Real-Time Risk and Cost Management of a Grid Connected Micro-Grid

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ABSTRACT

In this paper, a detailed mathematical model of a grid-connected micro-grid including wind-turbine, photo voltaic cells and CHP(Combined Heat and Power) with respective uncertainties in electrical loads, thermal loads, PV and wind power outputs with normal distributions is presented. Moreover, the effects of the considered uncertainties on the micro-grid's operation cost are modelled as risk; and this risk is reduced through the battery and heat storage system, both of them separated into dynamic and static capacities. The dynamic capacity reduces the operation cost risk and the static capacity reduces the main (or expected) operation cost; and for this a new Real-time Risk and Cost Management System is developed. Finally, a suitable cost function considering both the cost of risk and expected cost is used for assessment of the proposed model using Monte-Carlo simulations.

INTRODUCTION

Grid connected micro grids could reduce their operation cost by participating demand response and increasing their reliabilities [1-3]. They confront with excellent opportunities in smart grid infrastructure. The evolution of smart grid, especially in advanced metering equipment, presents great chances to improve the accuracy of prediction and components' models [4-6].
In a smart grid infrastructure, normal users (end users) could get more chances for participating in daily operation of power system to reduce costs of their electricity consumptions which make it much friendlier. Moreover, they could manage their daily operation to minimize the expected cost and risk of cost.
In a grid connected micro-grid, the most important sources of cost risk has been known as: 1) uncertain parameters such as of micro-grid's components model and 2) error in estimated input data. Many efforts have been performed to minimize these uncertainties in favor of improving the precision of forecasted cost to reduce the risk. Even if models of components be completely accurate but these efforts could not eliminate the risk because of unpredictable nature of electrical and thermal load consumption.
In this work, an applicable method is developed based on eliminating the unpredictable source of uncertainty which is the estimation error of energy producer and consumer components. The method is based on using electrical/thermal storage systems which are capable of real-time management to compensate the estimation error of predicted electrical/thermal energy consumption.

This paper is organized as follows. Section II describes the studied micro-grid structure. Section III introduces the proposed module of Real Time Risk and Cost Management. In section IV a detailed mathematical model for both the cost and risk management is illustrated. Section V presents the simulation results. Finally, section VI provides conclusions and indicates directions for future works.

MICRO-GRID STRUCTURE

The structure of the grid connected micro-grid is divided into two parts, the power supply and heat supply loops. The studied micro-grid consists of wind power, PV, battery storage, CHP system, heat recovery boiler, heat storage tank, thermal and electrical loads that are illustrated in Fig.1. The renewable energy sources in this micro-grid system work on their maximum available output powers. The power flow between the main grid and this micro-grid is bidirectional; either buying electricity from the grid, or selling excess power to the grid.

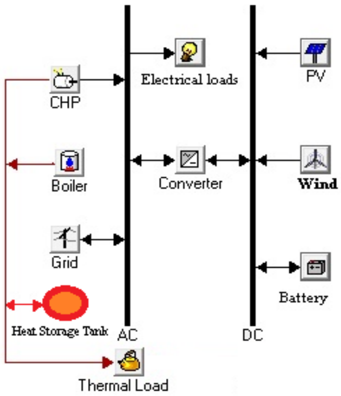

Figure 1. Micro-Grid Structure

REAL TIME RISK AND COST MANAGEMENT MODULE

In this paper, an applicable method for reducing the risk of daily operation costs is illustrated. This method provides a Real-Time Risk and Cost Management System added to the EMS for Day-Ahead, CPP and TOU grid price tariffs to make a trade-off between reducing the daily operation cost risk and its expected value in a micro-grid. The scheme of proposed module for a grid connected micro-grid is shown in figure 2. This scheme has two main parts: 1) the EMS, where the forecasted data of the electrical and thermal loads, price of fuel and

