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A multi-criteria decision analysis-based approach for dispatch of electric microgrids

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ABSTRACT

This paper presents a decision support system (DSS) for multi-objective dispatch of an electric microgrid considering cost of operation, peak load reduction, and emissions. Discrete compromise programming (DCP) is used as the multi-criteria decision analysis (MCDA) technique for providing the decision support to the distribution system operator (DSO) by ranking various alternatives based on preference of the objectives. The focus of this paper is the application of DCP-based MCDA to select feasible dispatch solutions closest to the preference of the DSO when multiple objectives are considered in the microgrid dispatch. This technique obtains non-dominated solutions in case of conflicting objectives without generating a Pareto front, and hence avoiding prohibitive computational cost. DCP can be used for MCDA in both exact and metaheuristic dispatch algorithms. Uncertainty in renewable energy forecasting and load demand is included through a scenario-based approach by sampling empirical distributions. The dispatch algorithm considers a two hour look-ahead time horizon. Simulations are performed on a notional electric microgrid with diesel generator, solar photovoltaic, and energy storage. The microgrid is based on the IEEE 13-node test feeder and the results are presented.

1. Introduction

Dispatch is a fundamental problem in electric power engineering that has been solved as a constrained optimization problem using various direct and heuristic techniques [1–8]. Traditionally, objectives such as operation cost, emissions, loss reduction, physical security and reliability along with physical limits of the power system as constraints are considered [1–5]. The increasing interest and progress in the development of the electric microgrid concept through demonstration projects, deployment, and testing indicates a few fundamental differences from the traditional electric power system (EPS) [7–11]. According to some well accepted definitions of an electric microgrid, the salient points that differentiate a microgrid from EPS are: local generation in the form of renewable and distributed energy resources (DER); demand response (DR); the ability to operate in grid-paralleled and islanded modes; and, the appearance to the EPS as a single controllable entity [12–18]. Other differences are based on the functions that the microgrid performs in context of the grid-connected or islanded modes of operation. A microgrid can be designed and used to serve various purposes such as reducing the peak load and losses in distribution grids, powering critical loads, enhancing reliability, reducing emissions through the deployment of renewables, maximizing profits from selling energy and ancillary services, and maintaining or improving power quality [16–19]. Thus, dispatch in microgrids can be posed as a constrained multi-objective optimization problem that can seek a near-optimum solution for a subset of objectives from the abovementioned list [18,20–23]. Moreover, the preference of the objectives might not be available before the solution alternatives are obtained, and can also vary over the horizon of the dispatch. The variability and uncertainty due to the prediction errors of renewables makes the dispatch challenging. The uncertainty is handled though statistical distributions in [24–26] to identify intra-hour ramping/balancing needs in wind and solar integrated power system under California ISO. Stochastic scheduling is adopted with scenario-based approach in [27], and scenarios are used for day-ahead bidding for microgrids using hybrid stochastic/robust optimization in [28]. Scenario-based approaches can be computational expensive and appropriate scenario reduction must be employed, as used in [29–31] for electricity markets, decision-making for planning and optimization. A state-of-the-art review of such techniques can be found in [32]. In [33–35], real time energy management in microgrids is presented with energy storage, and renewable uncertainties for finite-time horizon. The

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abovementioned applications and methods explore uncertainties with either single or aggregated objectives. In this work, we present the application of decision-making while considering multiple criteria through scenario-based finite-time horizon day-ahead dispatch. Due to the differences mentioned above and variety in functionalities, the dispatch in electric microgrids typically considers multiple objectives and therefore is more challenging than the dispatch in traditional EPS.

In this paper, a multi-criteria decision analysis (MCDA) based approach is presented for scheduling the dispatch in microgrids. Goal attainment programming is used to solve the multi-objective dispatch functional and discrete compromise programming (DCP) is applied as the MCDA technique for ranking the dispatch alternatives each hour for the decision maker (DM). DCP-based MCDA is a reference point technique where the best achievable value for each objective is used as reference for decision making. DCP does not require a Pareto front to be generated for tradeoff amongst multiple objectives, and non-dominated solutions can be selected using L^p norms [36,37]. The rest of the paper is organized as follows: Section 2 presents the formulation of the dispatch problem, goal attainment programming, DCP, and decision support system (DSS); Section 3 describes the simulation setup and relevant input data; Sections 4 and 5 present the results and conclusions, respectively.

2. Material and methods

2.1. Dispatch in electric microgrids

Apart from the reasons mentioned in the previous section, the dispatch in microgrids is also challenging due to difference in contribution to the objectives to be met. The inherent characteristics of the dispatchable and non-dispatchable DERs might affect the objectives differently, at different times of the day. External factors such as policies, restrictions, controllability of DERs due to ownership, markets, and requirements of the DSO can also be crucial. To effectively dispatch the DERs to meet the objectives, these intrinsic heterogeneities and external factors must be considered in the dispatch methodology. Since the external factors are system specific and can vary with the domain of utility control, we focus on the intrinsic features of DERs. The uncertainty in output of DERs due to variability and forecasting errors are included in the day-ahead dispatch. In this regard, a multi-objective day-ahead dispatch methodology is presented by considering the influence of the DERs on the dispatch objectives. It is assumed that the DSO is the DM and has complete controllability of the dispatchable DERs. However, the DM does not have the perfect knowledge of the preference of the objectives due to the interdependence and conflict of different objectives, and hence an interactive support system for decision making is presented in the form of MCDA.

