Bounds of Supercapacitor Open-Circuit Voltage Change after Constant Power Experiments

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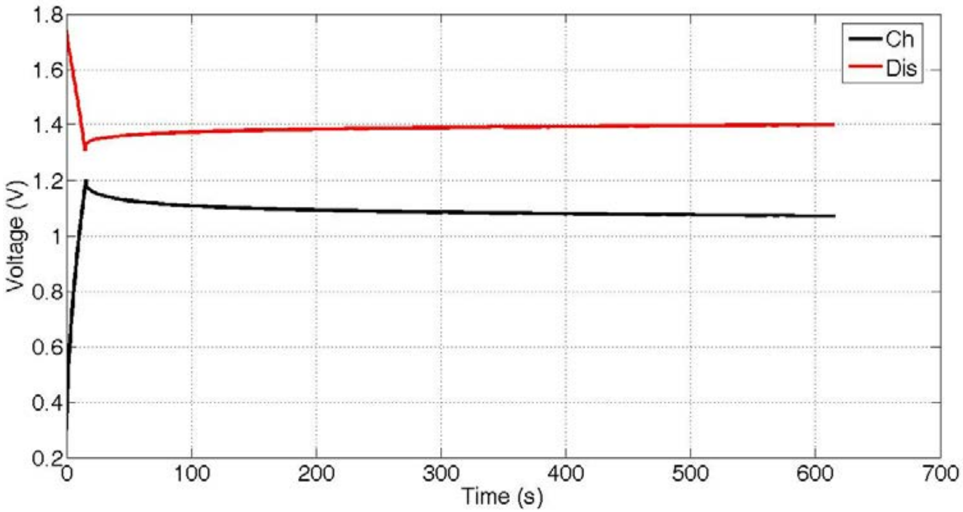
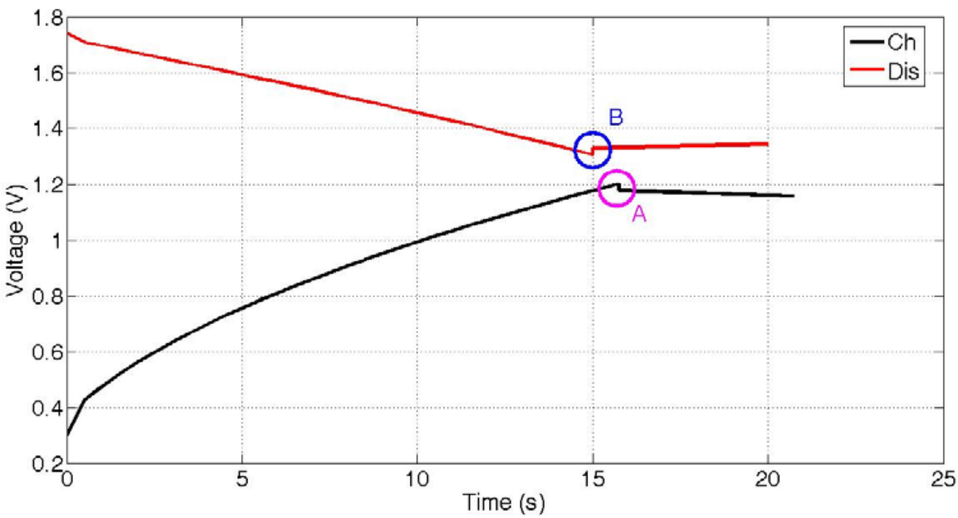
Introduction

- Supercapacitor as an energy storage technology
  - Pros
    - High power density
    - Long cycle life
  - Cons
    - Low energy density
    - High self-discharge rate
- Applications of supercapacitor-based systems
  - Smart grid, electric and hybrid vehicles
  - Embedded systems (wireless sensor nodes, biomedical devices, etc.)
  - Cyber-physical systems (autonomous robots, etc.)

