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Intra-day electro-thermal model predictive control for polygeneration systems in microgrids

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ABSTRACT

This paper is framed within the context of intra-day optimal control of polygeneration systems and storage connected to microgrids. In particular, the paper proposes an optimal control strategy that accounts for both electrical and thermal processes taking place in multi-building energy networks. To this end, the proposed optimal control strategy, based on the use of a Model Predictive Control, has been developed with the aim of providing optimal resource set-points for the coming 24 h. The proposed approach takes into account: day-ahead and spot prices of electricity, resource prices in terms of fuel cost and shut-down, start-up costs as well as the presence of electrical and thermal storage. The ability of this thermo-electric optimal control strategy is then demonstrated through simulations considering three case studies, namely: (a)fixed electricity price, (b)electricity spot-price and (c)different seasonal cases. The paper also studies the shaving of peaks through the use of optimally sized units in a system with the proposed method.

1. Introduction

The evolution of the electrical and thermal demands, together with the need of highly efficient systems, is changing the paradigm of electrical distribution grids towards systems capable of importing and exporting power/energy. Within this context, the inherent connection between electrical and thermal networks justifies the investigation of specific control strategies that account both these systems in order to maximize the overall efficiency by maintaining the electrical grids within their safe operation conditions.

Modern grids make use of a mix of deterministically dispatchable units like: cogeneration devices, heat pumps and boilers that together with stochastic renewable resources, must satisfy the consumer's demand. These devices, along with the use of thermal and electric storage systems, are also used to maximize the entire system efficiency. Microgrids represent a promising integration platform for all the above-mentioned elements. They can, indeed, use these devices while improving the security and quality of the grid, without overhauling the entire system (e.g. Lasseter et al. [1]). In a scenario without DSM (Demand Side Management), the stochasticity in the user demand requires the use of a robust control strategy to achieve, for instance the maximum microgrid efficiency, [2]. MPC (Model Predictive Control) is one of the most adopted methodologies in this context as has been shown prior to this by Collazos et al., Kriett et al. and Prodan et al. [3–5]. For an MPC strategy, optimal sizing of the components in the system is vital. However, such a task cannot be decoupled from the definition of the optimal control strategy. Within this context, this work aims at proposing a methodology for the optimal control of various energy conversion components of a modern microgrid where an optimal predictive control is handling the thermal and electrical power flows. Most studies [6–11] as has been shown in great detail in Section 2, conducted till now, either focus on the thermal flows or the electrical flows owing to the differing inertia and the resulting dynamics. The paper is putting forward an MPC strategy that is able to not only integrate both the flows, but also maintain the quality of said electrical and thermal flows in the grid within standards demanded by industry and improve the total system efficiency, while satisfying the comforts of the end-users. For the purposes of proper assessment, this model predictive control strategy has been tested on an IEEE microgrid test benchmark [12]. The paper also shows how to couple the proposed MPC strategy with a sizing

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Nomenclature

Part 1

ΔT	temperature difference
$\dot{El}$	electric active power
$\dot{m}$	mass flow (fuel or streams)
$\dot{Q}$	thermal power
η_{th}	thermal efficiency for CHP units
$\mathcal{N}$	number of buses of the electrical grid
$\mathcal{S}$	number of slack buses of the electrical grid
$\tau_{y,i}$	annualised interest
c_r	cost
CHP	combined heat and power unit
CO_2	yearly carbon dioxide emissions
COP	coefficient of performance of heat pumps
E	voltage
EIB	European installation bus
HP	heat pump
I	investment cost
$Im[S]$	reactive power
INVC	yearly investment cost
J	Jacobian matrix used in Newton–Raphson method
MFH	multi-family house
MOO	multi-objective optimisation

Part 2

MPC	model predictive control
n	number of modes
OPC	yearly operating cost
$RE[S]$	active power
s	number of storage tanks
SFH	single family house
SIA	Schweizischer ingenieur-und architektenverein (Swiss Society of Engineers and Architect)
SOC	state of charge
t	time
T_{min}	minimum switch on time
TC	total cost
u	number of units/devices in system
V	volume of storage
V2G	vehicle-to-grid implementation
VPP	virtual power plant
y_x	integer variables for (x = start-up) start-up and (x = on) switch on
$C_{s,n}$	sizes of the storage devices in the system
$C_{u,n}$	sizes of the units in the system

process of the cogeneration, heat pumps and thermal storage devices. The validation of the proposed MPC is carried out through the use of a specific microgrid under development at the author's laboratory. The paper is structured as follows: Section 2 clarifies the need for an integrated approach of control for a microgrid using references as a yardstick for the control strategy demonstrated in this paper and further details the scientific originality and novelty of the paper, Section 3 gives a concise explanation of the optimal sizing problem, Section 4 describes the methodology employed and the equations associated with the methodology, Section 5 shows the system by describing its different elements, Section 6 explains the different simulations that have been performed and the adopted conditions. The final two sections explore and analyse the results and provide conclusions.

2. Need for an integrated thermal-electrical control in active distribution networks

The promotion of RERs (renewable energy resources) and, in general, DG (distributed generation) has resulted in an increasing attention by all stakeholders on electrical DNs (distribution networks). The number of connections of energy-resources to DNs is rapidly increasing in a way such that, in several countries, operational constraints are already attained. In this respect, the progressive penetration of DG into electrical medium and low voltage networks will cause, in principle, an important re-engineering of this part of the electrical infrastructure. One of the main obstacles preventing maximum penetration of traditional and renewable DERs (distributed energy resources) into DNs is represented by the lack of optimal control strategies for DERs by DNOs (distribution networks operators).

An important element that must be considered is the need of control of thermal loads since they represent, in general, the major elements of demand for both residential and industrial customers. The paper aims at demonstrating that a suitably-defined optimal control strategy that takes into account both of the above mentioned aspects, can achieve the maximisation of the global system goals like end-user comforts, energy savings, grid efficiency and economic savings.

The thermal/electrical grids have CHP (combined heat and power) units and storage systems which have the ability to interact with the system as and when needed and thus, can be used to provide support to the system needs. But, at the same time, without proper control, the stochastic sources and CHP units supplying into the system have the potential to create non-optimal or critical operation conditions which can/may be able to take down parts of the grid or cause massive losses of electrical power.

At the same time, users receiving the power, both thermal and electric, need to be satisfied and enjoy the comforts from these devices. This necessitates the need for an effective control strategy for the control of both the thermal and electrical flows, such that the electrical and thermal flows satisfy the comfort defined for the user, while providing stability and improving efficiency.

Several authors have proposed various control strategies in this context. However, most of the papers that deal with this topic have shortcomings or have a tendency to overlook one of the many aspects that all need to simultaneously included for a full and complete control strategy. Most of the papers continue to deal with the problem as either an electric or a thermal one, which leaves much to be desired. For example, Katiraei et al. [6] and Barklund et al. [7] outline the large number of microgrid management techniques, mainly from the power management side involving voltage and frequency controls, but this does not involve forecasting and management with a larger picture in purview. Parisio et al. [8], Kriett et al. [5], and Collazos et al. [3] all provide similar approaches with subtle differences for an end-user in a grid. Collazos et al. [3] propose a MPC strategy that studies the problem from a thermal perspective but, omits electrical storage and power flow calculations, Kriett et al. [5] use the electrical devices as well, but fail to include part-load characteristics of the CHP units and heat pumps used in the systems and uses simplified electrical flows while sacrificing electrical and thermal buffers. Parisio et al. [8], use similar approaches to both Collazos et al. and Kriett et al., but use quadratic cost functions which provide a much more detailed and