Electric Power Systems Research 141 (2016) 104–113

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Optimal management of unbalanced smart microgrids for scheduled and unscheduled multiple transitions between grid-connected and islanded modes

Karim Hassan Youssef

Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt

ARTICLE INFO

Article history:
Received 7 August 2015
Received in revised form 12 June 2016
Accepted 16 July 2016

Keywords:
Demand Response (DR)
Distribution optimal power flow (DOPF)
Model Predictive Control (MPC)

ABSTRACT

The paper proposes a novel optimization framework for smart microgrids for both scheduled and unscheduled multiple transitions between grid-connected and isolated modes. The optimization aims at maximizing the overall microgrid profit, from selling energy to grid, and minimizing consumption costs by scheduling dispatchable loads and generation, energy storages, and load curtailment while satisfying all network and operational constraints. For unscheduled transitions, the time of mode transitions in the planning period is not known in advance. So, the optimization is reinitialized and restarted online after considering the most updated state. Network constraints for three-phase unbalanced distribution microgrid model are adopted in details in convex formulation. Bidirectional energy trading with the grid is considered. Moreover, Model Predictive Control (MPC) is used for handling uncertainty in renewable generation and load. Comprehensive simulation results are given for validating the proposed algorithm and comparison is made between results of scheduled and unscheduled optimization.

1. Introduction

Microgrids are distribution systems that contain, loads, generation from conventional and renewable sources, and Energy Storage (ES) devices. Microgrids are connected to the main grid through substations and can be operated in either grid-connected mode or isolated mode. Smart grids have two directional power flow, and communication between energy producers and consumers. In smart microgrids, both loads and generation are intelligent so that they can communicate each other and communicate the central Energy management systems (EMS) for distributed, decentralized or centralized optimization of the microgrid operation. Intelligent optimization of loads, by optimizing periods of power exchange and power reduction, is known as Demand Response (DR) [1–3].

Transition between grid-connected and islanded modes may be scheduled, for substation maintenance, transmission congestion management, or may be unscheduled due to fault in the substation or the incoming transmission line, or load shedding after loss of generation. In islanded mode, conventional dispatchable generators are responsible for controlling power balance, by their own droop characteristics, and providing reactive power. In this case, frequency deviation should be minimized while satisfying other network constraints. After removal of the islanding cause, the system returns to grid-connected mode after proper synchronization and this operation may be repeated number of times during the scheduling period.

Most of publications in microgrid energy management address optimization in either grid-connected [4–7] or isolated [8,9] modes or both modes but with no mix between them as in Ref. [1]. In Ref. [10], microgrid generators are scheduled for minimizing local generation cost with sufficient reserve to ensure stable islanding while not concerning voltage constraints, energy storage, or controllable loads. In Refs. [5–7,9,10], no network model is adopted and the main concern is only balancing between active power generation and consumption.

When dealing with network constraints, such as bus voltages, line currents, line losses, and line power flows, Optimal Power Flow (OPF) is required. Distribution system may also be unbalanced due to phase configurations and unbalanced loading. Unbalance distribution optimal power flow (DOPF) that takes into account constraints on bus voltages is done in Refs. [11–15] for only grid-connected mode and in Ref. [16] for islanded mode and both are only for fixed loading snapshot without Demand Response.

In the literature, uncertainties in model-based optimization have been handled using Linear Quadratic Gaussian (LQG) control [17], Artificial Intelligent (AI), Stochastic Programming (SP) con-

---

E-mail address: khmyoussef@yahoo.com

http://dx.doi.org/10.1016/j.epsr.2016.07.015
0378-7796/© 2016 Elsevier B.V. All rights reserved.

sidering probabilities of different scenarios [18–20], and Model Predictive Control (MPC).

Model Predictive Control is a model-based control framework effective in dealing with model uncertainty, un-modeled disturbances and disturbances with unknown characteristics. MPC has been used in for microgrid optimization and scheduling [21–24]. In the proposed work MPC is used in dealing with uncertainty in renewable generation and load.

In this paper, optimization of smart microgrid is proposed for both scheduled and unscheduled multiple mode transitions during scheduling period. The time of mode transitions in the planning period is known in advance in the scheduled transitions and unknown in the unscheduled transitions. The central EMS collects information from smart loads, generators, and grid. EMS performs optimization according to the predetermined schedule of mode transitions or according to the switch status upon occurrence of unscheduled transitions. The EMS then send power setting back to each microgrid member. Information exchange in the proposed method is shown in Fig. 1. The main contributions of the proposed method are as follows.

1. Microgrid optimization is done for both scheduled and unscheduled multiple transitions between grid-connected and islanded modes for maximizing microgrid profit considering bidirectional energy trading with the grid with different prices.
2. Unscheduled transitions are handled where the time of mode transitions in the planning period is not known in advance. After each transition, the optimization is reinitialized after considering previous consumed energy with the assumption of no more mode transitions until the end of the scheduling period.
3. Constraints on the change of variables before and after transitions are adopted. Load sharing among generating units, steady-state frequency deviation during islanding, and cost of power interruption of loads with different priorities are all augmented in the optimization.
4. Detailed network model of three-phase unbalanced distribution system and network constraints is given in convex forms.
5. Model Predictive Control is proposed for accounting uncertainty in renewable generation and load.