Supercapacitor Charge Redistribution

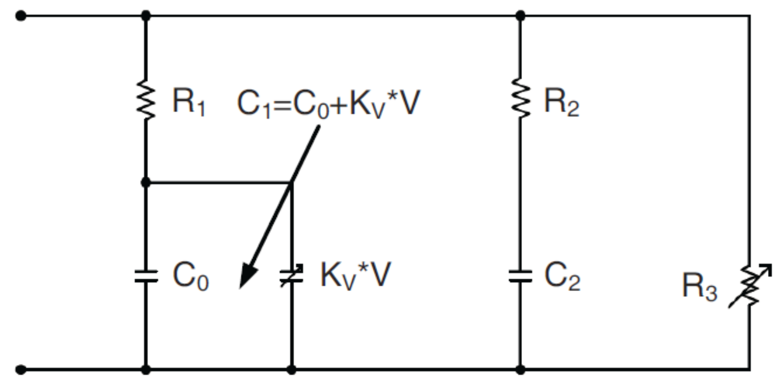
- Two experiments
  - Sample: 10 F, 2.7 V
  - Power: 0.4 W
  - Redistribution: 600 s
- "Ch": voltage drop
  - Total: 0.1294 V
  - ESR: 0.0237 V
  - Redistribution: 0.1057 V
- "Dis": voltage recovery
  - Total: 0.0944 V
  - ESR: 0.0241 V
  - Redistribution: 0.0703 V



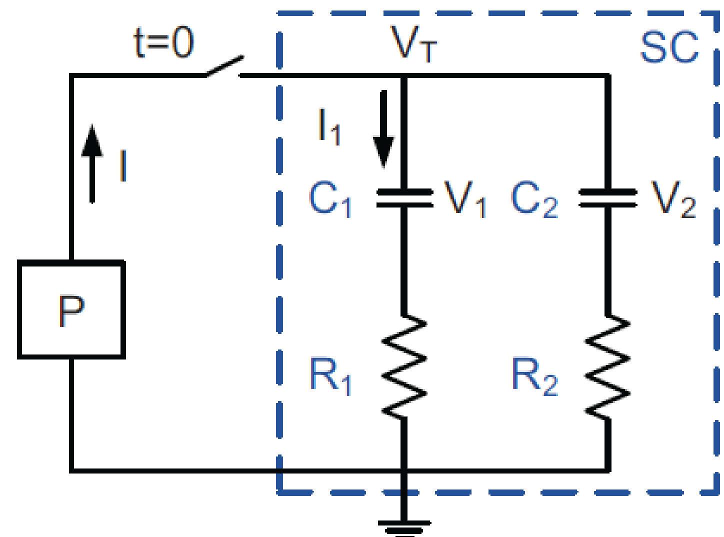


Supercapacitor Models

- Variable leakage resistance (VLR) model [1]
  - Immediate branch: R_1 and C_1
  - Delayed branch: R_2 and C_2
  - VLR: R_3



- Simplified model
  - R_3 is removed: self-discharge is long-term effect
  - C_1 is constant
  - $C_2=\alpha C_1$ (0.11δαδ0.25) [2]
  - R_1 takes ESR value



Bounds of Voltage Change

- Supercapacitor terminal voltage at t=0-

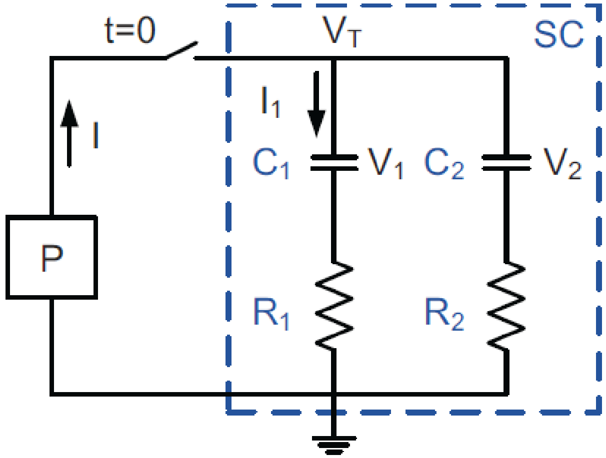
$$V_T(0-) = V_1(0-) + I_1(0-)R_1 \quad (1)$$

