Grid Interconnection protocols for largely dispersed minigrids/microgrids for electrification of rural India

Reference minigrids and minigrids controllers for rural India

Background information for subsequent simulation studies

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About MultiGrid

Minigrids are heterogeneous in nature since they can include different type of energy sources and generators technologies. Hence, their dynamic operational characteristics varies from one another, for example, a mini-grid with power electronic converter interfaced RES will behave differently compared with a mini-grid with 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 minigrids without affecting the stability and voltage quality of the grid.

In MultiGrid project, synchronization strategies will be drafted for multiple minigrids by carefully driving the relevant synchronization criteria. A reference controller will be selected in the beginning of the project from the range of controller schemes available in the literature. Furthermore, in this project, the developed interconnection protocols and controllers will be validated numerically and experimentally.

Partners

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Executive Summary

To validate operating guidelines that ensure the seamless interconnection of minigrids with each other and with the main grid relevant reference minigrids and synchronization controllers are needed. This project memo, with the context of rural India, presents potential minigrids for simulation study together with relevant synchronization controllers. The selected minigrids and synchronization controller will be studied further in simulations to infer implication to interconnections.

1 Introduction

Minigrids are defined in a recent World Bank Document as 'electric power generation and distribution systems that provide electricity to just a few customers in a remote settlement or bring power to hundreds of thousands of customers in a town or city' [1]. In [2], minigrids are defined as *systems involving small-scale electricity generation (10 kW to 10 MW) serving a limited number of consumers via a distribution grid that can operate in isolation from national electricity transmission networks*. For the purpose of this study, this definition is adopted for minigrids. Also, the terms minigrid and microgrids are used interchangeably quite often. For example, microgrid can be understood as a localised power system that uses microsource generation at distribution level to cater to the local loads. In other words, a grid of smaller capacity when compared with conventional grid.

1.1 Minigrids vs Microgrids

As per US Department of Energy (US DoE), microgrid can be defined as group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. As defined by European Union, microgrid is a LV distribution system with DERs, storage devices and flexible loads. Such systems can be operated in both non-autonomous way or in an autonomous way.

Therefore, it can be understood that the main difference between the minigrid and the microgrid is the size of the system. Adhering to the definitions of prominent publications such as [3] and to avoid confusions, classifications of gird types are presented in Table 1.2.

	Size	Function	AC/DC
Supergrid	>10 MW	Centralized	AC/ HVDC
Macrogrid	>10 MW	Centralized	AC
Minigrid	10kW-10MW	Local	AC or DC
Microgrid	1-10 kW	Distributed	AC/DC
Nanogrid	0.3-1 kW	Leisure telecom, household	AC/DC
Picogrid	0-0.3 kW	telemetry, phone charging	DC

Table 1.1 - Types of electric grids

1.2 Roles of minigrids

In recent years the number of populations without electricity access has decreased significantly. In 2019, the number of people without electricity access dropped to 770 million, a record low in recent years [4]. In India alone, the number of populations with electricity access has increased from 43% in 2000 to 99% in 2019 (see Figure 1.1). To address the electricity access problem, the Indian government is aiming to meet energy needs with renewable energy sources (RES) through its flagship programs and National Missions [4]. In addition to large scale RES, the Ministry of New and Renewable Energy (MNRE) of India is promoting decentralized solutions especially in rural areas. With this approach, the MNRE targets to achieve deployment of at least 10,000 RES based minigrid projects across the country [5] amounting to 500 MW of installed minigrid capacity within the next 3 to 5 years (assuming an average rating of 50 kW for each minigrid) to cater to around 237 million people experiencing energy shortage [5]. It has given a great push to the deployment of minigrids, due to which the prevalence of minigrid in India has expanded significantly in the recent past, realized through increased involvement of private players, local banks, and the government through the MNRE's Remote Village Electrification Programme and the Village Energy Security Programme [6]. As of 2019, according to the data gathered by the Energy Sector Management Assistance Program (ESMAP), the number of minigrids in India are estimated to be 2800. Also, the International Energy Agency (IEA) anticipates that more than 50% of the rural population currently without energy access are best supplied with electricity via minigrids.

