Online Monitoring of Supercapacitor Ageing

Authors:

Zhihao SHI, François AUGER, Emmanuel SCHAEFFER, Philippe GUILLEMET, Luc LORON

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  - Advantages of EDLCs
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  - EDLCs Ageing
- Online Identification
  - Principle
  - Mathematical model of EDLCs system
  - Observability of EDLCs system
  - Identification methods
- Experimental Results
- Conclusion and future work

Applications

Electronics

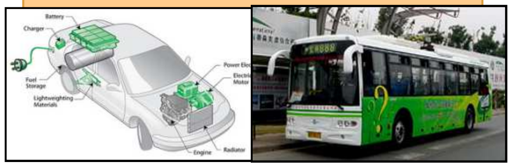
- PC
- Mobile Phone
- Digital Camera

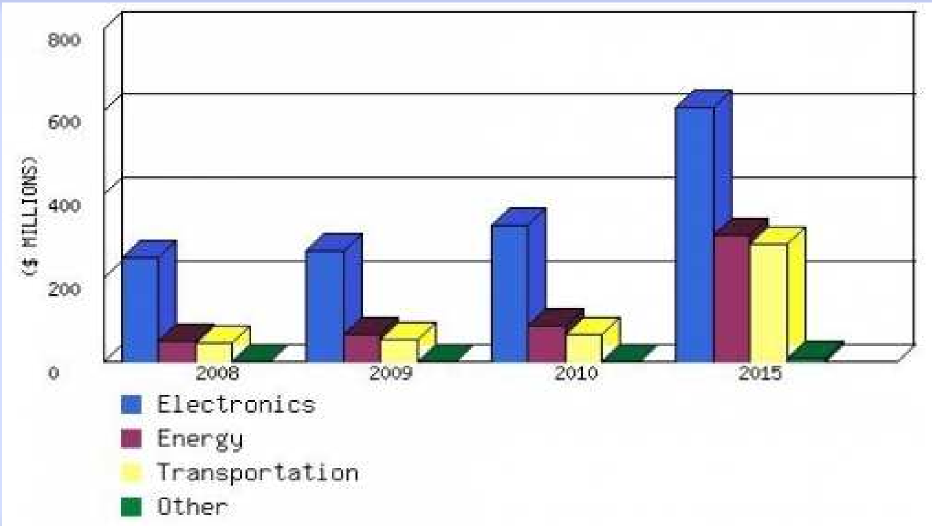
Energy

- Solar Cell
- Wind Power
- Fuel Cell

Transportation

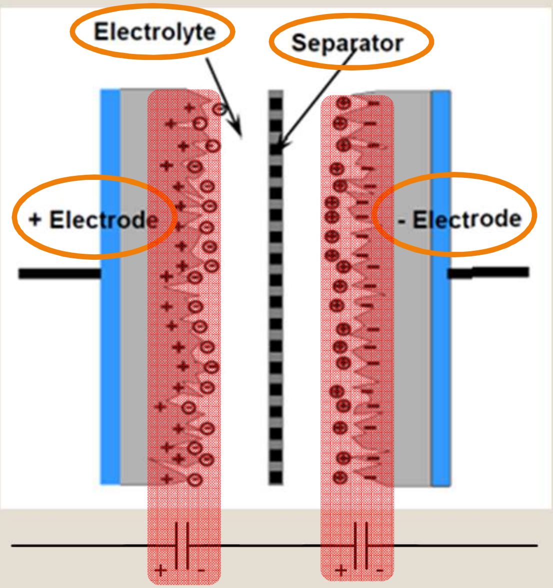
- Electric Vehicle (EV)
- Supercapacitor Bus





Global market for supercapacitors for 2008-2015

EDLCs (Electric double layer capacitors)

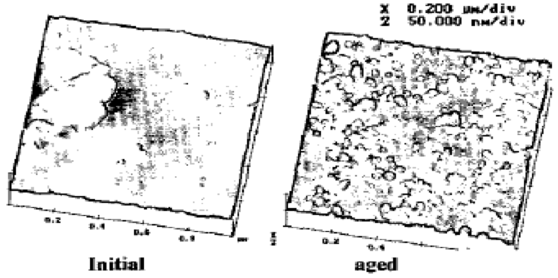


	Conventional Capacitor	Ultra-capacitor	Lead acid battery
Charge time	10^{-3} - 10^{-6} s	0 - 30 s	1 – 5 h
Discharge time	10^{-3} - 10^{-6} s	0.3 – 30 s	0.3 – 3 h
Energy density (Wh/kg)	0.1	1 - 10	10 - 100
Power density (W/kg)	100000	10000	1000
Cycle life	>500000	>500000	1000
Charge/discharge efficiency	>0.95	0.85-0.98	0.7-0.85

- High C
  -> Higher energy density
  than a conventional capacitor
- High Power Density
  -> Faster charging/discharging
  than a battery
- Long life cycle

EDLCs Ageing

Initial and aged
Activated-carbon
surfaces



AFM photographs of the positive polarizing electrode by *T. Umemura* etc.

CAUSE: Parasitic electrochemical reactions

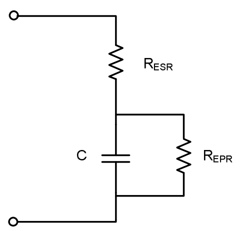
Eg. *Decomposition of the electrolyte*

CONSEQUENCE: Reduce the life expectancy of EDLCs

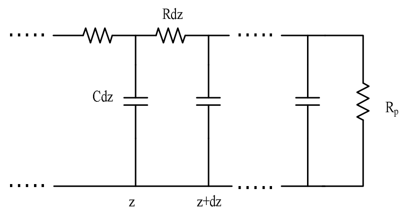
RESEARCH AIM:

Monitor the ageing process of the EDLCs
→ Detect when the end of life criteria occurs
→ Replace the old EDLC to avoid catastrophic events

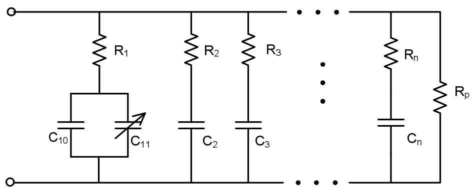
EDLCs models



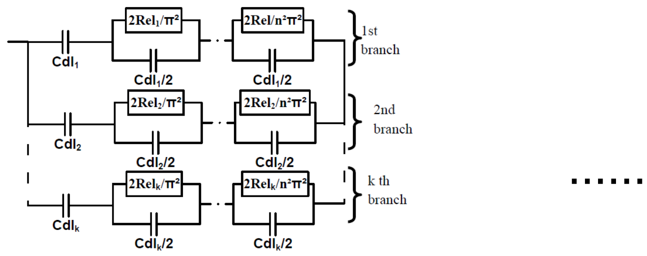
➢ Classic RC model[1]



➢ Transmission line model[2]



➢ N-branch model[3]



➢ Multi-pore model[4]

[1] D. R. Cahela and B. J. Tatarchuk, "Overview of electrochemical double layer capacitors", Proceedings of the IECON'97 23rd International Conference on Industrial Electronics, Control and Instrumentation, Vol. 3, pp. 1068-1073, November 1997

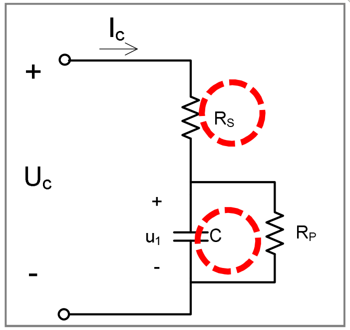
[2] R. de Levie, "On porous electrodes in electrolyte solutions: I. Capacitance effects," Electrochimica Acta, vol. 8, no. 10, pp. 751–780, Oct. 1963.