- Constant power

$$P = V_T(0-)I \quad (2)$$

- Rewrite (1) with $I_1(0-)=I$ and $R_1=R$ (ESR value)

$$V_T(0-) = V_1(0-) + IR \quad (3)$$



Bounds of Voltage Change (Continued)

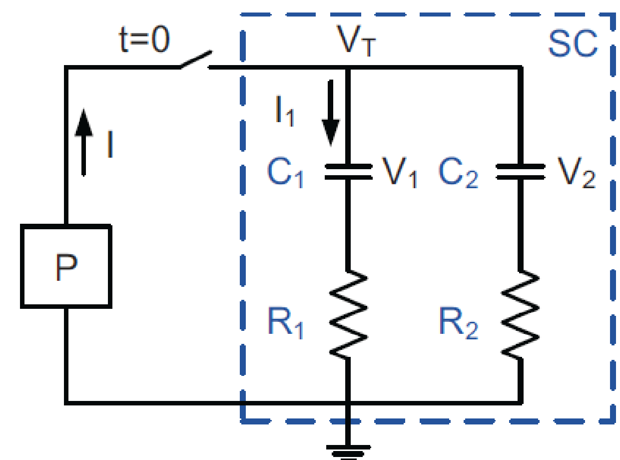
- Supercapacitor terminal voltage at t=□

$$V_1(0-)C_1 + V_2(0-)C_2 = V_T(\infty)(C_1 + C_2) \tag{4}$$

$$V_T(\infty) = \frac{V_1(0-) + \alpha V_2(0-)}{1+\alpha} \tag{5}$$

- Voltage change

$$\Delta V_T = V_T(\infty) - V_T(0-) = \frac{\alpha(V_2(0-) - V_1(0-))}{1+\alpha} - IR \tag{6}$$



Bounds of Voltage Change (Continued)

- Relate V_1(0-) to V_T(0-) (denoted as V_M)

$$V_1(0-) = V_M - IR \tag{7}$$

- Range of V_2(0-) (V_R: rated voltage)

$$0 \leq V_2(0-) \leq V_R \tag{8}$$

- Bounds of voltage change

$$\frac{-\alpha V_M - PR/V_M}{1+\alpha} \leq \Delta V_T \leq \frac{\alpha(V_R - V_M) - PR/V_M}{1+\alpha} \tag{9}$$

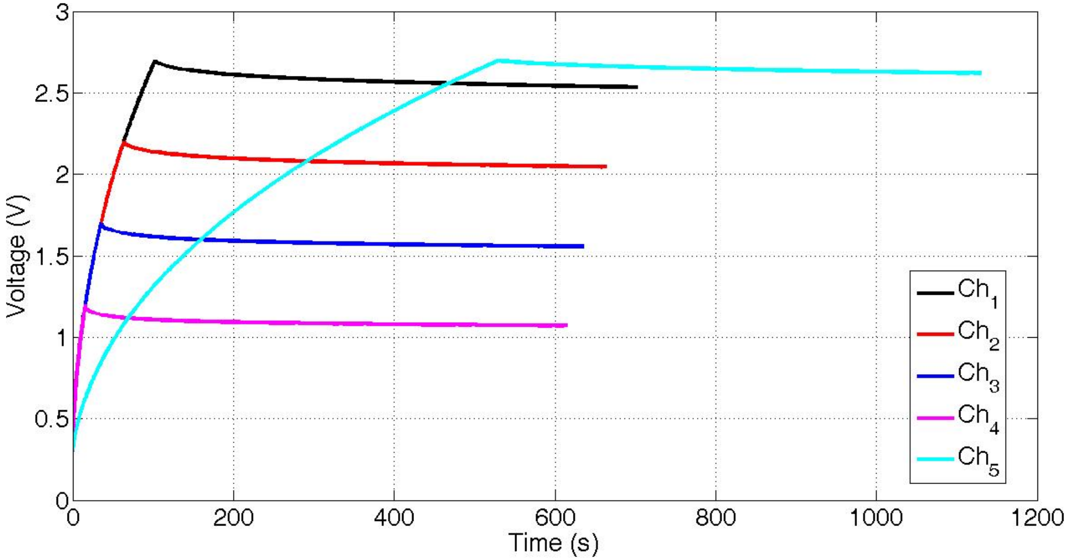
- Information needed to estimate bounds
  - V_R and R: supercapacitor datasheet
  - V_M and P: terminal voltage and constant power at t=0-
  - Parameter α: $C_2=\alpha C_1$ ($0.11 \delta \alpha \delta 0.25$)

