Framework Design for Smart Micro-Grids

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Abstract—**The 3DMicroGrid project is developing a hybrid control architecture for AC microgrids, incorporating both centralized and decentralized principles in a multi-agent scheme. Software components are being developed and tested using models based on real-world pilot sites under different topologies, locations and sizes. To assess the results from both the simulation models and the control paradigms created, various key performance indicators (KPIs) have been defined, encompassing economic and technical terms such as assets costs, environmental aspects, quality of supply, voltage and frequency control performance in island operation. The microgrid system of the German Jordanian University (GJU) is used as a pilot site in the simulations. The evaluation of selected indicators for certain simulation scenarios are presented to reveal the site and modelling constraints. The results will later also be used to benchmark the 3DMicroGrid control framework. Integration of the envisioned control software with the simulation environment will allow further real-time performance evaluation in preparation of potential on-site deployment.**

***Keywords*—microgrids; modelling and simulation; renewable energy; efficiency; key performance indicators**

I. INTRODUCTION

Microgrids (MGs) have been gaining more and more attention over the last decade with more real case applications taking place all over the world [1]. Therefore, it has become imperative to explore in details the peculiarities of such systems in large scale applications, including the integration with the utility grid and the various energy markets. Much research has been funded to analyze and understand the limitations of such integration, while investigating new methods and technologies to overcome challenges arising as progress is made. The most interesting challenge, that still eludes an actual solution, is the optimization of renewable energy resources usage in generation scheduling. Their volatile and intermittent nature introduces various aspects that require special attention, especially when designing MG islanded operation.

Many proposed solutions so far are still at the simulation level. However, a few technological breakthroughs (e.g. multi agent systems for decentralized control [2]) have become good candidates for actual deployment and are continuously being evaluated and validated for further improvement. Furthermore, cooperation with energy storage systems (ESS) [3], flexible loads [4], as well as other technologies has been suggested to enhance power balancing and reserve provision. So far, the majority of larger MG deployments still rely on fossil fuel (e.g. diesel) generators in orders to ensure reliability and overall stability [5]. Within this technological context, a novel control approach is currently being investigated in the context of EU project “3DMicroGrid”. The project aims towards actual pilot deployment at 2 sites as an end-goal.

This paper describes the current state of the 3DMicroGrid project, presenting the specific pilot case study of German Jordanian University (GJU) campus. Potential benefits have been evaluated through basic key performance indicators. The remainder of this paper is structured as follows: Section II presents briefly the project and the proposed framework for AC MG control, Section III outlines the simulation model of one of the pilot sites included in the project, whereas Section IV introduces the key performance indicators (KPI) defined and used in the presented work. Following, Section V present the simulation scenarios, results and challenges from the existing infrastructure, which are then addressed in Section VI where the application of the novel framework is discussed. Finally, the work is concluded in Section VII.

II. THE 3DMICROGRID FRAMEWORK

3DMicroGrid is an ERANETMED funded project aiming towards designing and developing a MG framework, ideally including a pilot proof of concept implementation at a university campus in Malta and/or Jordan. The project is a collaborative effort with university and industry partners from Jordan, Malta, Germany, Turkey, Spain, Cyprus, Algeria, and Greece. Currently, having gone over the half of the project’s lifetime, the various software components are still under development. Phasor and discrete models of the demo and pilots sites have already been concluded.

On a high level, business scenarios and technical use cases have been designed to cover basic MG functionalities, and requirements on technical and organizational levels have been collected and analyzed. Information about the projected pilot sites has been collected and data acquisition for designing components has been going on for several months. System models representing components on various levels, including electromagnetic transients (EMT), phasor models, and software coordination strategies, have been developed and are being validated in order to allow further high-level analyses. In parallel, an extended list of KPIs has been defined, appropriate simulation tools are set up, and optimal power flow algorithms are implemented.

Technically, the project aims to deliver a hybrid control architecture that incorporates both centralized and decentralized principles in a multi-agent scheme, based on the Java Agent DEvelopment Framework (JADE), which will handle the information flow on all control levels adopted [6]. Furthermore, an Optimal Power Flow logic is employed to optimize aspects related to the energy market and day-ahead planning, whereas system stability and reliability in real-time operation are taken care of by a more lightweight optimization toolkit.

Since the software implementation regarding the enriched control schemes proposed is still under development and the extended simulation scenarios currently experimented upon are not yet finished, the 3DMicroGrid framework has not yet been applied to the foreseen pilots. However, the simulation models of the pilot sites have been concluded and some first baseline results regarding the challenges and peculiarities present in each pilot case can be extracted. One of the pilots engaged in the project is given below as a case study for the presented work.

