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Table of Contents

List of Figures

List of Tables

List of Abbreviations

IEA	International Energy Agency
RES	Renewable Energy Source
ROCOF	Rate of Change of Frequency
LTC	Load Tap Changers
DGs	Distributed Generations
POI	Point of Interconnection
IEEE	Institute of Electrical and Electronics Engineers
PSO	Particle Swarm Optimization
DERs	Distributed Resources
PCC	Point of Common Coupling
PHIL	Power-Hardware in loop
THD	Total Harmonic Distortion
PLL	Phase Locked Loop
POI	Point of Interconnection

Executive Summary

In recent years the people without electricity access has decreased significantly. Globally energy consumption in the last-half century has rapidly increased and is expected to continue to grow over the next 50 years. The International Energy Agency (IEA 2010) estimate the global energy use will increase at an annual rate of 1.2 % in 2035. To address the increased demand for electricity, the governments are promoting the minigrids/microgrids in electric power networks. However, the interconnection of new system to the existing system is a major concern to stability of power system due to the lack of proper standards and protocols.

With this motive and with reference to the definition of minigrid/microgrid, this project aims to address the gap in guidelines and protocols for connection of multiple minigrids with each other and to the main grid. However, to investigate the existing guidelines and to propose the operating guidelines that would ensure a seamless interconnection of minigrids with each other thereby demonstrating the effectiveness of these protocols, both with a numerical and an experimental validations of reference minigrid(s) are necessary.

During the three weeks Transnational Access (TA) detailed in this report, various tests were carried out over heterogeneous generating sources forming multiple microgrids/minigrids configurations for transition from island to interconnected mode with the other microgrid. A synchronization controller along with its reference protocols is validated in real time scenario for interconnection of two or more micro/minigrids, based on laboratory infrastructure.

Primary Focus:

- Stable and Sustained operation of microgrid in islanded mode
- Stable and satisfactory transition from islanded mode to interconnection mode for microgrids with heterogeneous sources
- Stable and sustained operation of heterogeneous mini/microgrids in Interconnection mode
- Achieving the desired power flows along with other stability parameters

Preliminary Findings:

- Microgrid having rotating machine based DGs having less transient duration compared to static DGs based microgrid, thereby reaches near steady state quickly.
- The peak of transient current in static DGs based microgrid is to be regulated using the controller such that the current should not shoot up beyond the capacity of the converter switches.
- At the time of interconnection, the power flows/current flows at interconnection point will be having high frequency transients as the switching frequency of the converter is high, say KHz, where the microgrid with rotating machines the transients are of low frequency.
- Even though microgrid is perfectly synchronized, one can observe low frequency oscillations, like inter-area oscillations, if damping is not perfectly tuned.
- After the interconnection, there will be some power flow through the interconnection point depending on the load in the interconnected system and their respective power sharing droops and the then power availability.

1 Lab-Access User Project Information

1.1 Overview

User Project Acronym	Multigridcon
User Project Title	Grid Interconnection protocols for Largely Dispersed minigrids/microgrids
Main Scientific/Technical Field	Energy System – Smart Grid, Microgrids
ERIGrid Reference	870620-155
ERIGrid 2.0 TA Call No.	H2020-INFRAIA-2019-1
Member1	Dr. Chandrasekhar Perumalla
Member2	Amit Gupta
Duration	21 Days

1.2 Research Motivation, Objectives, and Scope

Recently, it has been observed that the world's electricity systems are beginning to "decentralize, decarbonize, and democratise," in many cases from scratch. The necessity to reduce electricity costs, replace ageing infrastructure, improve resilience and reliability, and provide reliable electricity to rural and island community is driving these trends, also known as the "three D's." Moreover, In India, an average village has a total electricity demand of 1,826 kWh per day, with about 52% contributed by households, 7% by enterprises, and the remainder by agriculture. Various sources of electricity, including diesel generators, serve this electricity demand. However, many rural places still don't have grid access in their area, and where the grid is available, potential consumers may be dissuaded from connecting to the electric grid because of supply insecurity and the length of a power outage. Almost half of all those who rely on the electrical grid experience daily outages of eight hours or more. An unstable electricity supply is inconvenient for customers and also results in costly power backup systems. Microgrids have emerged as a versatile architecture for deploying distributed energy resources (DERs) that can meet the necessity of reliable electric requirements from urban to rural area.

Efficient Microgrid/Minigrids are heterogeneous in nature since they can include different type of energy sources and generation technologies. Hence, their dynamic operational characteristics varies from one another, for example, a mini-grid with power electronic converter interfaced renewable energy sources (RES) will behave differently compared with a mini-grid with directly connected rotating generators for the same transient disturbance or change in operating condition. The integration of two heterogeneous mini-grids is a challenging task especially if each of the two mini-grids is serving appreciable number of local loads. Hence, it is critical to define protocols for connecting and disconnecting mini-grids without affecting the stability and voltage quality of the grid.

The policy and regulatory aspects of mini-grids and their interconnection protocols are yet to be defined clearly, if not completely. Such protocols on grid integration and islanded operation as well as interconnection of mini-grids are highly dependent on the grid type, location and specific combination of energy sources. The present protocols are not comprehensive enough and do not cover sufficiently the needs for interconnection of multiple mini-grids. Moreover, the lack of clear integration protocols for the mini-grids is resulting in stranded and abandoned assets when the main grid is extended to the area.

In this connection, the objective of the work is;

- To validate the proposed interconnection scheme along with its specifications when interfacing the two or more heterogeneous mini/microgrids

- To validate the developed control scheme along with its reference protocols for interconnection of two or more micro/minigrids, based on laboratory infrastructure

Adapt the interconnection protocols and control schemes from test results for better performance, if required.

1.3 Structure of the Document

This document is organised as follows: Section 2 briefly outlines the state-of-the-art, objective and motivation of the work. Section 3 describes the executed experiments including methodology, set-ups, system description and control schemes. Section 4 summarizes the results and conclusions, whereas potential open issues and suggestions for improvements are discussed in Section 5.

2 State-of-the-Art/State-of-Technology

Minigrids are localized power networks, usually without infrastructure to transmit electricity beyond their service area. They tend to rely on distributed generation technologies such as solar PV, wind turbines, small-scale hydropower and diesel generators. Electric grids with range of kW to multiple MW capacity are usually termed as microgrids. The integration of several mini/microgrids into the conventional power grid can facilitate the electricity supply to unserved population in the rural areas. However, it also increases the complexity of the power system and requires new operational and control strategies as well as clearly defined interconnection, islanding and seamless transitioning requirements.

Future electric power system in rural areas are expected to be relatively weak and with higher penetration of converter interfaced RES [1]. The primarily system designed for unidirectional power flow while bi-directional power flows are inevitable in a minigrid connected to the other microgrid or main grid. Responding to the active network technical challenges and interconnection of bidirectional microgrid, several methods and controller techniques have been proposed in the literature. The general consensus is that the control design and operation of the power electronics converters is essential in minigrids where inverter interfaced RES are more prevalent than directly connected rotating machines form of generators. Besides, to adapt to the continuous change in network parameters, local controllers shall be able to operate using limited local information and required to be distributed without the need for central controller and complex communication network [2]. The process of interconnecting two independent electrical systems requires their synchronization with a matching of variables as frequency, voltage amplitude and phase before their electrical interconnection. In the last decade there has been an extensive research on grid synchronization algorithms for power converters [3]-[5]. These algorithms (e.g. PLL-based detection) perform very well for synchronization to a strong system but are less reliable for synchronization to a weak system. Another technical aspect to consider during the synchronization is that incoming microgrid/minigrid will need to adapt its voltage amplitude and phase in the shortest possible time without violating the operation of microgrids and continuous to feed power to their respective local load without any disturbance. This is in principle simple when only a single generator is present in the connecting microgrid but can be more challenging in case of multiple generators and their associated regulators.