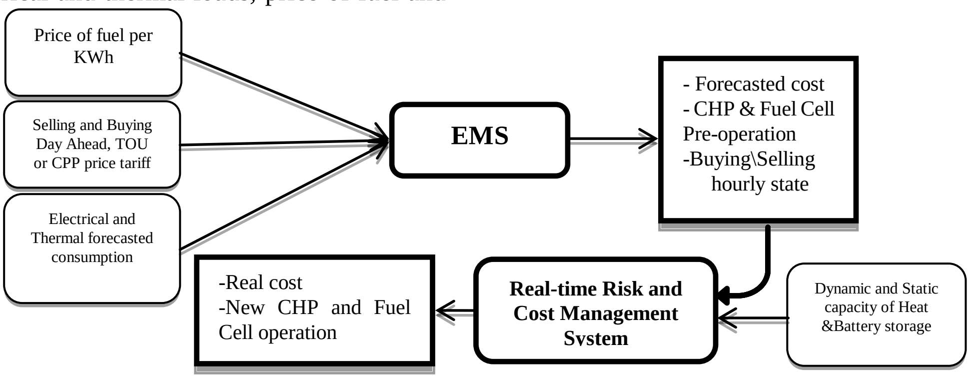

Figure 2. Schematic of the real-time risk and cost management module for a micro-grid

price tariff received from the main grid are sent to the EMS; then the outputs of the EMS would be the forecasted daily cost, CHP hourly outputs and hourly state of the buy/sell from/to the main grid. 2) the risk manager that computes the trade-off between reducing the risk and expected cost of the micro-grid daily operation by dividing the capacities of the thermal and electrical storage systems into dynamic and static parts using two parameters, α_h and α_e, respectively. The storage capacities are divided into dynamic and static capacities using Eq. 1 as follows:

$$\begin{cases} \alpha_{h,e} \times 100\% & \text{Percent of static capacity} \\ (1-\alpha_{h,e}) \times 100\% & \text{Percent of dynamic capacity} \end{cases} \qquad (1)$$

Where, $0 \le \alpha_{h,e} \le 1$.

The effect of increasing the dynamic capacity on the CDF of thermal/electrical loads uncertainties with normal distributions (for the real-time forecast error compensation) is shown in figure 3. As the Figure shows, by increasing the dynamic capacity the STD will reduce.

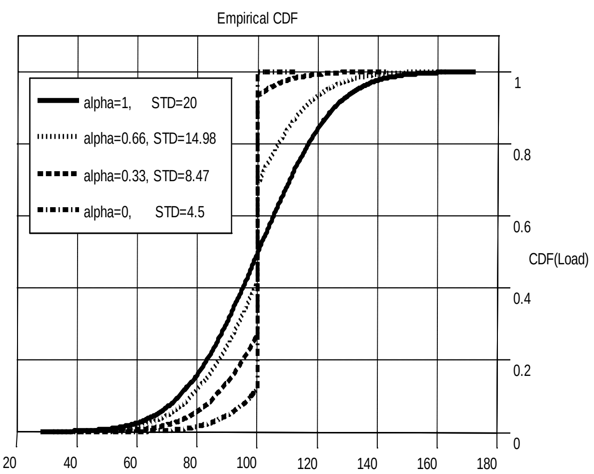

Figure 3. Effect of dynamic capacity in real time compensation of forecasted error

PROBLEM FORMULATION

Cost Function

As the input variables are gathered in the EMS, an optimization problem should be solved in order to determine the optimal forecasted dispatch of units according to a defined cost function based on forecasted data over a pre-specified time frame.