Constant Power Experiments

- Supercapacitor samples [3]

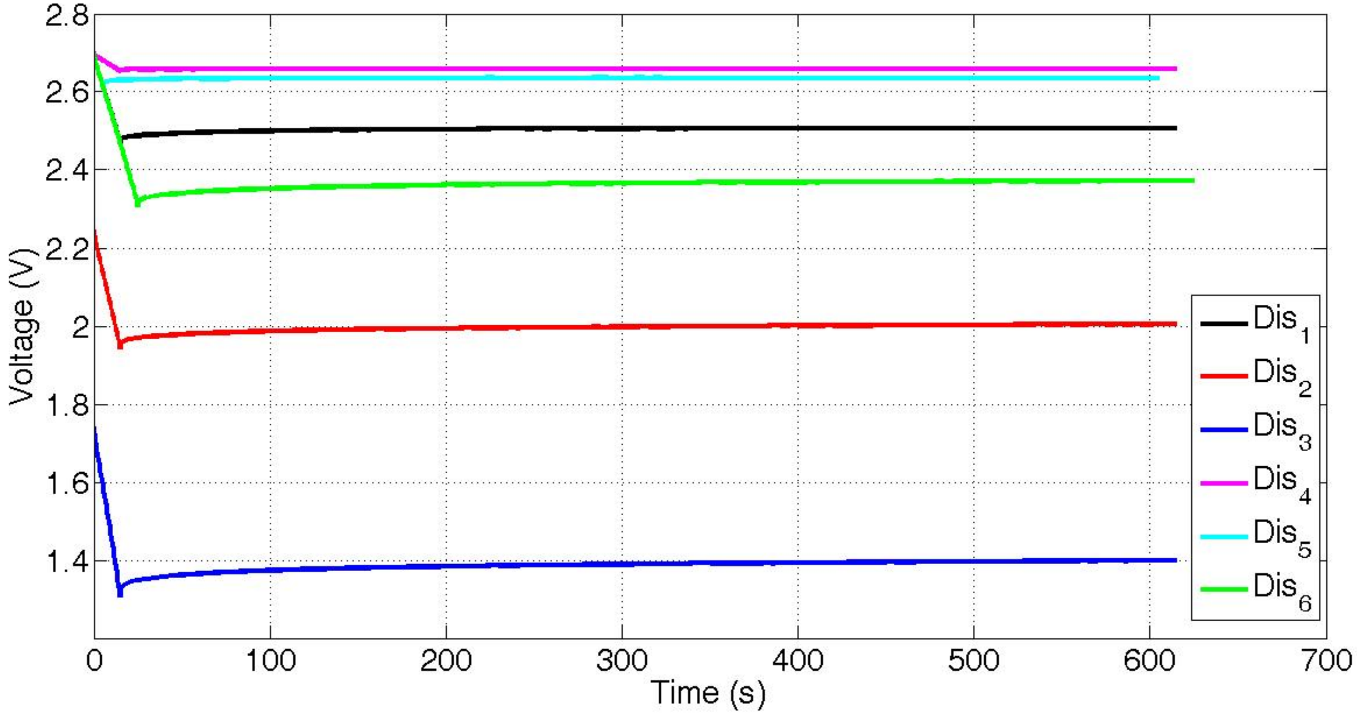
Sample	1	2	3	4
Manufacturer	Cooper Bussmann	Maxwell	Maxwell	Maxwell
Model	PB-5R0V104-R	BCAP0001	BCAP0010	BCAP0100
Capacitance (F)	0.1	1	10	100
Voltage (V)	5	2.7	2.7	2.7