III. GJU CASE STUDY - PILOT SITE MODEL

The actual implementation of the 3DMicroGrid framework is considered at two locations: a university campus of Malta College of Arts Science and Technology (MCAST) and a university campus of German Jordanian University (GJU). In this paper, the analysis focuses on the GJU campus in Jordan whose assets and topology are described in Table 1 and Figure 1.

This MG pilot covers the whole campus of GJU. The university grid is connected to the utility grid via two 33/11 kV transformers. The campus distribution network is configured as an 11 kV ring and includes six 11/0.4 kV transformers. The MG is equipped with six backup diesel generators designed to feed emergency loads in case of any outage of the utility grid. Additionally, there is a total of 1.84 MWp solar PV generation capacity installed on the campus, distributed over multiple PV units. The peak load of the whole campus is approximately 1600 kW.

TABLE I. GJU MG PILOT SITE MODEL ASSET RATINGS AND LOAD ASSUMPTIONS USED IN THE SIMULATIONS.

Bus	**Synchronous generator** (kVA)	**PV** (kWp)	**Load (kW)**	
			Max	Min
1	400	-	2.6	2.6
2	150	498	788.6	26.8
3	703	-	324.5	78.1
4	150	392	322.4	2.6
5	400	708	103.5	20.1
6	703	246	30.4	2.6

For the analysis of this MG power system, simulation models have been set up in MATLAB/Simulink, in DIgSILENT PowerFactory and in Homer. The MATLAB and PowerFactory models comprise the whole grid including all lines, busbars, transformers, generators, PV plants and loads (see Figure 1). The diesel generators and PV plants including their control system are represented with generic models implementing the required functionality.

Since the control framework developed in this project is not yet available for integrated testing in simulations, the simulations presented in this paper are based on simplified assumptions concerning the coordination of assets (selection of generation units and assignment of setpoints and control modes). More detail on the methodology and assumptions is presented in Section V for each of the analyses.

IV. KEY PERFORMANCE INDICATORS (KPIS) FOR MICROGRIDS

The MG concept aims to maximize reliability of electricity supply for an ensemble of electricity consumers without relying solely on an external electricity supply grid. In order to achieve this at reasonable investment cost and electricity price levels (economic criteria), the MG needs to be efficient in its use of resources. Hence, measuring the performance of a MG entails quantification of certain key aspects [7][8][9][10], namely: a) Economy, b) Environment, c) Reliability, d) Resiliency, e) Power Quality, and f) Efficiency.

As these KPIs cover a vast range of performance metrics that can only be assessed through computational means, a selection of some basic KPIs have been made towards demonstrating the GJU case study under the selected operational scenarios.

In the following chapter, the paper looks at selected performance criteria investigated in simulations: the criteria explored are voltage and frequency limits, greenhouse gas (GHG) emissions, and integration of variable renewable energy sources (VRES). Where applicable, results are compared with requirements from relevant international standards (voltage and frequency limits).

V. ANALYSIS OF SELECTED KPIS USING SIMULATIONS

A. Voltage

Aiming to assess the ability of the GJU MG to keep voltages within a range, two different scenarios, described in Table 2, have been modelled. Special focus has been given on island mode of operation since it is characterized by more severe and frequent voltage drops. Both scenarios therefore assume islanded operation. Simulations are performed in PowerFactory using the Quasi-Dynamic Simulations calculation tool.

TABLE II. GJU MG SCENARIOS FOR VOLTAGE KPI.

Scenario	**Mode**	**Load & Irradiance**	**Gen set online**
U1	Island	Summer week	2x 703 kVA weekdays 2x 150 kVA weekend
U2	Island	Winter week	2x 703 kVA weekdays 2x 150 kVA weekend

In the scenarios, load and available solar energy correspond to real measured data. Summer weekdays are characterized by high electricity consumption and high generation from PV. According to measurements, winter weekdays are characterized as particularly challenging due to the variability of the PV generation combined with medium electricity consumption. As can be expected for a