The micro-grid operation cost function is defined as follows:

$$\mathrm{Cost}_{\mathrm{Forecasted}} = \sum_{h=1}^{24} \left\{ \begin{array}{l} \rho_{buy}^{h}\, E\left\{P_{trade}^{h}\right\} S_{trade}^{h} \\ +\rho_{sell}^{h}\, E\left\{P_{trade}^{h}\right\} (1-S_{trade}^{h}) \\ +\rho_{NG}^{h}\, P_{NG\_CHP}^{h} + \dfrac{\rho_{NG}^{h}\, E\left\{P_{boiler}^{h}\right\}}{h_{boiler}} \\ +STC_{CHP}^{h} + EC_{CHP}^{h} + OM_{CHP}^{h} \end{array} \right\} \qquad (2)$$

Where,

h	*Time index in hour*
ρ_{buy}	*Buying price of electricity from grid (€/Kwh)*
ρ_{sell}	*Selling price of electricity to grid (€/Kwh)*
ρ_{NG}	*Price of heating value of natural gas (€/Kwh)*
P_{trade}	*Electricity power traded through the grid (Kw)*
P_{NG_CHP}	*Input power of natural gas to CHP (Kw)*
P_{boiler}	*Thermal heat power generated by boiler (Kw)*
η_{boiler}	*The efficiency of boiler*
S_{trade}	*State of trading (for buying is 1 and selling is 0)*
STC	*Start-up cost of CHP unit*
EC	*Emission cost of CHP unit*
OM	*Operation and maintenance cost of CHP unit*

Forecasted thermal power of boiler and electrical power traded with the main grid can be calculated in EMS as below:

$$E\left\{P_{boiler}^{h}\right\} = E\left\{P_{th\_load}^{h}\right\} - P_{th}^{h} \qquad (3)$$

$$E\left\{P_{trade}^{h}\right\} = E\left\{P_{load}^{h} - P_{PV}^{h} - P_{WT}^{h}\right\} - P_{el\_MT}^{h} \qquad (4)$$

Fuel Curve

Power generated via CHP which is a dispatchable generator has a variable efficiency with respect to output electrical and thermal injected power. From [7-9] the relevance between electrical/thermal output power and input natural gas power is shown through electrical/thermal efficiency of CHP as below:

$$\eta_{CHP} = \frac{P_{th}^h + P_{el}^h}{P_{fuel}^h} \tag{5}$$

$$\eta_{el\_CHP}^h = \frac{P_{el}^h}{a \times P_{el}^h + b} \tag{6}$$

$$P_{th}^h = \eta_{th\_CHP} \times \frac{P_{el}^h \times (1 - \eta_{el\_CHP}^h)}{\eta_{el\_CHP}^h} \tag{7}$$

$$0.3 \times P_{el\_max} < P_{el}^h < P_{el\_max}$$

$$P_{NG\_CHP}^h = m_{NG}^h \times LHV_{NG}^h \tag{8}$$

Where, a and b are constants related to electrical efficiency curve of CHP.

Optimization Problem

The main objective of the EMS is to minimize the expected cost function of micro-grid in a specified time frame. In this paper, the objective of EMS will reduce daily cost of micro-grid based on one variable which is P_{CHP} as below:

$$\underset{P_{el}}{\text{Min}}\, E\{\text{Cost}_{Forecasted}\} \tag{9}$$

$$\text{Subject to:}$$

$$\begin{cases} P_{el\_min} < P_{el} < P_{el\_max} \\ P_{trade\_min} < P_{trade} < P_{trade\_max} \\ 0 < P_{boiler} < P_{boiler\_max} \end{cases}$$

The main point in the defined objective function of EMS is the operation of electrical and thermal storage systems which are not considered to be optimized in Eq.9. Their participation is discussed in the Real Time Risk and Cost Management system.

Real Time Risk Management

In real time, the actual quantity of forecasted data will be visible and by considering thermal and electrical storage systems, a complementary management system is required to improve the operation of micro-grid. The most important requirement is to satisfy electrical and thermal loads which are formulated as below:

$$P_{boiler}^h = P_{th\_load}^h - P_{th}^h - P_{St\_static}^h \tag{10}$$

$$P_{trade}^h = \begin{cases} P_{load}^h - P_{PV}^h - P_{WT}^h \\ - P_{el}^h - P_{Bat\_static}^h \end{cases} \tag{11}$$

Where $P_{ST\text{-}static}$ and $P_{Bat\text{-}static}$ are respectively static parts of thermal and electrical storage systems.