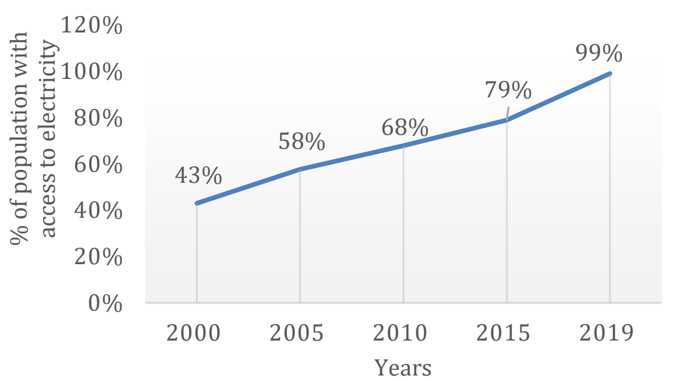

Figure 1.1 - Proportion of population with Electricity Access for India [4]

1.3 Challenges of operating Minigrids

The operation of a power system composed of a large number of minigrids could present several technical difficulties. Indeed, when multiple minigrids have to be interconnected together and possibly with the main grid, the following challenges must be addressed:

- A smooth transition from frequency control mode to frequency follower mode in islanded and grid connected mode, respectively.
- Local voltage and frequency controllers should adapt to the frequent changes in the network configuration and in the generation and load profile.

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

In India, the definition of interconnection standards, policy and regulatory aspects of minigrids is still in progress. Such guidebooks on grid interconnection and islanded operation of minigrids are strongly 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 minigrids. Moreover, the lack of clear integration protocols for the minigrids is resulting in stranded and abandoned assets when the main grid is extended to the area.

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 between 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 and/or to the main grid thereby demonstrating the effectiveness of these protocols, both with a numerical and an experimental validation, reference minigrid(s) is(are) necessary. In this connection, this report reviews and identifies the required reference minigrid.

Rest of this report is organized as follows: Section 2 presents status of different minigrid in India and the existing challenges in rural minigrids in the Indian context while Section 3 present relevant reference minigrids which can be used to study the technical challenges identified in Section 2. The criteria in selection of the reference minigrids are discussed in Section 4 along with description of the selected reference minigrids. Section 5 presents different control and operational philosophies. The last section, Section 6 summarizes the discussions in this report.

2 Status of minigrids/microgrids in India

There are multiple aspects one has to consider in the development of minigrids. In India, multiple stakeholders are involved (see example in Table 2.1) in the process of minigrids development in the last decade. Nevertheless, Indian minigrid systems face risks including uncertain demand, unproven business models, low power availability (compared to the grid), and limited ability of consumers to pay cost-reflective tariffs.

Group	Role in minigrid development	Stakeholders
NGO/advisory groups	Collect and disseminate data; represent consumers; advise government on policy; provide funding	TERI, GIZ, Clean Energy Access Network, ShaktiFoundation
Renewable energy policy representatives	Design and implement minigrid policies; oversee renewables development	National level - MNRE; State level - Uttar Pradesh New and Renewable Energy Development Authority (UPNEDA)
National grid representatives	Promote expansion of national grid; responsible to ensure countrywide electrification	Central Electricity Authority; Uttar Pradesh Power Corporation, Ltd.; Uttar Pradesh State Load Dispatch Centre
Minigrid developers	Develop, implement and operate minigrid systems on local scale	OMC Power; Mera Gao Power; TERI; Grassroots and Rural Innovative Development Private Limited

Table 2.1 - Some stakeholders involved developing minigrid in India [7]

One of the challenging aspects is the condition when the main grid or other minigrids arrive in the vicinity of the already built minigrid. The interconnection of multiple minigrids or minigrids to the main grid faces uncertainties in relation to lack of appropriate business models as well as clear technical requirement for grid interconnection. Usually, Minigrids are owned by private minigrids developers or local community administration. Hence, there is a challenge concerning grid interconnection to what stakeholder form the owners will evolve to, example to distribution system operators, energy producers or others. This aspect itself warrants extensive research, however, in this report the focus is on the technical challenges. For a minigrid to qualify for grid connection, the technical requirements of the main utility need to be met. These include overall network safety needs, frequency and voltage regulation, the integration of the distribution system into the utility system, whether the minigrid system is able to “island” in the event of grid failure, whether it is used as a “dispatchable” asset of the grid [2] and other protection related issues.

Minigrids/microgrids may comprise of different heterogeneous energy sources, like diesel, solar photovoltaic (PV), micro-hydro and biomass gasification, or may employ hybrid technologies such as wind-diesel and PV-diesel, including storages. Traditionally, diesel based microgrids are in use, however, due to technological developments and financial feasibilities, PV based systems are gaining popularity while thanking the omnipresence of sun light.