The optimization model presented in this paper can be extended to account for all uncertainties in the decision making process of Distribution Network Operator (DNO) using Information Gap Decision Theory (IGDT) [25] by modification of objective function and constraints. If information about behavior of uncertainties is available, other probabilistic and fuzzy methods can also be used. Customer behavior can also be incorporated in the present work by considering time-dependent probabilistic load models and considering multiple scenarios in the objective function. Scenario reduction techniques can be used to reduce computational burden.

The paper is organized as follows. Problem formulation for scheduled multiple transitions is presented in Section 2, while, for unscheduled multiple transitions is given in Section 3. Uncertainty in renewable generation and load is discussed in Section 4. Model Predictive Control is suggested in Section 5 for dealing with uncertainties. Results and discussion are given in Section 6 and conclusions are extracted in Section 7.

2. Problem formulation for scheduled mode transitions

In scheduled multiple mode transitions, time of transitions in the whole planning period is known in advance. The purpose of the optimization problem is to maximize the microgrid profit or to minimize the overall cost of buying energy from the grid (or maximizing the profit from selling energy to grid). Cost of local energy generation is to be minimized, while affording reduction in controllable, ordinary, and critical load.

2.1. Objective function

The objective function for scheduled transitions between grid-connected GC, and islanded I modes; $f_{\mathrm{GC}-I}$ can be formulated as:

$$f_{\mathrm{GC}-I} = w_1 \left\{ \sum_{t=1}^{T} (f_c^t - f_r^t)\hat{p}_{\mathrm{grid}}^t + \sum_{t=1}^{T} (f_r^t p_{\mathrm{grid}}^t) + \sum_{t=1}^{T} \sum_{g=1}^{n_g} (f_g^t p_g^t + h_g^t (p_g^t)^2) + \sum_{i=1}^{n_c} f_i x_i + \sum_{t=1}^{T} f_d^t x_d^t + \sum_{t=1}^{T} f_{\mathrm{cr}}^t x_{\mathrm{cr}}^t \right\} + w_2 \left\{ f_\omega \sum_{t=1}^{T} (\Delta\omega^t)^2 + f_q \sum_{t=1}^{T} (q_{\mathrm{grid}}^t)^2 \right\} \qquad (1)$$

where, at time slot t, $\hat{p}_{\mathrm{grid}}^t = \max\left\{p_{\mathrm{grid}}^t, 0\right\}$, P_{grid}^t is active power imported from grid in kW, f_r^t is price of power generated to grid at in \$/kW h, f_c^t is cost of energy imported from grid in \$/kW h, p_g^t is generated power of generator g in kW, f_g^t is linear coefficient of cost of power generation of generator g in \$/kW, h_g^t is quadratic coefficient of cost of power generation of generator g in \$/kW^2, f_{cr}^t is cost of undelivered power of the critical load in \$/kW, x_{cr}^t is load shedding of critical dead load power in kW, f_d^t is cost of undelivered power of ordinary load in \$/kW, x_d^t is reduction of ordinary load power in kW, f_i is cost of reducing consumption of controllable load i in \$/kW h, x_i is saved energy of controllable consumer i in kW h, w_1, w_2 are weighting factors, T is number of scheduling hours, n_c is number of consumer with controllable loads, n_g is number of conventional generators, $\Delta\omega^t$ is frequency deviation from nominal frequency in rad/s, q_{grid}^tZ is reactive power imported from grid in kVAr.

This formulation ensures convexity of the objective function (see Ref. [26]). The first term contains the cost of energy imported from grid (or the profit from energy exported to grid) cost of producing energy from local conventional generators, cost of reduction

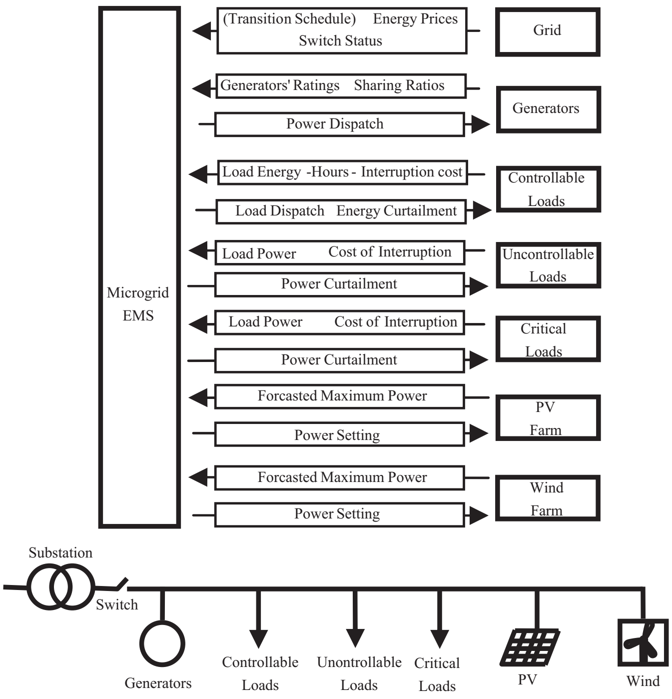

Fig. 1. Information exchange in the proposed smart microgrid.