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# Considering uncertainty in the optimal energy management of renewable micro-grids including storage devices

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ABSTRACT

This paper proposes a new probabilistic framework based on 2*m* Point Estimate Method (2*m* PEM) to consider the uncertainties in the optimal energy management of the Micro Girds (MGs) including different renewable power sources like Photovoltaics (PVs), Wind Turbine (WT), Micro Turbine (MT), Fuel Cell (FC) as well as storage devices. The proposed probabilistic framework requires 2*m* runs of the deterministic framework to consider the uncertainty of *m* uncertain variables in the terms of the first three moments of the relevant probability density functions. Therefore, the uncertainty regarding the load demand forecasting error, grid bid changes and WT and PV output power variations are considered concurrently. Investigating the MG problem with uncertainty in a 24 h time interval with several equality and inequality constraints requires a powerful optimization technique which could escape from the local optima as well as premature convergence. Consequently, a novel self adaptive optimization algorithm based on θ-Particle Swarm Optimization (θ-PSO) algorithm is proposed to explore the total search space globally. The θ-PSO algorithm uses the phase angle vectors to update the velocity/position of particles such that faster and more stable convergence is achieved. In addition, the proposed self adaptive modification method consists of three sub-modification methods which will let the particles choosel the modification method which best fits their current situation. The feasibility and satisfying performance of the proposed method is tested on a typical grid-connected MG as the case study.



## 1. Introduction

In recent years, the participation of Renewable Energy Sources (RESs) in the forms of Wind Turbines (WTs), Photovoltaics (PVs), Fuel Cells (FC), Micro Turbines (MT), etc has resulted in more reliable and efficient operations with better power quality and flexibility especially in distribution systems [1–4]. Therefore, it is expected that RESs would have a notable role in the near future of electricity supply and low carbon economy [5,6]. However, from the operation and management points of view, the high utilization of the Distributed Generations (DGs) can cause unexpected challenges which a part of them is addressed by Micro-Grids (MGs) problem. In definition, the MG problem is the aggregation of DGs, electrical loads and generation interconnected among themselves and with distribution network [7]. Therefore, in recent years, several studies have been implemented to investigate the MG problem deeply.

In Ref. [8], Pipattanasomporn et al. investigated the recent developments in the multi-agent system to control a PV-based MG. In Ref. [9], Khodr et al. simulated a renewable MG in the laboratory to propose an intelligent methodology for the optimal management of the next week (672 time interval) in a deterministic environment. In Ref. [1], Hafez et al. assessed the optimal design, planning, sizing and operation of a hybrid renewable energy based MG with the goal of minimizing the lifecycle cost. In Ref. [10], Morais et al. proposed a new approach based on mix-integer linear programming to locate the optimal scheduling of the renewable MG. Tsikalakis et al. investigated the interactive effect of the MG and utility on each other when the objective function is reducing the total amount of power produced [11]. Chedid et al. in Ref. [12] proposed a new method based on linear programming to minimize the total cost of a hybrid solar-wind MG. The role of storage devices to reduce the total cost of the MG was investigated by Chakraborty et al. in Ref. [13]. Here linear programming technique is utilized as the optimization tool. In Ref. [14], Dukpa et al. presented a participation method to assess the unit commitment

*Abbreviations:* FC, fuel cell; WT, wind turbine; PV, photovoltaic; NiMH-battery, nickel-metal-hydride battery; PEM, point estimate method; DG, distributed generation; MG, micro-grid; MT, micro turbine; RES, renewable energy source; SAM-θ-PSO, self adaptive modified θ-PSO; PSO, particle swarm optimization.

