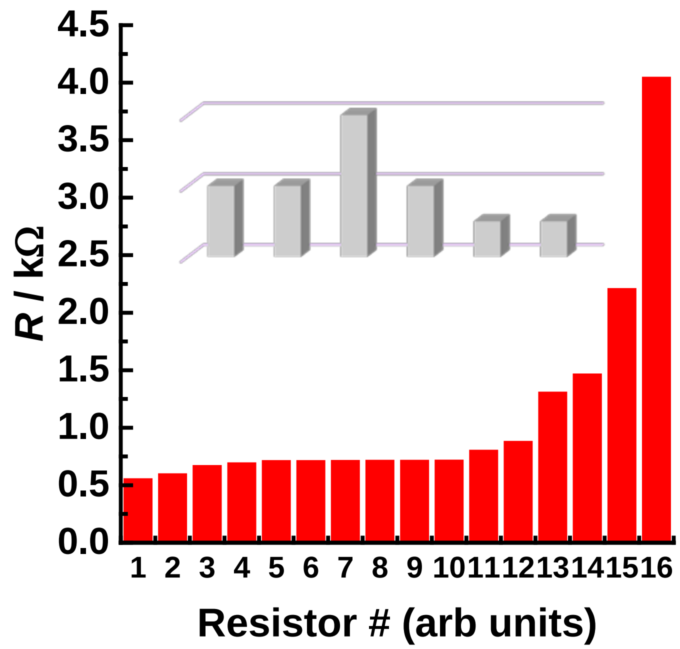
# A.C. Impedance of Commercial Device

A.C. impedance of NEC 10 mF device shows strong evidence for distribution of pore resistance



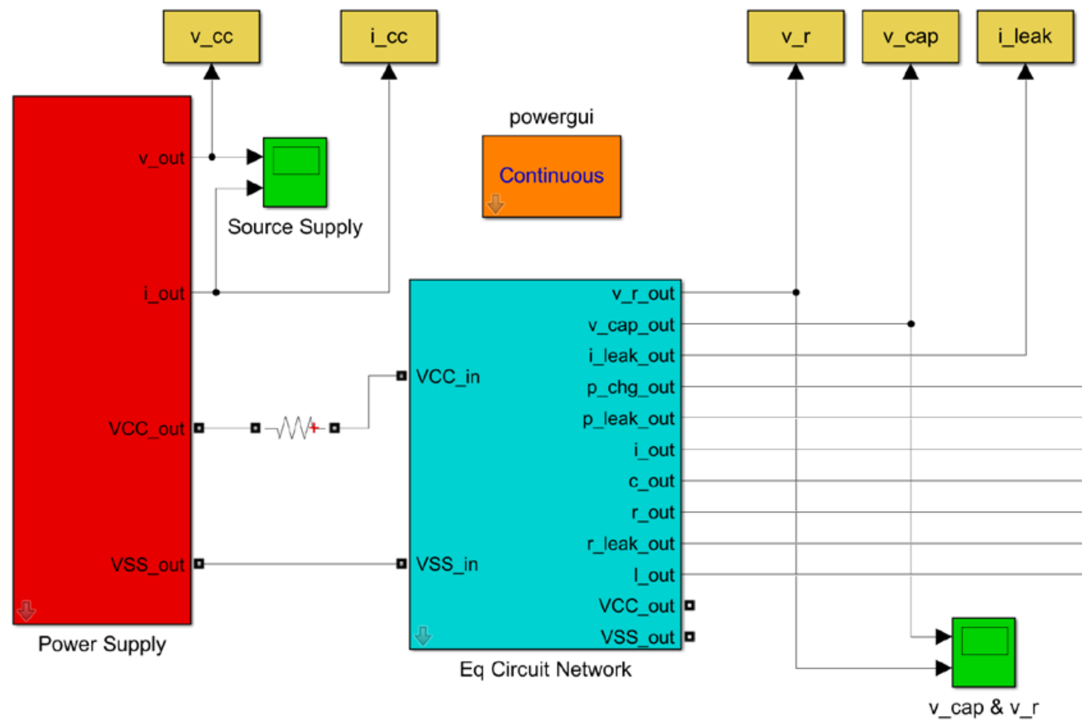




# Matlab & SIMULINK

```
%% System Dynamics
figure('Name','System Dynamics','InvertHardcopy','off','Color',[1 1 1]);
set(gcf,'DefaultAxesColorOrder',map);
clearvars -except fig_count map dataset my_type;
load(dataset);

[hAx,hLine1,hLine2] = plotyy(tout, v_cc,...
    tout, i_cc);
title(strcat('System Voltage & Current', ' (',
xlabel('Time /s');
%ylabel('Power loss /W');
ylabel(hAx(1),'Voltage /V') % left y-axis
ylabel(hAx(2),'Current /A') % right y-axis
set(hLine1, 'Color', 'Red');
```

