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Multi-Level Energy Management and Optimal Control of a Residential DC Microgrid

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Abstract—Extensive exploitation of renewable energies together with the increased role of low-voltage DC (LVDC) micro-sources in the generation mix of the future electricity networks, have become the driving force behind the DC microgrid applications. In this paper, an optimal dispatch model of a residential DC microgrid (R-DCMG) with different distributed generations (DGs) and loads is proposed and implemented as an optimal hierarchical control strategy. A system-level optimizer is designed to calculate the optimal operating points of the controllable energy sources (CESs) when needed, while lower-level controllers are utilized to enforce the CESs to follow optimal set-points.

I. INTRODUCTION

With the technological advancements in power electronics together with the increasing penetration of DC loads and sources especially in residential sector, DC microgrids (DCMG) have attracted more attention and become the subject area for many ongoing research works [1]-[4]. A number of initiatives have been paid a particular attention to demonstrating the advantages of DCMG over the existing AC networks and some others have been focused on DC networks topologies and inverter interfaced technologies [5]-[6]. However there exist several challenges in control and operation of residential DCMGs (R-DCMGs) where conventional energy sources and loads are being replaced by efficient power electronic-based DC micro-sources (such as photovoltaic systems (PV) and fuel-cells (FC)) and advanced consumer electronics [7].

In this paper, an optimal dispatch model of a R-DCMG with

different means of distributed generation (DG) (such as small-scale wind turbines (WTs), PVs, FC-based micro-combined heat and power generator (FC- μ CHP) and energy storage options) is proposed and implemented as a hierarchical control strategy. In a strategic control layer, an optimizer is designed and operated to track the system behavior in real-time and to update the operating points of the controllable energy sources (CESs) during the study period, while in the operation layer, device-level controllers are designed and utilized to enforce the CESs to follow optimal set-points coming from the system optimizer. The mentioned optimal operation and dispatch model is formulated as a mixed-objective optimization problem with different constraints stemming from the real technical and operational limitations of the system's components and is solved using General Algebraic Modeling System (GAMS) as the optimization engine.

II. DC MICROGRID MODELING AND OPTIMAL CONTROL

A. System Architecture

Fig. 1 illustrates a grid-tied R-DCMG used as a benchmark in this paper. The system includes a cluster of residential buildings as loads and different DGs in forms of non-dispatchable (renewable sources such as PVs and WTs) and dispatchable (such as FC-mCHP and batteries) as energy sources. As shown in the figure, all dispatchable units are operated in power control mode (PCM) to follow a power reference received from the system optimizer, while the upstream power grid is operated in voltage control mode to

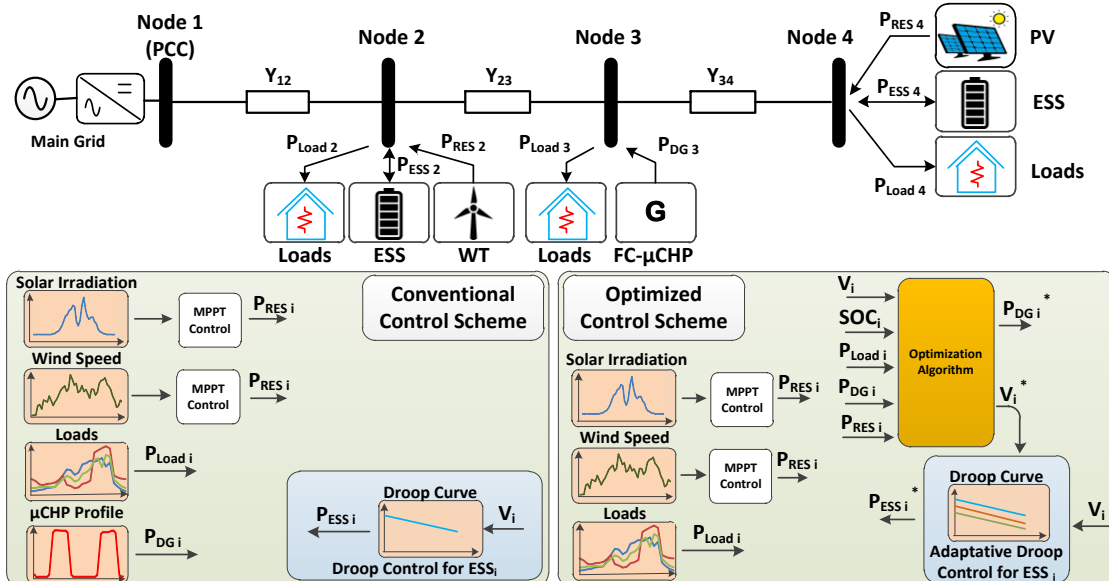


Fig. 1. System architecture and control scheme of the examined grid-tied residential DC microgrid.

keep the PCC voltage constant and provide the required system stability.