Classification of static and dynamic part of thermal and electrical power is formulated based on defined parameters α_H and α_E. Since the static part of storage system is used to decrease cost of micro-grid in a 24 hour time frame, a practical strategy is proposed for thermal storage tank as below:

$$P_{ST\_static}^h = \begin{cases} P_{th}^h - P_{th\_max}^h & \text{CHP On} \\ \text{Discharge} & \text{CHP Off} \end{cases} \tag{12}$$

$$\text{S.t} \quad \begin{cases} \alpha_H\, P_{ST\_min} < P_{ST\_static} < \alpha_H\, P_{ST\_max} \\ \alpha_H\, soh_{ST\_min} < soh_{ST\_static} < \alpha_H\, soh_{ST\_max} \end{cases}$$

$$soh^h = (1 - \varepsilon_{ST})\, soh^{h-1} - E_{ST}^h$$

$$P_{ST}^h = \frac{E_{ST}^h}{Dh},\ E_{ST}^h < 0.1 \times soh_{max} \tag{13}$$

Where, soh_{ST_static} is the static state of charge of heat storage tank. ε_{ST} is the self-discharge rate of the heat storage system. New CHP operation will be created in real time through Eq.12 which shows that static part of heat storage system will be charged when the CHP doesn't work on its maximum capacity to improve its efficiency and will be discharged with a consistent rate when CHP is off to be recovered for being charged.

Same as thermal storage system, battery storage system has a static part. It should operate to decrease cost of micro-grid through solving the following optimization problem:

$$P_{Bat\_static} = \arg\max\{\sum_{h=1}^{24} (\rho_{real}^h - \rho_{mean})\, P_{Bat\_static}^h\} \tag{14}$$

$$\rho_{real}^h = \rho_{buy}^h\, S_{trade}^h + \rho_{sell}^h (1 - S_{trade}^h)$$

$$\text{S.t} \quad \begin{cases} \alpha_E\, P_{Bat\_min} < P_{Bat\_static} < \alpha_E\, P_{Bat\_max} \\ \alpha_E\, soc_{Bat\_min} < soc_{Bat\_static} < \alpha_E\, soc_{Bat\_max} \end{cases}$$

$$soc^h = (1 - \varepsilon_{Bat})\, soc^{h-1} - \eta_{Bat}^h\, E_{Bat}^h$$

$$P_{Bat}^h = \frac{E_{Bat}^h}{Dh},\ E_{Bat}^h < 0.1 \times soc_{max} \tag{15}$$

Where,

soc^h Available battery bank capacity (Kwh) at hour h

η_{Bat} Battery efficiency (during discharging process, the battery discharging efficiency was set equal to 1 and during charging, the efficiency is 0.75)

ε_{Bat} Self-discharge rate of the battery bank

The main contribution of this paper is definition of dynamic capacity for thermal and electrical storage systems to manage the risk of estimated cost in 24-hour time frame. To achieve this goal, an appropriate formulation is defined to decrease the estimation error in real time as below:

$$P_{ST\_dynamic}^h = P_{th\_load}^h - E\{P_{th\_load}^h\}$$

$$\text{S.t} \begin{cases} (1-\alpha_H)\, P_{ST\_min} < P_{ST\_dynamic} < (1-\alpha_H)\, P_{ST\_max} \\ (1-\alpha_H)\, soh_{min} < soh_{dynamic} < (1-\alpha_H)\, soh_{min} \end{cases} \tag{16}$$

$$P^{h}_{Bat\_dynamic} = \begin{cases} E\left\{P^{h}_{load} + P^{h}_{PV} + P^{h}_{WT}\right\} \\ -P^{h}_{load} - P^{h}_{PV} - P^{h}_{WT} \end{cases} \quad (17)$$

$$S.t \begin{cases} (1-\alpha_E)P_{Bat\_min} < P_{Bat\_dynamic} < (1-\alpha_E)P_{Bat\_max} \\ (1-\alpha_E)soc_{Bat\_min} < soc_{Bat\_dynamic} < (1-\alpha_E)soc_{Bat\_max} \end{cases}$$

In this formulation the estimation error will be reduced in real time.