[3] R. M. Nelms, D. R. Cahela, and B. J. Tatarchuk, "Modeling double-layer capacitor behavior using ladder circuits," IEEE Transactions on Aerospace and Electronic Systems, vol. 39, no. 2, pp. 430–438, Apr. 2003.

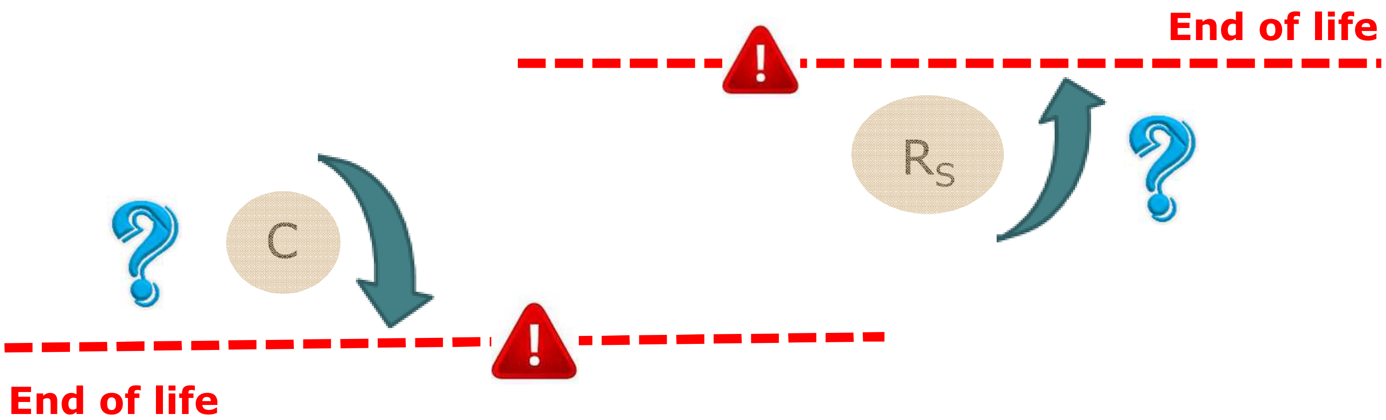
[4] R. German, P. Venet, A. Sari, O. Briat, J. M. Vinassa, "Comparison of EDLC impedance models used for ageing monitoring," in 2012 1st International Conference on REVET, pp. 224–229, 2012.

Quantification of EDLCs Ageing

Ageing → Visible by → Variation of Parameters

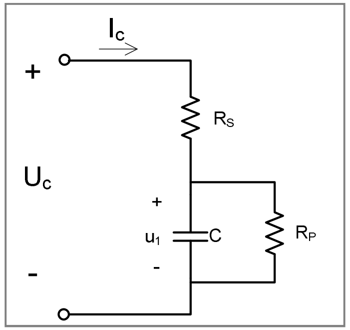


An example:



Estimate → State of Health (SOH) | State of Charge (SOC) $E = \frac{1}{2} C V^2$

Identification



EDLCs Ageing Diagnoisis

EDLCs Parameter Identification

Offline Identification

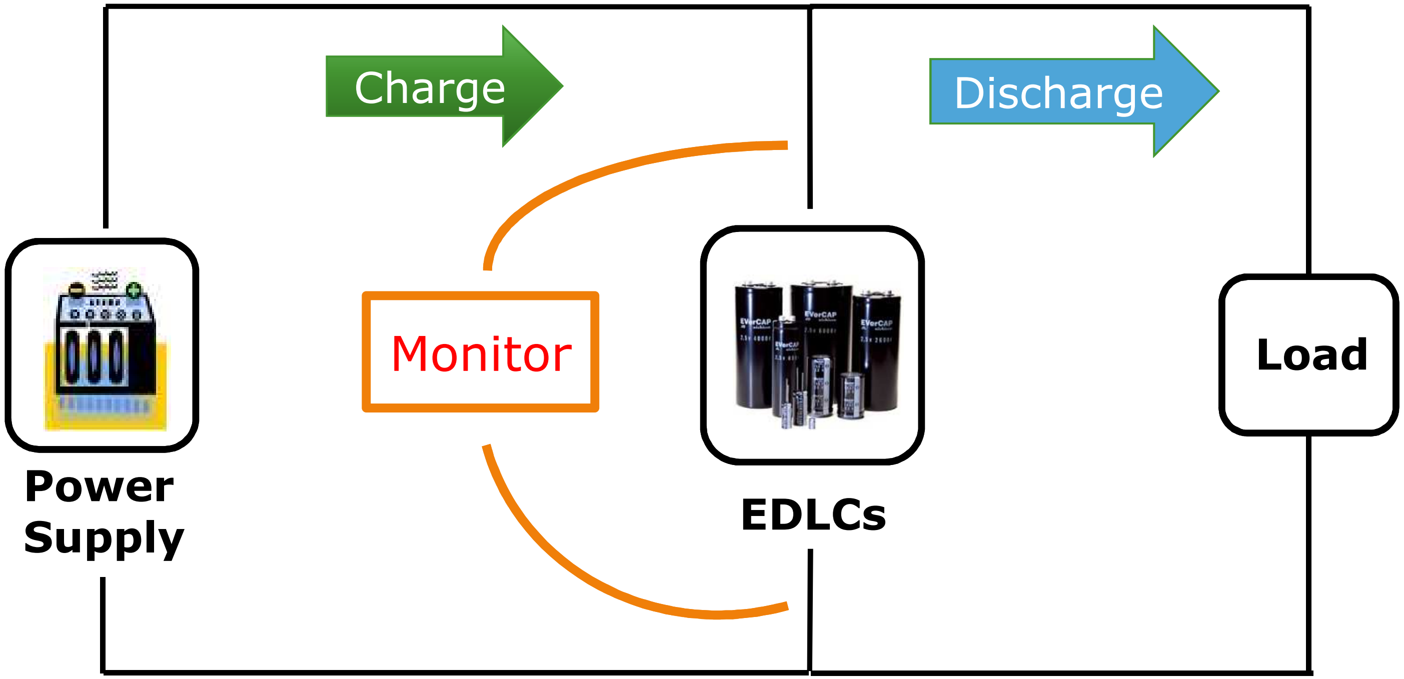
- Laboratory technique
- Require EDLCs to be **removed** from their application

