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A flexible design methodology to solve energy management problems[☆]

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ABSTRACT

This paper investigates the design and simplification of energy management problems (EMP) through a dedicated functional model for energy systems. The proposed framework extends the concept of energy-hub by adding a layer of information based on standardized communication ports. As a result, the EMP can be expressed directly from the model as a nonlinear multi-objective optimization problem. Taking advantage of the modularity of the approach, methods to substantially reduce EMP complexity are proposed: one manages the energy demands based on a discrete set of precomputed local regulators (configurations); another decomposes the problem using an appropriate set of sub-problems. The framework and the methodology are shown to be flexible and efficient through the case study of a hybrid serial refrigerating truck.

1. Introduction

Over the past years, carbon emission have increased the global temperature at a fast rate, to the point where our climate is drastically changing. The significant concern of countries for the consequences on environment and economy has lead at the 2015 United Nations Climate Change Conference (COP 21) to an agreement of limiting this global warming. This challenge must address the key point of how to produce, distribute and use energy in an efficient and clean manner. It leads to abandon centralized power systems to design distributed energy systems that aggregate local renewable and recoverable energy resources (RRERs) with energy carriers (e.g. electricity, heat). Such a design guarantee flexibility and security of supply to the benefit of economical and environmental goals. However, the system's complexity increased drastically, especially when large network such as GRID are considered. In addition, the RRERs integration are benefit only if energy flows are managed properly. As the result, energy system modelling and Energy Management Strategy (EMS) design became open questions of great interest.

A typical model-based approach uses the laws of physics to construct a realistic model of the subject and then deduce an appropriate strategy. On a small system, a stability or a tracking problem can be formulated and specific solutions derived from optimal control theory [1–3]. These approaches show their limitations for energy systems, notably because of the diversity of energy carriers, but also because of the multiple objectives and constraints involved in the optimization problem such as cost-emission reduction [4–6] or cost-reliability optimization [7,8].

Due to their multi-energy nature, energy systems must be analysed from new perspectives, notably their multi-service, network, and multi-fuel aspects [9]. In this context, suitable computer-assisted models are essentials. In [10], a selection of methods and models for generation planning and system design are presented. The authors analyse their capabilities and highlight the necessity of an interoperable optimization framework. To this question, they depict a first methodology in the form of a flow diagram that generically describes the optimization process. The procedure is quite interesting, however it does not exploit yet the network structure of the energy systems.

A network model represents by abstraction the topological invariants of a system. They can be generalized to multi-physical systems by focusing on their functional and structural aspects, using e.g. *Energetic Macroscopic Representation* (EMR) [11]; or by aggregating storages and converters elements into power-to-load boxes. The latter was introduced as *energy-hub* models in [12,13].

Mathematically, an energy-hub maps inputs to outputs through a linear matrix relation. It clarifies the energy system operation situation and therefore is frequently associated to energy system design, sizing and flow optimization. In the latest category, studies proposed robust control techniques [14,15], decentralized solution [16,17], or multi-objective optimization [18,6].

Solving algorithms for multi-objective problems are various. Meta-heuristics approaches like e.g. particle swarm optimization [19,20] or

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Nomenclature

EMP	Energy Management Problem
RHC	Receding Horizon Control
$\mathscr{P}_N$	global EMP
$\mathscr{P}'_N$	scalarized EMP with RHC
$\mathscr{P}_{N_1}$	hybridization EMP
$\mathscr{P}_{N_2}$	conversion EMP
$\mathscr{P}_{N_3}$	competition EMP
$\mathscr{P}'_{N_3}$	configuration-based competition EMP
$\mathscr{C}_{op},\mathscr{C}_{ec},\mathscr{C}_t$	EMP's objectives
$\boldsymbol{\nu_c},\boldsymbol{\nu_s}$ and ν_δ	EMP's decision variables
λ_{c_i}	configuration-based decision variable
$\mathscr{S}_N,\overline{\mathscr{S}_N}$	sets of active/passive sources
$\mathscr{C}_N,\overline{\mathscr{C}_N}$	sets of active/passive clients
S_{c_i}	client satisfaction function
Ec_{s_j}	source energy cost function
α_i	client priorities
β_j	source priorities
γ_k	scalarizing weights
$(n)_{c_i}^m\vert_T$	need signal over time horizon T
$(a)_{s_j}^m\vert_T$	availability signal over time horizon T

genetic algorithms [21] have been studied for hybrid energy system (the reader can find more details and comparison in [22]). For demand-side management, a common approach is to seek for a Nash equilibrium applying game theory principle [23,24] (see [25] for a complete review). However, the procedure is still in two steps: first to assume the energy hub model, then to set the Energy Management optimization Problem (EMP).

This paper tackles the design of EMS to operate complex energy system by proposing a new functional framework based on three modules. The novelty of this work is the additional informative layer embedded in the model. It provides synthetic information that allows to: (i) distinguish sources and storing elements, (ii) model complex phenomenon, (iii) deduce directly the (EMP) formulation for network operation. The modules corresponds to functional attributes tailored for energy systems: to produce an economic and ecological energy, to distribute efficiently, to satisfy a service. Unlike the others modelling approaches, the methodology lets the EMP being inferred directly from the energy system topology itself rather than being manually imposed by the control designer.

