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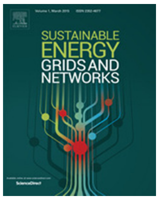

Economic and network feasible online power management for renewable energy integrated smart microgrid

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ABSTRACT

In this paper, an online power management (OPM) problem is proposed using measured/short term forecasted data. It improves the cost and dynamic performance of microgrid along with the consideration of interval uncertainties in renewable energy and loads. Additional options of grid power trade and demand response (DR) are provided for operational cost reduction, consumer participation and enhanced network performance. A combination of stochastic weight tradeoff particle swarm optimization (SWT-PSO) and interval arithmetic (IA) is proposed to analyze the effects of interval uncertainties of nodal power injections (due to renewable energy sources (RES) and loads) on microgrid cost and power flow variables. The effectiveness of the proposed approach is investigated by adding different power balancing resources one by one, to the residential feeder of CIGRE LV benchmark microgrid. The results are found to be improved in terms of reduction in fuel and emission costs, improved nodal voltages and network feasible OPF solution in interval forms corresponding to system volatilities. Moreover, settling time of online dispatch is reduced, thereby improving the dynamic response of distributed energy resources (DERs). In addition, the paper justifies the use of RES, DR, grid power trade (over islanded mode) and SWT-PSO (over priority listing).

1. Introduction

The development of microgrids with increasing rate of load demand growth, motivates the studies on new techniques for power management. In microgrids, dispatchable and non-dispatchable DERs can be easily connected in a localized manner. This can be achieved by connecting micro-sources (below 100 kW) directly to the low voltage (LV) distribution feeders [1]. Other than local DERs, the microgrid uses other resorts like grid power trade, DR, battery storage etc. for power balance and the associated technical and economic aspects are dealt by the microgrid operator. The operator maintains source–load balance, facilitates DR schemes, maximizes system benefits, transacts power with the main grid and schedules reserves [2]. To execute these tasks in online mode, the microgrid operator requires an efficient, fast and feasible OPM approach which takes care of both economic and network benefits of the microgrid system. The approach should also accommodate the uncertainties in power injections from RES and their effects on microgrid benefits.

Acronyms

OPM	Online power management
RES	Renewable energy sources
N-R	Non-renewable energy sources
DER	Distributed energy resources
SWT-PSO	Stochastic weight tradeoff particle swarm optimization
OPF	Optimal power flow
DR	Demand response
MGCC	Microgrid central controller
IA	Interval arithmetic
PF	Power flow
BFS	Backward–forward sweep
FC	Fuel cell
MT	Microturbine
DG	Diesel generator

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Many researchers have carried out studies on formulation of OPM in microgrids. Mesh adaptive direct search (MADS), sequential quadratic programming (SQP) and genetic algorithm (GA) were used in [3]. The target was to minimize fuel and emission costs through a central controller. SQP gave the best results in terms of cost and computation time. In [4], the authors proposed a method for explicit and distributed real-time control of grid status, based on a common abstract model in which sub-systems are aggregated into virtual devices that hide their complexity. Thus, it is adaptable to systems of any size or complexity, enabling smart grid management and communication through agents hassle free. However, the consideration of DR, operational fuel and emission costs and stochastic effects of renewable energy and loads on the extent of indecision in the planning horizon, is not discussed. In [5], the same problem in [3] was solved using priority listing technique to achieve the best execution time, fuel and emission cost values. But, the aforementioned literatures emphasized on cost only, rather than checking the network feasibility. Moreover, they failed to investigate the possibility of accommodating extra resorts such as grid power trade, DR etc. So, Refs. [6–9] implemented DR using responsive loads for scheduling and achieved further reduction in fuel and emission costs. Other means of economic energy management were investigated in [10] through grid power trade, by utilizing it at off-peak hours at cheap power prices. A multi-objective function for optimizing both emission and fuel costs was formulated and solved using data mining approach in [11]. But these works could not consider the effects of nodal power uncertainties due to RES on power flow and cost variables.