- Charge experiments (10 F sample)
  - Termination voltage: Ch_1-Ch_4 (2.7, 2.2, 1.7, and 1.2 V)
  - Power: Ch_1 and Ch_5
    - Ch_1: 0.4 W
    - Ch_5: 0.08 W

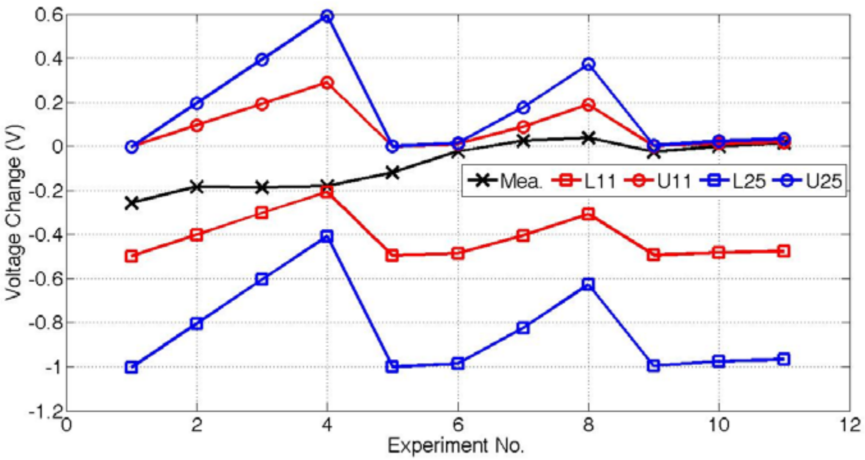


Constant Power Experiments (Continued)

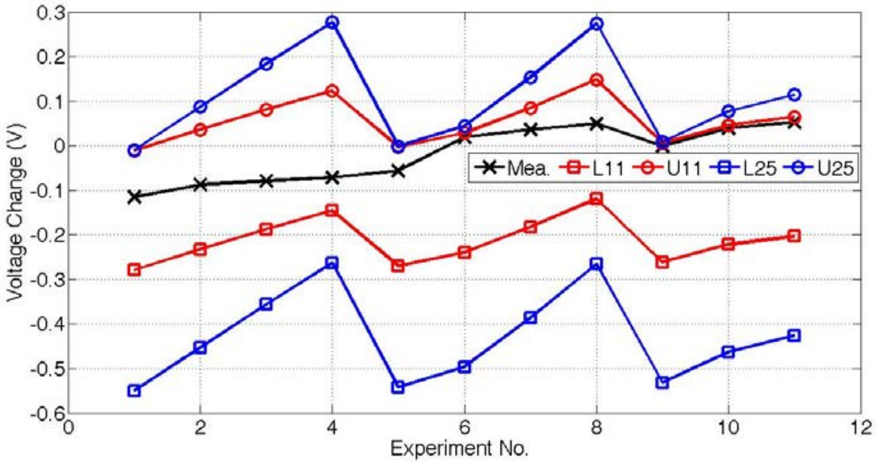
- Discharge experiments (10 F sample)
  - Beginning voltage: Dis_1-Dis_3 (2.7, 2.2, and 1.7 V)
  - Power: Dis_1 and Dis_4 (0.4 and 0.08 W)
  - Time: Dis_1, Dis_5, and Dis_6 (15, 5, and 25 s)



