Development of a Simulation Tool for Evaluating the Performance of the Pilot Microgrid at Gaidouromantra-Kythnos

Evangelos Rikos and Stathis Tselepis

Centre for Renewable Energy Sources and Saving,
19th km. Marathonos Ave., 19009, Pikermi-Athens, Greece
{vrikos,stselep}@cres.gr

Abstract. The concept of "Microgrid" is one of the most promising architectures expected to support the transition from present to future Electricity Grids by integrating large amounts of Renewable Energy Sources. The numerous benefits of microgrids have attracted attention and during the last decade several projects and researches have focused on this field. Within different European projects the pilot microgrid located at Gaidouromantra, in Kythnos island was constructed in order to electrify a number of vacation houses. In this paper, a simulation model for this microgrid together with some simple guidelines for modeling such systems are presented. The model was developed for testing the system performance under different operating conditions as a subtask of the FP6 EU project More-Microgrids. Specifically, the selected mathematical models and assumptions are presented. In addition, simulation results and discussion of them are given compared also with real data measurements which validate the model accuracy.

Keywords: Microgrids, Simulation, Renewable Energy Sources, Distributed generation, Photovoltaics.

1 Introduction

The need for increased penetration from RES (Renewable Energy Sources) as well as the transition from the current to the future Electricity Systems has led to research of alternative technologies and architectures which will support and allow a smooth change into the future power systems by exploiting at the maximum possible degree the benefits from RES and DER (Distributed Energy Resources), reducing also the related problems [1]. One of the most interesting and promising architectures, expected to play critical role in the next years is the 'microgrid'. By definition, microgrids are parts of the LV (Low Voltage) distribution grid with some specific features as mentioned in [2-4]:

- Incorporation of different types of small power sources such as micro-turbines, fuel cells, PVs (PhotoVoltaics), etc. called MicroSources, together with storage devices, (i.e. flywheels, energy capacitors and batteries), and controllable loads.

N. Hatziargyriou et al. (Eds.): E-Energy 2010, LNICST 54, pp. 144–152, 2011.

- They are interconnected to the MV (Medium Voltage) distribution grid through transformers and static switches and due to this they can also operate in isolated mode, in case of faults in the upstream network.
- From the customer's point of view, microgrids can provide both thermal and electricity needs, and in addition enhance local reliability, reduce gas emissions, improve power quality by supporting voltage and reducing voltage dips, and potentially minimize costs of energy supply.

A pilot microgrid system, which is used to electrify a cluster of houses, is located in Gaidouromantra-Kythnos [5]. Specifically, it electrifies 12 vacation houses and one control room in a small valley in Kythnos, an island in the cluster of Cyclades situated in the middle of the Aegean Sea. The installation of the system began in 2001, as part of the projects PV-MODE, JOR3-CT98-0244 and MORE, JOR3CT98-0215. Some of the most important features of the system are the following:

- The system is permanently islanded because there is no physical connection with the public utility.
- The main energy producers are PVs.
- The consumption profile deviates from normal household profiles because the houses are used only in holidays and equipped with high efficiency loads.

In the framework of the project More-Microgrids the system was upgraded and used as test field for investigation of different control strategies. In addition, one of the project subtasks included the development of a simulation model for testing the operation of the microgrid. This tool provides capability of investigating the operation under different production or consumption scenarios offering versatility regarding the system configuration. In addition this model can be used for testing alternative technologies before used in the real system (e.g. control strategies, connection of extra sources and loads, configuration changes etc.). Due to this, the model can be used not only for power flow analysis but potentially for dynamic tests. In this paper, the selected mathematical models with all necessary assumption are described. The presented assumptions can be used as guidelines for designing such tools. Moreover, some key results from 24-hour simulation tests are given, and also compared with real data in order to deduce the model accuracy.