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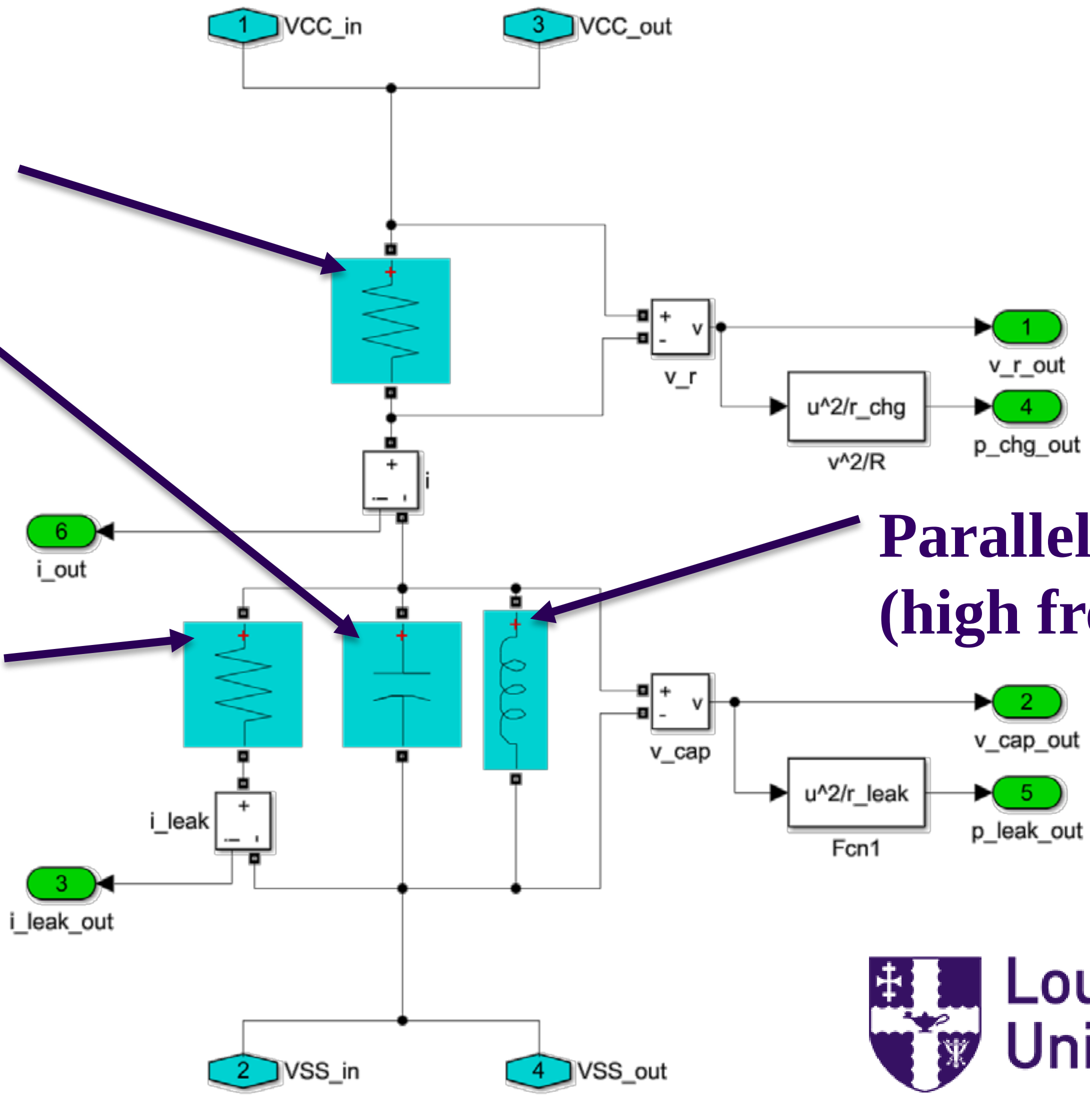
# Non-Ideal Capacitor Equivalent Circuit