For example, Odisha Renewable Energy Development Agency (OREDA), a nodal agency in Indian state of Odisha, has developed around 120 minigrids, including 3-phase and 1-phase connectivity. They are powered either by solar-PV or by Biomass, however, all of them are operating in islanded mode. The efforts to establish grid-connected microgrids are at preliminary stage. In addition, India is successfully operating microgrids/minigrids on its islands for decades. These islands were powered by diesel engines traditionally, however, in the last decade they have been integrated with PV systems and storages.

Different states like Bihar, Uttar Pradesh, Karnataka, Maharashtra, Chhattisgarh, West Bengal and others have minigrids/microgrids of different capacities. However, as said earlier, they are operating as islanded systems. Different government agencies involved are West Bengal Renewable Energy Development Agency (WBREDA), Chhattisgarh Renewable Energy Development Agency (CREDA),

Many of the Indian minigrids/microgrids are developed, and operated in public-private partnership (PPP) model or with the help of community activities and non-government organizations (NGOs).

Different private players involved are DESI Power, Gram Oorja Solutions, Gram Power, Mera Gao Power, Omnigrid Micropower Company, Tata BP Solar, SunEdison, Husk Power Systems and etc.

The success of microgrid mainly depends on reliability and financial feasibility. Key challenges in operation of microgrid/minigrids in India are lack of scalability, need of demand side management, community adaptation to seasonal variability, supply of required feedstock, poor maintenance, lack of community cooperation, personnel safety and system protection, training of local manpower, local affordability, inertia related stability and importantly **the abandoning of microgrid/minigrid infrastructure due to grid extension**.

Though the merits of microgrid operations are well known the ceasing of microgrid/minigrid operations due to grid availability/accessibility indicates the necessity to develop interconnection

protocols for integrated operations of Minigrids/microgrids, which is the prime objective of this project.

In this connection, focusing on the Indian rural minigrids context, reference minigrids are selected and presented in this report for them to be used in the subsequent studies of interconnection protocols and minigrids synchronization controllers.

3 List of considered minigrids

3.1 Microgrids under Odisha Renewable Energy Development Agency

As mentioned in section 2, there are multiple renewable energy based microgrids under operation in Odisha for which OREDA is administering as State Nodal agency. One such microgrid is in Badapur, the details are follows.

S. No.	**Particulars**	Make	**Specification**
1	SPV Modules	Empire	Polysi type 60 Cells 250Wp
2	Solar PCU	Statcon	Standalone 15 KW , 3P-440V AC , Off-Grid inverter. PWM MPPT with IGBT based design. 4 wire 50Hz. Inverter efficiency shall be 94% at full load. IEC 62093, IEC 60068. With RMS Feature
3	Battery Capacity	NED	240V/450Ah capacity @ C10 rate
4	Module Mouting Structure		Fixed with Seasonal adjustment provision
5	Fencing for the power plant		1.8mm height with barbed wire

Table 3.1 - Detail components of a microgrid in Badapur

As it can be understood form Table 3.2 that the Badapur microgrid is powered either by PV or Battery, no other source is integrated with this.

Similarly, there are other microgrids under OREDA with Biomass as primary energy source. This category of microgrids are established in Koraput, Mayurbhanj, Ganjam and Cuttack districts of Odisha.

However, as in the earlier category of microgrids, there are no other sources integrated in the microgrids, inferring that these microgrids are powered by homogeneous sources. In addition, all these microgrids are operating in isolated/islanded Mode.

3.2 Bilaput-Khajuripadar, Odisha, India

The minigrids under development in Bilaput contain Gasifier and PV-battery system with loads such as Electric Chiller, household loads, cashew processing units, flour mill etc., including some community facilities as shown in Figure 3.1. Due to the active involvement by project partners, there is great access opportunity for data and specifications of this minigrid. However, these minigrids are highly going to be over capacity and with low operational dynamics. Hence it is proposed to look for additional reference minigrids with increased dynamics.

