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A non-linear convex cost model for economic dispatch in microgrids

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HIGHLIGHTS

- A cost model for a microgrid has been presented.
- It incorporates the effects of battery pack degradation and intermittent DGs.
- The model takes into account load demand and generation balance.
- The non-linear cost model has been proved to be convex.
- Cost savings is more when compared to generic models of economic dispatch.

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ABSTRACT

This paper proposes a convex non-linear cost saving model for optimal economic dispatch in a microgrid. The model incorporates energy storage degradation cost and intermittent renewable generation. Cell degradation cost being a non-linear model, its incorporation in an objective function alters the convexity of the optimization problem and stochastic algorithms are required for its solution. This paper builds on the scope for usage of macroscopically semi-empirical models for degradation cost in economic dispatch problems and proves that these cost models derived from the existing semi-empirical capacity fade equations for $LiFePO_4$ cells are convex under some operating conditions. The proposed non-linear model was tested on two data sets of varying size which portray different trends of seasonality. The results show that the model reflects the trends of seasonality existing in the data sets and it minimizes the total fuel cost globally when compared to conventional systems of economic dispatch. The results thus indicate that the model achieves a more accurate estimate of fuel cost in the system and can be effectively utilized for cost analysis in power system applications.

1. Introduction

The World Energy Outlook (WEO) database on electricity access states that till 2016, an estimated 1.2 billion population (16% of the global population) do not have access to electricity. Around 95% of the deprived population belong to the remote areas [1]. In the present scenario, efforts are being made to design efficient microgrid solutions to aid penetration of power supply in these remote areas through components like energy storage, photovoltaic (PV) generation and diesel generators [2]. These efficient designs can be achieved through optimal sizing grid components [2], operation cost minimization [3,4], optimal energy storage sizing [5], real time energy management using stochastic techniques [6–11], quadratic approximations to the optimal power flow problem [12], deploying distributed algorithms for efficient convergence rates [13], designing load management strategies [14,15] and analyzing techno-economic feasibility [16]. Of all these available resources, the techno-economic feasibility model has been widely explored for achieving viable off grid solutions [17]. Wies et al. [18] developed a techno-economic feasibility model of hybrid system which reduced the operation cost of the system drastically. Techno-economic feasibility is judged by the economic dispatch of the diesel generators in the grid under operational constraints.

Economic dispatch can be defined as a process to retrieve generation in a grid at minimum cost [19]. With the incorporation of more and more system constraints, energy management at reduced cost becomes a complicated problem to solve. The present day economic dispatch problems consider incorporation of system constraints like security [20], appropriate power levels [21], daily averages of solar irradiation [22] and operational cost of the energy storage devices in the hybrid microgrid system [23]. Renewable generation cost can be correlated to linear functions of output power from their respective devices [24] and they contribute to the load demand of the system whose stochastic

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Nomenclature

P_{G-L}	variable representing power flow from the diesel generator to the load at any instant (kW)
a, b	fuel generation cost coefficients
P_{PV-L}	variable representing power flow from the PV array to the load at any instant (kW)
P_{PV-ES}	variable representing power flow from the PV array to the energy storage device at any instant (kW)
P_{ES-L}	variable representing power flow from the energy storage device to the load at any instant (kW)
P_{pv}	variable representing power output from the PV array at any instant (kW)
A_c	variable representing area of the PV array (m^2)
η_{pv}	efficiency of material of PV array
PV	photovoltaic generator
SOC^{min}	minimum state of charge of the storage device
DOD	depth of discharge of the energy storage device
DG	diesel generator
G_1	unit cost of energy consumption for generator
G_2	unit cost of energy generation from PV array.
P_{G-L}^{min}, P_{G-L}^{max}	minimum and maximum bounds of power flow from the generator
P_L	load demand of the network (kW)
Q_C	energy storage device capacity during charging (kWh)
Q_D	energy storage device capacity during discharging (kWh)
t_∞	life time of the energy storage device (hrs)
V_0	terminal voltage of the energy storage device (V)
R	internal resistance of the energy storage device
η_c,η_d	charging and discharging efficiency of the energy storage device
SOC	state of charge
SOC^{max}	maximum state of charge of the storage device
I_{pv}	hourly solar irradiation on the PV array (kWh/m^2)
BESS	battery energy storage system
G_3	unit cost of energy flow into the energy storage device
G_4	unit cost of energy flow away from the energy storage device

