High-Gain Adaptive Observer for Floating Voltage Estimation and Capacitor Aging Monitoring in Multicell Converters

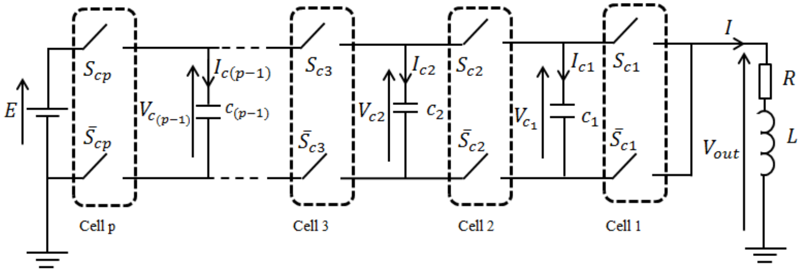
M. GHANES

Nantes University-Centrale Nantes-LS2N-CNRS, France

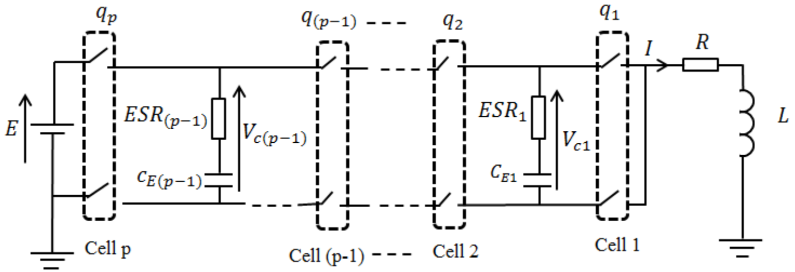
Joint work with **B. NAIT-SLIMANI** and **S. DJENNOUNE**,
UMMTO, Tizi-Ouzou, Algeria

Outline

- Multicell DC-DC converters [T. Meynard and H. Foch, IEEE TIE, 2002]:
  - Medium and high power applications.
  - Multilevel voltage generation.
  - Reduced voltage stress on semiconductor devices.
  - Improved power quality.



- Design of adaptive high gain observer for both capacitor voltage estimation and capacitor aging monitoring in multicell converters.
- Floating capacitors, responsible for nearly 30% of failures [W. Zhang et al., IEEE TIE, 2023].
- Aging manifests itself as an increase in ESR [H. Soliman et al., IEEE TIE, 2016] and a decrease in capacitance [K. Hasegawa et al. Microelect. Reliability, 2018], causing voltage imbalance.
- Extension of our previous work on voltage estimation (Laamiri et al. (IFAC CEP 2019)).



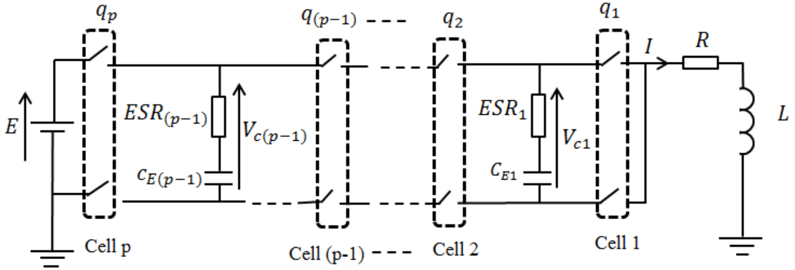
Control objective:

- Current tracking: $I \rightarrow I_{ref}$.
- Floating voltage balancing: $V_{c1}, V_{c2}, ..., V_{c(p-1)}$.

Estimation and Monitoring objective:

- Capacitor voltage estimation.
- ESR estimation.
- Capacitance estimation.
- Online diagnosis.

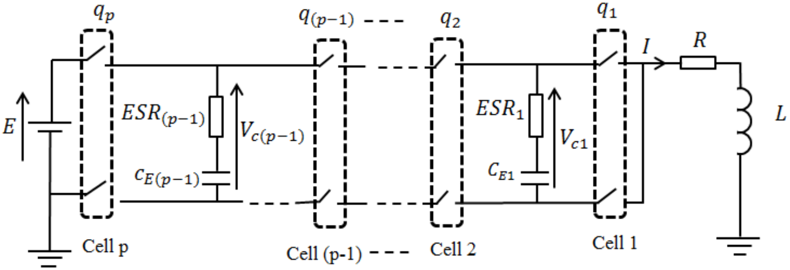
Constraint: Only current sensor



- **Continuous states:** $I,\ V_{c1}, ..., V_{c(p-1)}$
- **Discrete states:** $q_1, \ldots, q_p$
- **Hybrid (instantaneous) model:**

$$\dot{I} = -\frac{R}{L} I - \sum_{k=1}^{p-1} \frac{q_{k+1} - q_k}{L} V_{ck} + \frac{q_p}{L} E$$

$$\dot{V}_{ck} = \frac{q_{k+1} - q_k}{C_{Ek}} I + (q_{k+1} - q_k) ESR_k \dot{I}$$