B. Optimal Control Methodology

To optimally manage and control the behavior of the described R-DCMG, a coordinated operation between the system-level optimizer and device-level controllers is needed. More importantly, a well-defined action plan for the strategic control layer, where the system optimizer exists, is required. Conventionally, proportional power sharing strategy based on droop control has been widely adopted for DG management. However, this power management strategy is not an optimized solution in terms of operation economies. In this work, optimal control of DG units is proposed from a cost-effective viewpoint. Regarding this, a mixed-objective function with related constraints, as stated in (1), is considered as the proposed optimization model. For each time interval which triggers the decision point, the system optimizer collects the required operating data (e.g., nodal voltages V_i , DG outputs $P_{DG,k}$, and loading levels L_j) and solves the mentioned optimization model to find the optimal power dispatch of controllable DG units ($P_{DG,k}^* = \{P_{G,k}^*, P_{ESS,k}^*\}$).

$$\begin{aligned} \text{Min: } F(x) &= [f_1(x), f_2(x), \dots, f_m(x)] = \sum_{k=1}^m \psi_k f_k(x) \\ \text{s.t. } g_i(x) &\leq 0 \quad ; \quad i = 1, \dots, q \\ h_j(x) &\leq 0 \quad ; \quad j = 1, \dots, p \end{aligned} \quad (1)$$

where $F(x)$ is the vector of objectives (which is defined as the weighted sum of total operating cost and power loss of the R-DCMG in this paper) and ψ_k is the weighting coefficient reflecting the significance of the corresponding objective from the system operator's prospective. $g_i(x)$ and $h_j(x)$ denote the inequality and equality constraints for the examined system.

III. RESULTS AND DISCUSSION

The proposed multi-level energy management and optimal control strategy has been tested through computer case studies and Hardware in the Loop simulations (HIL) and its performance has been demonstrated against a conventional droop control method. The results are depicted in Fig. 2 in terms of output powers of DGs and bus voltages. As can be seen in the upper subfigure, the proposed energy manager dispatches the controllable units in a cost-efficient manner, and accordingly reduces the global operational costs of the R-DCMG over the studied period, by taking into account the real-time electricity prices (RTP), degradation cost of the energy storage units, power losses over the distribution lines, and the fuel consumption cost of the FC- μ CHP.

In comparison with the conventional control strategy, although the average deviation of the nodes' voltages is increased by use of the proposed strategy, it is still within the allowed range. It is noteworthy that there is a trade-off between the system operating cost and voltage deviations in nodes which can be further studied through a modified multi-objective optimization process.

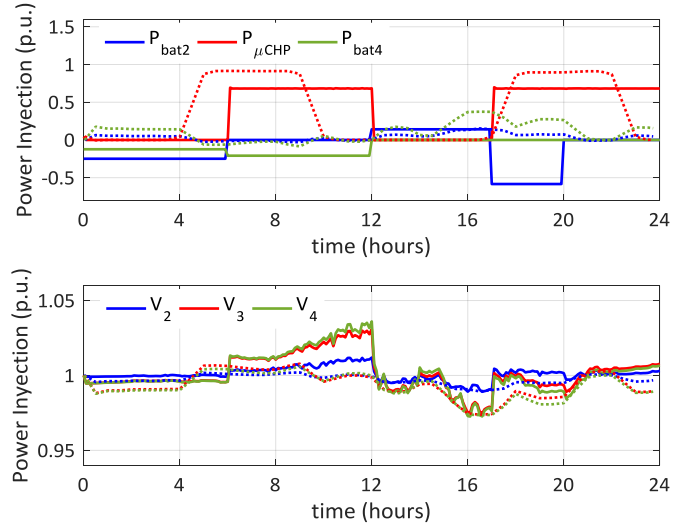


Fig. 2. Upper subfigure: Active power generation of the dispatchable units without optimal control (dashed) and with optimal control (solid). Lower subfigure: Voltage level at the nodes without optimal control (dashed) and with optimal control (solid).

IV. CONCLUSIONS

An optimal energy management and power sharing model for a grid-tied residential DC microgrid based on the principles of hierarchical control was presented and verified through computer simulations and experimental studies. The proposed optimal dispatch model not only reduced the running cost of the system throughout the network, but also satisfied system's constraints (e.g. allowed voltage deviation, DG units' power and energy capacities, etc.) under any working conditions. It also reduced the power losses in the network by making a better power balance at each node (i.e., through optimal dispatch of DGs to supply their local loads), thus reducing the power flow between the nodes.

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