**Series resistor (current limiter)**

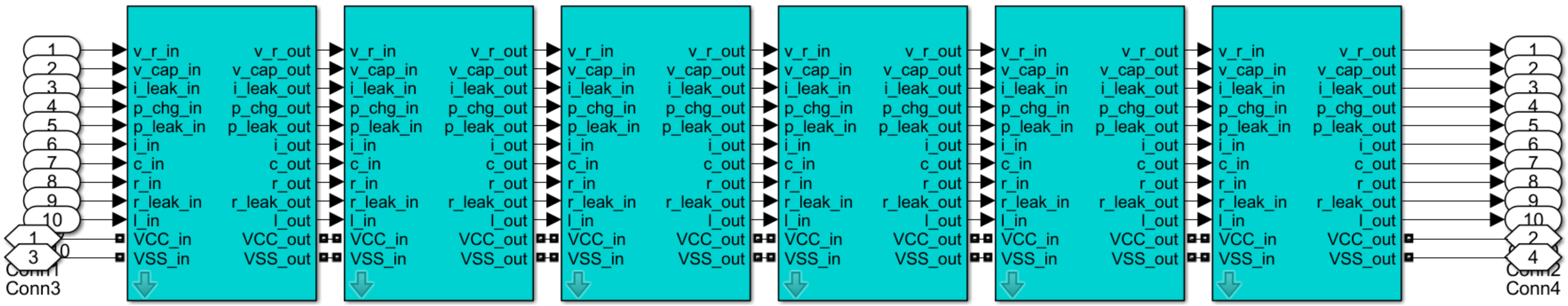
**Ideal capacitor**

**Parallel resistor (self discharge)**

**Parallel inductor (high freq only)**



# Making the Pascal Model – One Rung

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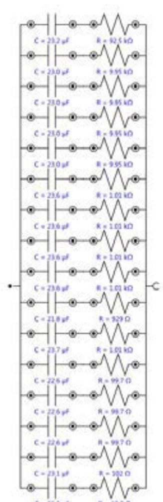

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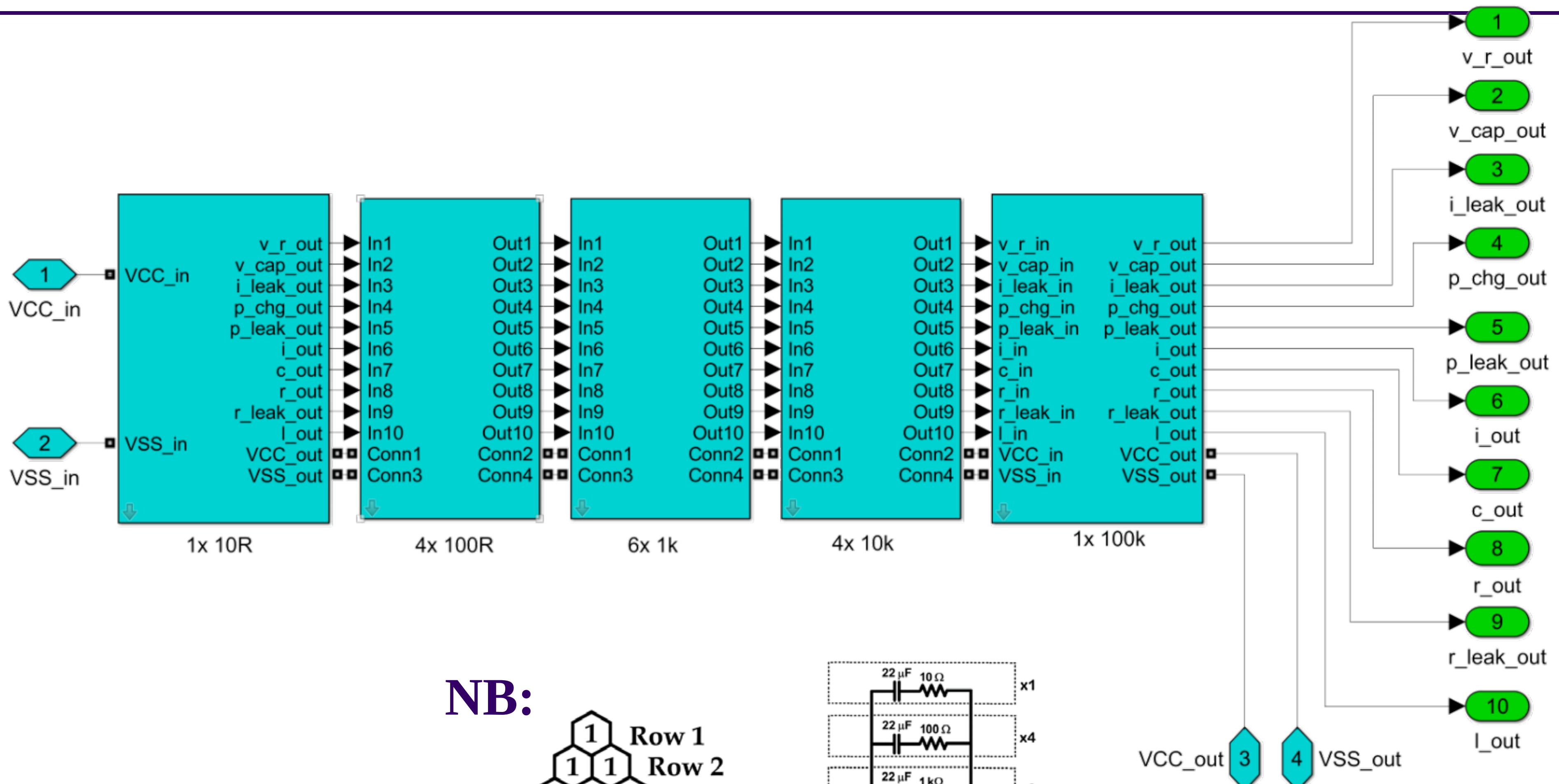
# Making the Pascal Model – Full

