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Energy management of a microgrid via parametric programming

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Abstract: An energy management system (EMS) for efficient and tractable coordination of distributed energy sources in a residential level microgrid is presented. Sources of energy include renewable (solar photovoltaic and wind turbine), conventional systems (microturbine and utility grid connection) and battery energy storage system. The overall problem is formulated using parametric mixed-integer linear programming (p-MILP) via parameterizations of the uncertain coordinates of the wind and solar resources. This results in a bi-level optimization problem, where choice of the parameterization scheme is made at the upper level while system operation decisions are made at the lower level. The p-MILP formulation leads to significant improvements in uncertainty management, solution quality and computational burden; by easing dependency on meteorological information and avoiding the multiple computational cycles of the traditional online optimization techniques. The problem is solved offline on a day-ahead basis, allowing online implementation to be achieved via real-time system state updates. The proposed parametric programming approach extends the state-of-the-art in microgrid energy management methods, and the simulation evidence its feasibility and effectiveness.

Keywords: Microgrids; Energy management; Parametric optimization; Scheduling

1. INTRODUCTION

Local power quality and environmental concerns associated with the conventional energy systems have spurred a move towards an improved grid system consisting of distributed, hybrid energy sources (renewable and non-renewable) and loads - a microgrid (MG). In the face of external uncertainties arising from electricity demand, price, and the availability of renewable resources, the microgrid system is required to operate seamlessly and optimally with or without interactions with a central grid network. To achieve this coordinated operation requires sophisticated and efficient system-level integration and management of the constituent energy systems in a microgrid. However, a major challenge is that renewable energy is not dispatchable due to the apparent intermittency in the resource availability. Therefore, managing this uncertainty in renewable resources is a critical hurdle before all hybrid energy coordination algorithms.

Substantial research efforts have been devoted to developing methods and techniques for intelligent operation of microgrids within the larger electricity grid. Microgrid optimal energy management problems often have objective functions that may include cost or profit (continuous) functions and activation or deactivation (binary) decisions (Trifkovic et al., 2014; Bacha et al., 2015). The solution methods can be broadly divided into heuristic and deterministic routines. Heuristic methods allow for a reasonable solution to a difficult problem to be obtainable, albeit mostly at the expense of any systematic form of guarantee of optimality (Papadaskalopoulos et al., 2014). Deterministic algorithms assume some level of understanding of the sources of system uncertainty; which makes the set of expected outcomes to be finite, thereby providing for closed form solution(s) of the problem to be attainable (Wang et al., 2014).

The aim of this paper is to present an optimal energy management strategy for a set of microgrid technologies consisting of a wind turbine (WT), solar photovoltaic (PV) system, battery energy storage system (BESS), microturbine (MT) and utility grid connection. The goal is to develop an operational scheduling strategy that allows all the microgrid components to be operated seamlessly and in sync - in the face of uncertainties from wind power, solar power, electricity price and load demand - in order to ensure high penetration of renewable energy and regular satisfaction of the local load demand at the minimum net cost. To achieve this purpose, we develop models of the individual energy devices in the microgrid and pose the energy management goal as an optimization problem with a bi-level decision structure. Then we exploit the bounded uncertainties in the power outputs of the WT and PV through parameterizatons of their renewable resource inputs; which leads to a transformation of the problem from a MINLP to a p-MILP. The two-layered nature of the formulation allows us to determine the optimal operational trajectory at the upper layer through the solutions of a net cost minimization problem at the lower layer. This results in higher renewables integration and improved ease of microgrid coordination.

2. METHODOLOGY

The system modelling, renewable power paramterization and the mathematical programming problem are presented in the following subsections.

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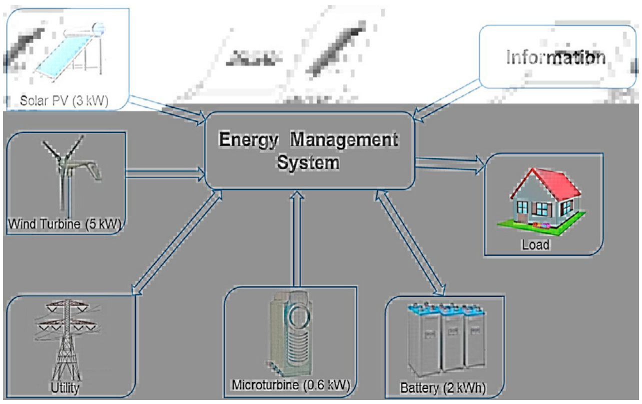

Fig. 1. Microgrid system components and their specifications based on the existing system in Lambton College, Ontario.