Furthermore, microgrids play a vital role in electrification in rural and island areas. Today's researchers focused on interconnecting multiple microgrids to create a big cluster of microgrid arrangements to maintain the stability and reliability of the system. However, till now the majority of research papers focused on microgrids interconnected with the utility grid. The parallel operation of different source based DGs and their associated challenges is covered in [6]. Droop-based synchronization controllers have been described in [6]–[9] for synchronization with utility grids where the frequency and voltage are set by the utility grid. However, choosing the reference voltage and frequency for interconnection of the microgrids is crucial and challenging task. Pre-synchronization of parallel DGs of a microgrid using master-slave technology is described in [10]. Before connecting with the grid, it synchronised DGs using a temporary master-slave approach. However, it only considers microgrids with converter-based system. Microgrids with heterogeneous sources with both static and rotating machine described in [11]. However, the control schemes for synchronization is divided in several steps. The phase angle, frequency and voltage deviations are calculated in an intelligent electronic device situated at the connection point, making the control implementation complex. In [12], a renewable energy based microgrid synchronization with the diesel generator set during low renewable power generation is explored. More precisely, the inverter-based DG is synchronized with diesel generator. In [13], [14], the control actions are implemented to correct the frequency difference and phase difference in sequential manner. As it is evident, this approach involves multi-step process and delays the synchronization.

A further technical aspect to be assessed when interconnecting mini-grids is the stability of the resulting combined power system. The interconnection will modify the configuration of the existing system and several of the controllers may have to switch their operating mode. For example, standalone minigrids are mainly operated to control active and reactive power and supply local load without disturbance while in interconnected mode the control objectives are modified to set the terminal voltage amplitude and frequency with the other system. It should be noted that system stability issues and change in operating mode of controllers also need to be addressed when switching from standalone to interconnected mode. However, these process are still in an early development stage and still an active research area.

3 Executed Tests and Experiments

3.1 Test Plan, Standards, Procedures, and Methodology

3.1.1 Test Plan

The test aims to validate the developed control strategies for seamless interconnection of microgrids and transition from islanded to interconnected mode and vice-versa for the selected reference microgrids. The reference microgrid established with heterogeneous generating sources which are electrically isolated with a provision to interconnect based on the compliance with the defined protocol with the help of a developed controller and associated subsystems, including protection.

The primary objective was numerical validation of the connecting/disconnecting strategies for power system consisting of several microgrids with heterogonous DGs with focus on stability and power quality. In this context, two cases with heterogonous microgrid consisting inertia and non-inertia based DGs had been considered to test stable and sustained operation of microgrids in islanded and interconnected mode.

Case 1: Non-Inertia Minigrid/Microgrid interfaced with Inertia Microgrid

Case 2: Inertia Minigrid/Microgrid interfaced with Inertia Microgrid

In all these test configurations, the loads and generators are established physically as well as virtually.

Table 1 Work done during access period

Week 1	15/11/2022	Discussion of the system to be established
	16/11/2022	Starting mapping the microgrid setup as lab requirement
	17/11/2022	Lab visit and safety Tests
	18/11/2022	Validating the model in Opal-RT
Week 2	21/11/2022	Making test setup ready and scaling physical and virtual microgrid
	22/11/2022	Case 1 execution with inverter based system-Preliminary tests
	23/11/2022	Case 1 execution with inverter based system-Controller adaptions
	24/11/2022	Case 1 execution with inverter based system and physical load change
	25/11/2022	Repeated the test for validating the synchronization, there by successful integration
Week 3	28/11/2022	Preliminary Result assessment
	29/11/2022	Case 2 execution with synchronous machine-Preliminary tests
	30/11/2022	Case 2 execution with synchronous machine and load change-system adaption
	01/12/2022	Repeated the test and controller adjustments
	02/12/2022	Result assessment

3.1.2 Standards and Procedures

Synchronization is a procedure that achieves a satisfactory and stable connectivity of two electrically isolated systems with generating units and, may be, loads as well. Differences in voltage, frequency, and phase must be within safe limits prior to the synchronisation for it to be successful interconnection. In the absence of this, the system could become out of sync and the related equipment or devices might sustain harm and even can lead to system collapse. The following possibility can occur if the systems are not synchronized;

- If the systems with phase difference out of specified limits are interconnected, there will be heavy inrush current flowing in the systems, creates a very high torque in the generator and damages the generator equipment. It also may cause overheating in the armature core of the generator.
- If the systems with voltage difference out of specified limits are interconnected, there will be heavy inrush currents, however, due to reactive power flows from one generator to the other.
- If the systems with frequency difference beyond the specified limits are interconnected, there will be varying phase differences and resulting high inrush currents, capable of damaging the generator and associated equipment.
- With incompatible phase sequence, either or all of the above three conditions will arise and will be a severe threat to the systems to be synchronized.

Therefore, it is must to achieve the synchronization conditions before interconnecting two systems with DGs. There are multiple standards across the globe that define the interconnection protocols. For example, the IEEE 1547 [15] defines the protocol as in Table 2 to achieve successful synchronization. The synchronization limit should only be applicable once DGs are within the voltage and flicker limit of standard IEEE 1547. Other international standards like Canadian grid code C22.3 No.9-08 [16] and CAN/CSA-C22.2 No. 257-06 [16] and California Electric Rule 21 [17] accepted the synchronization limit of IEEE 1547.

Table 2 Synchronization limit as per IEEE 1547

Aggregate rating of DR units (KVA)	Frequency (Δf, Hz)	Voltage (ΔV, %)	Phase angle (ΔΦ, °)
0-500	0.3	10	20
>500-1500	0.2	5	15
>1500-10 000	0.1	3	10

3.2 Test Set-up(s)

3.2.1 Description of Testbed

The main objective of the test setups was to validate the protocols for interconnection of multiple microgrids operating in island mode. Furthermore, it aims to validate the developed synchronization controller along with its reference protocols for interconnection of two or more micro/minigrids. The primary task of controller is to follow interconnection protocols such that incoming microgrid should interconnect without disturbing the pre-existing microgrid. Therefore, it was crucial to have a benchmark monitoring system that would serve to determine the correct time stamps, magnitude, and angle measurements without having the real world latencies and limitation such as transmission lines losses and noise.

In this regard, the experiment setups built for the interconnection of two microgrids using the designed controller following the synchronization protocols. It has been planned to connect the physical microgrids at the bus 3a. The first microgrid system that has been developed is a virtual power system that is operating in real-time in the Opal-RT system, therefore, all of the three-phase terminals of bus 3a have been physically brought out. However, the terminals displayed by the Opal-RT system are virtual representations of the original terminals. These terminals, which are exposed for access, operate at low voltage (20V at most) and are incapable of supporting currents of more than a few milliamperes.

On the other hand, the microgrid that is expected to link to the virtual power system running in Opal-RT with a rotating machine and/or real converter-based microgrid that operates at the actual system voltage of 400V and is supposed to deliver powers in the order of KW and KVAr. Therefore, it is necessary to use a power amplifier (EGSTON), as illustrated in Figure 1, to connect the real DGs to the virtual bus from the Opal-RT. The reference model is verified in power hardware in loop (P-HIL) based on OPAL-RT platform in two different case studies when the interfaced minigrid has inertia DG and non-Inertia DG.