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**Nomenclature**

| | |
|---|---|
| $B_{Gi}(t)$ | the bid of *i*th DG at time *t* |
| $X$ | state variables vector |
| $B_{Sj}(t)$ | the *j*th storage device bid at time *t* |
| $S_{Sj}(t)$ | start up/shut down cost of *j*th storage device at time *t* |
| $S_{Gi}(t)$ | start up/shut down cost of *i*th DG at time *t* |
| $P_{Grid}(t)$ | active power bought (sold) from (to) the utility at time *t* |
| $B_{Grid}(t)$ | utility bid at time *t* |
| $u_i(t)$ | state of the *i*th unit denoting ON/OFF statuses |
| $n$ | number of the state variables |
| $N_g$ | number of generating units |
| $N_s$ | number of storage devices |
| $P_g$ | vector including the power generation of all power units |
| $U_g$ | vector including ONN/OFF statuses of all power units |
| $T$ | number of time intervals |
| $P_{G,i}(t)$ | active power production of *i*th power unit |
| $P_{G,i,\min}(t)$ | minimum active power production of *i*th power unit at *t* |
| $P_{G,i,\max}(t)$ | maximum active power production of *i*th power unit at *t* |
| $P_{s,j,\min}(t)$ | minimum active power production of *j*th storage device at *t* |
| $P_{s,j,\max}(t)$ | maximum active power production of *j*th storage device |
| $P_{Grid,\min}(t)$ | minimum active power production of the grid at *t* |
| $P_{Grid,\max}(t)$ | maximum active power production of the grid at *t* |
| $P_{L,i}(t)$ | the amount of *l*th load value at time *t* |
| $N_L$ | total number of load levels |
| $W_{ess}(t)$ | amount of stored energy inside the battery at time *t* |
| $W_{ess,\max}/W_{ess,\min}$ | maximum/minimum stored energy inside the battery |
| $P_{charge}/P_{discharge}$ | permitted rate of charge/discharge during a finite time period ($\Delta t$) |
| $\eta_{charge}/\eta_{discharge}$ | battery efficiency during charge/discharge period |
| $P_{charge,\max}/P_{discharge,\max}$ | maximum permitted rate of charge/discharge during a finite each time period ($\Delta t$) |
| $Z$ | input vector of the investigated problem |
| $S$ | output vector of the investigated problem |
| $m$ | number of uncertain variables |
| $\mu_{zl}$ | mean of $f_{zl}$ |
| $\sigma_{zl}$ | standard deviation of $f_{zl}$ |
| $\lambda_{l,3}$ | skewness coefficient of $z_l$ |
| $\zeta_{l,k}$ | standard location of $z_{l,k}$ |
| $\omega_{l,k}$ | weighting factor of $z_{l,k}$ |
| Var | variance mathematical operator |
| $\rho$ | inertia weighting coefficient in PSO |
| $c_1$ & $c_2$ | accelerating coefficients in PSO algorithm |
| $k$ | iteration number |
| $V_i^k$ | velocity of *i*th particle at *k*th iteration |
| $P_{best,i}^k$ | best experience of *i*th particle till *k*th iteration |
| rand | Mathematical operator for random value in the range [0,1] |
| $\varphi_1,\ldots,\varphi_5$ | random numbers in the range [0,1] |
| $\theta_i$ | phase vector of *i*th particle corresponding to $X_i$ |
| $\rho_{\min}/\rho_{\max}$ | minimum/maximum values of the inertia weight $\rho$ in PSO |
| $X_{\max}/X_{\min}$ | maximum/minimum values of the control vector X |
| $T_F$ | a random constant value equal to 1 or 2 |
| Iter | number of iterations passed |
| $N_{sw}$ | total number of particles in the population |
| *Log* | logarithm mathematic operator |
| $N_{Mod_\theta}$ | number of bees which have chosen θth modification method |
| $\theta_{\max}/\theta_{\min}$ | maximum/minimum of the phase angle |
| $\text{Prob}_\beta$ | probability success of $\beta$th sub-modification method |
| $\text{Acum}_\beta$ | accumulator variable of $\beta$th sub-modification method |
| $Weg_i$ | weighting factor of *i*th solution |
| $N_{Mod_\beta}$ | number of particles which have chosen $\beta$th sub-modification method |
| $\gamma$ | a constant to balance between the probability of the sub-modification method in the last iteration with that of the current iteration |

problem in a MG consisted of WT and storage devices. In Ref. [15], Chen et al. used the real-coded genetic algorithm to formulate a three phase method based on prediction, storage and management to find the optimal operating point of the MG. While each of these works has studied the MG problem from a significant point of view; the main deficiency with all of them is the deterministic analysis. In fact, neglecting the influence of the uncertainty can affect the total operation schedule such that the final optimal solution may not be the best operating point in the reality. In this regard, the high penetration of RESs in the new power market has changed the way that power systems are operated. This situation necessitates the reassessment of the traditional methods in a new random environment. In order to deal with the uncertainty effect, the utilization of the stochastic frameworks can be useful.

According to the above descriptions, in this paper, the stochastic behavior of the uncertain variables is considered by the use of two point estimate method. In this regard, each uncertain variable is replaced by two deterministic points located on each side of the mean value of the relevant distribution function. Therefore, one of the main benefits of the proposed probabilistic framework is low computational cost. In fact, for $m$ uncertain variables, $2m$ deterministic analysis is required. The proposed probabilistic method would capture the uncertainty of load forecast error, WT and PV output power variations and the market bid changes simultaneously. The investigation is examined on a grid-connected MG considering different types of RESs such as WT, PV, FC and MT. Also, in order to show the positive role of the storage devices to reduce the total cost, Nickel-Metal-Hydride Battery (NiMH-Battery) is considered in the MG. The analysis would be implemented in a 24 h time interval to highlight the charge/discharge process of the NiMH-Battery at different hours clearly. The main idea of utilizing NiMH-Battery is to charge at low cost hours to be able to discharge at high cost hours. Considering all the above assumptions will require a powerful optimization tool to find the main global optima when escaping from local optimal points as well as premature convergence. Therefore, a new self adaptive modification technique based on θ-Particle Swarm Optimization (θ-PSO) algorithm is proposed to explore the total search space, globally. The θ-PSO algorithm is a new optimization algorithm based on the phase angle vector which can generate a high-quality solution within the shorter calculation time in comparison with the original PSO and other evolutionary methods. Moreover, a novel self adaptive modification method consisted of three sub-modification approaches is proposed to let each particle choose the best