

Development of a Field Data-based Virtual Test Bed for Microgrid Integration of Building Automation Technologies

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Abstract

Microgrid is one of the promising solutions to achieving sustainable and efficiently operating power systems. With increasing number of distributed generators, dispersed storage systems and advancing load control capabilities, microgrids are going to play an important role in the future smart grid structure. The recent focus in this area of study is on using the field data gathered from pilot applications to develop virtual test beds to be used during replication, testing of various cases and estimating long term outcomes of microgrids with different specifications. This paper describes development of a virtual test bed focused on analyzing microgrid and utility power flow relations using the field data and energy management logic of a microgrid laboratory. In addition to modeling a flexible structure that can be scaled and modified according to research interests, a KNX controlled dimmer is also simulated for analyzing the integration of an existing home automation technology into microgrid control actions.

1. Introduction

Electric power systems have faced major changes in the areas of planning, control, security and troubleshooting. Widely encountered issues such as peak demand, voltage fluctuations and grid bottlenecks are expected to become more challenging problems in the near future. Increasing penetration of intermittent renewable sources in generation, together with expanding electrification of core sectors and raising concerns on CO₂ emissions motivate researchers, operators and policy makers to develop and try more innovative approaches.

Microgrid is one of the prospective solutions for increasing the sustainability and the efficiency of power grids. Particularly because of comprising small scale generation and storage assets together with some manageable demand that can be monitored and controlled locally, microgrids have positive impacts in grid operations. While each asset in a microgrid can operate independently, their coordination through a management system makes it possible to benefit more [1]. Similar to several other subtopics of smart grid, preliminary studies on microgrids have mainly focused on simulation and pilot applications. In [2] modeling and simulation of a microgrid with multiple energy resources using PSCAD/EMTDC was proposed. Shi et. al.

modeled a microgrid prototype using MATLAB/Simulink [3]. Development and validation of a microgrid using PSCAD can be found in [4]. In [5], authors modeled a microgrid with battery and wind turbine. A laboratory test bed with three feeders comprising loads and microsources was presented in [6]. An outdoor microgrid including up to 517.5 kW generation capacity was described in [7]. In [8], design, development and hardware setting of a microgrid at University of Texas was explained. In [9] authors presented their work on the 13.8 kV microgrid laboratory test bed of University of Arkansas. The paper given in [10] reviewed several microgrid field application and test systems. Although studies in the literature and applications in the field mainly focused on islanding, harmonics and transients, more effective use of microgrid equipment through energy management systems is also a considerable subtopic. Furthermore, many researchers prefer the use of non-standardized experimental infrastructures to apply their new solutions. These systems need further product development, testing, standardization and marketing for an extensive use. On the other hand, existing and commonly used automation technologies, standards and protocols represent useful frameworks for innovative microgrid studies. This paper, presents a virtual microgrid test bed for steady state energy management studies. It was developed using the field data from an experimental microgrid laboratory. A previously presented microgrid energy management algorithm in [1] is adapted to the virtual model for more effective use of batteries and local generation from renewables. Additionally, a home automation technology is integrated into the test bed through the realistic model of a remotely controllable dimmer. In section 2, microgrid laboratory equipment together with management logic and its capabilities is explained. Section 3 includes virtual test bed modeling. Section 4 reveals the details of the case study and the last section is devoted to the discussion of the results.

2. The Microgrid Pilot and the Energy Management Algorithm

2.1. The Pilot Application

The microgrid of Technological Educational Institute of Western Macedonia (TEIWM), Department of Electrical Engineering consists of two groups of PV panels with 2.2 kW total maximum capacity, a 1 kWp wind turbine, a battery group

with a total capacity of 600 Ah and several type of loads with a total 2.5 kW consumption. The loads in the microgrid are a 1000 W induction motor, 90 W refrigerator, 12 incandescent lamps with a total 1000 W maximum consumption and 4 compact florescent lamps with maximum 144 W consumption. Each local generation and storage asset is connected to the main AC bus of the microgrid through the inverters. The topology of the microgrid is given in Fig. 1.