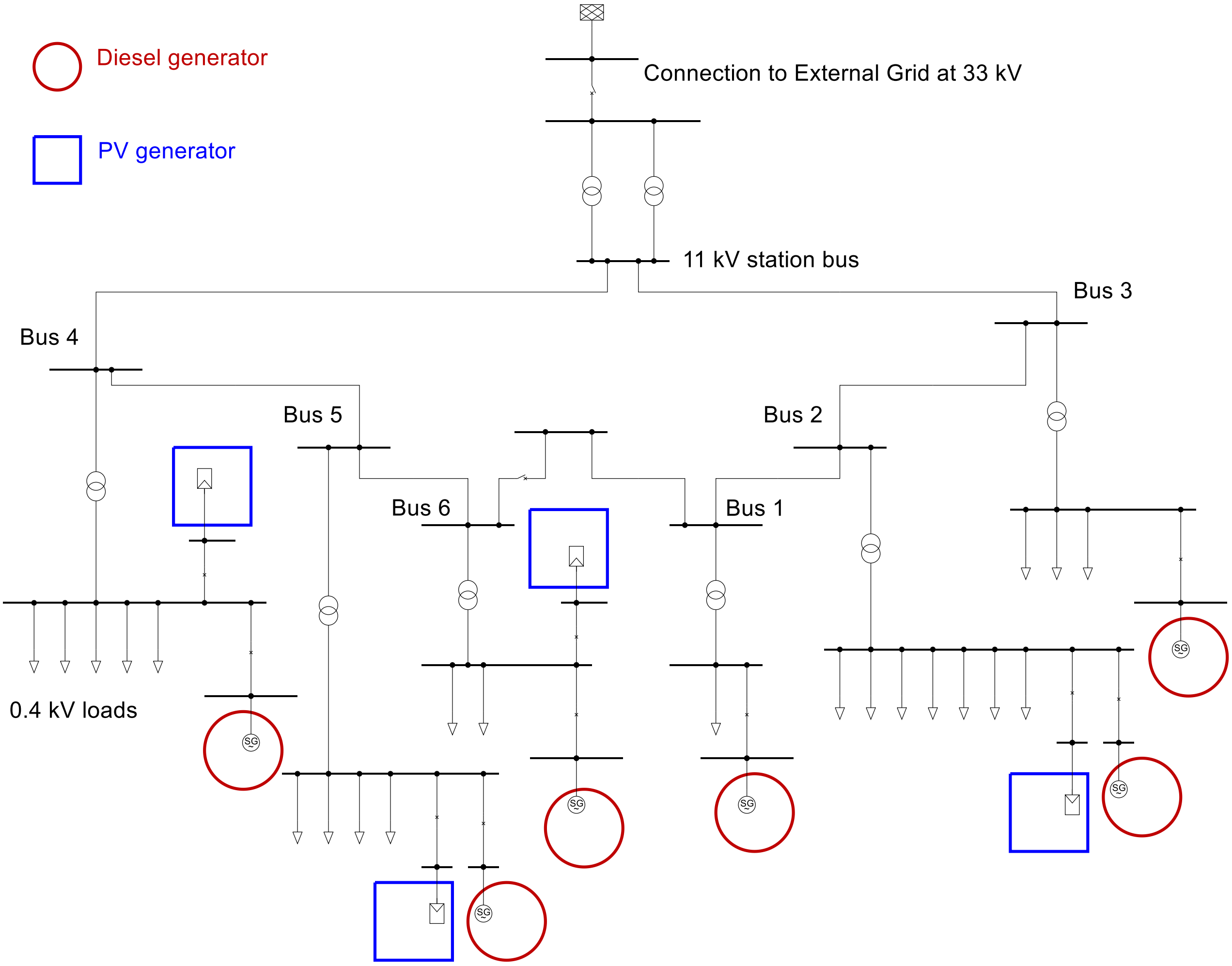

Figure 1. Model of the Microgrid of GJU campus

university campus, consumption during weekends is constantly low (see Figures 2-5).

In order to determine the set of generators online, the needs of dispatchable generation in GJU MG are estimated for each day. These needs are calculated as the maximum between the spinning reserve requirements and the net load:

- The net load is defined as the load minus the PV generation. In island mode, if the net load is positive, it must be met by the synchronous generators, while if negative, it means that PV generation must be curtailed.
- Spinning reserve requirements are determined based on the generation fluctuations that may occur in the system. The inherent variability of irradiance according to geographical and climate factors must be taken into account. The GJU MG is located in a small enclosure that can be covered by clouds reducing the active power output of the PV units by 80% within seconds. Therefore, the MG is operated with enough dispatchable generation online to cover this potential variability.

The selection of diesel generators online at each point in time also considers the minimum loading levels of each generator. Very low net load implies that only one or two generators can be running, which however also results in low amounts of available spinning reserve. If these requirements conflict, then reducing PV power output solves the problem.

Subject to the aforementioned constraints, the selection of online generators and their respective output power is based on a merit order. The PV units are above the Diesels in the merit order in order to minimize overall fuel consumption. However, in all cases there is at least one synchronous generator in operation. Regarding grid formation, the largest diesel generator is considered the master unit that controls voltage and frequency. In order to mitigate voltage deviations, PV units are assigned a Q(V) droop characteristic.