nature can be forecasted using sophisticated techniques such as neural networks [25], ensemble learning [26] and reinforcement learning models [27]. However, the operational cost of the energy storage devices heavily depends on their respective capacities that fade over time due to varying charge and discharge efficiencies during subsequent charge/discharge cycles [28,29]. Capacity degradation is thus one such inherent property which incorporates complexity in designing hybrid systems. The most accurate models for battery degradation have been modeled using electrochemical models as PDE observers [30,31]. However, the states of the system heavily rely on the stability of the estimator. The other methods include designing non-linear empirical models to relate high level system parameters like state of charge and voltage based on experimental observations [32]. These models are highly non-linear in nature and depend on stochastic algorithms for solution [33].

Present research considers economic dispatch under the influence of non-uniform load distribution and non-linear battery degradation models. Incorporation of these variations lead to the development of non-linear optimization problems which require genetic algorithms [21] and inbuilt commercial software packages for solution [34,35]. A commercial program (Hybrid Optimization by Genetic Algorithm-HOGA) [34] determines the optimal configuration of a hybrid PV-DG system using genetic algorithms. The package incorporates non-linear characteristics of system components like load demand and uncertainty in renewable energy supply. A commercial software called HOMER (Hybrid Optimization Model for Electric Renewables), developed by National Renewable Energy Laboratory, USA is used to judge the dimensioning of hybrid power systems based on system cost, operation constraints and load demand through hourly simulations [35]. In [36], battery degradation cost was considered in designing a hybrid standalone system which aims to minimize the total operating cost. A genetic algorithm was utilized to solve the problem and the strategy achieved a net cost reduction of 37.7% when compared to generic load following strategies [37]. Although these studies are extensive, they are strictly dependent on stochastic methods for solution. The non-linearity of these characteristics impose uncertainty on judging whether the costs are globally optimal or not. Therefore, it is techno-economically more feasible to design convex optimization problems for these hybrid systems in order to get an accurate estimate of the total system cost and escalate fuel savings. Tazvinga et al. [38] considered dynamic variation of load demand to calculate a dispatch strategy to minimize the operation cost. They formulated the techno-economic feasibility problem as a convex problem and showed that dynamic variation of fuel costs drastically affects cost savings of the generator. However, their model did not consider the cost of energy storage and intermittent renewable generation which alters the optimality conditions of the design problem.

From the above literature, it is evident that the economic dispatch model is a non-linear problem for optimization and incorporation of parameter variation may result in sub-optimal solutions. The paper develops an optimal pathway towards finding the minimum cost solution for such dynamic non-linear fuel saving based cost models. A non-linear operational convex cost model incorporating energy storage dynamics and intermittent renewable generation has been proposed in this paper. Cell dynamics has been incorporated using a well-established semi-empirical relation between cell capacity and its rated power for a class of an energy storage device. The paper further proves the convexity of the non-linear cost model and provides the conditions under which the conditions of convexity will hold.

2. Contribution to research

The phenomenon of undercharge and under-discharge reduces the available capacity of the battery pack when compared to its nominal value [39]. This reduction in capacity affects the operation of energy management problems where BESS forms an integral part. In order to address an efficient dispatch strategy, researchers integrate battery degradation cost in their objective for optimization. The degradation cost modeling is an important avenue for research in this scenario. There are mainly two approaches to modeling degradation cost. The first being the incorporation of a decaying degradation trend through estimation of life cycle curves (also known as DOD Swing) and the second being the incorporation of cell degradation cost as a stochastic process. Xiao et al. [40] utilized a non-linear decaying lifetime cumulative degradation cost model based current DOD status for a real time DC microgrid scheduling. In [41] an optimal utilization strategy was designed for minimizing operational cost through additional degradation cost modeling by the same technique as [40]. They solved the optimization problem using both GAMS and CPLEX solvers. In [42] a similar life cycle estimation technique was utilized for combining storage systems with wind generation units. They utilized the CPLEX framework for the solution. However, the solvers were reported to exhibit a negligible but finite optimality gap. The other technique refers to introduction of cell degradation as a stochastic process. In [43], the battery pack degradation was modeled as a Weiner process. However, the technique has not been applied to economic dispatch models in the past. Both the techniques described in the literature are stochastic in nature and are theoretically poised to provide sub-optimal solutions.