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Optimal dispatch for a microgrid incorporating renewables and demand response

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ABSTRACT

This paper proposes an optimal economic dispatch of a grid connected microgrid. The microgrid consists of solar photovoltaic, diesel and wind power sources. An Incentive Based Demand Response Program is incorporated into the operations of the grid connected microgrid. The optimal dispatch strategy is obtained by minimizing the conventional generators fuel cost, the transaction costs of the transferable power and maximizing the microgrid operator's demand response benefit whilst simultaneously satisfying the load demand constraints amongst other constraints. The developed mathematical model is tested on two practical case studies and sensitivity analysis of the model to key parameters was also performed. Case study 1 consists of three conventional generator units, one wind generator, one solar generator and three rural customers. Case study 2 is a much larger microgrid and was chosen to test the applicability of our model to larger microgrids and also to verify the scalability of our algorithm. Results show that the demand response program curtails significant grid relieving amounts of energy in the two case studies considered and integration of an incentive based demand response programs into the microgrid energy management problem introduces optimality at both the supply and demand spectrum of the grid.

1. Introduction

Microgrids as distinct from a major power grid consists of distributed generation units, storage devices and controllable loads sited close to the customer and spanning a limited physical area [1]. The generation units in micro grids can either be conventional power generators or renewable energy sources. Examples of renewable energy sources are wind power or solar power. Conventional power generators can either be thermal generators or diesel generators. Storage devices in microgrids include batteries, flywheels and pumped storage [1,3]. Typically modern microgrid systems can either be operated in the grid connected mode or in the islanded mode. In the grid connected mode, the microgrid is connected with the main grid, whilst in the islanded mode, the microgrid can be disconnected from the main grid in the event of a system emergency and still supply local load. Thus microgrids are also able to ensure localized power system operation in the event of a blackout or brownout. Advantages of microgrids include improvement of reliability of electricity supply, sustainability, power quality and lower electricity costs, transmission and distribution line losses [1]. As stated earlier, the generation units in micro grids can either be conventional power generators or renewable energy sources. However, in recent times Renewable Energy Sources (RES) have become preferred for use in microgrids because of their long term environmental and cost benefits over conventional generation sources [4]. They are used either singly or in conjunction with other RES. Recently, the focus of researchers has been on the optimal operation and control of microgrids. This field of research endeavour is commonly referred as the energy management of microgrids and involves minimizing or maximizing some predetermined objective function (minimizing cost, maximizing microgrid reliability, etc) and determining the optimal dispatch (economic dispatch) and commitment (unit commitment) of the conventional generators, RES and storage devices. An optimal control strategy for a microgrid operating in the islanded mode and containing RES is investigated [5]. The objective is to minimize the electricity generation cost and determine the optimal operational schedule of the microgrid considering the stochastic nature of RES. Grid connected interconnected microgrids with variable electricity

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prices and having the objectives of maximizing financial gain and PV energy consumption are investigated [6]. A microgrid consisting of wind, PV energy sources with battery storage is researched [7] with the objective of maximizing the overall economic benefit of the system and determining the optimal output of power sources whilst satisfying load balance constraints. In Ref. [8], a microgrid made up of wind, PV energy sources with batteries is considered. The microgrid is grid connected and investigations are carried out under different grid market policies and Particle Swarm Optimization (PSO) is utilized in solving the obtained mathematical model. The optimal control strategy for a hybrid microgrid consisting of PV and diesel power source and a battery storage system was proposed [9]. The objective function is to minimize the cost of the diesel generators and determine the optimal power output for the power sources under winter and summer conditions. This work was further expanded and improved [10] with the inclusion of wind power sources and the application of a Model Predictive Control (MPC) strategy to handle variations in demand. Another work proposes a switched model predictive control strategy for a PV, diesel and battery hybrid power system [11]. The advantage of the switched MPC over conventional MPC is that it is able to efficiently handle cases when the battery is not permitted to charge and discharge simultaneously. Other works that deal with the energy management of microgrids are [1,2,7]. However, the aforementioned works do not incorporate Demand Response (DR) into the optimal energy management problem of microgrids. Failing to include DR into the energy management problem of micirogrids can lead to suboptimal operation of the microgrid. This is because the energy management problem is concerned with the optimal commitment and dispatch of conventional generators, RES and storage devices at the supply side whilst DR programs are concerned with providing demand relief at the demand side [12]. Inclusion of DR programs would make for a better and more reliable microgrid as this would ensure optimal operating conditions at both the supply side and demand side of the microgrid [12]. It has been observed that DR programs lead to reduced microgrid operational cost and improved operations [12,13]. Furthermore the addition of DR programs into the microgrid mix provides some degree of grid flexibility and helps to mitigate the effect of having intermittent RES [13].