The paper is organized as follow. Section 2 introduces the modules and the standardized signals of the functional energy system model. Section 3 sets the EMP, while Section 4 discusses existing and contributive approaches to simplify it in order to cope with real-time simulations. Two new methods are emphasis: a model decomposition, and a clients management by configurations. Finally, the global methodology (modelling and simplification contributions) is illustrated in Section 5 by simulation of a hybrid truck with a refrigerating compartment and its EMS, using a Branch and Bound algorithm [26] and a particular optimization-based predictive control from [27].

2. A functional model for energy systems

2.1. Client and source modules

The proposed framework identifies an energy system at a functional level according to two modules, called *client* module and *source* module, as well as an interconnection module named *node*. They are built upon organic components, where no specifications are required at this level of modelling.

- *The client module* is an *energy consuming* element, which can be related to a specific mission (e.g. vehicle mobility, thermal comfort, etc.). It will be noted c_i, where subscript i identifies the client.
- *The source module* is an *energy supplying* or *energy storing* element, which has capacity limits and can possess reversibility. It will be noted s_j, where subscript j identifies the source.
- *The node* is an *energy distributing and converting* element, which connects multiple clients and sources. It will be noted N.

These modules are exchanging both energy and information. In Fig. 1, a plain link corresponds to instantaneous powers $P_{s_1}^{c_1}(t)$ and a dotted green link represents either a *need* signal $(n)_{c_1}^{s_1}|_T$ or an *availability* signal $(a)_{s_1}^{c_1}|_T$, both defined over a time interval $T=[t_i;t_f]$.

The need signal is generated by a client c_i and transferred to a module m. It is denoted $(n)_{c_i}^m|_T$ and contains the following information defined for $t\in T$:

$$(n)_{c_i}^m|_T := \begin{cases} P_{c_i}^{m+}(t): & \textit{maximum admissible power},\\ P_{c_i}^{m-}(t): & \textit{minimum admissible power},\\ R_{c_i}^{m}(t): & \textit{requested power},\\ S_{c_i}(P_{c_i}^{m}(t)): & \textit{satisfaction function.} \end{cases} \tag{1}$$

$P_{c_i}^{m+}(t)$ and $P_{c_i}^{m-}(t)$ are bounds that limit the admissible power by the client. $R_{c_i}^{m}(t)$ is the power requested by the client to satisfy its own mission. The *satisfaction function* $S_{c_i}(P_m^{c_i})$: $\mathbb{R}\to[0;1]$ is a nonlinear function that qualifies the success of its mission with regards to the energy received. It achieves its maximum when exchanged power $P_{c_i}^{m}(t)$ equals the requested power $R_{c_i}^{m}(t)$.

The availability signal is generated by a source s_j and transferred to a module m. It is denoted $(a)_{s_j}^m|_T$ and contains the following information defined for $t\in T$:

$$(a)_{s_j}^m|_T := \begin{cases} P_{s_j}^{m+}(t): & \textit{maximal available power},\\ P_{s_j}^{m-}(t): & \textit{minimal available power},\\ D_{s_j}^{m}(t): & \textit{available energy},\\ Ec_{s_j}(P_{s_j}^{m}(t)): & \textit{energy cost function.} \end{cases} \tag{2}$$

$P_{s_j}^{m+}(t)$ and $P_{s_j}^{m-}(t)$ are bounds that limit the power supplied by the source, and $D_{s_j}^{m}(t)$ is the available energy. The *energy cost function* $Ec_{s_j}(P_{s_j}^{m}(t))$: $\mathbb{R}\to[0;1]$ is a nonlinear function, possibly time dependant, that evaluates the energy cost for a power request.

Note that the main behaviour of client is to consume energy while a source will supply it. However, in particular cases, a client may temporarily act as a source and delivers energy to the network, e.g. during brake recovering situation for electric-cars. Distinguishing these module is then tenuous and relies on the fact that: the clients energy is always free and limited in time.

2.2. Module's control causality

As depicted in Fig. 1, the proposed framework allows one module to

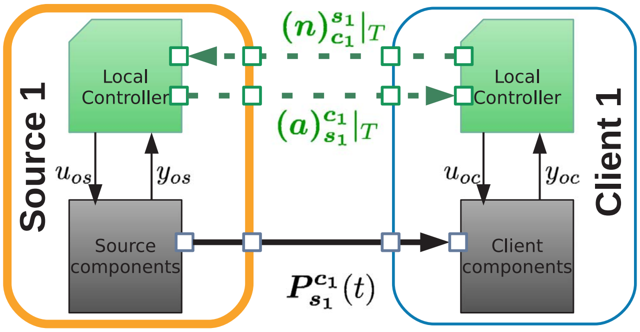

Fig. 1. Energy functional links between a passive client and an active source modules.