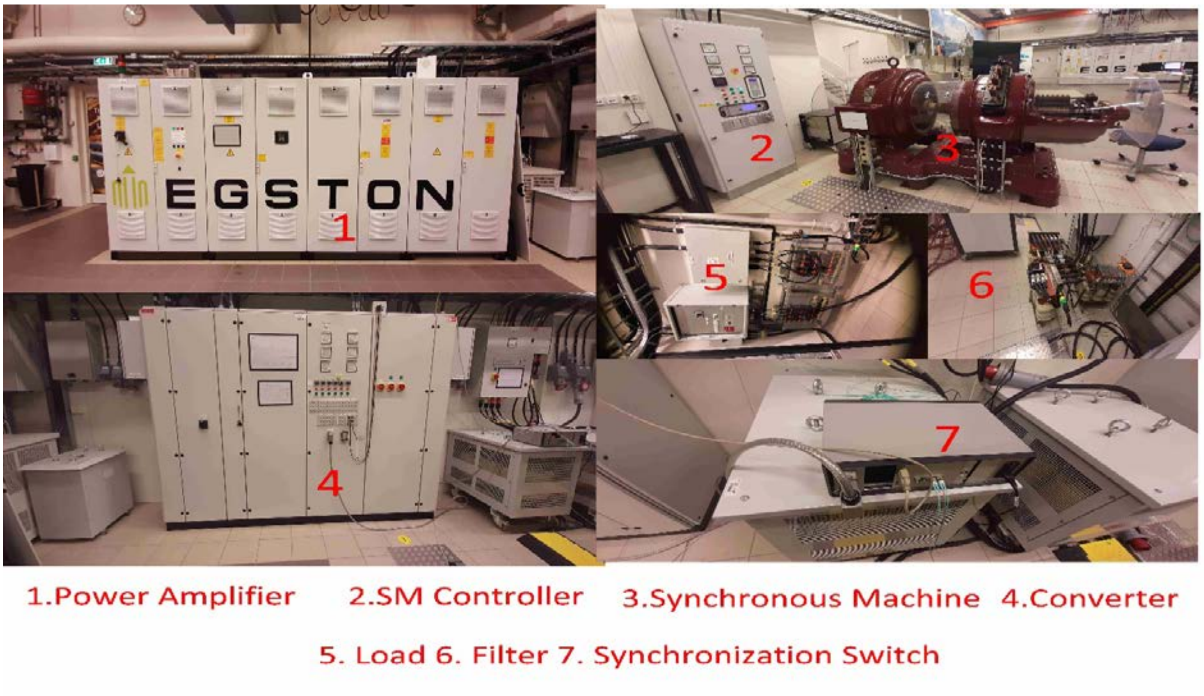


Figure 1 Experimental Setup

3.2.2 System Description

An existing islanded microgrid model is taken to verify the synchronization controller and to understand the challenges in a real-time scenario. The considered islanded network is depicted in a simplified single-line form in Figure 2. The network consisting heterogeneous sources of DG systems with different dynamic characteristics operating in standalone mode. The figure shows that a 33 kV feeder line is at bus 2, and the load is directly connected to a 33kV line. bus 1, 3a, and 4a substations are also connected with 33 kV lines. The maximum demand of the system is at the bus 1 end, i.e., 18.6 MW. Bus 5 and 3a interface the large number of feeders and generators. Any divergence in supply and demand will cause the interconnection between the substations to break, and they will then operate independently. Bus 1 is a converter based interfaced system, bus 5 and bus 4b consist of a Diesel turbine. Hydro turbines are installed near the 33kV feeders at bus 4a and bus 3a sub-station. A gas-based power plant is present at bus 2, supplying the load of 50MW. The distance between the two PCC lines is listed in Table 3.

Table 3 Distance between the bus

Line	Distance (km)
Bus 1 to Bus 2	15
Bus 1 to Bus 3a	10
Bus 2 to Bus 4a	10
Bus 1 to Bus 4a	12
Bus 3a to Bus 4a	6
Bus 3a to Bus 5	2
Bus 4a to Bus 5	4

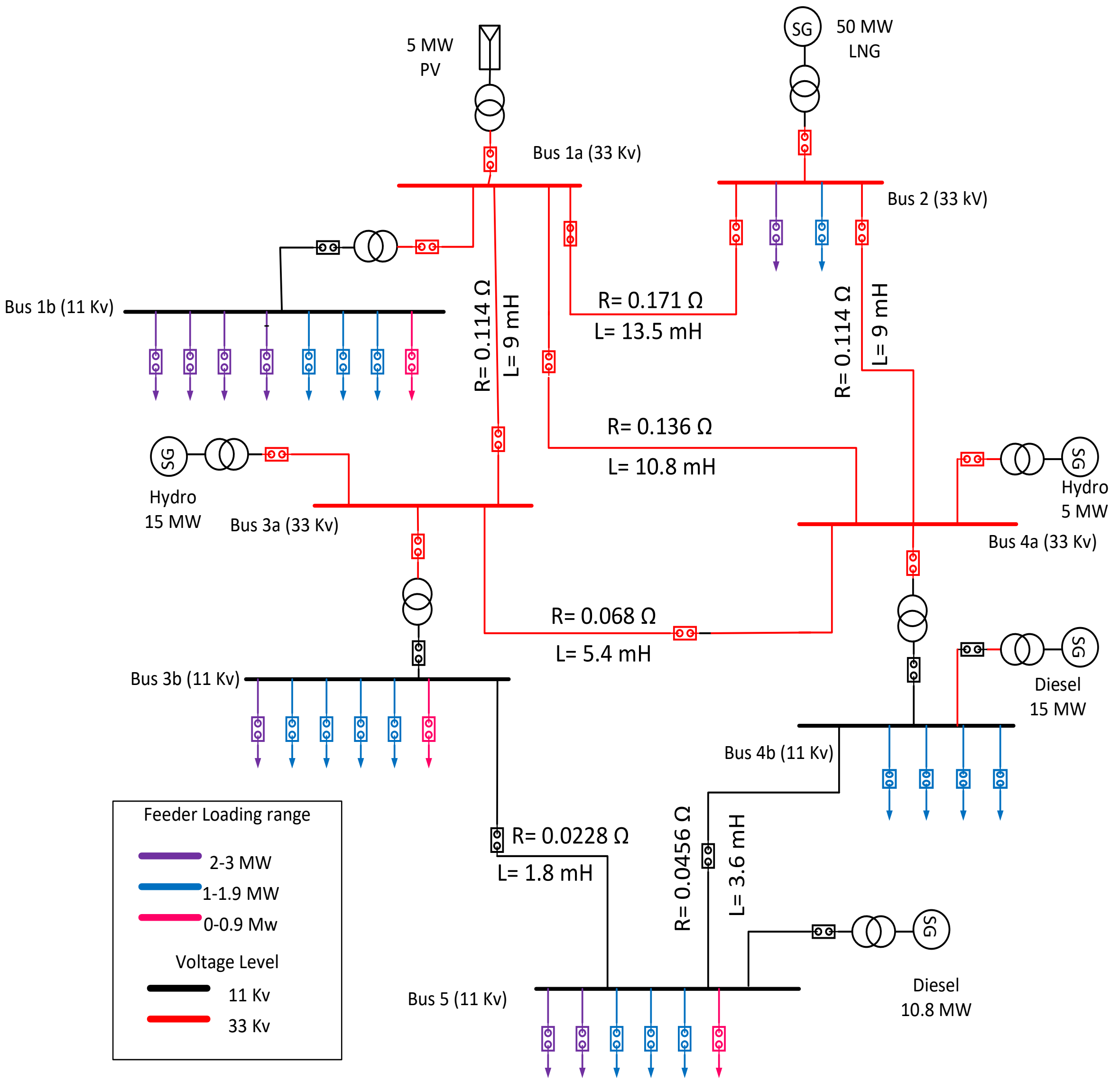


Figure 2 Reference microgrid model

3.2.3 Control Strategy

The master-slave technique of [11] is being theoretically adapted, but it has been altered for performance reasons. In this method, the voltage and frequency set points for the microgrid are determined by a selected master unit. A comparatively more stable system is typically chosen to act as a master unit. The slave microgrid tries to follow the master microgrid after the synchronisation controller is engaged, deviating from its operational condition if necessary. The synchronisation switch is managed only to activate when the grid code limits of voltage, frequency, and phase differences across the interconnection point are met.