Online Identification

- In situ
- More **practical** in an application

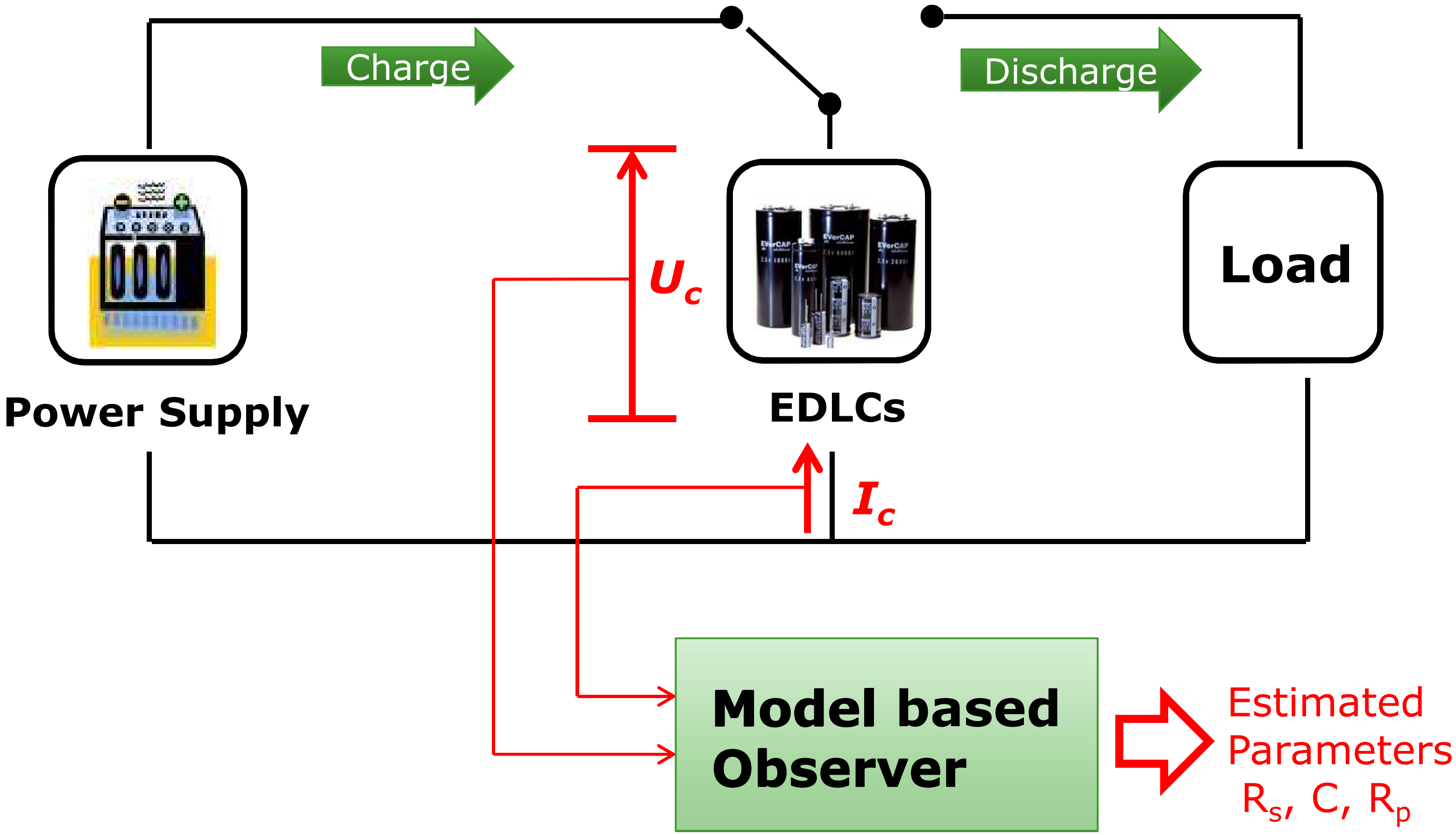
Online Identification

Particular charge to provide an accurate parameter estimation.



Online identification does not disturb the way the load consumes the energy stored in the EDLC.

Online Identification



Extended state space model of EDLCs

Unknown Parameters

$$\begin{cases} \dot{u}_1 = -\dfrac{1}{R_p C} u_1 + \dfrac{1}{C} I_c \\ U_c = u_1 + R_s I_c \end{cases}$$

Linear state space model

Add three state variables:

x_1 : u_1

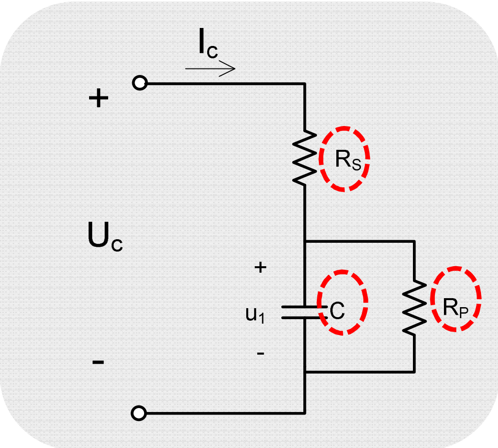
x_2 : R_s

x_3 : $1/C$

x_4 : $-1/(R_p C)$

$$\begin{pmatrix} \dot{x}_2 = 0 \\ \dot{x}_3 = 0 \\ \dot{x}_4 = 0 \end{pmatrix}$$

Extend to



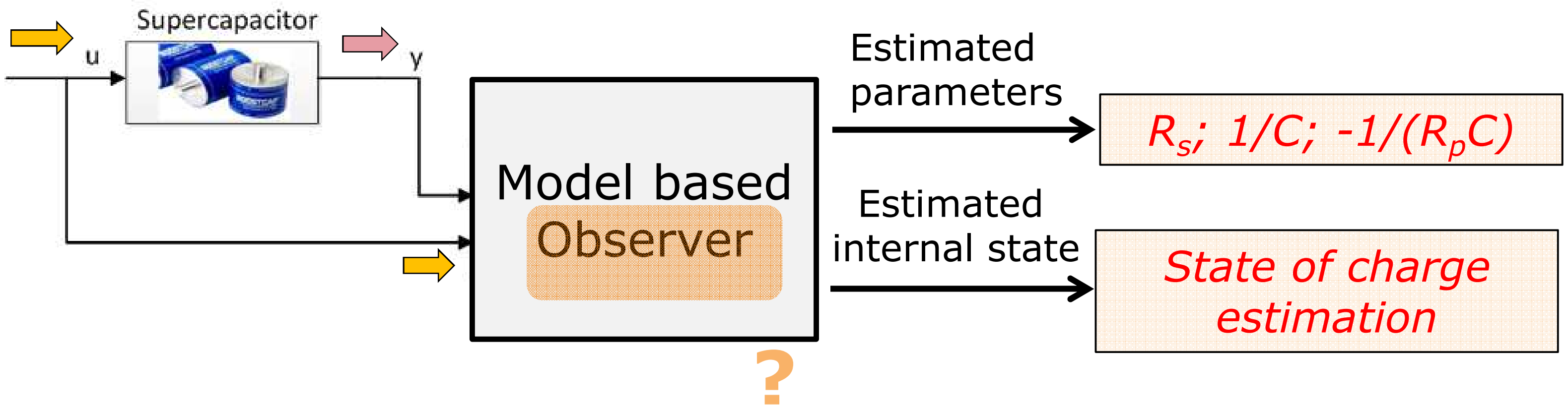
$$\Sigma : \begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_2 = 0 \\ \dot{x}_3 = 0 \\ \dot{x}_4 = 0 \end{cases}$$