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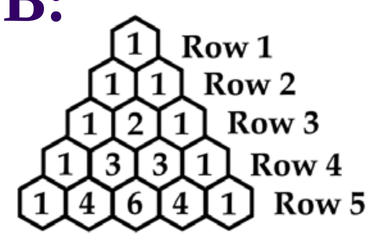
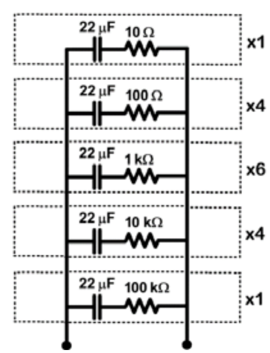
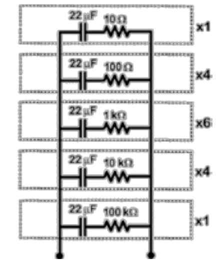


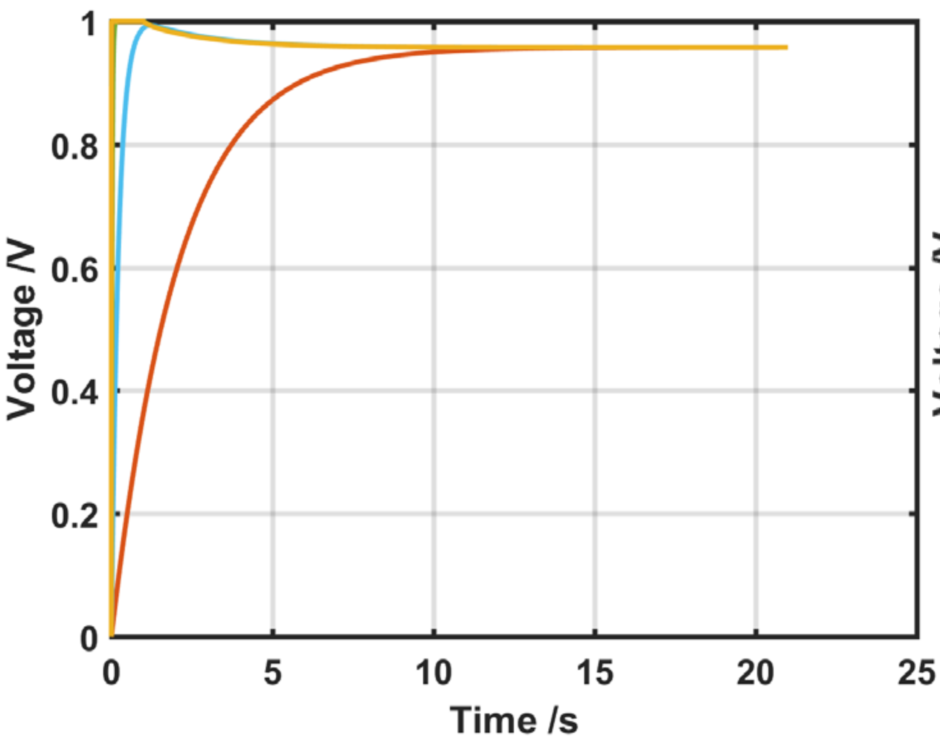



**NB:**

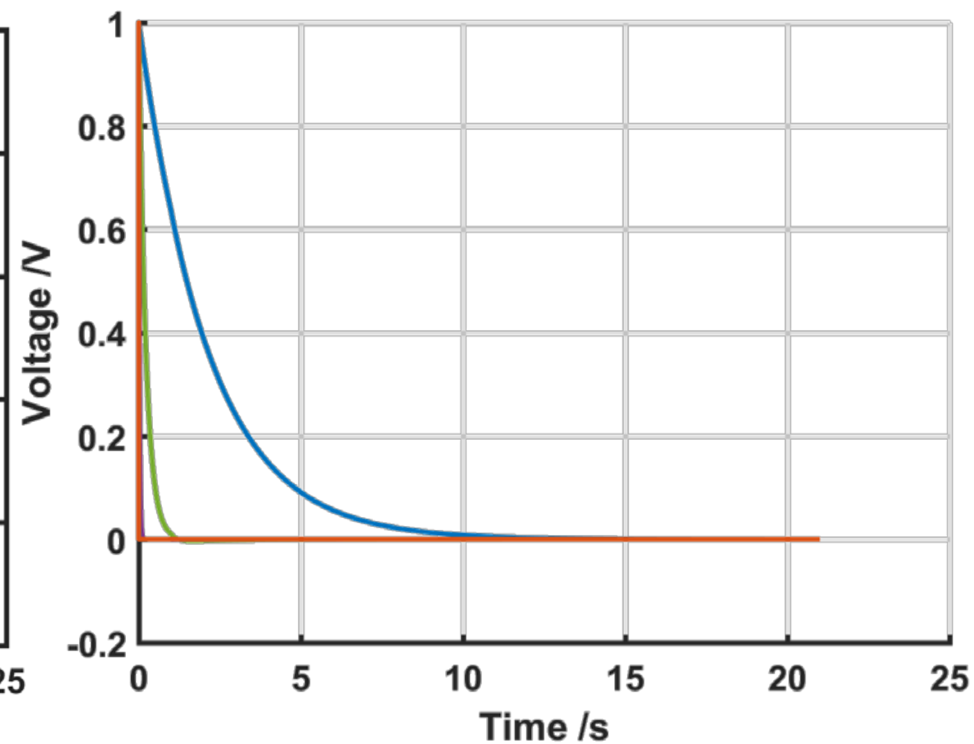



# Charge then OCV

## *Voltage across `ideal caps'*




## *Voltage across resistors*

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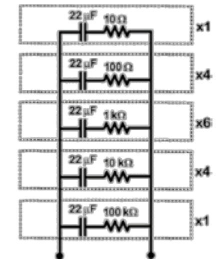