2.1 Systems modelling

The microgrid system components and their specifications are shown Fig. 1. Component selection and sizing is adopted from an experimental microgrid in Lambton College, Ontario. Models of the microgrid components are presented below, with a focus on system level modelling.

Solar photovoltaic model A number of models have been proposed for PV systems with various levels of detail. The harnessed solar power considering instantaneous efficiency η_g, the surface area of one cell A_m, solar incident radiation H, and the number of panels N, is given by:

$$P_s = \eta_g N A_m H \quad (1)$$

With maximum power point tracking (MPPT) system, power production of the PV array is shown to be directly proportional to the incident solar radiation:

$$P_s(t) = P_{s-rated} \frac{H(t)}{H_{rated}} \quad (2)$$

Ordinarily, the rated power refers to the power output at $1000\ W/m^2$ and 25^oC, which is roughly the upper limit of insolation at standard environmental conditions.

Wind turbine model The output power of a wind turbine can be related to wind speed using the rated output power of the design and the fractional availability of the rated power as (Zachar et al., 2015):

$$P_w(t) = f_w(t) P_{w-rated} \quad (3)$$

$$f_w(t) = \begin{cases} 0 & \text{if } (v(t) \leq v_{ci} \text{ or } v(t) \geq v_{co}), \\ \dfrac{v(t)^3 - v_{ci}^3}{v_r^3 - v_{ci}^3} & \text{if } (v_{ci} \leq v(t) \leq v_r), \\ 1 & \text{if } (v_r \leq v(t) \leq v_{co}). \end{cases} \quad (4)$$

Battery energy storage model For batteries, information on the state of charge (SOC) is paramount. The SOC during the charging or discharging processes can be estimated using (5):

$$SOC_b(t) = SOC_b(t-1)[1-\sigma] + [E_+(t) - E_-(t)]\eta_b \quad (5)$$

where η_b is the battery efficiency, σ is the rate factor, $E_+(t)$ is the charging power, and $E_-(t)$ is the discharging power. The SOC_b must be constrained between minimum and maximum states to safeguard the battery.

$$SOC_{b,min} \leq SOC_b(t) \leq SOC_{b,max} \quad (6)$$

The state of charge limits are usually chosen to avoid deep discharge and allow for storage leakages.

Microturbine model Commercial microturbines are available in a limited number of fixed capacities. In order to promote green energy, microturbines are mostly used as backup resources should the battery system be unable to supply the load during operation. Due to decreasing efficiency at low set points, microturbines have to be constrained to operate above 50% of their power rating, $P_{m-rated}$, according to (7):

$$0.5 P_{m-rated} \leq P_m(t) \leq P_{m-rated} \quad (7)$$

The fuel consumption is related to power output through (8) as;

$$G_m(t) = \frac{P_m(t)}{\eta_m} \quad (8)$$

2.2 Problem formulation

The operational scheduling problem is modelled using a parametric programming formulation with linear discrete-time state-space representation, akin to the work by Kopanos and Pistikopoulos (2014). This enables easier interaction and exchange between the energy management layer and the implementation control system.

Renewables parameterization Using the concept of solution profiles and critical regions from the literature in parametric programming, one finds that all economic operational decisions for operating a microgrid with solar and wind resources will favour more harvesting of the renewable energy resources since they are mostly incentivised and there is no marginal cost to produce additional power until the rated capacity of the system is reached. Considering Fig. 2, where three scenarios of wind and solar power parameterizations are shown in Cartesian coordinates for the purpose of illustration; let us identify each of the three parametric spaces - representing alternative bounds on the operational space - as critical regions CR_i. Then it is observed that economic operational decisions fall on the top right vertex of each critical region because solar and wind resources are free.

The basic idea of this scenario mesh approach is to obtain optimal operational strategies of the microgrid system based on the parameterized wind and solar production scenarios. To do this, we exploit the fact that the wind turbine operation is well bounded on the design cut-in and cut-out speeds. Also, the maximum solar irradiance at any choice location for a PV system can be considered as constant. In other words, maximum harvestable insolation