A few works have incorporated DR into the energy management problem of microgrids like [12,13]. While in Ref. [13] DR is incorporated into the microgrid and provides reserve capacity, in Ref. [12], DR is modelled with detailed residential household appliances consumption information incorporated into a microgrid. The model setup is investigated under a single consumer and under multiple consumers. Both works have as their objective the minimization of the microgrid fuel costs. Other recent examples of the integration of DR programs into microgrid problems include [14,15,22]. There is still the need to investigate and provide a comprehensive practical framework for incorporating DR into the energy management problem of a microgrid in a way that is beneficial to participating DR customers and does not just seek to minimize microgrid fuel costs. It is imperative that DR programs accurately captures the customers outage cost and factor these costs in the design of the DR programs to be incorporated into the energy management problem of microgrids. The DR program presented in this work is an incentive based DR program [23] and one of the core constraints in the DR model is that there should be incentive compatibility, that is customers must see economic benefit in participating in the DR program and that they are adequately compensated for their level of participation. This work builds on the work done in Ref. [23] where a DR program was incorporated into the Dynamic Economic Emission Dispatch (DEED) problem [24,26]. In this work we incorporate this incentive based DR program into the microgrid energy management problem under the grid connected operational mode. It is important we provide in our model instances when the microgrid is in a grid connected mode and there is need to import or export power from the main grid into the microgrid. To the best of the knowledge of the authors of this paper, there has been no work that has provided this nature of DR program integrated into the microgrid energy management problem. The developed model is able to provide grid flexibility and helps to mitigate the effect of having intermittent RES whilst simultaneously using DR to provide relief to the system. The DR model actively incentivises customers to participate in the DR program and ensures that their incentive is greater than the cost of curtailment. Furthermore practical constraints like budgetary and customer maximum load constraints are built into the model. The rest of the paper is organized as follows: Section 2 presents the mathematical models for the microgrid incorporating the demand response model. Section 3 focuses on the methodology deployed in the numerical simulations whilst Section 4 presents obtained results. The paper is concluded in Section 5.

2. Mathematical model of microgrid

The microgrid used in this work, consists of conventional generators and RES at the supply side and demand response formulations at the customer side. The RES consists of a PV system and a wind energy system. The hourly energy output of a PV generator S_t is given as [10]:

$$S_t = n_{pv} A_c Ipv_t, \tag{1}$$

where n_{pv} is the efficiency of the solar PV generator/array, Ipv_t (kW h/m^2) is the hourly solar irradiation incident on the solar PV array, A_c is the area of the PV array and S_t is the hourly energy output from a solar generator [10]. The hourly output of a wind generator is highly dependent on the wind speed and the wind speed is given as [10]:

$$vhub_t = vref_t \left(\frac{hhub}{href}\right)^{\beta}, \tag{2}$$

where $vhub_t$ is the hourly wind speed at the desired height $hhub$, $vref_t$ is the hourly wind speed at the reference height $href$ and β is the power law exponent that ranges from $\frac{1}{7}$ to $\frac{1}{4}$. For the purpose of this work, $\frac{1}{7}$ is used. The mathematical formula used to convert hourly wind speed to electrical power is as follows [10]:

$$W_t = 0.5 n_w \rho_{air} C_p A V^3, \tag{3}$$

where V is the wind velocity at hub height, ρ_{air} is the air density, C_p is the power coefficient of the wind turbine, depending on the design, A is the area of the wind turbine rotor swept area, n_w the efficiency of the wind generator and W_t is the hourly energy output from the wind generator.

The mathematical models for the microgrid at the supply side and the demand response model at the demand side are presented in the following subsections.

2.1. Grid-connected microgrid

In this work, we assume that a trading scheme exists whereby power can either be transferred or sold from the main grid to the microgrid and vice versa. This trading scheme exists to cater for the intermittent nature of RES. Thus if W_t is the forecast (maximum) wind power obtainable from the wind generator while S_t is the forecast (maximum) solar power obtainable from the solar