Each equipment in the microgrid is connected to the main bus using special control units (SCU). These units are capable of monitoring operational parameters through the current transformers as well as switching the devices on or off through the branch relays. Additionally, utility side and microgrid side bus voltages are measured using two separate voltage transformers. Interconnection to the main grid is also controlled with another SCU. Every SCU has a communication module for sending information to and receiving commands from a microgrid-dedicated PC. In the computer, a LabVIEW application is used to process the incoming data from sensors and relays; while an energy management algorithm coded in MATLAB and embedded into LabVIEW software application derives the output command in every duty-cycle [1].

As a modification, KNX home automation technology supported devices are implemented in the context of Smart Electrical Energy Management and Buildings Energy Efficiency Technologies (SEEMBEET) bilateral project led by TEIWM from Greece and Istanbul Technical University (ITU) from Turkey (Fig. 2). The fourth load's SCU is replaced with a KNX supported dimmer. Moreover, one KNX-ethernet adapter (for connection with the management system) and OPC Server are added to the system. By the use of a home automation technology supported dimmer, automated continuous dimming became possible instead complete dismissal of the related load. Details of home automation system adaptation to the existing system can be found in [11].

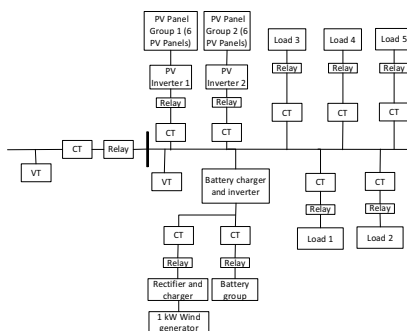


Fig. 1. TEIWM microgrid topology

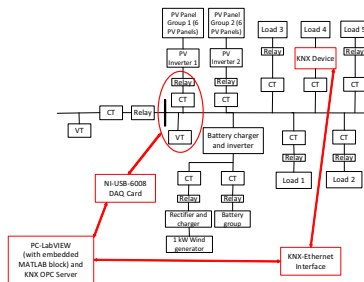


Fig. 2. Integration of home automation technology supported devices to the microgrid

2.2. The Energy Management Algorithm

The microgrid energy management algorithm has two main tasks; namely,

1. Continuous real-time voltage and frequency regulation through corrective operations such as switching on/off units.
2. More effective energy storage in the battery group by coordination of local sources with the grid operation and switching the loads according to their user-assigned priority levels.

Details of the management logic are given in Fig. 3.

3. Virtual Test Bed Development

Local generation, storage, loads and management system of the microgrid have different characteristics that should be considered during the modeling phase. Their distinct behavior and the modeling approach for each asset is described in this section.