2.1.1. Problem formulation

The day-ahead hourly dispatch is formulated as a multi-objective problem with three objectives: minimization of operation cost, peak load, and emissions. These three objectives are some of the most highly preferred functionalities of microgrids and have been used in several microgrid projects worldwide [9–15]. More objectives can be considered without loss of general applicability of the techniques presented in this work.

2.1.1.1. Objectives. The first objective for the dispatch is the cost of operation. It is calculated based on Time-of-Use (ToU) pricing of electricity from the bulk EPS, and cost of fuel expended to generate electricity using the DERs present in the microgrid. Renewable energy sources such as solar and wind are assumed to have zero fuel cost of operation. The cost function for the optimization problem is shown in (1).

$$\varphi_1 = \boldsymbol{c_e p_e} + \boldsymbol{c}_{\mu}^{T}\boldsymbol{p}_{\mu} \tag{1}$$

where c_e, $\boldsymbol{c}_\mu$ are the costs of generation in \$/kWh and p_e, $\boldsymbol{p}_\mu$ are the generation outputs in kWh.

The subscripts e and μ denote EPS and microgrid respectively, and the bold faced variable names denote vectors of length equal to the number of DERs in the microgrid. The microgrid considered here consists of a diesel generator, a solar photovoltaic (PV), and an electrical battery energy storage system (ESS) as DERs. The ESS is modeled as aggregated storage at the same node as PV. This can also be generalized as a community level ESS for aggregated residential rooftop solar [38]. The cost functions for EPS is the ToU pricing for electricity in Fort Collins, CO. The rate is based on Fort Collins Utilities' (FCU) 'ToU Rates Pilot Study' for residential customers during a summer weekday, and is given by (2) [39]. The on-peak hours are from 2 pm to 7 pm and all other hours are considered off-peak hours. The microgrid diesel generator quadratic cost function is given by (3) [40].

$$\boldsymbol{c_e} = \begin{cases} 0.0670\,\$/\mathbf{kWh}, & 1 \leqslant \boldsymbol{t} \leqslant 13, 20 \leqslant \boldsymbol{t} \leqslant 24 \\ 0.2249\,\$/\mathbf{kWh}, & 14 \leqslant \boldsymbol{t} \leqslant 19 \end{cases} \tag{2}$$

$$\mathbf{c_d} = \boldsymbol{F_{max}} \cdot \boldsymbol{f_d} \cdot \mathbf{C_d} \tag{3}$$

where F_{max} = 42.8 gal/h is the rated fuel usage of diesel generator in gal/h, $f_d = \alpha_2\phi^2 + \alpha_1\phi + \alpha_0$ is the fuel use rate, C_d is the cost of diesel in \$/gal, ϕ is the loading factor of generator in per unit, t is the time block in hours, and $\alpha_0 = 0.1524$, $\alpha_1 = 0.5780$, and $\alpha_2 = 0.2697$ are coefficients for diesel cost function in (3) [40].

The second objective is the load reduction during on-peak hours. The dispatch algorithm also allows the load reduction during the off-peak and on-peak hours. This objective is evaluated using the formula given in (4).

$$\varphi_2 = \sum \boldsymbol{p}_\mu \Big/ \left(\boldsymbol{p_e} + \sum \boldsymbol{p}_\mu\right) \times 100\% \tag{4}$$

The third objective is the reduction of emissions due to fossil fuel used for power generation. The CO_2 equivalents for traditional EPS generators and diesel generators are considered. Carbon emissions due to renewable sources and energy storage are considered zero. The emission factor multipliers and the objective function equation are given in (5).

$$\varphi_3 = \chi_e p_e + \boldsymbol{\chi}_\mu^T \boldsymbol{f}_\mu \tag{5}$$

where χ_e = 1.800 is emission factor for EPS [41], $\chi_\mu = \left[\chi_d; \chi_{pv}; \chi_{ess}\right]$ is the vector of emission factors for microgrid consisting of diesel (χ_d = 22.38 lbs/gal), solar PV ($\chi_{pv} = 0$) and ESS ($\chi_{ess} = 0$), $f_\mu = [f_d; f_{pv}; f_{ess}]$ is vector of fuel usage for diesel, solar PV, and ESS [42,43]. The values for emission factors are the upper limits on CO_2 emissions as per Environmental Protection Agency (EPA), and the diesel and EPS generation are assumed to operate at these limits without violations.

2.1.1.2. Constraints. The constraints for the optimization procedure are the physical capacity limits of DERs, the load demand and generation balance, ramp rates for the diesel generation, and physical voltage constraints. These constraints are coded in the dispatch algorithm but ramping constraints become inactive for hourly dispatch since the ramp rates are very fast (several seconds to a few minutes from standby to full load) for the diesel generator in the microgrid. Energy storage is constrained to lower and upper limits of state-of-charge (SOC) requirements. Cycling efficiency of ESS is also considered. These are shown as in (6a–g).