2 System Configuration, Model Characteristics and Assumptions

2.1 System Configuration

The power system of Gaidouromantra covers the needs of totally 13 houses. The main parts of the microgrid are briefly described below:

- PV generators: The system includes 7 PV panels with 11kWp total installed power.
- Two Lead-Acid (FLA) Battery banks, with 1000Ah/48V (main), and 480Ah/60V (secondary). The main system is managed through three single phase battery inverters (SMA-SI5048) while the secondary through one single phase inverter (SMA-SI4500). During the day, the two storages are connected together at the AC side. During the night, the two banks are disconnected and the secondary system

covers the control and monitoring equipment needs. The 3-phase configuration and the interconnection between the main and the back-up system are changeable according to each project requirements.

- Three-phase, 9kVA diesel back-up generator which is controlled by the Battery Management System (BMS) when State Of Charge (SOC) <30%.
- Loads (refrigerators, lamps and dwelling pumps) represented as ohmic and inductive constant and programmable loads.
- The microgrid includes Load Controllers for protection against overloading or extreme battery discharge. These devices are triggered from the frequency and shed loads when frequency goes under 49,14Hz. The load reconnection takes place at least two minutes after the frequency restore, in a random order to prevent instant reconnection of all the consumers. It is worth mentioning that in the frame of More-Microgrids a new generation of Intelligent Load Controller was installed in conjunction with the already existing equipment. These devices offer a number of capabilities regarding load and source management but their operation was not modeled in the specific study.

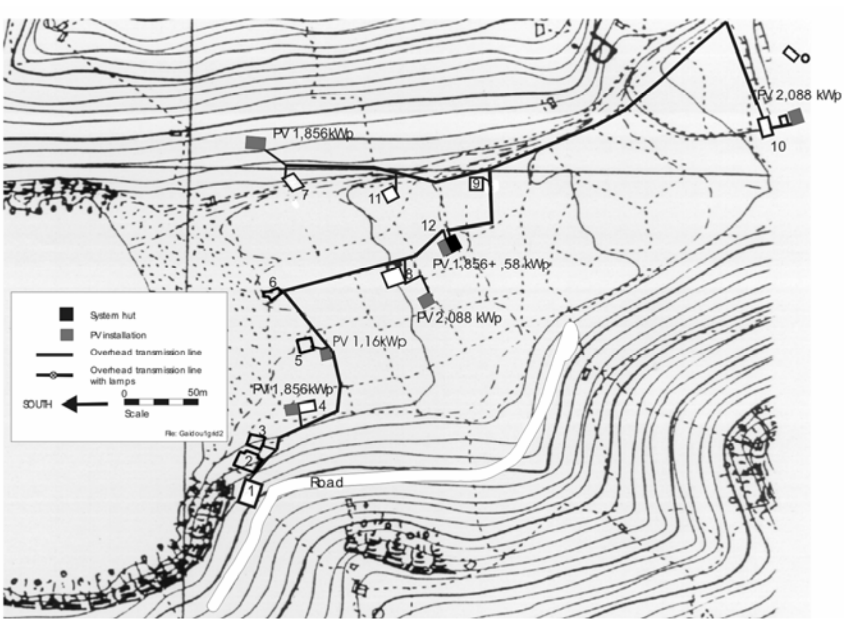

Fig. 1. The pilot microgrid located at Gaidouromantra, Kythnos

2.2 Main Features of the Developed Simulation Model

As it is evident the studied system presents a complexity due to the number and variety of parts and due to this, during modeling a set of parameters and features should be considered as more critical. This study focuses on some specific characteristics which were finally integrated in this model. Namely:

- The microgrid was modeled in 3-phase configuration but it can be changed to single phase with minor modifications.
- Each PV panel together with its inverter was modeled as taking into account the effects of irradiance and temperature. Every PV system includes MPPT (Maximum Power Point Tracking) algorithm based on the open-circuit voltage calculation. In addition, the ability of power derating versus frequency was modeled. This feature is used in order so as to prevent battery overcharge.
- Regarding batteries the selected model includes calculation of the terminal voltage, remaining Ampere-hours and maximum available capacity.
- The battery inverters were modeled as separate blocks into account their ability for grid-forming or grid-tied operation, battery SOC calculation and battery management. The latter is divided into frequency regulation according to the battery SOC and selection of the appropriate battery charging phase.
- The diesel genset was modeled as a simplified linear source with load-depended variable frequency.