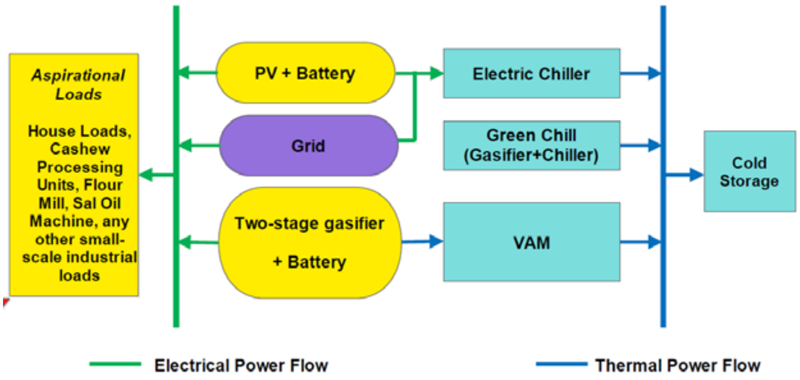

Figure 3.1 - Block diagram representation of Microgrids under development in India

3.3 Other minigrids

The single line layout is obtained for one of the existing microgrids of an Island in India. It contains PV-battery system as well as rotating machines, hence, it is a minigrid powered by heterogeneous sources. Its network consists of both primary as well as secondary distribution voltage levels. Due to security restrictions the network is not detailed further in this report.

4 Selected reference minigrids and criteria

The reference minigrids are planned to be used in the development of synchronization controllers for multiple minigrids. Hence, the selection of the minigrids shall be carried out to sufficiently represent the expected dynamics.

The primary criteria for selection of reference microgrid are as follows.

- It should be having renewable energy sources
- The renewable sources should be heterogenous in nature.
- The interfacing devices should be of both static (power electronic) as well as dynamic (rotating machine)
- The selected microgrid/minigrid should be in the vicinity of another microgrid/minigrid so that inter-connection is possible
- The selected microgrid should be having the access to the Main grid to enable the selected microgrid to study under grid-connected and islanded scenarios.

4.1 Load-generation mix

It is decided to categorise the loads into critical and non-critical loads, there by option of regulating the non-critical loads as part of demand side management (DSM) can be explored during contingencies.

The installed/considered generation mix is to be heterogeneous, however, the supply source will be decided based on the priority in order to maintain the stability.

4.2 Location

The case of Section 3.2 or adapted case of Section 3.3 will be considered to enable experimentation at the laboratory scale.

4.3 Selected minigrids/microgrids

The microgrids discussed in Section 3.1 are of homogenous in nature and are predominantly islanded microgrids, whereas microgrids discussed in Sections 3.2 and 3.3 are having heterogeneous power mix. In addition, these microgrids can be investigated for interconnected operations. Moreover, the microgrids discussed in Sections 3.2 and 3.3 can be examined for stability as they involve heterogeneous mix both on generation as well as load sides. These microgrids can also accommodate load control to some or other extent.

However, the microgrid discussed in Section 3.3 is having both primary and secondary distribution systems and is spread across a vast geographical area, where as microgrids discussed in Section 3.2 are being developed.

In view of the above, based on the feasibility, microgrids discussed in Section 3.2 will be considered as reference micro/mini grids. If it is found to be not feasible at the time of experimentation at laboratory, the minigrid discussed in Section 3.3 will be considered as reference minigrid.

Since it is a complex system to use directly in the simulation studies and hence it is decided that part of the network or some features of the network shall be considered for simulation studies. The same system will be adapted to suit the laboratory infrastructure.

5 Energy management and control structure

To successfully utilize minigrids and easily connect them with the main grid or other minigrids, it is essential to control them in an intelligent and coordinated way by using appropriate control systems. The control systems have to ensure the stability of the minigrid by making sure that the different units remain synchronized and are operating at the appropriate voltage and frequency. Due to the multiple objectives that need to be handled by the control system, it is often common to split it into several layers where each one of the layers are focusing on different control objectives.

5.1 Hierarchical control structure of microgrids / minigrids

Having synchronous generators in minigrid provides several advantages in terms of stability and reliability. This is mainly due to the inertia, damping, and load-sharing properties of synchronous generators. However, for many distributed generators (DGs) such as PVs, wind turbines, and batteries, this property does not hold and instead requires inverters to adjust the generated energy frequency and voltage level. To ensure stability and to provide better power quality, the frequencies and voltages need to be synchronized between all DGs to avoid circulating currents among the inverters [8]. Typically, this would require communication links with very high bandwidth between the inverters. However, using e.g., droop-control, active and reactive power can be shared between the inverters without any communication links [8], [9]. Although this approach achieves high reliability and flexibility, it will result in voltage and frequency deviations in the system that is dependent on the load. To solve this problem, an external control loop, often referred to as secondary control, is usually added to the control system to compensate for these deviations [9], [10]. On top of the secondary controller, an additional control layer known as tertiary control is used to determine the direction of the power flow as shown in Figure 5.1, where the aim is to determine the power flow between the different grids at the point of common coupling (PCC) [9], [10].