In Figures 6 and 7, voltages are plotted in the form of a histogram for the bus with the highest net load in the MG (Bus 2). Bus 2 has a 150 kVA synchronous generator and a PV installation of 498 kWp. The generator is not online during the weekdays in any of the scenarios, hence the PV installation is the only source that provides voltage support (through the Q(V) characteristic) at this bus during weekdays. This results in a maximum voltage drop to 0.96 p.u. in the summer week and to 0.97 p.u. in the winter week. In both cases, those voltage levels are reached in less than 5% of the time and they correspond to moments with peak of load. On the weekends, with the 150 kVA generator online, the voltage is maintained in its nominal value. The voltage ranges obtained in the simulations are summarized in Table 3.

When evaluating the maximum voltage drop (minimum steady state voltage) as a KPI in the case study, it should be noted that the 0.4 kV cable network has not been modelled. Therefore a voltage margin for further potential voltage drops between the low voltage transformers and individual consumer connections is reserved. Based on experience with other distribution system studies, a voltage margin of 4% is applied; hence effectively reducing the 10% tolerance established by international standard EN 50160 to an allowable 6% margin at the transformer terminals. The simulation results demonstrate compliance with these limits.

TABLE III. SUPPLY VOLTAGE VARIATIONS* OF THE GJU MICROGRID MODEL.

KPI Supply voltage variations	GJU Microgrid	EN 50160
Summer week	100% week voltage: [0.96,1]	95% week Voltage [0.9, 1.1] p.u.
Winter week	100% week voltage [0.97,1]	100% week Voltage [0.85,1.1] p.u.

* The per unit ranges comprise both the 11 kV and 0.4 kV levels

B. Frequency

With the aim of assessing underfrequency and overfrequency performance of the GJU MG two scenarios have been simulated. The results are described below.

1) Underfrequency

An underfrequency issue appears when the GJU MG is importing energy from the upstream grid and the grid breaker is opened. In such situation, only diesel generators can provide frequency support because PVs are operating at their maximum active power output. The maximum drop in frequency (Nadir) depends on the system inertia, the speed of the frequency control system (including the controller and the adjustment of the engine power output) and the deficit of generation. The maximum level of deficit that the GJU MG can withstand before the underfrequency protection relays of the diesel generators trip is investigated.

Simulation result plots are shown in Figures 9 and 11 and 13. Prior to the transition to island operation, solar and diesel power supplies do not cover the load and the GJU MG is importing 0.1 MW. This deficit corresponds to 6.25% of the peak demand. Diesel generators at Buses 3 and 6 are online but operating at their minimum active power output since costs of importing energy from the upstream grid are lower than diesel costs. After the transition to island mode, the MG operates with one of the diesel generators set as synchronous master. Due to the lack of active power generation within the MG, the frequency drops until the frequency control system of the synchronous master is able to respond and increases the power output. In the initial moments, the change of the frequency is determined by the inertial response of the system. It can be observed that the nadir of the frequency is 47.5 Hz. According to [13] and [12], underfrequency protection relays for synchronous generators trip for frequencies below 47.5 Hz. Therefore, in order to ensure continuity of service in the event of such a transition to island mode, the GJU MG cannot operate with a larger generation deficit.

2) *Overfrequency*

An overfrequency issue appears when the GJU MGis exporting energy to the upstream grid but the MG is forced to switch to island operation. In such situations, both the diesel and PV generators can provide frequency support by reducing their active power output. To avoid ramping the diesel generators below their minimum power output level, in the absence of any secondary control system that could prevent this, it is necessary to make the PV systems provide frequency support in this case. The maximum frequency reached depends on the system inertia, the speed of the frequency control loop and the surplus of generation. Similarly to underfrequency, the maximum level of surplus that the GJU MG can withstand before the overfrequency protection relays of the diesel generators trip is investigated.

Scenario and results are plotted in Figures 8, 10 and 12. Prior to the transition to island operation, there is enough power supply within the MG to meet the local consumption and to export 0.65 MW. This surplus corresponds to 50% of the momentary consumption within the MG. After the opening of the breaker, the excess of active power provokes an increase of the frequency characterized in the first instants by the inertial response of the system. It is in these instants where the frequency briefly reaches its maximum value, in this case 51.45 Hz. When the frequency support system of the PVs responds (droop control), the solar PV active power output is reduced and the frequency stabilizes at 50.9 Hz. The deviation to the nominal frequency (50 Hz) cannot be completely corrected by the droop control since it is a proportional control. According to [13] and [12], overfrequency protection relays for synchronous generators trip for frequencies above 51.5 Hz. Therefore, in order to ensure continuity of service in the event of a transition to island, the GJU MG cannot operate with a larger generation surplus.