- The hybrid model is decomposed into $(p-1)$ interconnected subsystems: (dedicated estimation for each floating capacitor)

$$\begin{cases} \dot{x}_k = A_k(\tilde{q}_k)x_k + B_k(x_1,\ldots,x_{p-1},q,\theta_k,u)\theta_k \\ \qquad + \varphi_k(x_1,\ldots,x_{p-1},q,\theta_k,u) \\ y_k = Cx_k \end{cases} \tag{1}$$

where $A_k(\tilde{q}_k) = \begin{bmatrix} 0 & -\frac{\tilde{q}_k}{L} \\ 0 & 0 \end{bmatrix}$, $x_k = \begin{bmatrix} I_k & V_{ck} \end{bmatrix}^T$, $\tilde{q}_k = q_{k+1} - q_k$, $C = \begin{bmatrix} 1 & 0 \end{bmatrix}$, $u = E$. $\theta_k = \begin{bmatrix} R & ESR_k \end{bmatrix}^T$ or $\theta_k = \begin{bmatrix} R & \frac{1}{C_{Ek}} \end{bmatrix}^T$, $B_k = \begin{bmatrix} -\frac{x_{k1}}{L} & 0 \\ 0 & \tilde{q}_k x_{k1} \end{bmatrix}$,
$\varphi_k = \begin{bmatrix} \frac{q_p}{L}u - \frac{1}{L}\sum_{j=1,j\neq k}^{p-1} \tilde{q}_j x_{j2} \\ 0 \end{bmatrix}$.

$$
\begin{cases}
\dot{\hat{x}}_k = A_k(\tilde{q}_k)\hat{x}_k + B_k(\hat{x}_1,\ldots,\hat{x}_{p-1},q,\hat{\theta}_k,u)\hat{\theta}_k + \varphi_k(\hat{x},q,\hat{\theta}_k,u) \\
\qquad + Q_k\left(S_k^{-1}C^T + \Lambda_k\Gamma_k^{-1}\Lambda_k^T C^T\right)(y_k - \hat{y}_k) \\
\dot{\hat{\theta}}_k = Q_k\Gamma_k^{-1}\Lambda_k^T C^T(y_k - \hat{y}_k) \\
\dot{\Lambda}_k = \left(A_k(\tilde{q}_k) - Q_k S_k^{-1}C^T C\right)\Lambda_k + B_k(\hat{x}_1,\ldots,\hat{x}_{p-1},q,\hat{\theta}_k,u) \\
\dot{S}_k = -\gamma_k S_k - |\tilde{q}_k|\left[A_k(\tilde{q}_k)^T S_k + S_k A_k(\tilde{q}_k)\right] + Q_k C^T C \\
\dot{\Gamma}_k = -\rho_k\Gamma_k + Q_k\Lambda_k^T C^T C\Lambda_k \\
\hat{y}_k = C\hat{x}_k, \quad Q_k = |\tilde{q}_k|\prod_{\substack{j=1\\ j\neq k}}^{p-1}\left(1-|\tilde{q}_j|\right), \quad \tilde{q}_k = q_{k+1} - q_k
\end{cases}
\tag{2}
$$

where $\hat{x}_k = \begin{bmatrix} \hat{I}_k & \hat{V}_{ck} \end{bmatrix}^T$ and $\hat{\theta}_k = \begin{bmatrix} \hat{R} & E\hat{S}R_k \end{bmatrix}^T$ or $\hat{\theta}_k = \begin{bmatrix} \hat{R} & \frac{1}{\hat{C}_{Ek}} \end{bmatrix}^T$.

[main reference]: B. Nait Slimani, M. Ghanes, S. Djennoune, High-gain adaptive observer for floating voltages estimation and capacitor aging monitoring in multicell converters, Engineering Science and Technology, an International Journal 65, 102036, 2025.

Lyapunov Approach

$$V = \sum_{k=1}^{p-1} \left(e_{xk}^T S_k e_{xk} + e_{\theta k}^T \Gamma_k e_{\theta k} \right), \qquad \dot{V} < -\sum_{k=1}^{p-1} \lambda_k V_k.$$

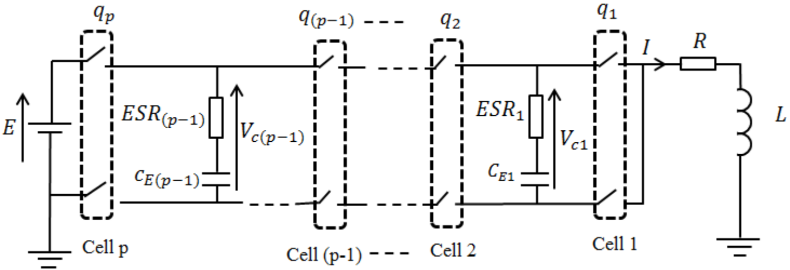
Main conditions

- States and paremters bounded,
- Persistency excitation (switching imposed sequence),
- Constants parameters or slowly variable variant.