2.3 Basic Assumptions

The model development requires some assumptions, which are necessary in order to reduce as much as possible model complexity, simulation time and burden of calculations. In order to obtain results for some days of operation a number of crucial simplifications were regarded:

- Use of continuous linear sources (current or voltage) instead of detailed Switch Mode Power Converter models because the switching behavior in software simulation tools increases dramatically the simulation time and it was considered out of the scopes of our study.
- Calculations by using phasors instead of instant values. This approach increases considerably the simulation speed because the electric quantities are treated as DC instead of AC values.

3 Model Development

Based on the aforementioned assumptions separate models for each part of the microgrid were developed. Each subsystem is described in the next lines.

3.1 PV System Model

The selected PV model for our study is the interpolation model [6] which is advantageous compared with the parametric one, because it involves parameters given by the manufacturers' data sheet while it involves the irradiation and temperature effects. The basic equation set describing the I-V characteristic is:

$$I = I_{SC}\left[1 - C_1\left(\exp\left(\frac{V_R}{C_2 V_{oc}}\right) - 1\right)\right] + D_I \tag{1}$$

$$C_1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right) \exp\left(-\frac{V_{mp}}{C_2 V_{oc}}\right) \text{ and } C_2 = \left(\frac{V_{mp}}{V_{oc}} - 1\right) \Big/ \ln\left(1 - \frac{I_{mp}}{I_{sc}}\right) \quad (2)$$

$$V_R = V + C_{TV}\left(T - T_{ref}\right) + R_s D_I \text{ and } D_I = C_{TI} G\left(T - T_{ref}\right) + I_{sc}\left(G - 1\right) \quad (3)$$

where: V_{mp}=MPP Voltage, I_{mp}=MPP Current, V_{oc}=Open Circuit Voltage, I_{sc}=Short Circuit Current, G=Solar Irradiance, T=Cell Temperature, T_{ref}=Reference Temperature(25°C), C_{TI} and C_{TV}=Coefficients of Isc and Voc variation depending on temperature, R_s=Series Resistance.

In addition to the PV modules a model for the PV inverters was developed. The main feature taken into account in the model is the MPPT in order to always obtain the maximum power from the PVs. Specifically; the selected algorithm calculates the maximum power point as proportional to the open circuit voltage [7] multiplied by 0,79. The coefficient selection was done so as to match the behavior of the specific modules. In a real system V_{oc} can be determined through sensing during instant open circuit condition. Although this technique was initially used in the model, finally, the selected V_{oc} estimation was based on the interpolation model given by:

$$V_{oc}^{*} = C_2 V_{oc} \ln\left(\frac{\left(1 - \left(I - D_I\right)/I_{sc}\right)}{C_1} + 1\right) - \beta\left(T - T_{ref}\right) - R_S D_I \quad (4)$$

if I=0. Moreover, two worth mentioning features of this model is its operation as current source, and the power versus frequency linear derating in order to prevent battery overcharging.

3.2 Battery Model

The battery storage units were simulated by using the KBM (Kinetic Battery Model) [8]. According to this, each battery can be described by a Thevenin equivalent circuit. In our study, two major components of the battery were calculated. These are the remaining charge q and the battery terminal voltage V. The battery capacity is calculated from the following equations set:

$$q = q_1 + q_2, \ \frac{dq_1}{dt} = -I - k\left(1 - c\right)q_1 + kcq_2, \ \frac{dq_2}{dt} = k\left(1 - c\right)q_1 - kcq_2 \quad (5)$$

where q=remaining charge, q_1=readily available charge, q_2=bound charge, I=battery current, k=rate constant, c=ratio of available charge capacity to total capacity. In addition to the above, the following equation set for the terminal voltage was adopted:

$$V = E - IR_{bat}, \ E = E_o + AX + CX/\left(D - X\right) \quad (6)$$

$$X = \begin{cases} q/q_{max}\left(I\right), & \text{charging} \\ \left(q_{max} - q\right)/q_{max}\left(I\right), & \text{discharging} \end{cases} \quad (7)$$