As described above, the first critical issue during the transition to island operation is to establish the power balance within the MG. The allowable frequency minimum and maximum are defined by the generator protection settings; too high or too low frequency will lead to generator disconnection within a few hundred milliseconds and hence a black out of the entire MG. The analysis provides imbalance limits within which the system can survive in the analysed cases. Once the system is running continuously in island operation, frequency control aims to maintain the frequency within the tighter limits set in EN 50160. This is subject to different conditions than the island transition and will be analysed by the project team in further publications.

C. *Greenhouse gas emissions and integration of variable renewable energy sources*

Variable renewable energy sources (VRES) such as solar and wind help to decrease greenhouse gases emission (GHG) reducing the carbon footprint of energy systems. Due to the inherent variability of these resources, energy available and demand do not always match, leading to curtailment of load or of clean energy sources in systems without the capabilities to reallocate these resources. In order to assess the performance of the GJU MG with regard to VRES penetration and GHG emissions, a model of the MG has been defined and simulated in the Homer MG optimization software. Parameters and scenarios are described in Tables 4 and 5. The implemented energy dispatch ensures that there is always synchronous generation within the MG to give continuity of service in case of islanding.

TABLE IV. GJU MG SCENARIOS FOR GHG EMISSIONS AND VRES INTEGRATION

Scenario	**Mode**	**PV** (MWp)
H1	Island	0
H2	Grid	0
H3	Island	1.84
H4	Grid	1.84

TABLE V. HOMER PARAMETERS GHG & VRES INTEGRATION ANALYSIS

Grid CO_2 emissions (g/kWh)	675
Diesel Generators CO_2 emissions (g/kWh)	715-870
Minimum active power limit for diesel generators (%)	25

Results in Table 6 show that, given the lack of energy storage systems, the only way of harnessing all the energy from the 1.84 MWp PV installed in the GJU campus is with an upstream grid connection. Comparing scenarios H3 and H4, one can observe that when a grid connection is available, curtailment of VRES as percentage of the annual GJU load decreases from 29.7 % to 0 %. The fraction of load directly covered by VRES is slightly lower in H3 than in H4. This is due to the minimum active power output constraint of the diesel generators, which triggers in certain moments an additional curtailment of VRES compared to energy imported from the grid which lacks such a constraint. GHG emissions are mainly determined by the amount of VRES integrated. CO_2 emissions in H4 are almost 35% lower than in H1. The source of the dispatchable generation in the utility grid also has an impact on the emissions. As described in [11], average emissions of the Jordanian power system are 675 g/kWh with a high weight of oil, diesel and natural gas based generation. Electricity from the grid is hence less carbon-intensive than electricity from the diesel sets of the GJU MG (see Table 5). However, emissions from diesel generators vary, depending on the load factor. It is this reason why in H1 emissions are larger than in H2.

The presented CO_2 emissions have been calculated with regard to the overall emissions generated to cover the demand of the GJU MG. However, if we also consider the balance of emissions in the Jordan power system, the surplus of solar generation sold to the grid in scenario H4 contributes to cut further 774 tons of CO_2 emissions.

Compared to the calculated scenarios, further reduction of GHG emissions generated to cover the electricity demand of the GJU MG will be possible when technologies such as battery energy storage or increased flexibilization of load are integrated. The 3DMicroGrid framework will provide the technical means to integrate such technologies in the MG control system. Simulations with assumed deployment of such technologies are planned to be performed in the further course of the project and will be presented in future publications.

TABLE VI. GHG EMISSIONS AND VRES INTEGRATION RESULTS OF GJU MG

Scenario	**Mode**	**CO_2 emissions** (tons)	**CO_2 emissions** (% rel. to scen. H2)	**VRES available** (% of demand)	**VRES curtailed** (% of demand)	**VRES Fraction** (% of GJU demand met by VRES)	**Diesel Generation** (% of demand)	**Grid Sales** (%)	**Grid purchases** (%)
H1	Island	3220	98.5	0	0	0	100	0	0
H2	Grid	3270	100	0	0	0	29.9	0	70.1
H3	Island	2140	65.5	74	29.7	44.3	55.7	0	0
H4	Grid	2124	65	74	0	44.9	29.9	29.1	25.2