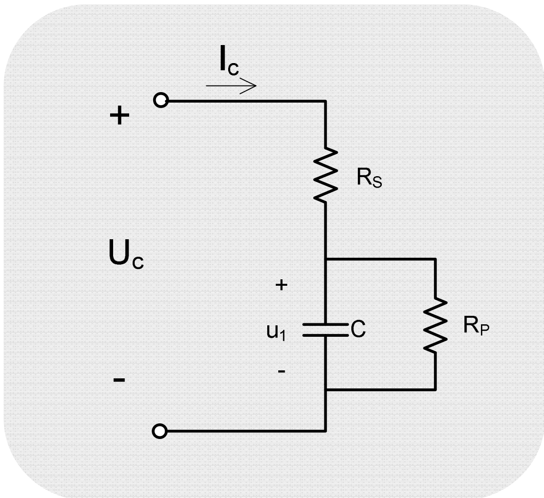
$$y = x_1 + x_2 u$$

$$\begin{pmatrix} u = I_c \\ y = U_c \end{pmatrix}$$

Nonlinear model

Online state and parameter estimation





$$\Sigma : \begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_2 = 0 \\ \dot{x}_3 = 0 \\ \dot{x}_4 = 0 \end{cases}$$

$$y = x_1 + x_2 u$$

$$\begin{pmatrix} x_1 = u_1 \\ x_2 = R_s \\ x_3 = 1/C \\ x_4 = -1/(R_p C) \end{pmatrix}$$

$$\begin{pmatrix} u = I_c \\ y = U_c \end{pmatrix}$$

Extended state space model

Nonlinear Observability

❖ The observability of the nonlinear system

- *If Jacobian matrix J at x_0 has full rank:*

$$J = \frac{\partial}{\partial x}\begin{bmatrix} h(x,u) \\ (L_f h)(x,u) \\ \vdots \\ (L_f^{n-1} h)(x,u) \end{bmatrix}, \quad rank(J)\big|_{x_0} = n$$

⟶ Locally Observable[1]

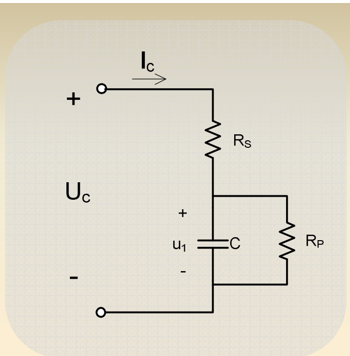
- If EDLC system satisfies

$$-x_2{}^3(x_1(\ddot{u}^2 - \dot{u}\dddot{u}) + x_4(\dot{u} + u^2\dddot{u} - 2u\dot{u}\ddot{u})$$
$$+x_1(x_3+x_4)^2(\dot{u}^2 - u\ddot{u}) + x_1(x_3+x_4)(\dot{u}\ddot{u} - u\dddot{u})$$
$$+x_4(x_3+x_4)(u^2\ddot{u} - u\dot{u}^2)) \neq 0$$

⟶ *locally observable*

Eg. When u = Constant; Sinusoidal signal; Exponential signal; ⟶ *system is locally unobservable.*

When u = $I_1 + I_2\sin(\omega t)$; (with $I_1 \neq I_2$ and $x_1 \neq 0$) ⟶ *system is locally observable.*



$$\Sigma: \begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_2 = 0 \\ \dot{x}_3 = 0 \\ \dot{x}_4 = 0 \end{cases} \quad y = x_1 + x_2 u \quad \longrightarrow \quad \begin{cases} \dot{x} = f(x,u) \\ y = h(x,u) \end{cases}$$

Nonlinear EDLC system

$$\begin{pmatrix} x_1 = u_1 \\ x_2 = R_s \\ x_3 = 1/C \\ x_4 = -1/(R_p C) \end{pmatrix} \quad \begin{pmatrix} u = I_c \\ y = U_c \end{pmatrix}$$

[1] R. Hermann and A. Krener, "Nonlinear controllability and observability," IEEE Transactions on Automatic Control, vol. 22, no. 5, pp. 728 – 740, Oct. 1977.

Nonlinear Observability

❖ The observability of the linearized system

Jacobian matrix of $f(x,u)$: $F = \dfrac{\partial f(x,u)}{\partial x}$

Jacobian matrix of $h(x,u)$: $H = \dfrac{\partial h(x,u)}{\partial x}$

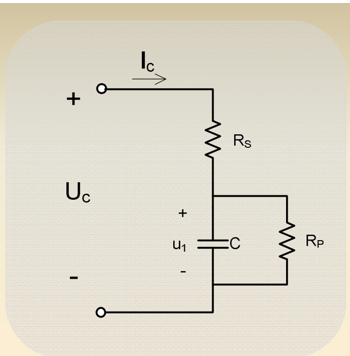
Observability Matrix O

$$O = \begin{bmatrix} H \\ HF \\ HF^2 \\ HF^3 \end{bmatrix}$$

$$det(O) = 0$$

Unobservable !

Linearization



$$\Sigma : \begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_2 = 0 \\ \dot{x}_3 = 0 \\ \dot{x}_4 = 0 \end{cases}$$

$$y = x_1 + x_2 u$$

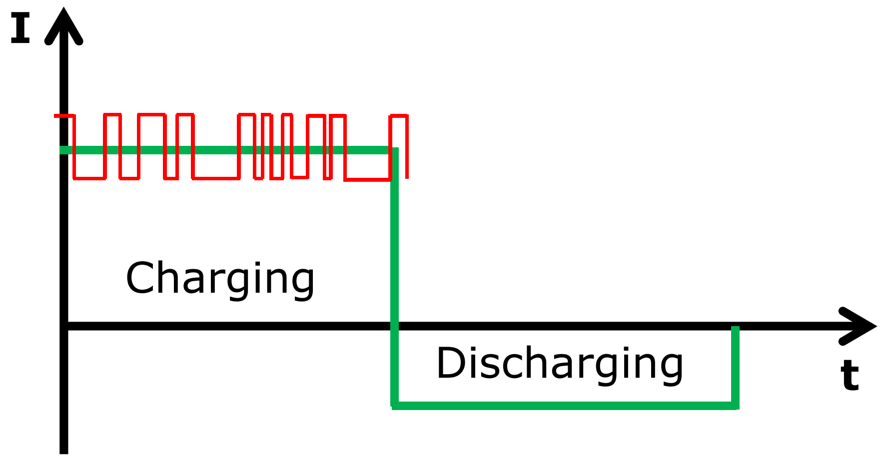
$$\begin{cases} \dot{x} = f(x,u) \\ y = h(x,u) \end{cases}$$

Nonlinear EDLC system

$$\begin{pmatrix} x_1 = u_1 \\ x_2 = R_s \\ x_3 = 1/C \\ x_4 = -1/(R_p C) \end{pmatrix}$$

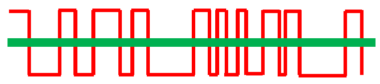
$$\begin{pmatrix} u = I_c \\ y = U_c \end{pmatrix}$$