$$q_{max}(I) = \frac{q_{max} kc \left(q_{max}(I)/I\right)}{1 - e^{-k\left(q_{max}(I)/I\right)} + c\left(k\left(q_{max}(I)/I\right) - 1 + e^{-k\left(q_{max}(I)/I\right)}\right)} \quad (8)$$

where E_o=fully charged/discharged internal battery voltage, A=Parameter reflecting the initial linear variation of internal battery voltage with state of charge, C & D=Parameters reflecting the decrease/increase of battery voltage during charging discharging.

3.3 Battery Inverters

Battery inverters play the most critical role in the system operation because they perform the energy management by regulating frequency either for load shedding or PV power derating. In addition they manage the diesel generator start-up. In our study the same model was used for both battery systems with minor differences. It includes: a) SOC calculation, b) Frequency regulation according to the battery SOC, c) Diesel genset start-up (only for the main system), d) Charging phases including temperature compensation and e) Grid forming or charging through the diesel genset. Below, a brief description of each feature is given.

SOC: The accurate calculation of the battery SOC is critical for an effective battery management. Among different calculation methods, the one selected in our study was the Ah-balancing. This method takes into account the charging/discharging current over time. The accuracy of the method increases if losses due to gassing [8] are considered. The equation set describing the method is:

$$SOC = \frac{1}{C_{10}} \int \left(I_{bat} - \frac{I_{go}}{100Ah} \exp\left[C_V \left(V_{cell} - 2.23V\right) + C_T \left(T - 20^{o} C\right) \right] \right) dt \quad (9)$$

where C_{10}=Battery capacity for 10-hour discharging, I_{go}=Normalized gassing current, C_V=Voltage coefficient, V_{cell}=Battery cell voltage, C_T=Temperature coefficient, T=Cell temperature.

Frequency regulation: In the specific system the frequency is used as communication signal between the power units in order to manage the generated/consumed energy and hence to extend the battery lifetime. For this scope the battery inverters were modeled to keep constant frequency at 50Hz under normal conditions. This value changes in three cases: a) when SOC falls under 30%, the diesel generator is set in operation and charges the batteries. In this case the battery inverter follows the generator frequency. b) When SOC falls under 15% the frequency becomes 47Hz in order to trigger the load controllers. c) If the battery voltage becomes high, the frequency changes from 50 to a value between 51 and 52 Hz in order to cause PV power derating.

Charging phases and temperature compensation: The charging phases as well as the temperature compensation where also modeled. Specifically, from the four possible charging phases the two most important of them were regarded: Boost charging which has maximum duration 90min, which is followed by float charging until SOC becomes 70% or more than 30% of the nominal capacity has been used. The voltage/cell for each of the previous phases is: 2,55V for boost and 2,23V for float