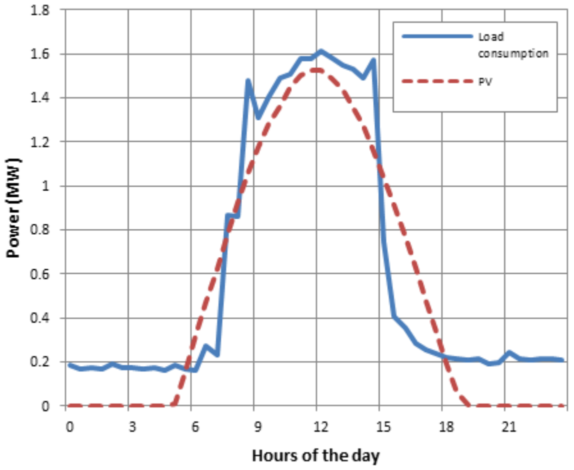

Figure 2. Load and PV available generation in GJU summer weekday

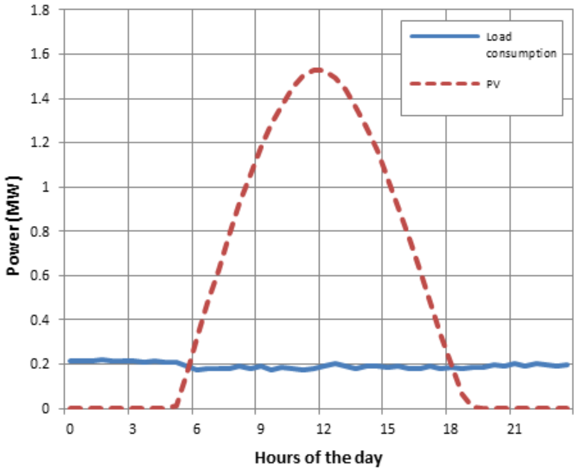

Figure 3. Load and PV available generation in GJU summer weekend day

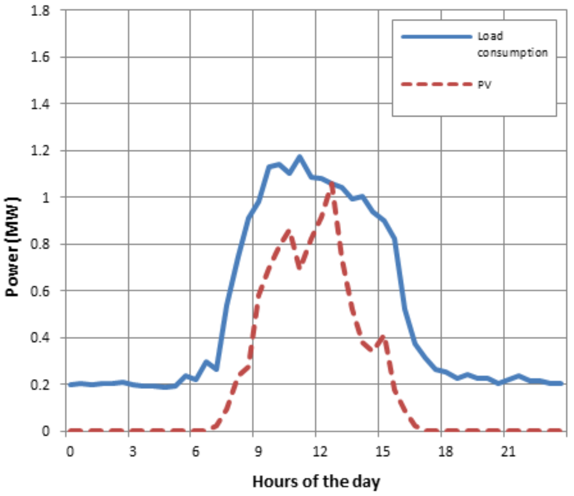

Figure 4. Load and PV available generation in GJU winter weekday

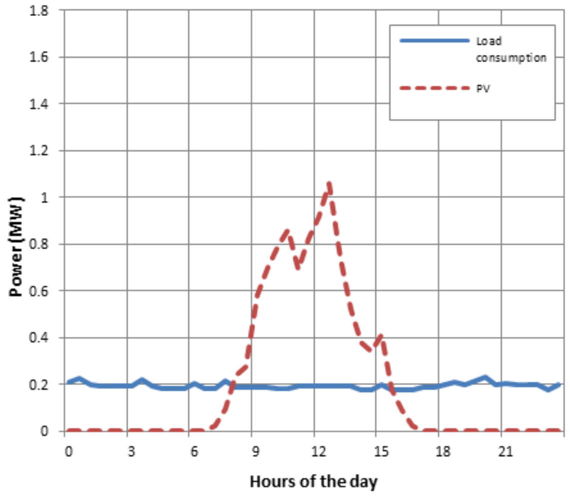

Figure 5. Load and PV available generation in GJU winter weekend day

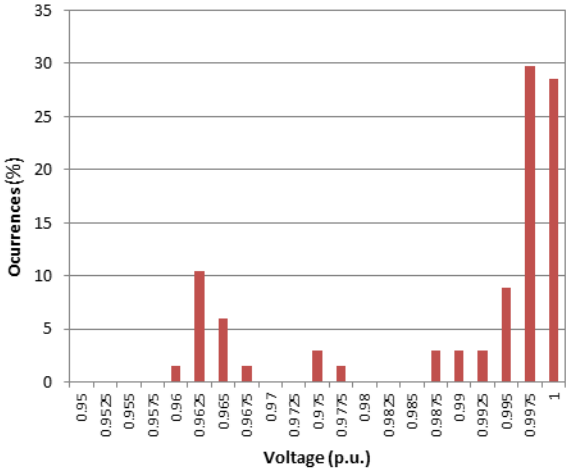

Figure 6. Voltage histogram in summer week scenario on Bus 2 in GJU microgrid

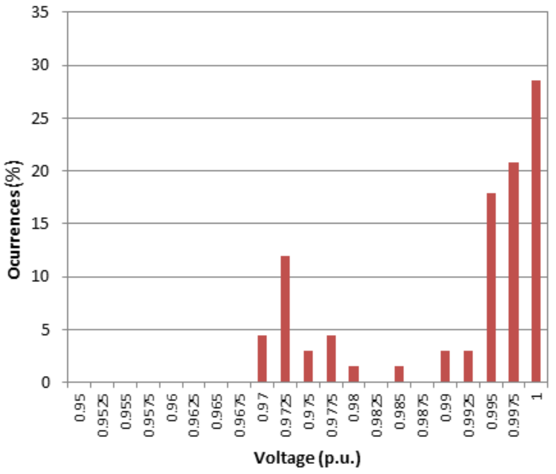

Figure 7. Voltage histogram in winter week scenario on Bus 2 in GJU microgrid

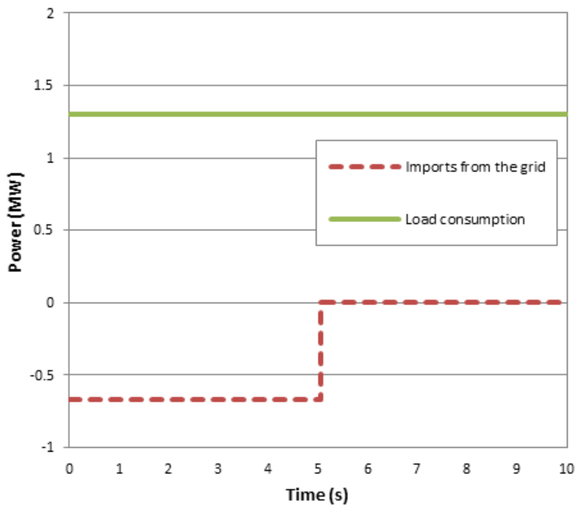

Figure 8. Load consumption and imports in overfrequency scenario

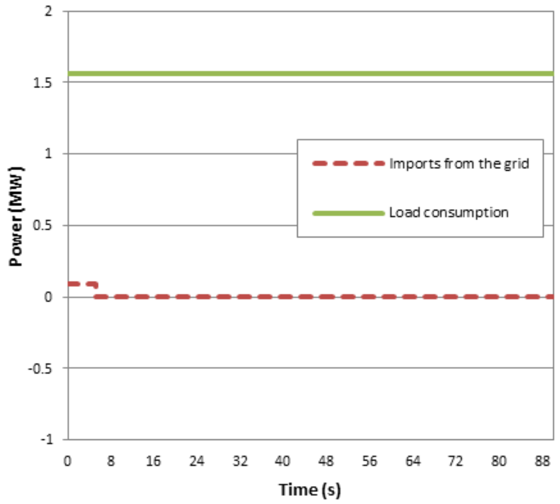

Figure 9. Load consumption and imports in underfrequency scenario

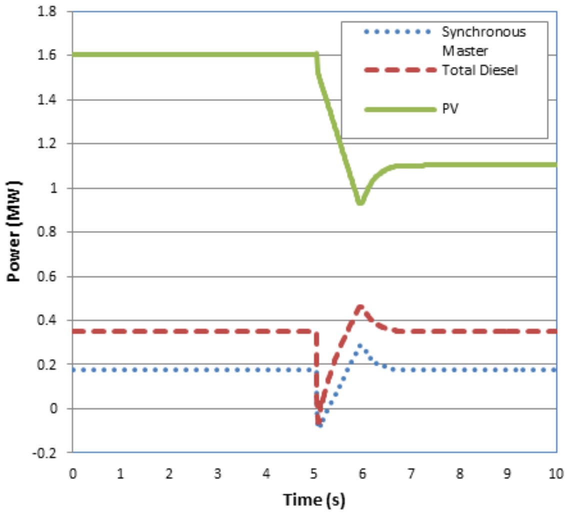

Figure 10. Generation in overfrequency scenario

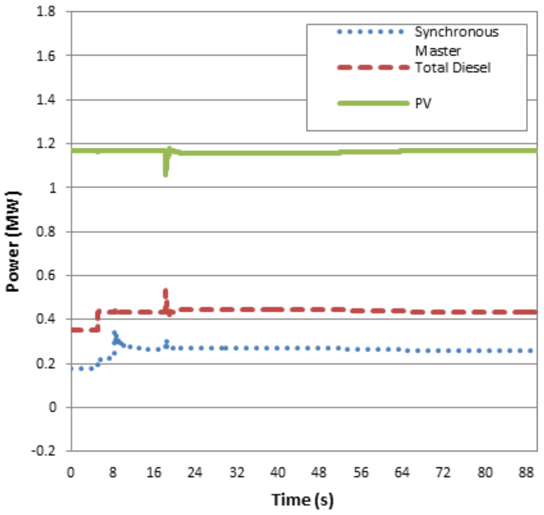

Figure 11. Generation in underfrequency scenario

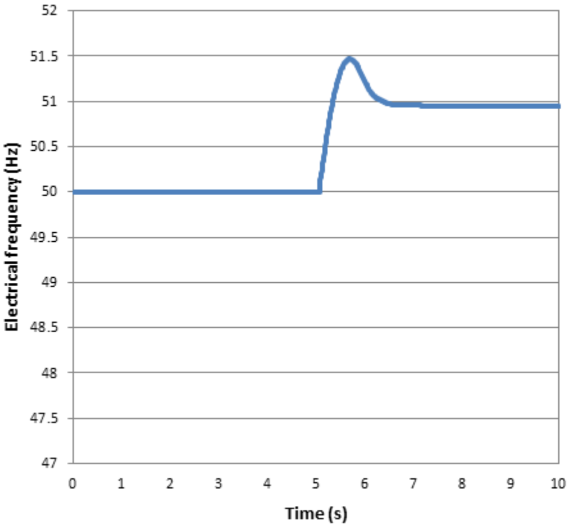

Figure 12. Electrical frequency in overfrequency scenario

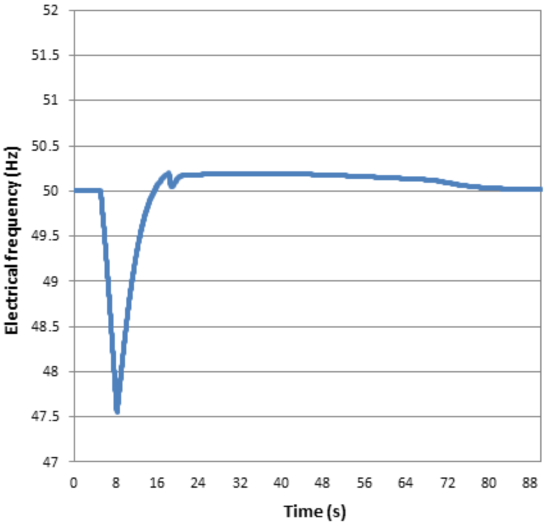

Figure 13. Electrical frequency in underfrequency scenario

VI. DESIGNING A SMART MICROGRID