Charging Current Design



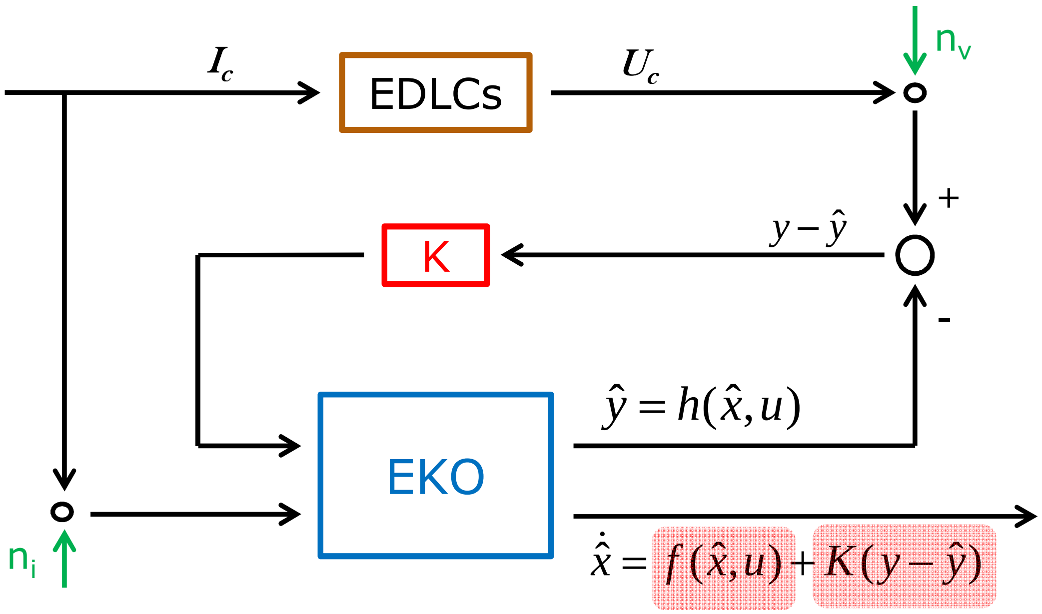
Solution:

Add PRBS *(Pseudo Random Binary Signal)* to the charging current



Extended Kalman Observer (EKO)

Extended system dynamics :	$\dot{x} = f(x,u) + w$	w : Process noise
Measured output :	$y = h(x,u) + v$	v : Sensor noise



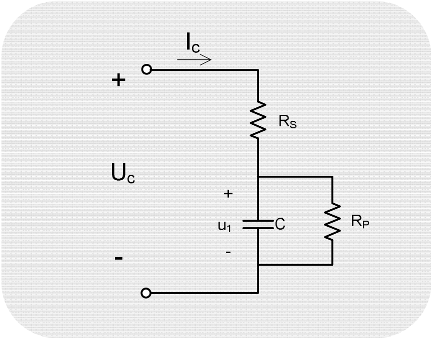
Parameter Estimation

$$\begin{pmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \\ \hat{x}_4 \end{pmatrix} \text{ for } \begin{pmatrix} x_1 = u_1 \\ x_2 = R_s \\ x_3 = 1/C \\ x_4 = -1/(R_p C) \end{pmatrix}$$

($\hat{x}$: *states estimated by the observer*)

Calculation of K: $K = PH^T R^{-1}$, with $\dot{P} = FP + PF^T - PH^T R^{-1} HP + Q$

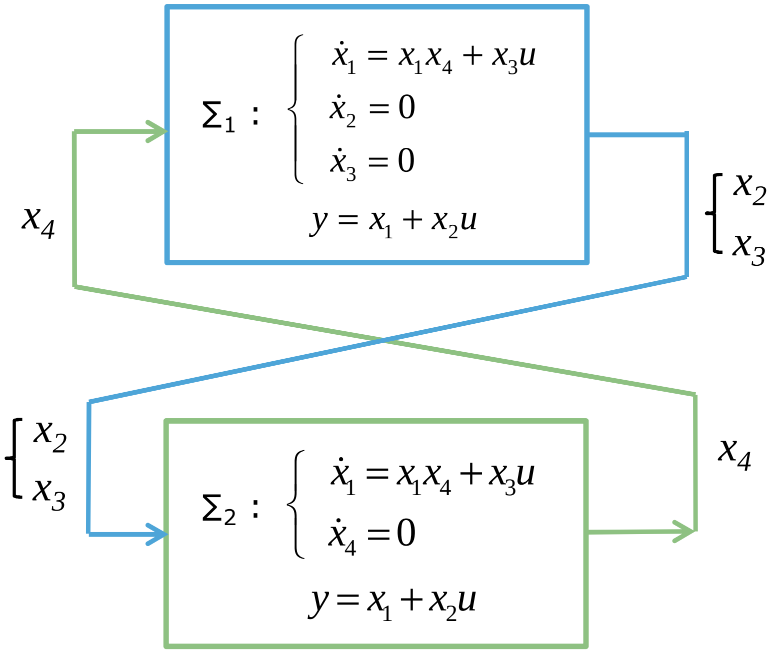
Interconnected Observers (IOs) [1]



$$\Sigma : \begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_2 = 0 \\ \dot{x}_3 = 0 \\ \dot{x}_4 = 0 \end{cases} \quad y = x_1 + x_2 u$$

Nonlinear EDLC system

$$\begin{pmatrix} x_1 = u_1 \\ x_2 = R_s \\ x_3 = 1/C \\ x_4 = -1/(R_p C) \end{pmatrix} \quad \begin{pmatrix} u = I_c \\ y = U_c \end{pmatrix}$$