As depicted in Figure 3, the master-slave synchronization approach is used to develop the synchronisation control for interconnecting multiple microgrids. The frequency and phase difference signals are obtained as indicated in Figure 3, from the measured voltages of the microgrids (Vabc1 and Vabc2). The PLL's sensitivity to the dc offset and low-order harmonics is a well-known issue. These issues have been studied for a very long time, and there are now a variety of viable solutions. However, as renewable energies and power electronic devices become increasingly integrated into the microgrid, other non-ideal microgrid problems, such as frequency variation and weak systems, become more severe, and these new difficulties can also have a significant impact on the performance of PLL. Thus, this work eliminates the usage of PLL for generating the frequency and phase difference.

The phase trigger block is added in the controller as shown in Figure 4 when the frequency difference is large, the Φweight factor gives almost zero value resulting in disabling the phase error, and the frequency error is only nullified using the PI controller. Once the frequency difference is less, the denominator of the phase trigger value becomes higher than the denominator resulting in phase error being dominated as compared to frequency error. The controller action for phase correction is started when the frequency deviation is within the required range, not necessarily the limit given in the grid code, allowing the parallel control action because the phase difference is particularly sensitive to frequency deviations. With the aid of parallel control action, the rapid synchronisation condition can be met.

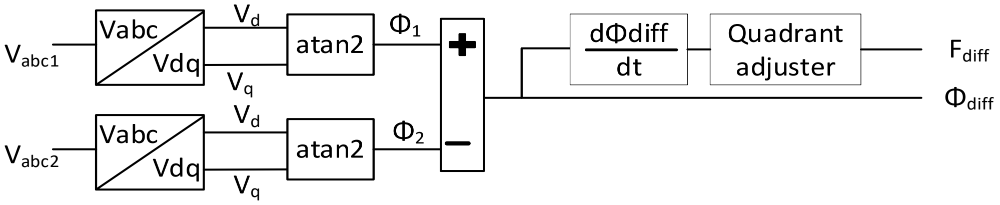


Figure 3 Controller for frequency and phase extractor

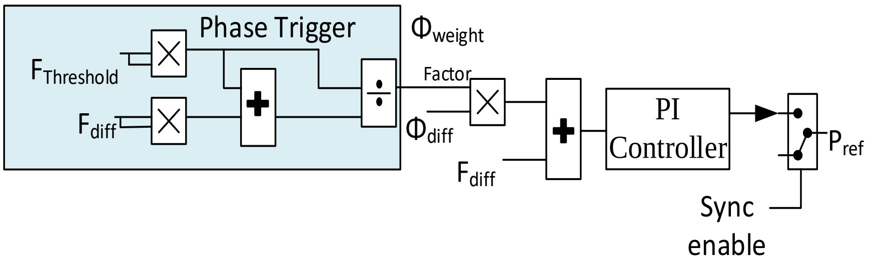


Figure 4 Synchronization control scheme

4 Results and Conclusions

4.1 Discussion of Results

Case I: Non Inertia Minigrid/Microgrid interfaced with Inertia Microgrid

Two microgrids are interfaced with a controlled synchronization switch, when microgrid voltage difference, phase difference, and frequency difference are within the synchronization limit. First microgrid having four DGs: two diesel generators and two hydro generators with their local loads, are designed in grid emulator running in real-time. The second minigrid is a physical system with PV as DG and a resistive load. The physical minigrid has a 60 kW generation capacity with rated voltage of 400 V.

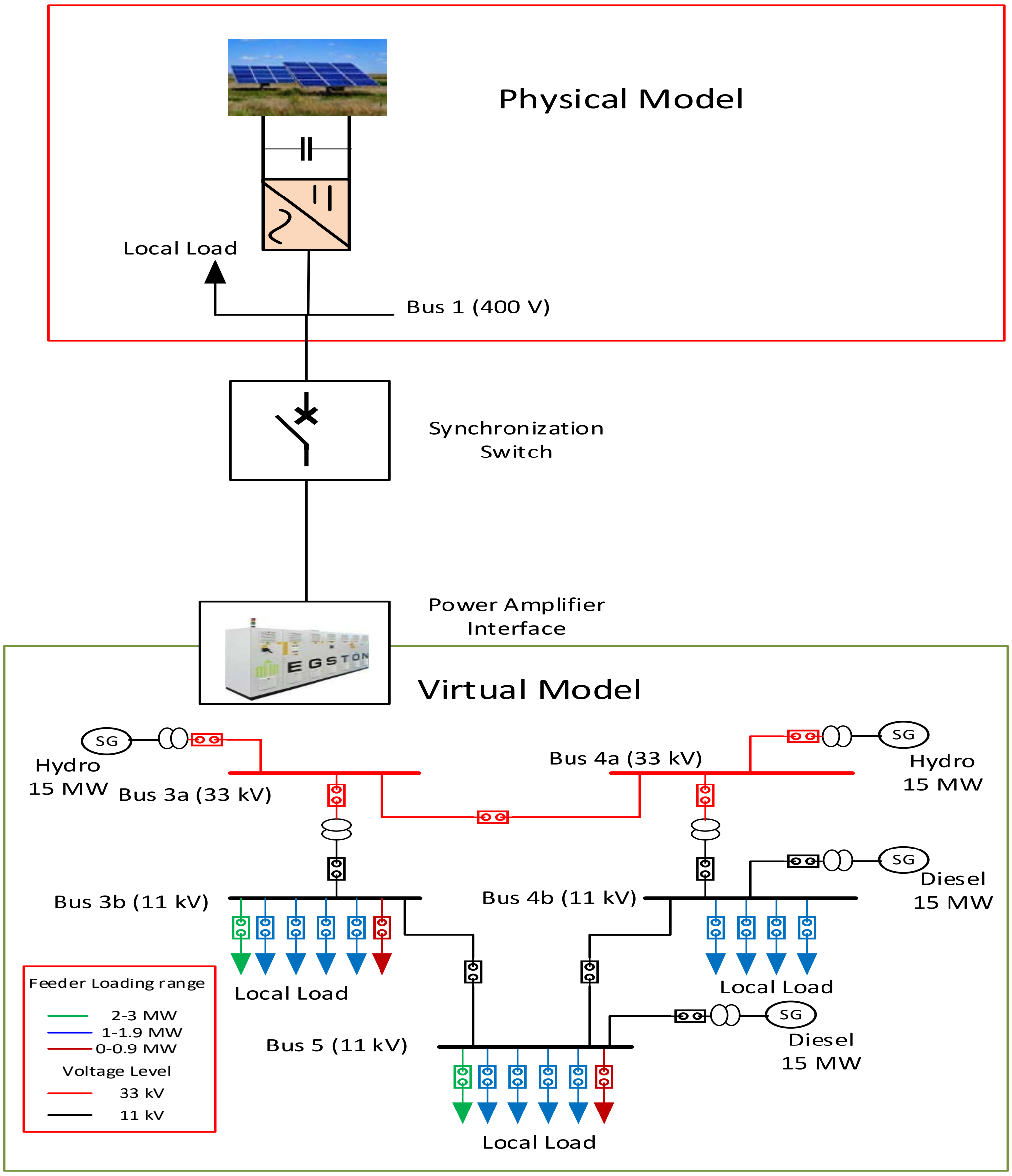


Figure 5 Microgrid setup for case 1

This experiment is designed to demonstrate a smooth and successful synchronization thereby transition from the islanded mode to the interconnection mode and establish minigrids/microgrids to operate reliably, steadily, and continuously in this mode. To further ensure the existing microgrid system's dependability, measuring and validating planned power flows and their practical viability is important.