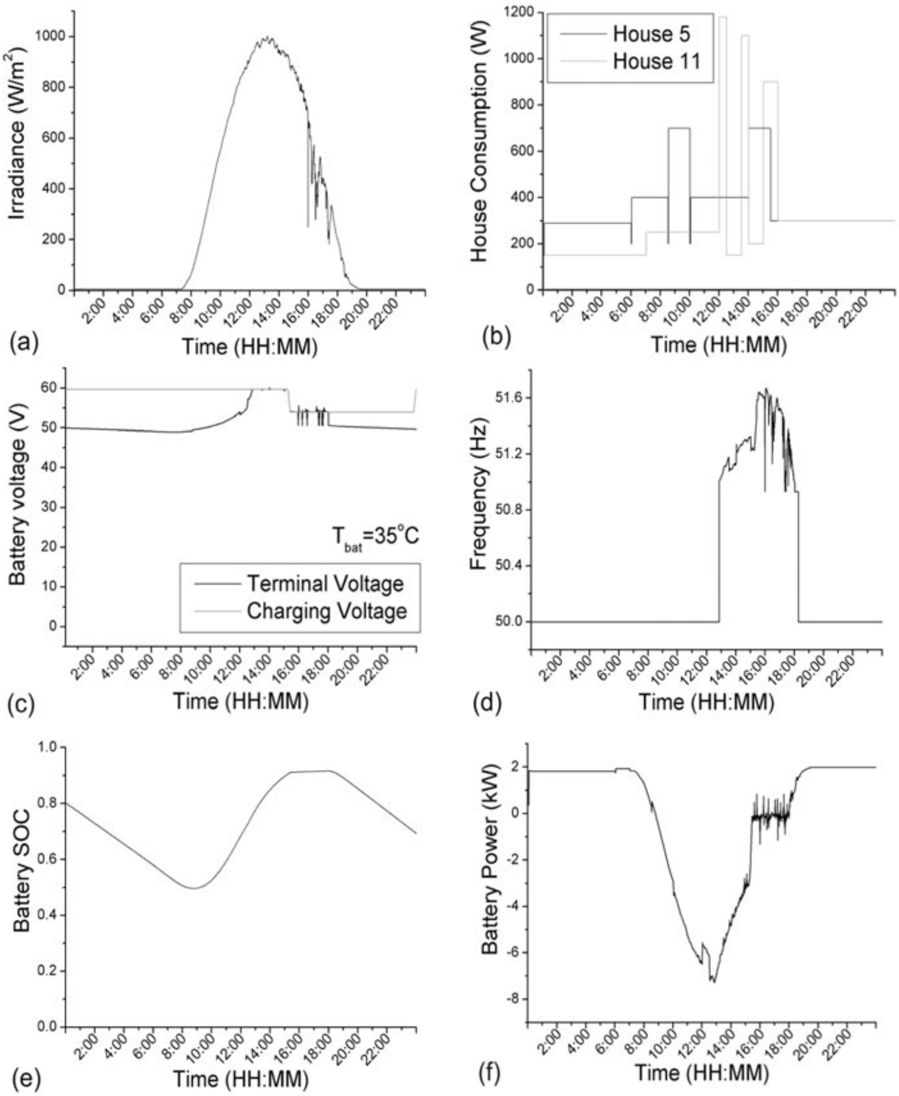

Fig. 2. 24-hour simulation test: a) insolation profile, b) two houses consumption, c) battery voltage, d) microgrid frequency, e) battery SOC, and f) battery power

charging. These values in the real system as well as in the developed model change according to the battery temperature with a coefficient of -0,4%/^{o}C for each cell.

3.4 Loads and Load Controllers

The consumers of the microgrid are modeled as programmable resistive and inductive loads enabling the user to implement input data files for simulating the consumption.

More specifically, each house was modeled as a combination of static and dynamic load. Also, each house is equipped with a load controller, which sheds specific loads when the frequency falls under 49,14Hz. The controller remains in this state until we have frequency restore and a minimum 2-min interval elapses before the load is reconnected. Then the reconnection is done randomly within a 2-min time frame.

4 Simulation Tests-Results

The simulation tests were divided into different parts covering the model validation and system performance evaluation. During the model validation, each part was separately tested while simulation tests related to the total system operation were done for different operating conditions and time intervals. More analytically, in figure 2 the results for a 24-hour test while in figure 3 the comparison between simulation results and real measurements are illustrated.

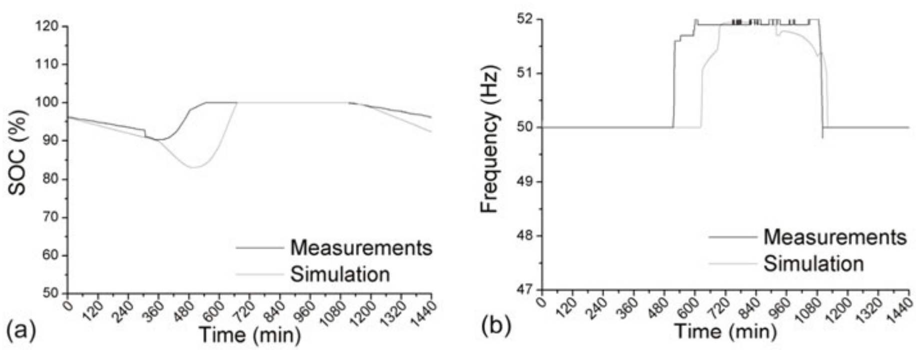

Fig. 3. Comparison between real data and simulation results: a) battery SOC and b) frequency