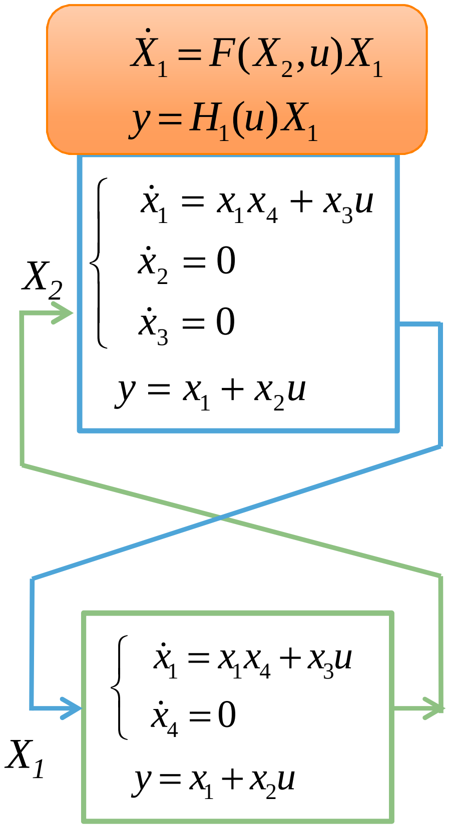


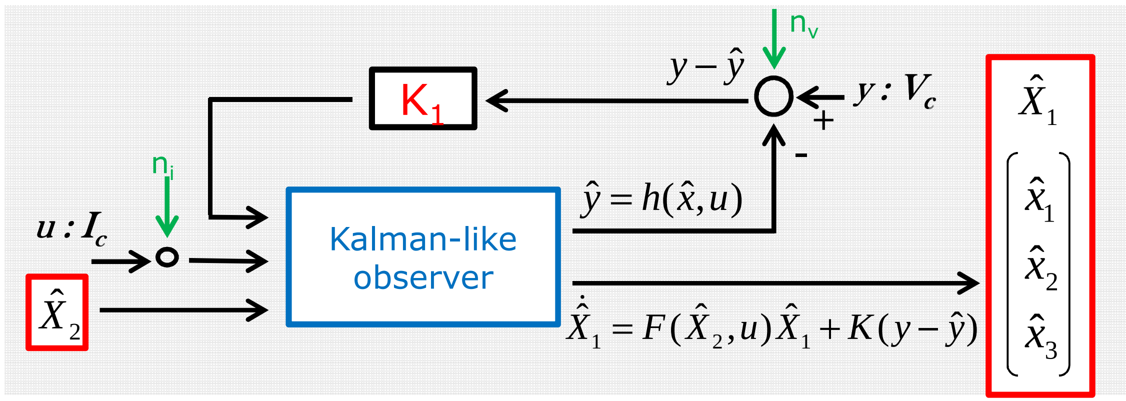
$$\Sigma_1 : \begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_2 = 0 \\ \dot{x}_3 = 0 \end{cases} \quad y = x_1 + x_2 u$$

$$\Sigma_2 : \begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_4 = 0 \end{cases} \quad y = x_1 + x_2 u$$

[1] G. Besançon and H. Hammouri, "On observer design for interconnected systems," Journal of Mathematical Systems, Estimation, and Control, vol. 8, no. 3, pp. 1 –25, 1998.

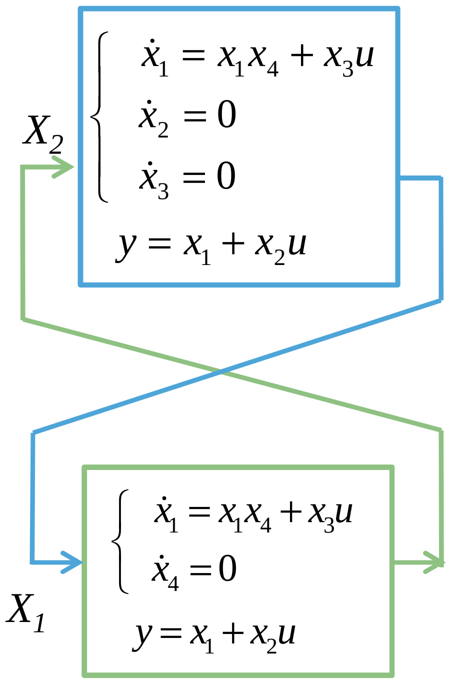
Interconnected Observers (IOs) - Kalman-like observer





<u>Calculation of K_1:</u> $K_1 = S^{-1}H^T$, with $\dot{S} = -\rho S - F^T(\hat{X}_2,u)S - SF(\hat{X}_2,u) + H^T H$

Interconnected Observers (IOs) - Reduced order Luenberger observer



Interconnected Observers (IOs) - Reduced order Luenberger observer

$$\begin{cases} \dot{x}_1 = x_1 x_4 + x_3 u \\ \dot{x}_4 = 0 \end{cases}$$

$$y = x_1 + x_2 u$$

New output : $y' = \dot{x}_1$

Order is reduced!

$$\begin{cases} \dot{x}_4 = 0 \\ y' = \dot{x}_1 = (y - x_2 u) x_4 + x_3 u \end{cases}$$

x_1 *can be deduced from y:* $x_1 = y - x_2 u$

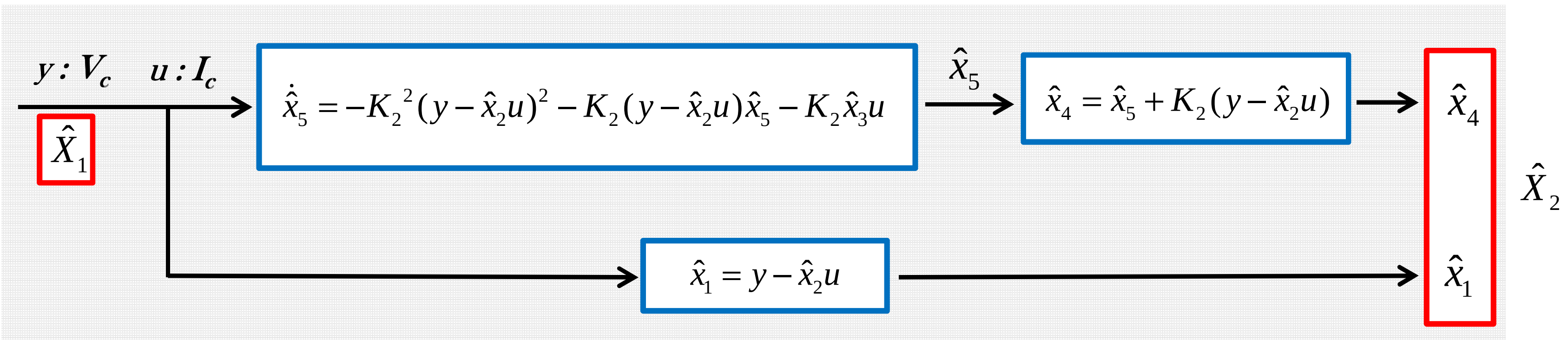
Luenberger observer:

$$\dot{\hat{x}}_4 = K_2 (y' - \hat{y}') = K_2 (\dot{x}_1 - \hat{y}')$$

$$\dot{\hat{x}}_4 - K_2 \dot{x}_1 = -K_2 \hat{y}'$$

$$\dot{\hat{x}}_5 = \dot{\hat{x}}_4 - K_2 \dot{x}_1$$

$$\hat{y}' = \hat{x}_4 (y - \hat{x}_2 u) + \hat{x}_3 u$$



Convergence of IOs

Estimation error from KLO: $e_1 = X_1 - \hat{X}_1$

Estimation error from ROLO: $e_2 = X_2 - \hat{X}_2$

Convergence ?

Lyapunove Function Definition

For KLO: $V_1 = e_1^T S e_1$

For ROLO: $V_2 = e_2^T T^2 e_2$

For Whole Observer: $V_0 = V_1 + V_2$

If : $\dot{V}_0 \le \delta(\rho, K_2) V_0$ and $\delta(\rho, K_2) < 0$

Estimations of IOs are convergent.