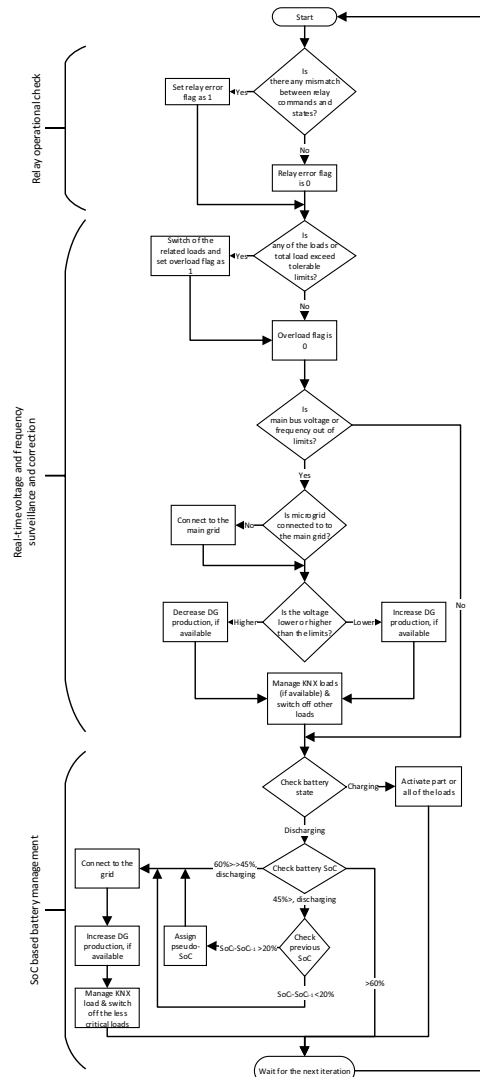


Fig. 3. Microgrid management logic

3.1. Modeling of Local Generation

The local generators in the microgrid are connected to the main bus through current controlled inverters. Both for grid-connected and for islanded steady state operations, inverters inject current to the system for the low values of bus voltage magnitudes. Thus, they are represented by current sources for steady state operating conditions in most of the modeling studies [12]. In addition, the relation between DC and AC currents at both sides of the converters can be mathematically formulated for simplified modeling purposes [13]. Virtual test bed for energy management studies requires the representation of long term operation of the microgrid equipment for different conditions, thus a detailed model was developed.

In order to include the influence of atmospheric conditions on the output of intermittent generation from renewables, source-power output relations were derived. For 2.2 kW PV panels, the relation between solar irradiance (I_r) in W/m^2 , temperature (T) in $^{\circ}C$ and power output (P_{pv}) in W is determined by curve fitting method. The first order equation given in (1) is used for PV modeling.

$$P_{pv} = 0.17121I_r - 0.13995T + 7.81336 \quad (1)$$

A new device block in PSCAD software that consists of both the logical and the analog parts is constructed. At first, the logical part reads the temperature and the solar irradiance values from an external file, then calculates the output power of PV generation (considering MPPT influence) and finally derives the current that will be injected to the system according to the measured bus voltage and frequency values. The analog part is an externally controlled current source that gets its reference from the logical part, follows the microgrid bus voltage and injects the proportional current to the system. Since the model includes so many logical and analog objects, all of them are embedded into a module together with the relevant input and the output nodes to the main simulation to be represented and used in a simpler way (Fig. 4a). Two additional nodes are added to the model for sending breaker commands (Bpv) and monitoring the power output (Ppv) of the panel group.

A similar approach is followed for modeling 1 kWp wind turbine of the microgrid [14]. The relation between the instantaneous wind speed (v_w) in m/s and output power (P_w) in W is represented with a 5th order equation.

$$P_w = 0.0002v_w^5 + 0.03v_w^4 - 1.49v_w^3 + 36.7v_w^2 + 334.4v_w + 997.6 \quad (2)$$

The developed wind turbine block has one logical input (wind speed values are read from an external file), three analog inputs (bus voltage, frequency, breaker status) and four analog outputs (connection to the main bus, active power, reactive power and current)(Fig. 4b).

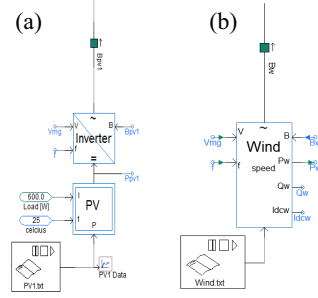


Fig. 4. Developed models (a) PV panel group (b) Wind turbine

3.2. Modeling of Local Storage

The 600 Ah lead-acid battery group of the microgrid is modeled as a union of two separate models representing the charging and discharging phases. During discharging period, from steady state power flow point of view, the battery group acts as a local generation source and supplies energy to the main bus while its converter is in voltage controlled mode. Consequently, discharging battery is modeled as a voltage source. Unlike typical local generators supplying the system with respect to their resource inputs (PV, wind, etc.), battery fills the supply/demand gap of the microgrid in islanded mode. After subtracting the amount of power generated by local generators from the local demand, the remaining mismatch is supplied by the battery group. In addition, it has a non-linear specific voltage/time curve for charging cycles. This behavior is simulated on PSCAD environment.

