A New Dynamic Energy Router

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Introduction

Achieving efficient transfer of electric energy between multi-domain subsystems that can generate, store, or consume energy is a problem that arises in many modern applications. An example of these systems are the electric cars which consist of fuel cell-based generating unit, batteries, supercapacitors and electric motors.

These devices in electric vehicles are used in order to transfer or receive energy depending on the electric load.
Formulation of the energy transfer problem

Energy management between storing, generating and load units interconnected through power electronic devices.
Current practice, limitations and objective

- Assume that system operates in steady state
- Translate power demand into current or voltage references
- Track references with PI controllers in the power converters
- Discriminate between fast and slow changing power demand via linear filtering
  \[ \Rightarrow \text{Behavior below par during transients and for fast changing demands} \]

Our objective is to propose a $\Sigma_I$ that

- Does not rely on steady–state considerations
- Allows to incorporate dynamic restrictions of the units
- Handles dissipation
Mathematical formulation of the problem

- Units modeled as multiports $\sum_j$ with port variables $v_j(t), i_j(t) \in \mathbb{R}^m$

- They verify the energy conservation law

$$H_j(t) - H_j(0) = \int_0^t v_j^\top(s)i_j(s)ds - d_j(t),$$

- $H_j(t)$ is the stored energy,
- The supplied energy is,

$$\int_0^t v_j^\top(s)i_j(s)ds.$$

- $d_j(t) \geq 0$ is the dissipation.
Duindam–Stramigioli Dynamic Energy Router (DS–DER)

- DS–DER is a power-preserving interconnection $\Sigma_I$ that transfer instantaneously the energy from one unit to the other. (Sanchez, et al., IEEE–CSM’10)

- Assume for simplicity, two ports

- $\Sigma_I$ is power preserving selecting

\[
\begin{align*}
\Sigma_I : \begin{bmatrix}
    i_1(t) \\
    i_2(t)
\end{bmatrix} &= 
\begin{bmatrix}
    0 & \Gamma(t) \\
    -\Gamma^\top(t) & 0
\end{bmatrix}
\begin{bmatrix}
    v_1(t) \\
    v_2(t)
\end{bmatrix}
\end{align*}
\]

Indeed,

\[
i_1^\top v_1 + i_2^\top v_2 = 0,
\]

for any $\Gamma \in \mathbb{R}^{n \times n}$.
Now, neglecting dissipation,

\[ \dot{H}_1 = v_1^\top i_1 = v_1^\top \Gamma v_2 \]
\[ \dot{H}_2 = v_2^\top i_2 = -v_2^\top \Gamma^\top v_1. \]

How to select \( \Gamma \)? Take, for instance

\[ \Gamma(t) = \alpha(t)v_1(t)v_2^\top(t), \quad \alpha(t) \in \mathbb{R} \]

then

\[ \dot{H}_1 = \alpha|v_1|^2|v_2|^2 \]
\[ \dot{H}_2 = -\alpha|v_1|^2|v_2|^2. \]

\( \alpha > 0 \) transfers all energy from \( \Sigma_2 \) to \( \Sigma_1 \), \( \alpha < 0 \), viceversa.

Selecting the “shape" of \( \alpha(t) \) we can regulate the energy transfer rate.
Design a control law for the DER switches, which ensures that the currents track their desired references

\[
\begin{bmatrix}
i_1^*(t) \\
i_2^*(t)
\end{bmatrix} =
\begin{bmatrix}
\alpha(t)v_1(t)v_2^2(t) \\
-\alpha(t)v_2(t)v_1^2(t)
\end{bmatrix}.
\]

\(\Sigma_1, \Sigma_2\) are supercapacitors.
Experimental results

- $\alpha(t)$ controls the direction and rate of change of energy flow.

- Fundamental problem: the power balance of the DER becomes

$$\dot{H}_I(t) = v_1(t)i_1(t) + v_2(t)i_2(t) - d_I(t) \leq 0,$$

energy decreases and it becomes non-operational.
Compensating the dissipation

Adding outer–loop PI's to a feedback linearizing control to regulate the voltage $v_C(t)$:

$$w_j(t) = -k_p \tilde{i}_j(t) - k_i \int_0^t \tilde{i}_j(s) \, ds - k_{pv} \tilde{v}_C(t) - k_{iv} \int_0^t \tilde{v}_C(s) \, ds, \quad j = 1, 2.$$
Currents of $\Sigma I$ and their Errors
Voltage of DC Link
Proposed solution: abandon power preservation

Define mappings $F_j(v)$ for the current references:

$$i^*_j(t) = F_j(v(t)), \quad j \in \bar{N},$$

Two different objectives:

- Ensure the desired power dispatch, $P^*_j(t) = v_j^\top(t)F_j(v(t))$.
- Compensate dissipation, $\sum_{j=1}^{N} v_j^\top(t)F_j(v(t)) = d_I(t)$.

Possible choice

$$F_j(v) = \delta_j \prod_{k=1, k \neq j}^{N} |v_k|^2 v_j, \quad \sum_{j=1}^{N} \delta_j(t) = d_I(t).$$

If $|v_j(t)| \geq \epsilon > 0$, fix

$$F_j(v_j(t)) = \frac{P^*_j(t)}{|v_j(t)|^2} v_j(t),$$

with $\sum_{j=1}^{N} P^*_j(t) = d_I(t)$. 
Geometric interpretation of the new DER and the DS–DER

Given $v$ and $d_I$, the set $F$ defines the admissible vectors $F(v)$, that satisfy

$$\sum_{j=1}^{N} v_j^T (t) F_j(v(t)) = d_I(t).$$
Simulation results of the new DER

A battery is added as a third port, to compensate the losses.

\[ P_1^* (t) = -P_2^* (t), \]

\[ P_3^* (t) = d_I (t) = R_1 i_1^2 (t) + R_2 i_2^2 (t) + R_3 i_3^2 (t). \]
Power of multiports

(a)
Voltage of DC Link
**Conclusion and future work**

- A practical limitation of the DS–DER was identified, therefore we propose a new DER that takes into account the dissipation.

- The new DER was tested in simulations using a simple PI scheme and an (approximate) input–output linearizing controller. It followed good performance in both cases.

- We obtain a better regulation of the DC link voltage.

- The experimental validation of the new DER is currently under way and will be reported in the near future. Also, we are currently investigating the application of these ideas for a realistic fuel–cell based system available in our laboratory.

- In the future an adaptive version of the new DER must be worked out.
Thank you