The examination of figure 2 reveals that the battery voltage initially decreases slowly (between 0:00 and 9:00) due to the fact that there is no generation from PVs. As the irradiance increases, there is an energy surplus and thebattery voltage increases up to the value defined from the boost charging phase (around 13:00). It is evident that at that point the frequency increases and a PV power derating begins. The frequency changes from 51 to 52 Hz so as to keep the battery voltage at 60V (a 35^{O}C battery temperature was regarded). In the voltages' diagram the reference value changes to 53V after the boost-charge phase time elapses. The frequency is kept above 51Hz until the battery voltage becomes lower than the reference value.

In figure 3, the comparison of the developed model with real measurements is shown. The most important points which worth some discussion are:

- In both cases the system behaviour is very similar proving so that the developed model has the desired effectiveness.
- There are some deviations between real and simulated values in both SOC and frequency and in addition there is a time shift in the simulation results due to the

fact that the input data used in our simulation test were not measured on-site. Specifically, due to absence of irradiance and temperature sensors on each PV plane an estimation of these quantities was used based on measurements performed in another site and date. This means that the real irradiance does not exactly coincide with the used data file. A second drawback was the absence of direct data representing analytical consumption profile for each house separately. Instead of this, the houses' consumption was estimated through the total power from the battery inverters. The above assumptions lead to the deviation in the resulted values and the synchronization of the curves.

5 Conclusion

In this paper, a simulation modeling of the pilot microgrid located at Gaidouromantra-Kythnos is presented. This work was realized in the frame of the European project More-Microgrids. For the needs of the project, a simulation model of the microgrid was developed in order to study the operation of the system under short or long term intervals and as a tool for tests before real implementation of desired experiments and modifications. Because of this the model was developed so as to be used not only for power flow analysis but also for potential dynamic tests (e.g. short circuit tests). The model development was based on some critical assumptions and mathematical models for the different parts. A number of simulation tests and comparison with real data reveal the accuracy of the used models and microgrid operation under different operating conditions and time intervals.

Acknowledgements. This work was funded within the project «Advanced architectures and control concepts for More Microgrids -More Microgrids» (contract no. SES6 019864).

References

1. Rikos, E., Tselepis, S., Hoyer-Klick, C., Schroedter-Homscheidt, M.: Stability and Power Quality Issues in Microgrids Under Weather Disturbances. J. IEEE Trans. on Geosc. and Rem. Sens. 1, 170–179 (2008)
2. Siddiqui, A., Asano, H., Hatziargyriou, N., Hernandez Aramburo, C., Marnay, C.: Microgrids: Engineering and Economics. Monograph-. Springer (2008)
3. Lasseter, R.H., Piagi, P.: Microgrid: A Conceptual Solution. In: 35th IEEE Power Electronics Specialists Conference PES 2004, Aachen, pp. 4285–4290 (2004)
4. Dialynas, E., Hatziargyriou, N.D.: Impact of Microgrids on Service Quality. In: IEEE Power Engineering Society General Meeting, Tampa-Florida, pp. 1–5 (2007)
5. MoreMcrogrids, http://www.microgrids.eu/index.php
6. Khouzam, K., Hoffman, K.: Real-Time Simulation of Photovoltaic Modules. J. Solar Energy 56, 521–526 (1996)
7. Holm, D.P., Ropp, M.E.: Comparative Study of Maximum Power Point Tracking Algorithms. J. Prog. Photovoltaics: Res. and Appl. 11, 47–62 (2003)
8. Manwell, J.F., McGowan, J.G., Baring-Gould, I., Stein, W.: Recent Progress in Battery Models for Hybrid Wind Power Systems. In: AWEA Annual Conference 1995, Washington (1995)