In this case, both the microgrids are operating in standalone mode at the beginning of the experiment. The virtual microgrid and the physical microgrid is prompted to interconnect with each other to maintain the stable and reliable operation of the system at time t1. Once the voltage, phase, and frequency synchronization conditions are met at time t2, the controlled synchronization switch is activated, and the physical microgrid is connected to bus 3a which can be confirmed from Figure 6. In between time t1 and t2, a jerk can be seen in frequency difference waveform due to high phase difference between the microgrids, since the frequency and phase are interdepending on each other and the jerk is due to shifting of phase from -2π to +2π.

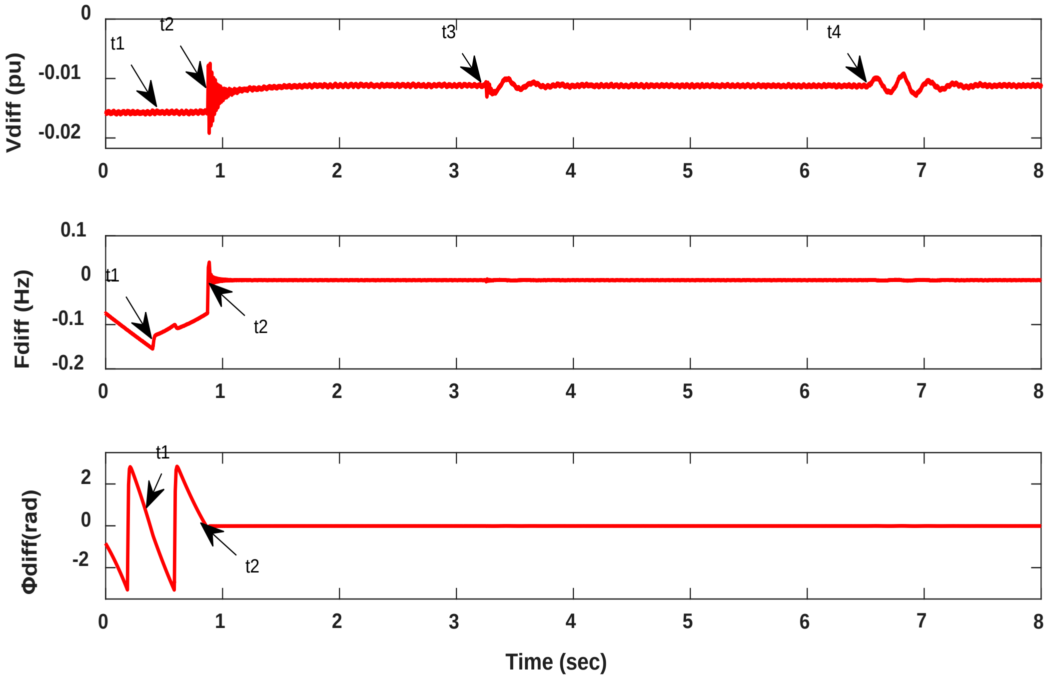


Figure 6 Voltage, frequency, and phase difference between the microgrids

The voltage and current corresponding to the interconnection point are shown Figure 7 and 8 respectively. It can be seen that, in the voltage no transient effect can be seen and remains unaffected. However, a peak inrush current of 50 A flow in between microgrids which gets settled around a peak value of 15 A after a few cycles.

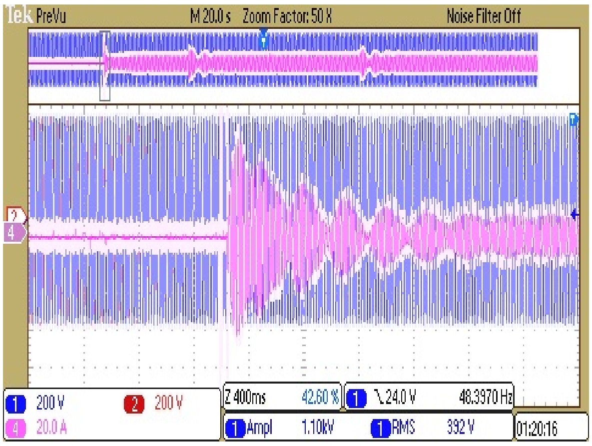


Figure 7 Voltage and current at POI

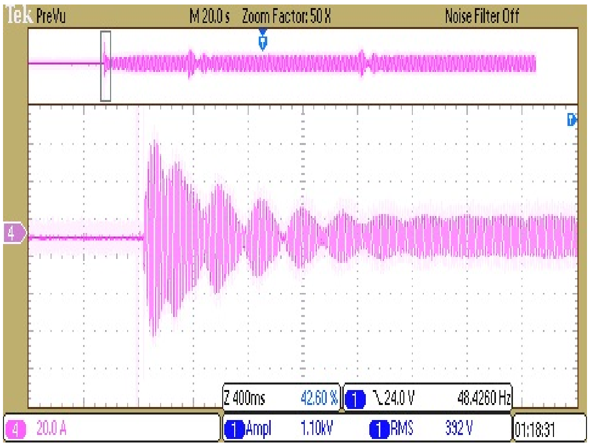


Figure 8 Current at POI

Furthermore, after the post synchronization to validate the power flow between the microgrids or to observe the post effect of load changes after the interconnection, a load of 7 KW in physical the microgrid model is increased at time t3. The current flow between the microgrids is shown in Figure 9 and 10 at two different load changes. The current flow from converter based physical microgrid is shown Figure 11 . It can be observed that when the load increases, the physical microgrid current tries to compensate for the increased load suddenly and a transient in the current can be seen and it got settled after a few cycles. However, in steady state the complete load increment is compensated by the virtual microgrid itself. Furthermore, 7 KW load is decreased at physical microgrid end at time t4, and again the transient appears in the current waveform as shown in Figure 11. However, the voltage does not get affected by any load changes. The effect of load change in virtual microgrid and synchronization can also be observed from the power flow in converter as shown in Figure 12. Once the microgrids are synchronized, the physical microgrid power increased and it start feeding to the virtual microgrid. Since, the physical microgrid is converter based non-inertia system, the power does not change even any load change occurs in system.