The GJU MG pilot site provides the basic facilities to implement a smart MG. However, the absence of energy storage systems and other technologies to flexibilize demand (e.g., power-to-X, electric vehicles) and supply impose considerable limitations on designing intelligent control schemes due to the high mandatory PV generation curtailment in island operation and the mandatory diesel generator usage for grid formation. This results in a quite inflexible MG, with significant untapped renewable energy potential.

As currently under development, the 3DMicroGrid framework can improve the GJU MG operation by providing unified and enhanced access to additional load flexibility. It is also currently being investigated whether PV converter controllers in the pilot sites can be enriched with grid formation algorithms. Based on this an even smarter MG management can be achieved through an enhanced multi-agent communication layer for data acquisition and control, which also introduces a more robust decentralized countermeasure for single fault scenarios.

Through the above enhancements it is expected to be able to demonstrate a more stable MG in islanded operation once the new framework is ready for more substantial testing. Even during the transition from/to islanded mode and in single fault scenarios, higher performance can be achieved. This will be expressed in KPIs: with higher levels of VRES utilization, and thus higher levels of GHG emissions reduction.

VII. FUTURE WORK & CONCLUSION

In this paper, a case study of an AC MG has been presented in the context of pilot realization in an ERANETMED funded project that aims to deliver a rather promising framework for designing Smart MGs. The simulation model of the GJU MG pilot case study has been presented in detail and its performance has been assessed via certain basic KPIs. The simulated MG is characterized by certain challenges and limited flexibility due to the lack of storage units and flexible loads, however the 3DMicroGrid Control Framework is expected to improve the overall MG performance and limit the so-far mandatory PV curtailment.

Prior to deploying such technologies, extensive testing and validating scenarios have to be run in a series of simulations in order to evaluate the robustness of the proposed control architecture. Since real case applications are expected to be proven more challenging than the simulation models, a third demo pilot has been selected at CERTH/ITI (one of the partners) to deploy gradually the new control framework and evaluate its performance.

VIII. ACKNOWLEDGEMENT

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