These three control layers result in a hierarchical control structure shown in Figure 5.1, which are commonly being used in microgrids or minigrids. Therefore, it has recently been proposed that this structure should be used as an attempt to standardize the control structure of microgrids and minigrids [9], [10]. Each control layer has its own objective and can use different control methods to accomplish its goal. The bandwidths of different control layers are normally separated by at least an order of magnitude, which allows the decoupling of the dynamics between the different layers. This feature simplifies the modelling and controller design, where the sampling speed gets slower when moving towards a higher control layer [11].

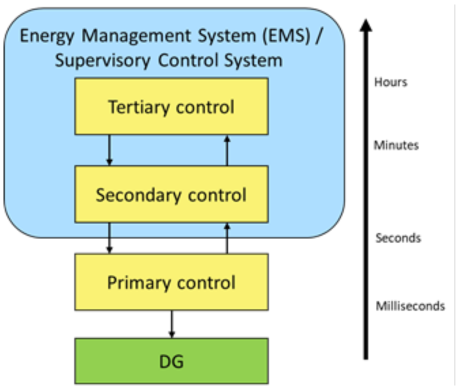

Figure 5.1 - A representative hierarchical control layer structure

Primary control (droop control)

The primary controllers are responsible for the local stability of the different DGs while simultaneously trying to achieve load sharing (active and reactive power) between the units [8]. Each inverter uses an external power loop based on droop control which allows each DG unit to operate autonomously. Depending on different configurations and droop control strategies, the inverters can be controlled in [12] (see Figure 5.2):

a. Grid-forming mode (as a voltage source),
b. Grid-feeding mode (as a current source),
c. Grid-supporting mode (as a voltage source),
d. Grid-supporting mode (as a current source).

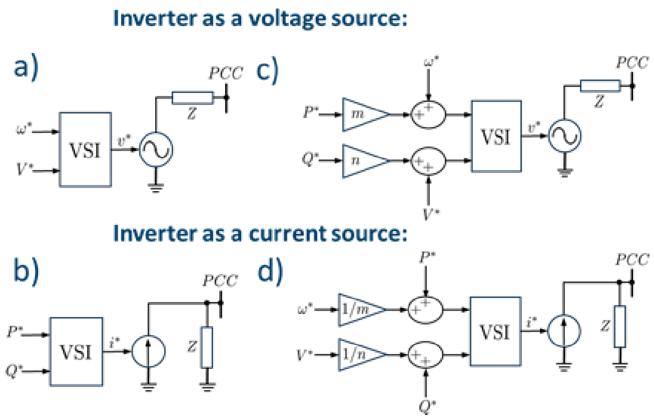

Figure 5.2 - A representation of grid-connected power inverters, adapted from [12]

However, whenever a minigrid is disconnected from the main grid, at least one DG has to be operated as a grid forming unit. The primary control is based only on local measurements and does not require communication between the inverters. Instead, the primary control follows the set-points given by the secondary control layer, which can also remove any deviation in the frequency and output voltage [10], [11].

Secondary control (frequency and voltage restoration and synchronization)

The secondary control appears on top of primary control and primarily deals with power quality control, such as voltage/frequency restoration and voltage unbalance and harmonic compensation [11]. It is also responsible for removing the deviations in frequency and voltage by correcting the set-points for the primary controllers [8], [10]. Typically, this is achieved using two separate feedback control loops with two PI controllers [13], as shown in Figure 5.3.

The PI controller computes the error value, which is the difference between the measured value (voltage amplitude or frequency) and the desired reference value. The PI controller uses a proportional and an integral term to calculate a correction signal based on the error value (see (1) and (2)).

$$\Delta f = k_p\left(f_{ref} - f_{MG}\right) + k_i \int \left(f_{ref} - f_{MG}\right) dt \qquad (1)$$

$$\Delta V = k_p\left(V_{ref} - V_{MG}\right) + k_i \int \left(V_{ref} - V_{MG}\right) dt \qquad (2)$$