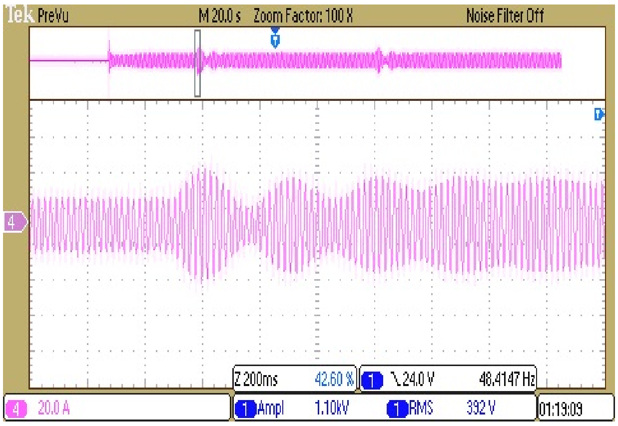


Figure 9 Enlarge image of current at POI for first load change

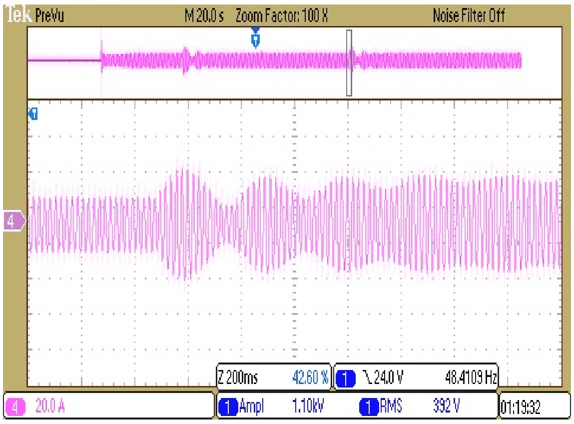


Figure 10 Enlarge image of current at POI for second load change

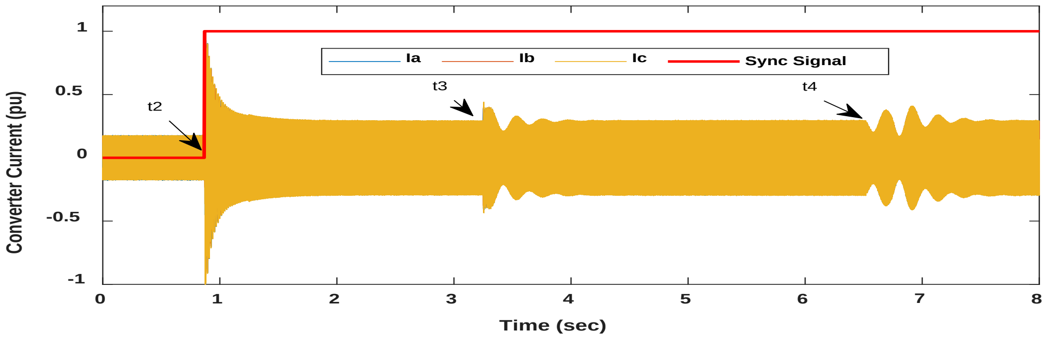


Figure 11 Current flowing through physical microgrid

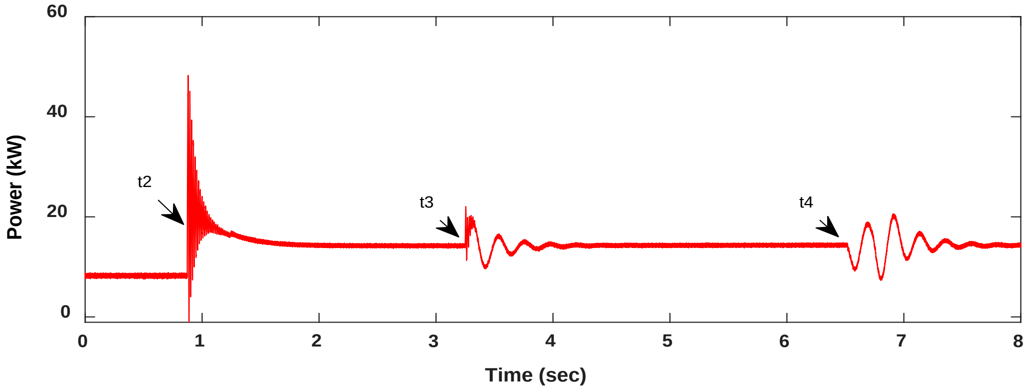
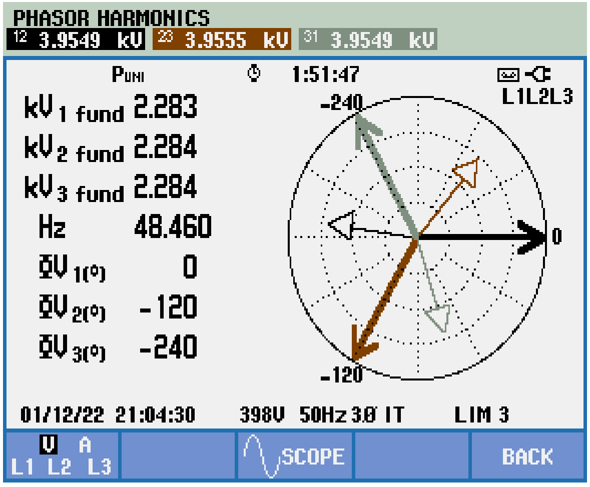


Figure 12 Power flowing in physical microgrid

To study the power quality, the phase voltages are recorded and are 230V (with 10X setting) per phase with 120^{o} displacement from each other, as can be seen in Figure 13. The currents are approximately 5 A, and are balanced, excluding the minor transients as shown in Figure 14. The THD is observed to be 2% in the outgoing current of physical microgrid as shown in Figure 15.



PHASOR HARMONICS
12 3.9549 kV 23 3.9555 kV 31 3.9549 kV
PUNI 1:51:47 L1L2L3
kV1 fund 2.283
kV2 fund 2.284
kV3 fund 2.284
Hz 48.460
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ΦV2(°) -120
ΦV3(°) -240
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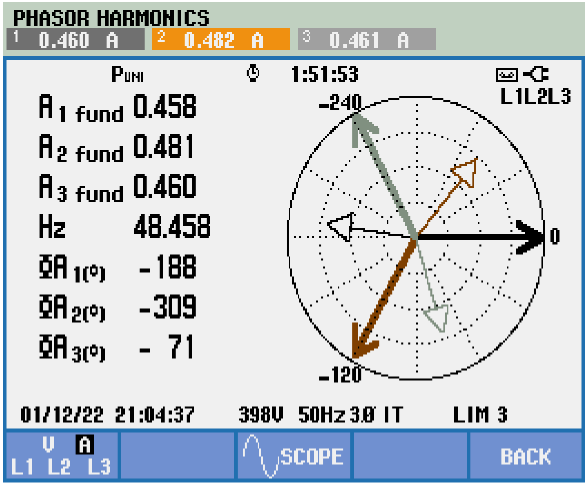

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A1 fund 0.458
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Hz 48.458
ΦA1(°) -188
ΦA2(°) -309
ΦA3(°) - 71
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Figure 13 Voltage phasor at converter end of physical microgrid

Figure 14 Current phasor at converter end of physical microgrid

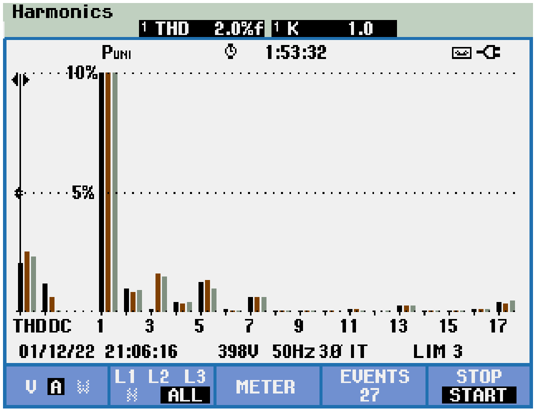


Figure 15 Current harmonics of physical microgrid

Case II: Inertia Minigrid/Microgrid interfaced with Inertia Microgrid

In this case, the first microgrid is designed in a grid emulator running in real-time. The second microgrid with a rotating machine based generator unit is realized in physical system. The physical model of minigrids/microgrid is implemented with a synchronous generator of 70 KVA and local resistive load. The test setup of the case is shown in Figure 16.