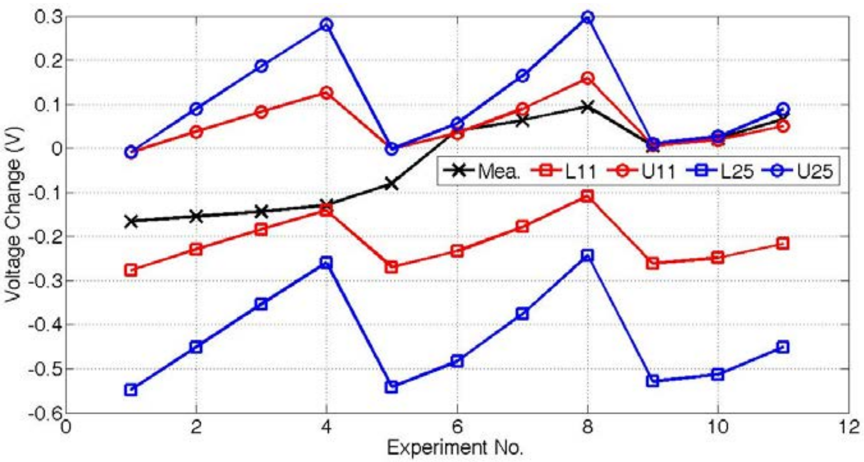
Results



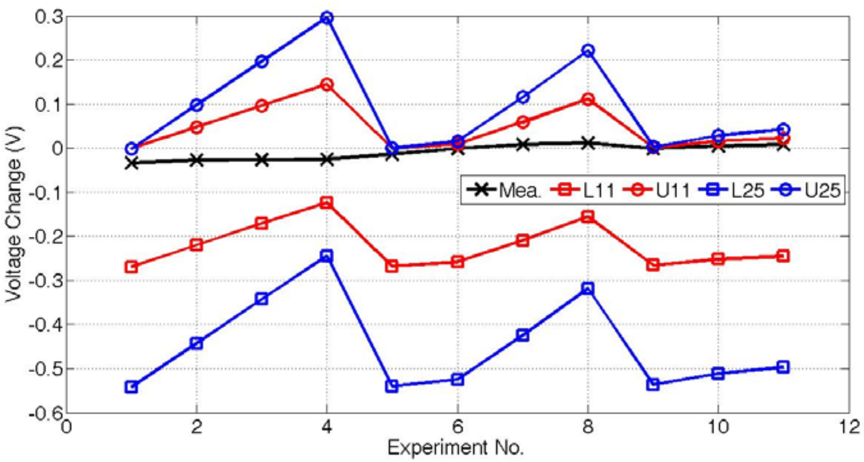
0.1 F



1 F



10 F



100 F

Results (Continued)

- For 0.1, 1, and 100 F samples
  - Measured voltage changes of all experiments (i.e. "Mea.") are within bounds when α=0.11 (i.e., "L11" and "U11").
- For 10 F sample
  - Measured voltage changes of three experiments (no. 6, 10, and 11) are not within bounds when α=0.11. They are confined by bounds when α=0.25 (i.e., "L25" and "U25").
  - Measured voltage changes of the other eight experiments are within bounds when α=0.11.

Conclusion

- Derived formulas can be used to estimate the bounds of the supercapacitor open-circuit voltage change after constant power experiments, which is due to ESR and charge redistribution.
- Part of the information needed to estimate the bounds can be extracted from supercapacitor datasheet and constant power experiment setup.
- Further work needs to be conducted to determine the parameter characterizing the ratio of the delayed branch capacitance to the immediate branch capacitance.

References

- [1] H. Yang and Y. Zhang, "Analysis of supercapacitor energy loss for power management in environmentally powered wireless sensor nodes," *IEEE Transactions on Power Electronics*, vol. 28, no. 11, pp. 5391–5403, 2013.
- [2] J. W. Graydon, M. Panjehshahi, and D. W. Kirk, "Charge redistribution and ionic mobility in the micropores of supercapacitors," *Journal of Power Sources*, vol. 245, pp. 822–829, 2014.
- [3] H. Yang, "Analysis of supercapacitor charge redistribution through constant power experiments," in *Proceedings of The 2017 IEEE Power & Energy Society General Meeting (PESGM 2017)*, 2017, in press.

Thank You!