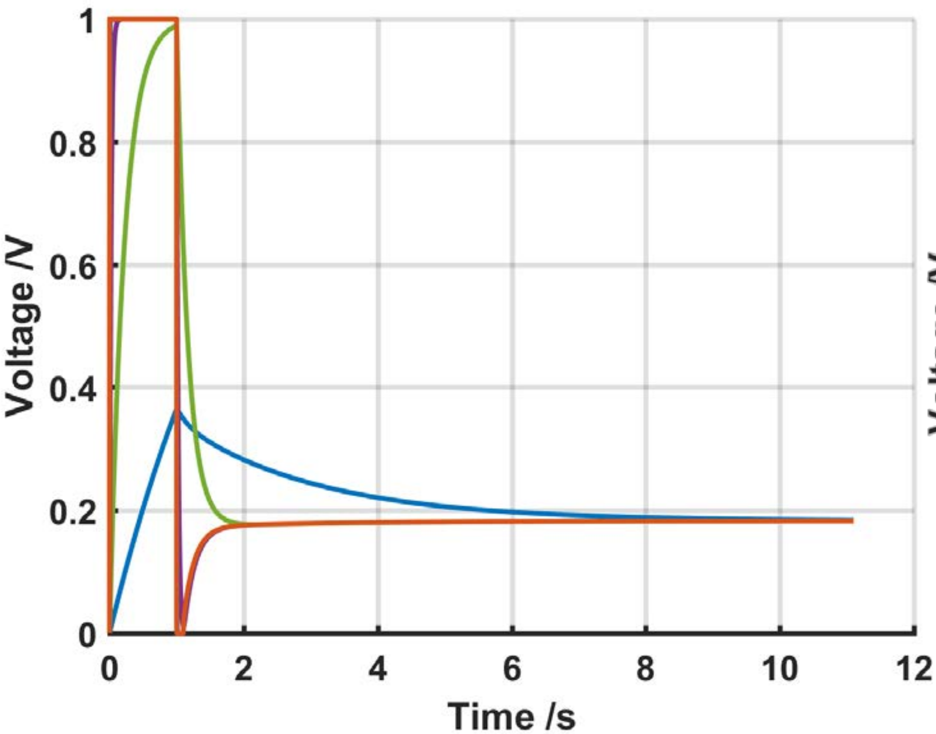
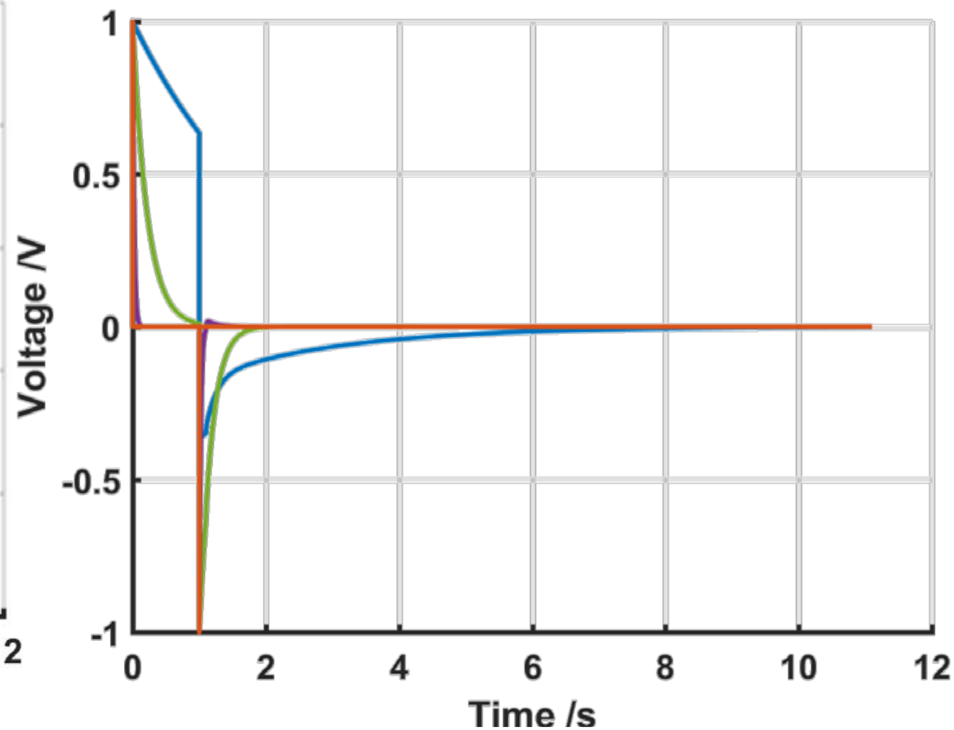
NB: 


# Charge, SC then OCV

*Voltage across `ideal caps'*




*Voltage across resistors*

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# Conclusions

- Carbon based supercapacitors can be represented by a parallel ladder RC network
- Pseudo-ideal components can be used to model this in hardware
- `Ideal' components can be used in software and a greater understanding obtained
- A greater understanding enhances higher level vehicle models

# Further Studies / Future Work

- Integrate the new model into the Electric Vehicle model
- Understand the impact of these phenomena on vehicle performance compared to a `traditional' capacitor model
- Task for the Chemists:
  - Develop a non-Gaussian distribution with a specifiable `fast' or `slow' performance

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