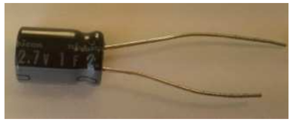
Comparison of the two kinds of observers

Extended Kalman Observer (EKO)	Interconnected Observers (IOs)
Is able to estimate the parameters online	Is able to estimate the parameters online
It is difficult to prove its convergence.	The convergence is guaranteed
More tuning parameters	Less tuning parameters

Ageing Experiments

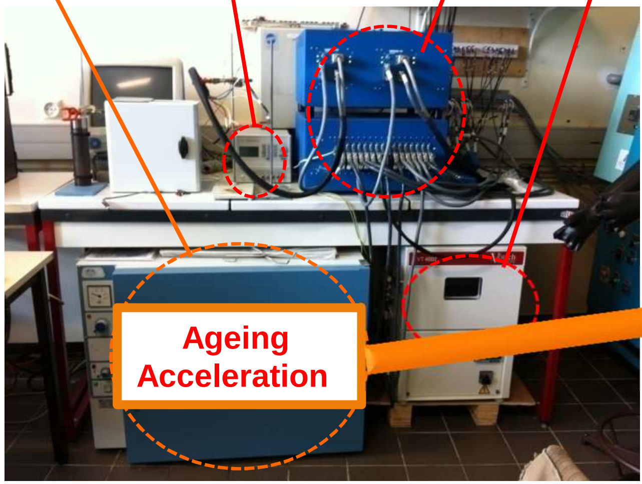
- EDLC tested:

Nichicon UM series 2,7V/1F



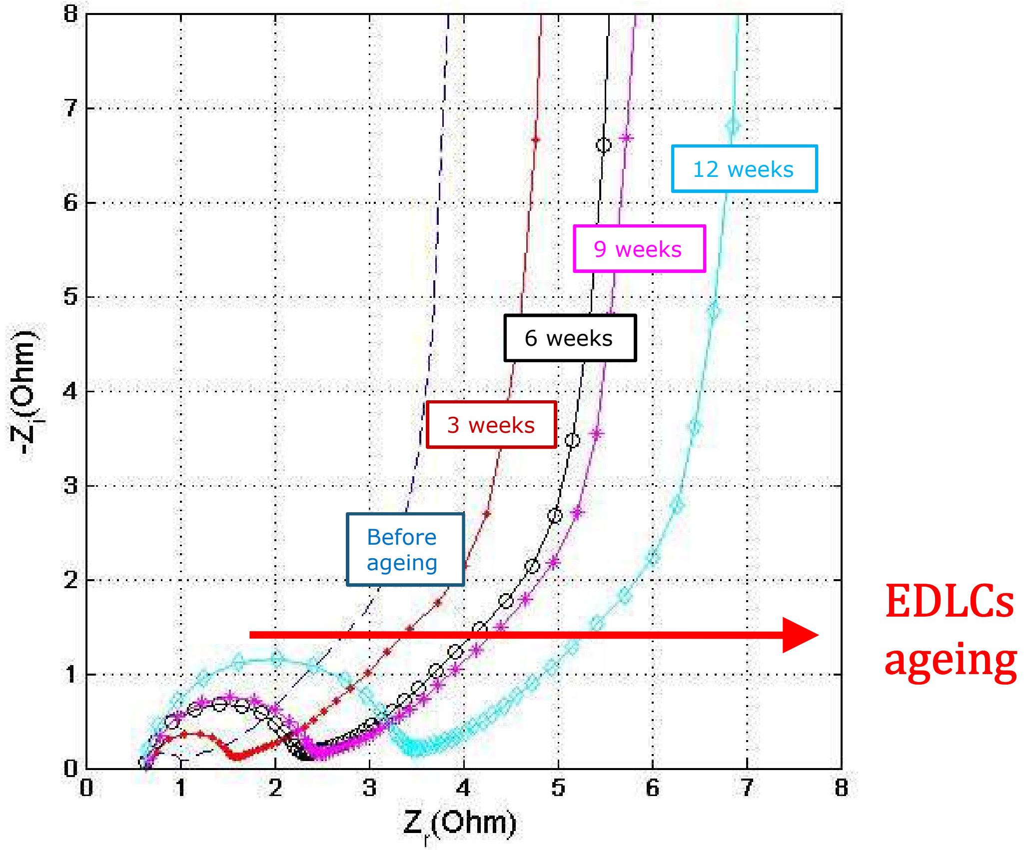
- Ageing test bench:

Stoves Voltage source VSP Thermostat



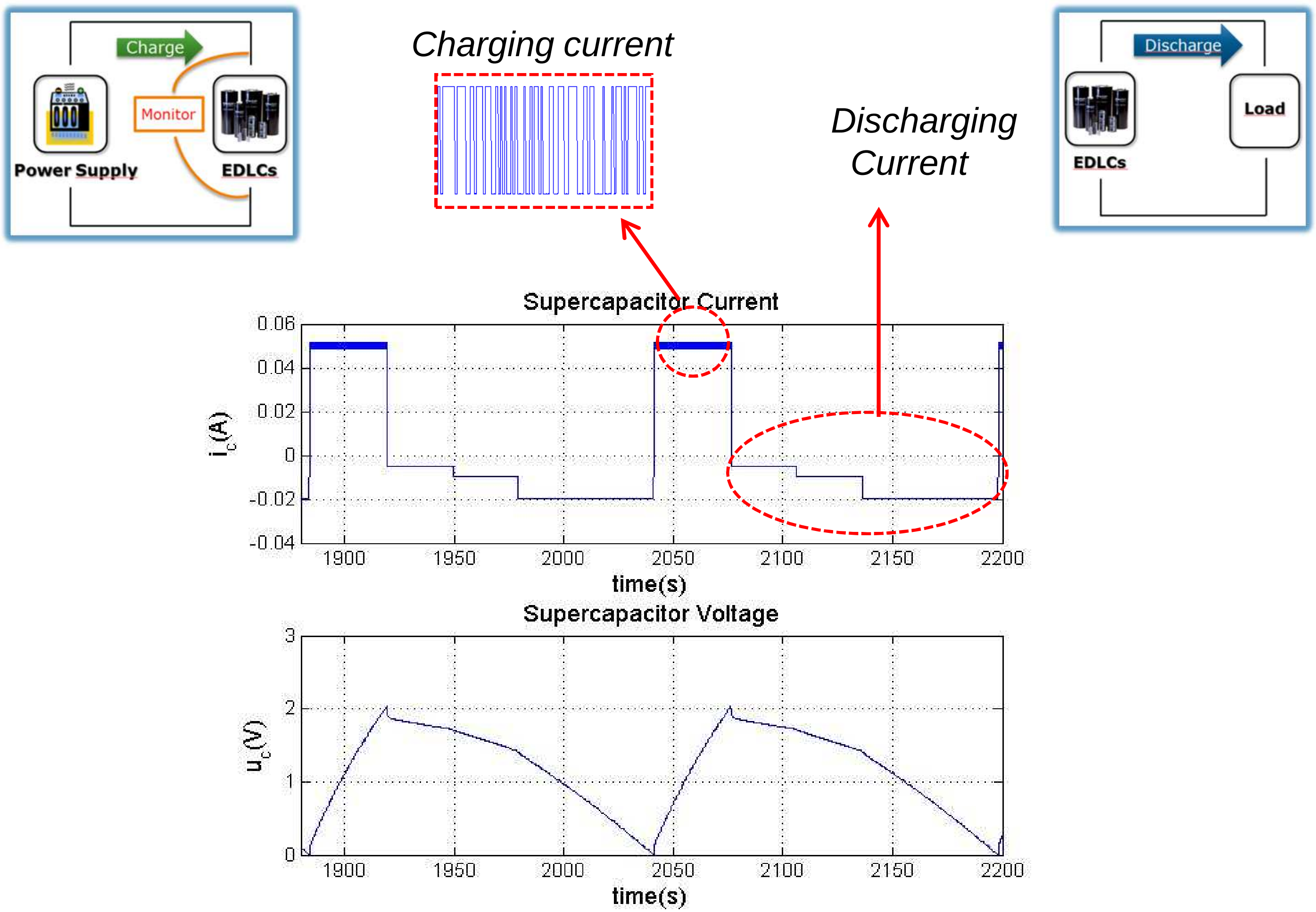
Experimental Results

Offline characterization by EIS [1]

