Optimization Approach for Improvement of Energy Efficiency of Buildings in a Microgrid

Vassil G. Guliashki[1] and Galia I. Marinova[2]

Abstract – **This article proposes an optimization approach to building design, which leads to a reduction of energy costs for heating, cooling and lighting. The main optimization parameters are: window to wall ratio (WWR) and the type of glazing. Other parameters are: the level of insulation, the orientation of the building, the use of shading means (shutters / sun-blinds and awnings) to reduce the necessary cooling energy during the summer season. The optimization problem is formulated for a microgrid consisting of three houses and operating in island mode (isolated from the main network). The simulations for summer and winter days, respectively, were performed using the open-source tool for modelling and simulation of complex systems - GridLab-D and the new Matlab-toolbox - GridMat. The optimization was performed using the Matlab-solver *fmincon*. The results show that the energy efficiency of buildings can be significantly improved through their optimal design.**

Keywords – **Energy efficiency optimization, GridLab-D, GridMat, Matlab, Microgrids.**

I. Introduction

Reducing the energy needs of our civilization is a key factor in overcoming the harmful effects on the climate and the global warming that we are witnessing. The increasing consumption of energy is connected mainly with energy waste in buildings [1]. Buildings are responsible for more than 40% of the total primary energy consumption [2, 3]. The huge part of the energy in the buildings gets lost into space and heats the atmosphere. In the last decade, it has become clear that optimizing energy consumption and minimizing energy losses through thermal insulation and the use of quality windows is extremely important. On the other hand, it is necessary to minimize environmental pollution (CO_2 and other harmful emissions), which is associated with the use of clean energy from renewable energy sources. The industrialized countries take measures in this regard, namely: 1) the efficiency of energy management in buildings and of the equipment used in them increases, 2) the percentage of energy produced by renewable sources increases, 3) the energy consumption in buildings decreases. In Europe, there are directives to reduce the energy needs: e.g. Directive 2018/844 and directives for promotion of implementation of renewable energy sources (Directive 2009/28/EC) [4]. At present, cooling energy needs appear to be increasing, which is connected with the climate change and the culture of comfort [5]. The excessive use of insulation may lead to increased overheating [6].

A model for energy efficiency optimization of the buildings in Turkey is proposed in [7]. It includes three minimization criteria: (i) building energy consumption (kWh), (ii) initial investment costs (USD, $), and (iii) CO_2 emission (kg CO_2 eq.). A bi-criterion problem for energy efficiency optimization in isolated microgrids is formulated and solved in [8]. The first criterion includes fabric and ventilation heat loss of the building, and the second - the CO_2 emission. A battery schedule in a microgrid is optimized in [9]. An economic model for an island microgrid is considered in [10].

Some researchers investigate a window-to-floor ratio [11, 12]. A number of studies have shown that the window-to-wall ratio (WWR) has a major impact on the energy efficiency of buildings [13, 14]. A simulation study illustrates the positive correlation between the WWR and the environmental impact in [15]. Simulation techniques for optimization of glazing efficiency and identifying a good WWR, which leads to minimization of cooling load and of energy consumption are presented in [16].

A single objective approach for identifying the optimal WWR and type of glazing in an isolated (islanded) microgrid is proposed in this paper. The objective function maximizes the used battery energy and minimizes the energy generated by a diesel generator. It includes also the energy loss by walls, roof, floor and windows. Four different WWR are investigated, each one with two types of glazing: double and triple glazing, corresponding for a typical winter and a typical summer day. In total 16 different scenarios are considered.

II. Optimization and Simulation Tools Used

A. MATLAB environment

The solver "*fmincon*" from "Optimization Toolbox" in the environment MATLAB is used to perform the optimization procedure.