It is a complex task to incorporate all the possible resources (DR, grid power, uncertain RES) to an OPM platform and dispatch each source, meeting these challenges. The technical infeasibility problem will persist due to the oversight of power flow analysis, and the avoidance of the effect of uncertainties. Hence, the fundamental OPM objective [5] is modified step by step in this paper, by adding N-R sources, DR, grid power trade and RES. The effects of each resource/power balance resort on the cost and power variables are separately analyzed. Though, the time frame is short (1 min/15 min/30 min/1 h), lower levels of uncertainties in wind and solar power in this period have to be considered for a realistic dispatch, which is also addressed in this work. It is not realistic to take computation time as the execution time for OPM since the overall execution time for real time dispatch is the sum of computation and settling time [3–5]. This paper attempts to consider both for evaluating the dynamic performance of DERs with the proposed method. In short, an attempt has been made to improve the overall performance of microgrid by designing an OPM problem in respect of the following aspects:

- To reduce the operational cost of microgrid by (1) using a robust SWT-PSO method over priority listing technique [5] (2) incorporating Grid Power Trade, DR and RES.
- To improve the dynamic response of DERs by considering network feasibility objectives and constraints, thereby reducing the settling time.
- To accommodate the short term uncertainties in nodal power injections from RES and loads to obtain realistic DER outputs and operational costs using IA-OPF.

The proposed online energy scheduling problem is purely static. However, to justify and demonstrate the possible benefits of real time dispatch with the designed set points, the implementation times are approximately evaluated and compared with the method reported in literature. The work does not delve in to a control problem rather limits itself to an optimization problem. 'Real time' dispatch in this paper refers to the dispatch based on measured generation and demand. It has discrepancies with forecasted data and it is represented by intervals in this work. If the intervals corresponding to possible uncertainties are known in the planning horizon itself, then it gives an idea of secondary voltage and frequency control.

The remainder of the paper is organized as follows. Objective formulation is given in Section 2. The methodology of online power management for different cases is detailed in Section 3. System studies are given in Section 4. The paper is concluded with the rundown of main points in Section 5.

2. Objective formulation

Formulations for five different cases are discussed in this section. In case 1, OPM is formulated for N-R sources only, in islanded mode. Case 2 includes an additional option of grid trade. Case 3 modifies the problem by including network feasibility terms in the objective and additional constraints. Case 4 gives an additional option of DR. Case 5 incorporates wind and solar energy source models (RES) as uncertain sources of power injection in the interval form.

Case 1: *OPM with N-R sources only*

In this case, the same problem of [5] (with the same measured data inputs) is used for online dispatch by the microgrid operator. But, the solution method is SWT-PSO rather than the priority listing used in [5]. In this paper, the microgrid is considered as a single player model where the scheduling decisions based on technical and financial consequences are taken by the microgrid operator [1]. Micro-turbine (MT), fuel cell (FC) and diesel generator (DG) are the N-R sources used in the study. Thus, the objective function considers sum of fuel and emission costs only. The objective function and constraints are:

$$\mathit{Minimize}\ F_1\,(P) = \sum_{i=1}^{n} P_{gi}\cdot f_i(P_{gi}). \tag{1}$$

Subject to constraints (2) and (3)

$$\sum_{i=1}^{n} P_{gi} = P_d \tag{2}$$

$$P_{gi}^{(\min)} \le P_{gi} \le P_{gi}^{(\max)} \tag{3}$$

where, n is the number of N-R sources in the system, $F_1\,(P)$ is the total generation cost function ($/h), P_d is the measured demand obtained from the PCC, $f_i(P_{gi})$ is the incremental cost (IC) function ($/kWh) for each DER '$i$' which is the sum of fuel and emission IC functions, P_{gi} is the active power generated (kW), $P_{gi}^{(\min)}$ and $P_{gi}^{(\max)}$ are the lower and upper bounds of active power generation (kW) of DERs. Eqs. (2) and (3) represent equality constraint of the microgrid and generation limits of the DERs respectively.

Case 2: *OPM with N-R sources and grid power trade*

In this case, the problem is modified with an extra option of grid trade to provide scope for cheaper options during off-peak hours. That is, the MGCC can buy/sell power from/to the grid, depending upon the open market price. The objective function and constraints are:

$$\mathit{Minimize}\ F_2\,(P) = \mu_1\cdot F_1\,(P) + \mu_2\cdot\left(C\times P_{grid}\right). \tag{4}$$

Subject to constraints (3), (5) and (6)

$$\sum_{i=1}^{n} P_{gi} + P_{grid} = P_d \tag{5}$$

$$-P_{grid}^{(\max)} \le P_{grid} \le P_{grid}^{(\max)} \tag{6}$$

$F_2\,(P)$ is the sum of operational cost and the cost incurred for buying power from the grid. C is the grid power price in $/kWh. If P_{grid} is negative, then it is the amount of power sold to the grid

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