Real Time Risk and Cost Management

To evaluate the performance of proposed real time risk and cost management module a typical objective function that minimizes the expected operation cost and its respective risk is used as Eq.18. The weight parameter (ξ) specifies the importance of the expected operation cost, and (1- ξ) specifies the importance of its associated risk. The cost function J will be minimized with respect to α_H and α_E parameters.

$$J = \zeta E\{\Delta Cost\} + (1-\zeta)Var\{\Delta Cost\} \qquad 0 \le \zeta \le 1 \quad (18)$$

$$\Delta Cost = Cost_{Real} - Cost_{Forecasted}$$

SIMULATION RESULTS

The simulation is performed on a sample system in a 24-hour time period in a typical day. Estimated daily profiles of wind power, PV, thermal and electrical loads are shown in fig.4.

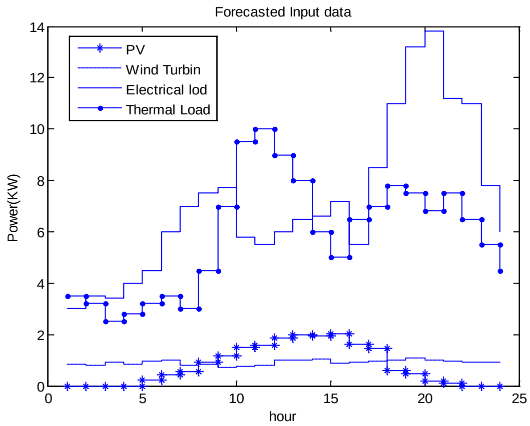

Figure 4. Forecasted data

The Monte-Carlo simulation is used for assessing the expected and variance part of objective function J with respect to the changes of uncertain parameters mentioned above.

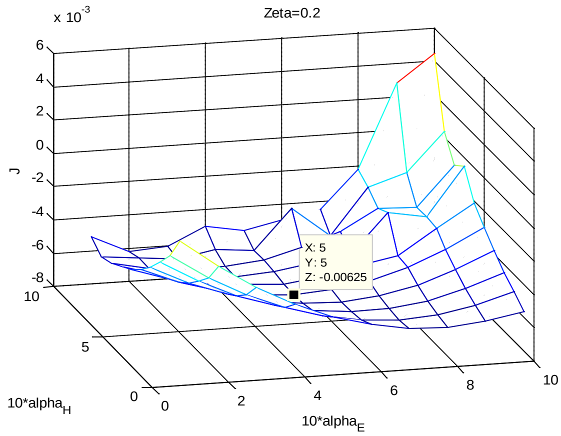

Figure 5. Risk and Cost management J function for ξ=0.2

The deviation of uncertain parameters is considered as 5% STD around Day-Ahead estimated data.

The simulation results shown in fig.5 and table.1 indicate that increasing the dynamic capacity reduces the operational cost risk and increases expected value of it. Moreover, for each ξ in the cost function J, the optimal values for (α_H, α_E) exist.

Table.1. Output results for different quantity of ξ

ξ	α^*_H	α^*_E	J^*
0.9	1	1	-0.12
0.5	1	1	-0.05
0.2	0.5	0.5	-0.0065
0.1	0.2	0.2	-0.0014

CONCLUSION

In this paper, a new dynamic model for using thermal and electrical storage systems has been proposed to manage the operation cost of a micro-grid in face of uncertainties (due to parameters forecast and modelling errors) in real-time. A detailed mathematical energy model was developed for the studied micro-grid to make an applicable trade-off between expected cost and risk of micro-grid in real-time management system. The case studies clearly showed that the developed EMS model for the micro-grid could reduce the operation cost variance (or risk) considerably.

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