B. GridLab-D simulation tool

The open-source tool GridLab-D is developed for modeling and simulation of complex systems and can be successfully used for simulation and investigation of microgrids. In [17] it is emphasized that this requires a "heterogeneous composition of physical, computational, and communication sub-systems". The simulation tool GridLab-D is created by the U.S. Department of Energy at the Pacific Northwest National Laboratory [18] for high-level modeling and simulation. It should be noted that GridLab-D includes techniques and high-performance algorithms to build high qualitative end-use models.

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C. GridMat tool

The disadvantage of GridLab-D is that it does not provide an user friendly interface for modeling the structure and the behavior of a studied microgrid. An additional Matlab toolbox has been created (see [17]) to integrate the modeling and simulation features of GridLab-D and the control features of Matlab. This toolbox is called GridMat. It represents an open-source tool for academic activities and research. GridMat is designed for "user friendly model creation, robust debugging, and intelligent grid impact analysis utilities" [17].

III. Experimental Setup

The experimental setup configuration is schematic presented in Fig. 1 (see [8, 9, 10]).

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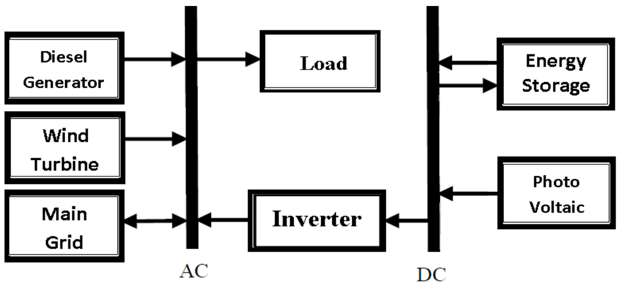

Fig. 1. Experimental setup system configuration

The experimental microgrid operates disconnected from the main Network in an Island mode. It uses a three-phase medium voltage alternating current (AC) system and two types renewable energy sources (RES): 1) a wind turbine, and 2) a photovoltaic system, consisting of a group of solar panels connected by an inverter to the three-phase microgrid. An energy storage system composed by a group of batteries is also connected to the microgrid by means of a DC/AC bi-directional inverter. In case in a given moment the RES are unable to produce enough energy to cover the loads, a diesel generator is turned on, which produces the required amount of energy. When the experimental microgrid uses an optimal energy schedule of battery bank this is a *smart* microgrid, since the energy storage system ensures the balance between the loads and the energy produced by the RES. In this way the fuel consumption by the diesel generator is minimized. The elements of microgrid energy system are the following:

- *3 Houses*. Each house has a built-up area 100 m^2 (10m×10m). The house has 3 flours, it is 10 m high and its heated volume is 720 m^3. The walls surface varies according the chosen WWR.

- *Photovoltaic power system*. Mono- crystalline solar panel modules 200W/20V [19] and an inverter, connecting the solar system to the AC network with the loads are used. The area of all photovoltaic modules system is 1500 ft^2, allowing a peak power production around 30 kW.

- *Wind turbine*. Different wind turbine types are considered in [20, 21, 22]. The wind turbine used in the experimental microgrid system is: *"Bergey 10 kW"*.

- *Battery*. The battery system has a charging/discharging schedule, which is determined by solving an optimization problem. The battery block is composed by Aqueous Hybrid Ion (AHI) batteries and an AC/DC inverter. AHI batteries have a lifetime of up to 10 years. The advantages of this type batteries compared to lead-acid batteries (PbA) are considered in [23]. The capacity of PbA batteries decreases significantly with temperature variation.

- *Diesel generator*. In this study is used a 35kW/44kVA KOHLER Systems diesel generator [24] having rated power of 41 kWm (engine type: KDI 2504TM-40).

