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Supervision control for optimal energy cost management in DC microgrid: Design and simulation

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ABSTRACT

The development of microgrids could facilitate the smart grid feasibility which is conceived to improve instantaneous grid power balancing as well as demand response. It requires microgrid control functions as power balancing, optimization, prediction, and smart grid and end-user interaction. In literature, these aspects have been studied mostly separately. However, combining them together, especially implementing optimization in real-time operation has not been reported. The difficulty is to offer resistance to optimization uncertainties in real-time power balancing. To cover the research gap, this paper presents the supervision design with predicted powers flow optimization for DC microgrid based on photovoltaic sources, storage, grid connection and DC load. The supervision control, designed as four-layer structure, takes into account forecast of power production and load power demand, storage capability, grid power limitations, grid time-of-use tariffs, optimizes energy cost, and handles instantaneous power balancing in the microgrid. Optimization aims to reduce the microgrid energy cost while meeting all constraints and is carried out by mixed integer linear programming. Simulation results, show that the proposed control is able to implement optimization in real-time power balancing with resistance to uncertainties. The designed supervision can be a solution concerning the communication between loads and smart grid.

1. Introduction

Aiming to avoid grid voltage fluctuations [1,2], or even blackout, at any time instant, the electric grid must balance power between the production and the consumption with a small margin of error. The grid capacity is built to satisfy the peak consumption. If the peak consumption can be shifted during a day, referred to as "peak shaving", the power adjustment, often ensured by excess capacities working in stand-by mode, could be largely reduced. To build a more robust utility grid, strategies and means of power management are being developed, as well as information on grid needs and availability [3], which could assist in power balancing by avoiding undesired injection and performing load shaving during peak hours. For this, the smart grid is being created to facilitate information exchange. Smart grid is electric networks that employ innovative and intelligent monitoring, control communication, and self-healing technologies to deliver better services for power producers and distributors, flexible choices for end-users, reliability and security of power supply [4,5]. Smart grid is expected mainly for the following aspects: bidirectional power distribution; bidirectional communication, and reduction mismatching between supply and demand.

The concept of microgrid is proposed for better renewable energy penetration into the utility grid and helps energy management to respond to some grid issues, such as peak shaving, and reduces energy cost [6–10]. Microgrids are considered as one of the possible approaches helping to develop the smart grid [11]. By aggregating loads and multi-source, renewable and traditional, microgrid can operate in both off-grid and grid-connected configuration. It is generally considered that microgrid controls on-site generation and power demand to meet the objectives of providing local power, ancillary services, and injecting power into the utility grid if required [8]. Concerning microgrid approach, several main advantages can be given: improving renewable energy penetration level, facilitating the smart grid implementation, better energy supply for remote areas, power balancing at local level with self-supplying possibility, and maintaining load supply during islanding operation or off-grid mode [12]. Thus, the microgrid controller becomes essential for balancing power and energy management, and facilitates the sources pooling during islanding.

Depending on the usage of AC or DC bus for coupling different elements within microgrid, AC microgrid, DC microgrid and hybrid AC/DC microgrid structures exist [13]. At present, the DC grid is not ubiquitous [14,15], but more HVDC transmission lines are being built in MW level, while low voltage DC grid is being adopted,