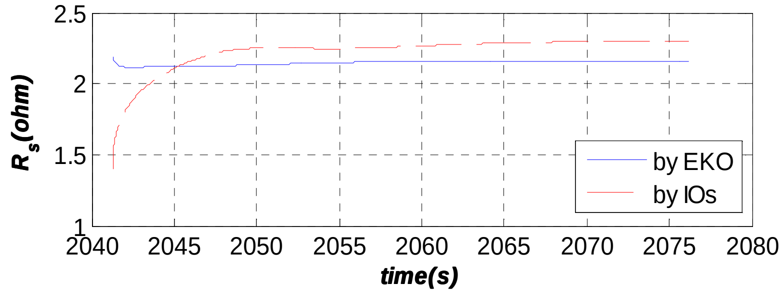


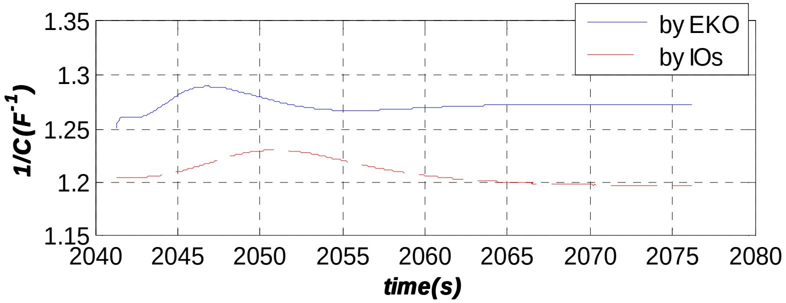
[1] EIS: Electrochemical Impedance Spectroscopy

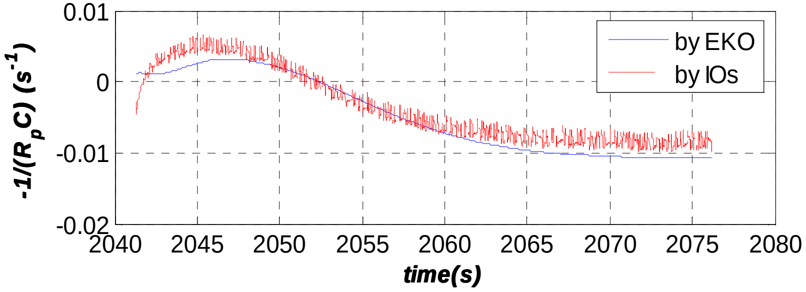
Experimental Results *- Current and Voltage record*



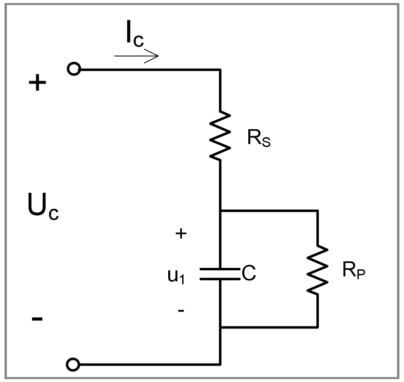
Experimental Results *- Parameters estimation before ageing*

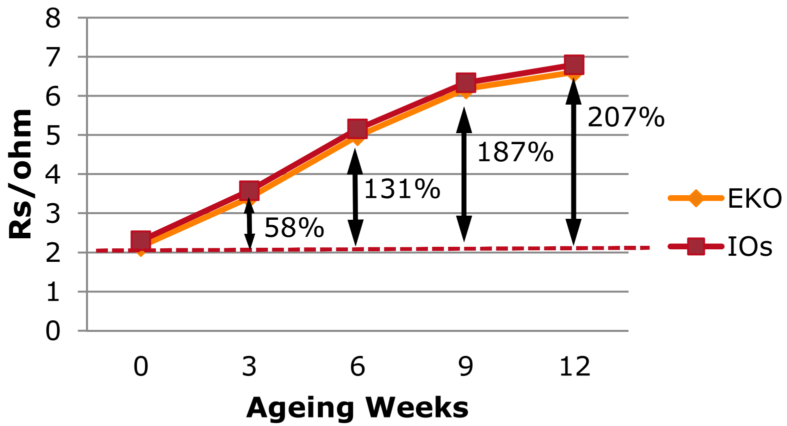


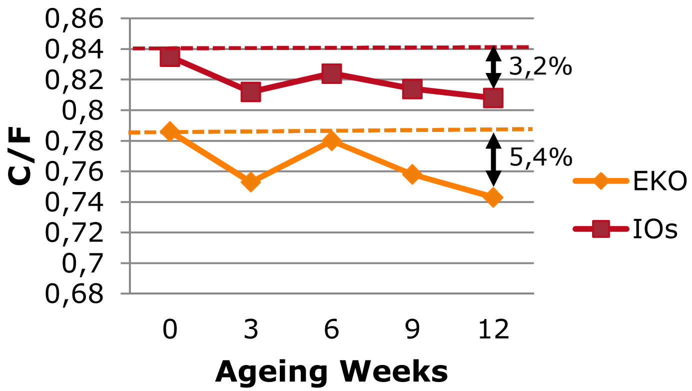


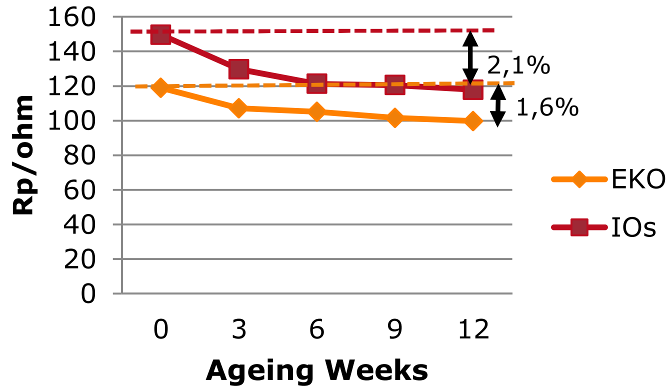


Experimental Results *- Parameters estimation during ageing*









Conclusions

- An online in situ monitoring method by means of real-time observers is proposed to monitor the EDLCs ageing.
- To monitor the parameter evolution online, two kinds of real time observers (EKO and IOs) are designed. Compared to EKO, IOs have a lower computational cost and a guaranteed convergence.
- Real ageing experimental data showed that both observers succeed to estimate the parameters in real time and to perceive their evolution.

Future Work

- Better EDLCs models will be used to the online observation of the ageing of EDLCs.

(This work has already been presented at the IEEE IECON 2013 conference in Vienna in Nov. 2013)

Thank you for your attention!

E-mail: zhihao.shi@univ-nantes.fr