The microgrid architecture is shown in Fig. 2 (see [8, 9, 10]):

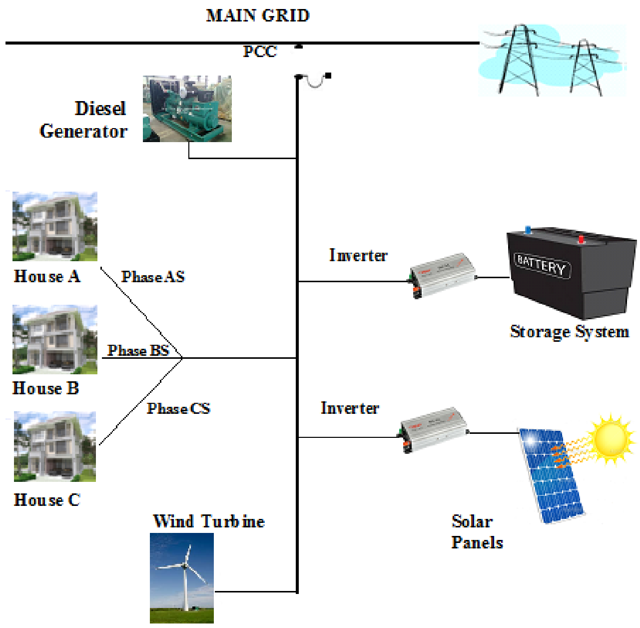

Fig. 2. Configuration of experimental microgrid

IV. Methodology

The data used in this study for microgrid energy consumption, wind speed and solar radiation are historical climate data from the GridLab-D Web-site [18] for Seattle city (USA) - for a typical winter day and a typical summer day. These data are used for simulation the behavior of the RES and the houses. A day ahead forecast data are simulated using the mentioned real data and taking into account the total heat loss of the houses. One day and one night time interval is considered. It is divided into 24 time steps, each with 1 hour length. Considering the energy flow in the described microgrid (see [8, 9, 10, 25]), the balance power P_B should satisfy the equations:

$$P_{RES} + P_B = P_L \quad (1)$$

$$P_B = P_{Bat\_d} + P_{DG}\ , \quad (2)$$

where P_L is the microgrid load, including the consumed energy by the devices in the houses, the heat loss and the battery system charging energy. P_B is the balance power and P_{RES} is the output power of renewable energy sources. P_{Bat_d} is the power from discharging the battery system, P_{DG} is the output of the diesel generator. Energy scheduling optimization in an island microgrid, based on an economic model is considered in [9, 10]. The idea of the current research is to minimize the produced diesel generator energy, using the maximal battery storage capacity and at the same time minimizing the heat loss. The energy loss by roof, floor, walls and windows in the houses is calculated. Four different WWR and two types of glazing (double and triple glazing) are considered in 8 scenarios for the winter period and 8 scenarios for the summer period.

A. Calculation of heat loss:

The heat loss through the walls, windows, roof and floor depends on the conduction, convection and radiation. The building elements have thermal performance, which is specified usually by an *U*-value, defined as follows:

- heat flow through one square metre = = *U*-value × temperature difference.

Based on this the *U*-value is equal to the heat flow per square meter divided by the temperature difference. Hence the *U*-value units are watts per square meter × Kelvin: [W m^{-2} K^{-1}]. The insulation is better when the *U*-value is lower.

U-values for windows with double-glazing (hard coat low-e, emissivity = 0.15, argon-filled) and with triple glazing (soft coat low-e, emissivity=0.05, argon-filled) are given in Table I.

TABLE I
U-VALUES OF WINDOWS

Glass type	***U*-value [W/(m^2.K)]**
Double glazing, argon filled	1,49
Triple glazing, argon filled	0,78

Let the windows area be denoted by Aw [m^2]. Parameters of one house for calculating the heat loss are given in Table II.