On the other hand, during charging phase, battery group acts as a load and consumes a fixed amount of energy from the system. It again differs from other kind of loads because of its non-linear distinct voltage/time curve (Fig. 5).

In addition to the power relation and non-linear voltage behavior of the two states, transitions between the states is also considered. If the microgrid is connected to the utility, it eventually switches to charging mode and remains idle when fully charged. When the microgrid is operated in an islanded mode, in the case of lack of supply, it fills the gap by discharging and whenever there is surplus generation in the system it turns into charging mode. A block that combines all the aforementioned features is developed.

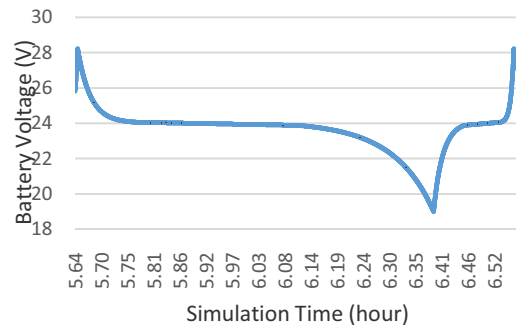


Fig. 5. Voltage/time curve during discharging and charging phases of the battery

3.3. Modeling of Loads

The loads are modeled by modifying the fixed load in the software library. The existing load model consumes a constant power in relation with the nominal voltage and frequency values. The modified version is capable of reading from an external file while adjusting the current that will be drawn considering bus voltage and frequency. In order to integrate home automation technology in the microgrid control actions, an automation system adaptable dimmer is modeled in load modeling part of the study. It is modeled as an additional block that can be connected to the power node of the previously mentioned load models (Fig. 6). The light is dimmed up when received 1 from the control input of the dimmer, whereas -1 is used for dimming down and 0 for keeping the same status without any change. This device is used as an alternative to direct on-off switching and provides more flexible way of demand management by changing the load without the loss of the related device. Moreover, it minimizes the negative impacts of on/off switching on the consumer comfort.

3.4. Adaptation of Microgrid Management System

In field application, the microgrid management system explained in section 2.2 reads the branch currents, breaker status together with microgrid main bus voltage and utility voltage at each duty-cycle (one second preferably). After processing the received inputs, it deploys the needed control commands by sending digital signals to the breakers and to the home automation system supported dimmer. In addition, there are numerous outputs that are calculated for SoC estimation and minutely average voltage-current value calculations in the control logic. They are needed to be transferred to the next iteration. The management system logic coded in MATLAB is directly adapted to the virtual test bed through array-based linkage between PSCAD and MATLAB. Furthermore, graphical indicators used in LabVIEW in the field application are similarly organized in PSCAD. At each iteration, 61 input values are collected from different parts of the virtual model, placed into arrays and sent to the control logic in MATLAB. 30 output values are received back as arrays, splitted into individual signals and applied to the system using signal labels.

For an improved monitoring, additional variables and corresponding values specified for each decision taking part of the algorithm are placed into the codes. Since the virtual test bed is intended to use for long-term power flow and energy management analysis with varying supply/demand profiles, the management system will deploy many control actions. Whenever a decision case is triggered by the inputs coming from the microgrid, the variable specified for that case takes a positive value that is different than of all other special variables. The decisions range from changing the status of breakers to showing flags for informing users about hardware errors.

In total, 229 specified parameters are placed into codes, transferred to the simulation through arrays and can be followed through graphical indicators used in PSCAD.