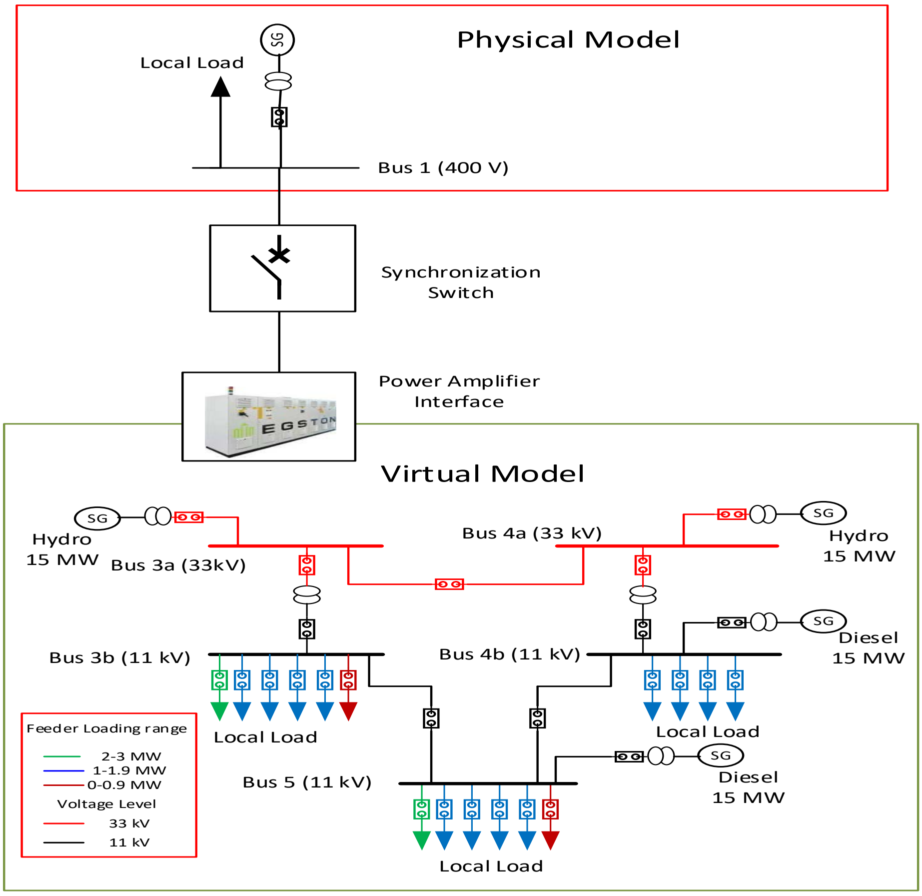


Figure 16 Test setup of microgrid for case II

Both the physical and virtual microgrid are running in standalone mode at the beginning of the test. Once the synchronization limit reaches near to zero at time t2 as shown in Figure 17, the synchronization switch is on. A peak current of 100 A flows for half cycle and reaches its steady state peak current of 20 A at the interconnection point between the microgrid, as shown in Figure 18. A smooth voltage waveform is achieved before and after synchronization as shown in Figure 19.

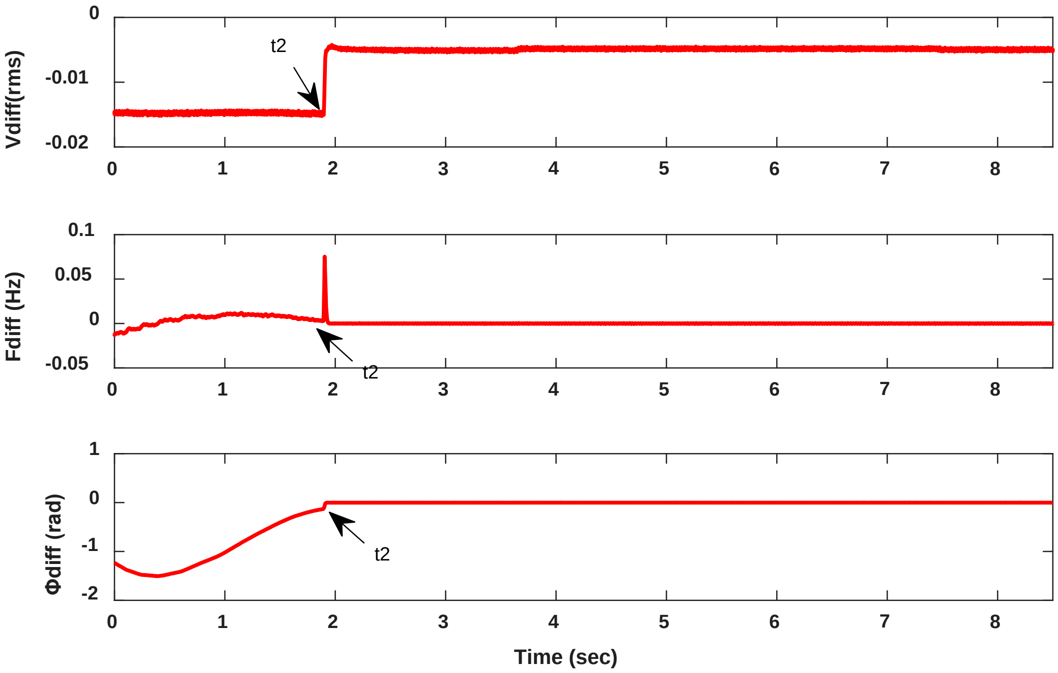
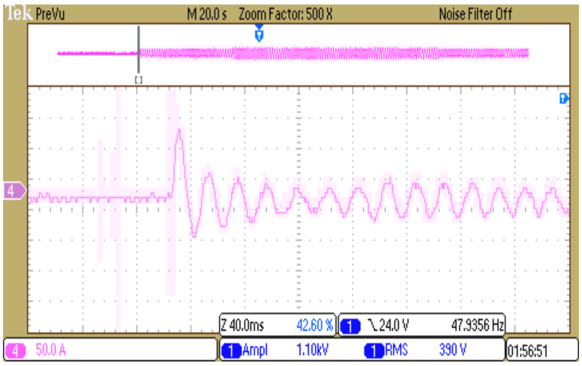


Figure 17 Voltage, frequency, and phase difference between the microgrids



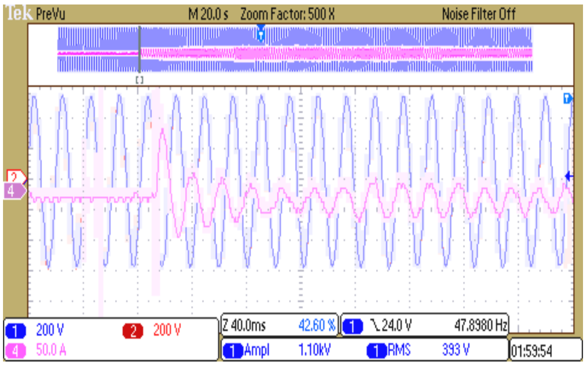


Figure 18 Current at POI

Figure 19 Voltage and current at POI

To observe the post synchronization effect, in this case virtual load has been varied, such that the local load at bus 3b is increased by 0.5 MW at time t3 and is decreased by same amount at t4. Prior to time t2, both the microgrids are operating stably in islanded mode, and at time t2, the synchronization, hence the interconnection between the microgrids has been established. As it can be observed in Figures 18 to 22, there in an initial transient at time t2 and has settled subsequently. As can be seen in Figure 22, the physical microgrid with rotating machines is loaded prior to interconnection, hence delivering nonzero power. However, due to high inertia of physical microgrid with rotating machine, though there are load changes at t3 and t4, they are not reflected in the power output of rotating machine. In addition, it can be observed that there is slight increasing tendency in the power output of physical microgrid's generator which needs damping.