TABLE II
PARAMETERS OF ONE HOUSE

Building elements	**Area [m^2]**	***U*-value [W/(m^2.K)]**	**WWR**	**Aw [m^2]**
Roof	122	0,18	0.125	50
Floor incl. attic	4×100	0,25	0.175	70
Walls	4×100 − Aw	0,35	0.225	90
Walls	4×100 − Aw	0,35	0.275	110

The total heat loss [26] includes total fabric heat loss and ventilation heat loss. The total fabric heat loss flow rate, denoted by Q_f is defined as the sum of all the *U*-values of the individual elements multiplied by their respective areas, and multiplied by the inside–outside temperature difference, ΔT.

$$Q_f = (\Sigma U_x A_x) \times \Delta T \text{ watts} \quad (3)$$

It can be assumed that the whole house has the same internal temperature, let say 20 °C. The outside temperature during the winter is assumed to be −5°C, and during the summer + 30 °C. Hence $\Delta T_{winter} = 25$ °C, and $\Delta T_{summer} = 10$ °C.

The ventilation heat is calculated by the formula (4):

$$Q_v = 0.33 \times n \times V \times \Delta T \text{ watts}, \quad (4)$$

where V is the volume of the house (m^3), and n is the number of air changes per hour (ACH). For the calculations it is assumed that the air change rate $n = 0.5$ ACH.

The total whole-house heat loss $Q_L = Q_f + Q_v$.

B. Optimization Task:

The following objective function is introduced:

$$\text{Min } F = \sum_{i=1}^{24} P_{DG}(t) - \sum_{i=1}^{24} [P_{Bat}(t)]^2 + Q_L \quad (5)$$

subject to the constraint system, defined in the model in [9, 10]. The above optimization problem is nonlinear with 169 constraints and 48 variables: the first 24 variables are for $P_{Bat}(t)$, t=1,…,24; and the next 24 variables: 25, 25,...48 are for $P_{DG}(t)$, t=1,…,24; It is assumed that the corresponding battery (charge/ discharge) power variables $P_{Bat}(t)$ are positive when the battery is discharging and negative when is charging. In case the microgrid operates connected, using energy P_{MG} from the main grid, the equation (1) has the form:

$$P_{MG} + P_{RES} + P_B = P_L \quad (6)$$

Then similar optimization problem could be formulated.

V. TEST RESULTS

The four different WWR values combined corresponding with double and with triple glazing give 8 optimization scenarios for the winter day period and 8 scenarios for the summer day period. 16 optimization problems are solved for the different scenarios. Corresponding *F*-values are denoted by *Fdg* for the case with double glazing and by *Ftrg* for the case with triple glazing. The obtained results are summarized in Table III:

TABLE III OPTIMIZATION RESULTS

Windows scenario	**Winter**		**Summer**		**Mean values**	
WWR =0.125	*F1dg*	11808.5040416576	*F9dg*	3320.7566085822	*Fdg*	7564.6303251199
	F2trg	10933.5040416576	*F10trg*	2970.7566085822	*Ftrg*	6952.1303251199
WWR =0.175	*F3dg*	12383.5040416576	*F11dg*	3550.7566084862	*Fdg*	7967.1303250719
	F4trg	11158.5040416576	*F12trg*	3060.7566104822	*Ftrg*	7109.6303260699
WWR =0.225	*F5dg*	12958.5040416576	*F13dg*	3780.7566084824	*Fdg*	8369.6303250700
	F6trg	11383.5040416576	*F14trg*	3150.7566085822	*Ftrg*	7267.1303251199
WWR =0.275	*F7dg*	13533.5040416576	*F15dg*	4010.7566084862	*Fdg*	8772.1303250719
	F8trg	11608.5040416576	*F16trg*	3240.7566085822	*Ftrg*	7424.6303251199

VI. Conclusion

Considering the mean values for the summer and winter period in Table III, and evaluating the percent of improvement there is possible up to 26,179% improvement in the objective function value when optimal WWR and glazing type are chosen. Hence the optimal windows design can lead to essential improvement of energy efficiency in the buildings.

Acknowledgement

This work is in the framework of CEEPUS network project № CIII-BG-1103-04-1920 and Project BG05M2OP001-1.001-0004-C01 Universities for Science, Informatics and Technologies in e-Society (UNITe).

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