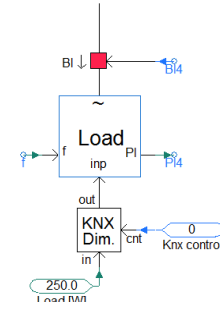


Fig. 6. Automation system adaptable dimmer and load blocks

4. Interconnected Operation of Models

The developed models are interconnected through the microgrid main bus forming the virtual test bed (Fig. 7). In order to test the power flow behavior of the models, a case scenario comprising 4 sequential events is used. The details of the events are given in Table 1. Power flow at the main bus, battery behavior and management system interventions are checked for each event. A voltage source that can receive voltage and frequency references externally is used for representing the slack bus. 4 hours of operation with varying local generation is simulated. Supply/demand behavior given in Fig. 8 shows that fully charged batteries are not used and surplus energy is supplied to the utility during interconnected operation with surplus local generation. Power flow between the microgrid and the utility reverses along the following hour since the local generation reduces. At the end of second hour, grid connection switch is opened and battery starts to fill the gap between the supply and the demand.

At the end of third hour, battery SoC reduces and management algorithm responds by dimming down the KNX controllable dimmer. Since the load decreases below the local generation, the battery starts charging itself with the surplus local generation. The amount of local generation increases after 3.5 h and battery charging power increases. At the extreme case where the battery is fully charged in islanded mode and there is still surplus generation, the management system switches on the previously switched off loads, tries to connect to the grid and if interconnection is not possible, switches of the surplus local generation. The virtual test bed exhibited identical behavior with the microgrid laboratory.

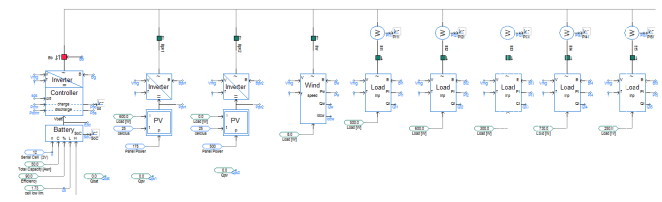


Fig. 7. Interconnected operation of developed models

Table 1. Studied Events

No	Operation Type	Supply/Demand Balance
1	Grid Connected Mode	Surplus local generation
2	Grid Connected Mode	Insufficient local generation
3	Islanded Mode	Insufficient local generation
4	Islanded Mode	Surplus local generation

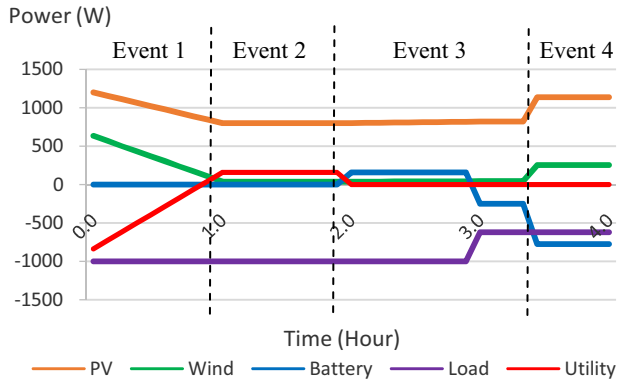


Fig. 8. Power supply/demand behavior of assets

5. Discussions

This study has presented a virtual test bed that was developed by modeling field data-based steady state behavior of generation, storage and load equipment of a microgrid laboratory. A previously proposed microgrid management system is implemented in the software environment. In addition to constant loads and on/off-based switching option, a home automation technology (KNX) supported dimmer model is designed and integrated into control actions.

Following the interconnection of the individual models, developed test bed is tested by a case study comprising 4 events representing the major operational states of the microgrid. The results showed that the supply/demand behavior of the assets and power flow on the main bus of the microgrid is consistent with the real system. Moreover, management algorithm is capable of controlling the equipment in a more effective way as it does in the field application. More flexible energy management can be achieved by integrating the load with home automation technology. Future work will cover extension of the test bed with distribution network model and investigating the impacts of local control actions on the grid side.

6. Acknowledgements

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