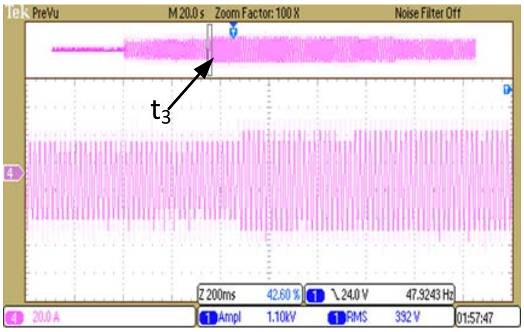


Figure 20 Enlarge image of current at POI for first load change

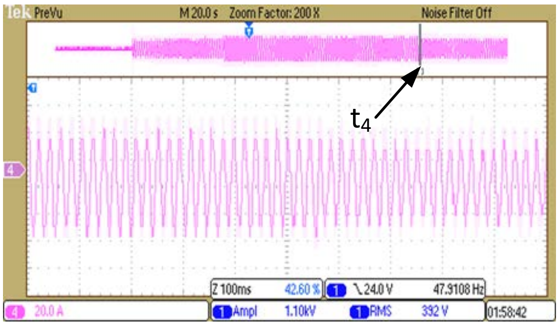


Figure 21 Enlarge image of current at POI for second load change

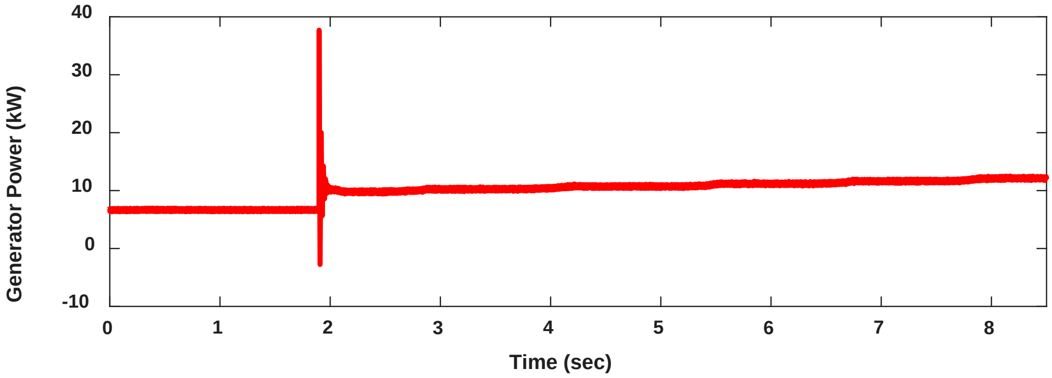
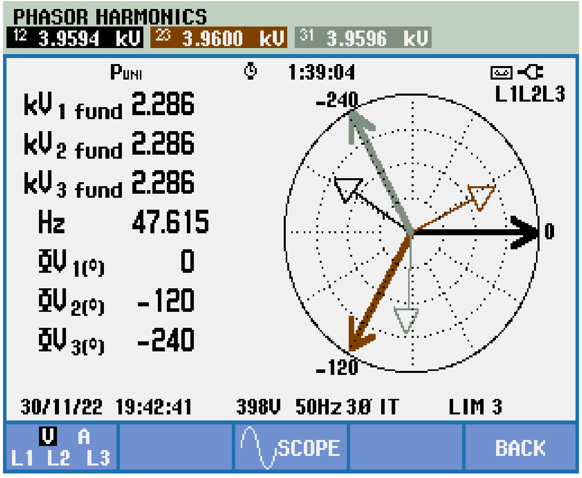


Figure 22 Power output from Synchronous generator of physical microgrid

The following Figures 23 to 25 describe the balanced voltage and balanced currents at POI with THD in current of 1.3% which is well within the limit specified by IEEE 1547.



PHASOR HARMONICS

12 3.9594 kV 23 3.9600 kV 31 3.9596 kV

PUNI 1:39:04 L1L2L3

kV_1 fund 2.286

kV_2 fund 2.286

kV_3 fund 2.286

Hz 47.615

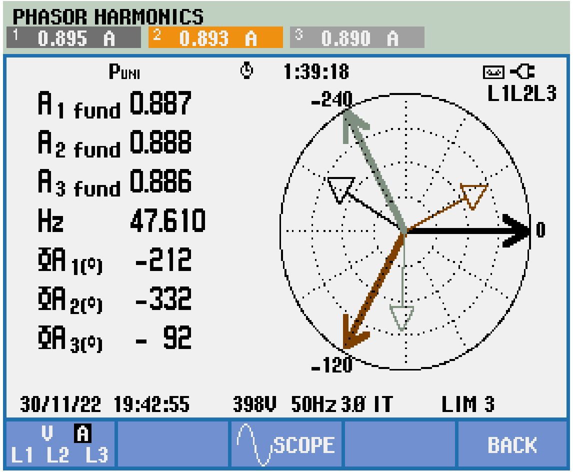
$\Phi V_1 (°)$ 0

$\Phi V_2 (°)$ -120

$\Phi V_3 (°)$ -240

30/11/22 19:42:41 398V 50Hz 3Ø IT LIM 3

Figure 23 Voltage phasor at converter end of physical microgrid



PHASOR HARMONICS

1 0.895 A 2 0.893 A 3 0.890 A

PUNI 1:39:18 L1L2L3

A_1 fund 0.887

A_2 fund 0.888

A_3 fund 0.886

Hz 47.610

$\Phi A_1 (°)$ -212

$\Phi A_2 (°)$ -332

$\Phi A_3 (°)$ - 92

30/11/22 19:42:55 398V 50Hz 3Ø IT LIM 3

Figure 24 Current phasor at converter end of physical microgrid

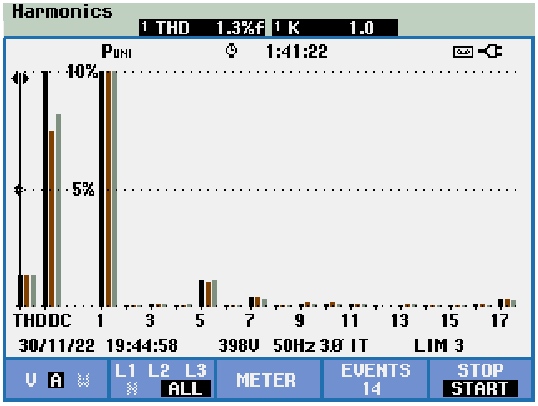


Figure 25 Current harmonics of physical microgrid

4.2 Conclusions

- In this ERIGrid 2.0 Lab Access programme, a real world microgrid system with multiple heterogeneous sources and many local loads which are interconnected through transmission/distribution network, has been successfully emulated using the Grid Emulator-Power amplifier setup available at SINTEF’s NSGL Norway.
- In addition, two physical microgrids with different kinds of sources, rotating machine based interface and a static interface, have also been successfully developed using the infrastructure available at SINTEF’s NSGL Norway.

Both these arrangements are critical to establish a real-world scenario in the laboratory environment, without which the experimentation on the real-time microgrids/minigrids would have been unrealistic.

- A simulation on MATLAB/Simulink platform has been developed in order to develop a control mechanism that can synchronize the two microgrids having different kinds of sources as the grid synchronization protocols defined in the internationally accepted grid codes.
- As part of the experimentation, a physical microgrid having a power electronic converter interface and local loads has been integrated with a virtual microgrid which is emulated with the help of Grid Emulator-Power Amplifier Set up as Case I
- In Case II studies, a physical microgrid having a rotating machine based generating source, representing a conventional generator, along with physical electrical loads has been integrated with the emulated Grid.
- In both the cases, a successful yet sustained synchronization of two heterogeneous microgrids which are operating in islanded mode has been carried out using a controlled synchronization switch as per the Grid Codes.
- In addition, in order to validate the behaviour of interconnected microgrids after synchronization, load changes have been carried out.
- In Case I, a physical load change has been done, where as in Case II a load that existed in virtually microgrid, the emulated microgrid, has been carried out.
- In both the case studies, not only the synchronization is successful, the developed test bed along with its controller has demonstrated a superior performance by adjusting the generations internally there by catering the changes in loads effectively and stably.

5 Open Issues and Suggestions for Improvements

- No doubt that the NSGL at SINTEF facility provides excellent infrastructure for the researchers and the workforce are very supportive.
- It is definitely of great help for researchers, if a follow-up access is provided such that the corrections, adaptions and extension of the findings from the first visits can be carried out.
- In this case of access, all the objectives of the proposal have been met to the large extent, however, as it is known that for a real researcher, the thrust for acquiring knowledge is never ending and the extend access or follow up access can address these issues to a large extent.

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