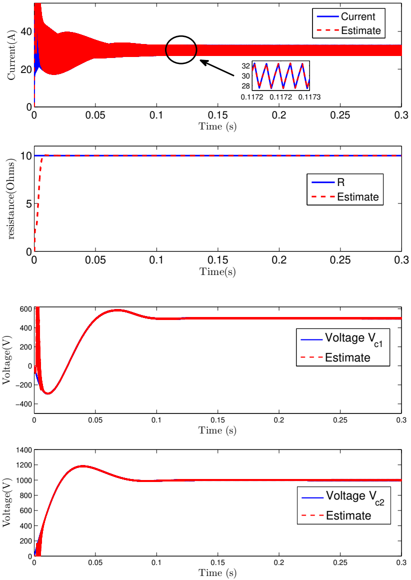
Under these conditions, the estimation errors converge exponentially to zero.

- joint state and parameter estimation for a class of hybrid dynamical systems, providing a unified framework for control (floating voltage reconstruction) and online diagnosis (capacitor health monitoring) without extra sensors;
- a gain-blocking strategy during non-observable phases (symbolized by Q_k in (2)) to better reflect the physical behavior of the converter, improve estimation accuracy and ensure stability;
- applicability to arbitrary p-cell converters and various capacitor aging mechanisms (ESR increase or capacitance loss).

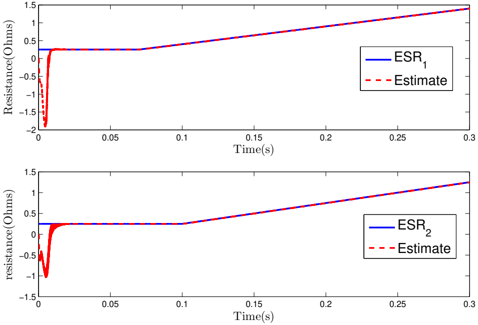
- MATLAB/Simulink for a three-cell converter ($p = 3$).
- System parameters: $E = 1500\,\text{V}$, $R = 10\,\Omega$, $L = 5 \times 10^{-4}\,\text{H}$ and $C_{E1} = C_{E2} = 40\,\mu\text{F}$.
- Two scenarios: a progressive increase of ESR_1 and ESR_2, and an exponential decrease of C_{E1} and C_{E2}.



STATE AND LOAD ESTIMATION RESULTS

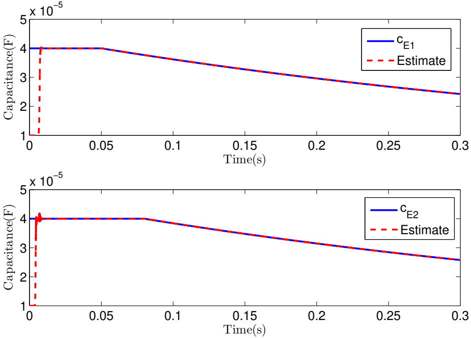


ESR ESTIMATION RESULTS



- Fast convergence.
- Accurate aging tracking.

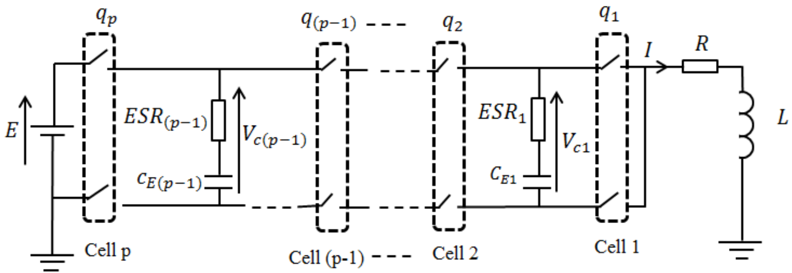
CAPACITANCE ESTIMATION RESULTS



- Good reconstruction.
- Early degradation detection.

SUMMARY OF RESULTS ($P = 3$ CELLS)

Variable	Estimated
Current I (measure)	✓
Voltage V_{c1}	✓
Voltage V_{c2}	✓
ESR_1	✓
ESR_2	✓
C_{E1}	✓
C_{E2}	✓



Conclusion

Main contributions

- Floating voltage estimation.
- Simultaneous state and parameter estimation.
- Online capacitor aging monitoring.
- Single current sensor solution.
- Gain-blocking strategy for hybrid systems.

Future work

- Experimental validation.
- Robustness analysis under noise.
- Control based observer.