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Nomenclature

C_G	grid energy cost (€)
C_{LS}	load shedding cost (€)
C_{PVL}	PV production limitation cost (€)
C_S	storage energy cost (€)
C_{total}	microgrid energy cost (€)
c_G	grid energy tariff (€/kW h)
c_{NH}	grid energy tariff for normal hours (€/kW h)
c_{PH}	grid energy tariff for peak hours (€/kW h)
c_{LS}	load shedding tariff (€/kW h)
c_{PVL}	PV production limitation tariff (€/kW h)
c_S	storage energy tariff (€/kW h)
C_P	proportional gain
C_{REF}	storage nominal capacity (Ah)
i_{PV}	PV current (A)
i^*_{PV}	PV current reference (A)
K_D	distribution coefficient
K_L	load shedding coefficient
$K_{L\_\lim}$	load shedding limit coefficient
p^*	power reference (W)
p_G	grid power (W)
p^*_G	grid power reference (W)
p_{G_I}	grid injection power (W)
p_{G_S}	grid supply power (W)
$p_{G\_I\_\lim}$	grid injection power limit (W)
$p_{G\_S\_\lim}$	grid supply power limit (W)
$p_{G\_I\_prediction}$	grid injection power prediction (W)
$p_{G\_S\_prediction}$	grid supply power prediction (W)
p_L	load power (W)
p_{L_D}	load power demand (W)
$p_{L\_\lim}$	load power limit (W)
$p_{L\_\max}$	load maximum power (W)
$p_{L\_prediction}$	load power prediction (W)
p_{PV}	PV power (W)
$p_{PV\_\lim}$	PV limited power (W)
$p^*_{PV\_\lim}$	PV limited power reference (W)
p_{PV_MPPT}	PV MPPT power (W)
$p_{PV\_prediction}$	PV power prediction (W)
p_S	storage power (W)
p^*_S	storage power reference (W)
p_{S_C}	storage charging power (W)
p_{S_D}	storage discharging power (W)
soc	storage state of charge (%)
$SOC_{\max}$	SOC upper limit (%)
$SOC_{\min}$	SOC lower limit (%)
SOC_0	initial soc (%)
v	DC bus voltage (V)
v^*	DC bus voltage reference (V)
v_{PV}	PV voltage (V)
v^*_{PV}	PV voltage reference (V)
$v^*_{PV\_\lim}$	PV limited voltage reference (V)
$v^*_{PV\_MPPT}$	PV MPPT voltage reference (V)
v_S	storage voltage (V)

Abbreviation

ACR	automatic current regulator
AVR	automatic voltage regulator
HMI	human–machine interface
MPPT	maximum power point tracking
NH	normal hours
PH	peak hours
PI	proportional–integral
PV	photovoltaic
P&O	Perturb & Observe
PWM	Pulse Width Modulation

starting with data centers, for the reason of more efficiency, less cost, less occupied space, lower lifetime cost and more reliability [16–18].

Paper [13] presents a three-levels hierarchical control according to ISA-95 and applied to AC or DC microgrids. This general approach of hierarchical control for microgrids is conceived for a large-scale power system, upstream in the utility grid hierarchy. Imitating the behavior of a grid synchronous generator control, the proposed hierarchical control strategy aims at balancing power between multi inverters coupled on the same bus without communication, while controlling the power at the point of common coupling (PCC) at the same time. The proposed hierarchical control is considered as a part of the central control and does not take into account the prediction of the power generation and the energy optimization.

In [18], support for autonomous DC microgrid applications is proposed by integrating the device-level service oriented architecture paradigm into the international standard IEC 61850 applications. In order to create self-manageable microgrid with semantic-enabled plug-and-play process for distributed energy resources, this solution provides generic middleware platform required for vertical communication. However, the proposed solution applied to the real microgrid power systems requires additional control and regulation policy.

A high-level energy management supervision, by means of multi-agent systems, is presented in [19]. In this work, the authors focus on two-level architecture for multiple interconnected microgrids aiming to manage distributed energy resources in order to match the buyers and sellers in the energy market.

A generalized formulation for intelligent energy management of a microgrid is proposed in [20] using multiobjective optimization to minimize the operation cost and the environmental impact. An artificial neural network ensemble is developed to predict renewable energy generation and load demand. In addition, a battery scheduling is proposed as a part of an optimal online energy management, seen as a decision-making process. However, smart grid data exchanges online or dynamic energy pricing are not considered.

To increase penetration of small PV production into the grid, a local hierarchical control with energy management is proposed in [22]. The system is presented as multi-layer control structure, each layer with a different function, and is based on an optimal power flow management with predictions, which considers batteries ageing and day-ahead approach into the optimization process. However, the exchange data with the smart grid, such as limitations of the grid capacity, is not taken into account. Moreover, due to uncertainty of prediction and lack of grid information, the grid power could be out of control.

Concerning the energy management two main approaches are considered: rule-based and optimization-based approaches. Rule-based approach manages the system according to prefixed rules, such as simple rule base, multi-agent system [19] and fuzzy logic approaches [20,21]. Optimization based approach manages the system by mathematical optimization, carried out with objective function and constraints. The optimization methods include the artificial intelligence joint with linear programming [20], linear programming [21] or dynamic programming [22,23], and genetic algorithms [24].