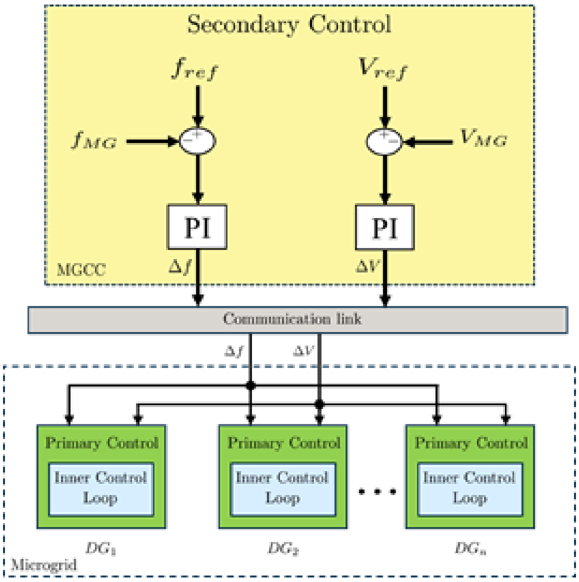

Figure 5.3 - Secondary control layer, adapted from [13]

Whereas the primary controllers are usually decentralized, the secondary control can further be divided into either a centralized or a distributed control structure [13], [14] (see Figure 5.4). Both structures pose different advantages and disadvantages that come with their own control challenges. However, most minigrids are governed by a single central controller, and thus, only centralized control architectures will be considered here.

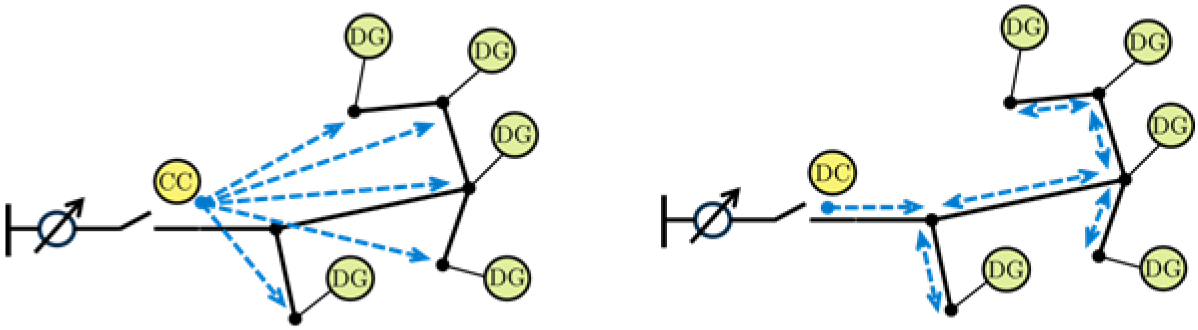

Figure 5.4 - Centralized and distributed control structure, adapted from [14]

Besides removing the voltage and frequency deviations between the DG units, it is also responsible for the synchronization and power exchange with the main grid when transitioning from islanded to grid-connected mode before making the interconnection [8], [11]. However, this will be discussed in more detail in section 5.2.

Tertiary control (P-Q import and export)

The tertiary control layer is responsible for regulating the power flows, e.g., by importing or exporting energy between the minigrid and the main grid at the PCC [8], [10]. However, the tertiary control layer must be decoupled when the minigrid is disconnected from the main grid and being operated in island mode to avoid voltage instabilities [10].

Supervisory control / Energy management system

The hierarchical control structure follows a top-down communication approach where the upper layer's controllers provide the lower controller with their respective set-points. The main purpose of these controllers is to ensure the stability of the system by having all the units operate at the appropriate voltage amplitude and frequency. However, these controllers do not account for the economics by, e.g., adjusting to changes in the energy market. Instead, these things are commonly determined through an energy management system (EMS), which is sometimes referred to as a supervisory controller [11].

The EMS coordinates with hierarchical control structure by providing it with set-points and determining optimal power flows for the minigrid. It can, thus, primarily be seen as part of the tertiary control layer. However, in [15], the EMS is placed as part of the secondary control layer, while tertiary control is used to coordinate multiple microgrids. Therefore, the EMS can be seen as an underlying function for either the tertiary layer, the supervisory layer, or both, depending on the structure of the minigrid and the objective of the EMS. However, the EMS operates at a time-scale that is too slow to be relevant for synchronization.

5.2 Active synchronization of microgrids / minigrids

When a minigrid that is being operated in island mode wants to connect with the main grid or some other nearby minigrid, they first have to be synchronized. Synchronization requires that the voltages, frequencies, and phase angles on both grids are matched before connecting them. Traditionally, synchronization has been handled manually, but for minigrids that consist of several generators and inverters with different characteristics, this becomes more challenging. As a result, active synchronization methods are being proposed in the research literature.

Active synchronization can be defined as a control method for automatic synchronization and connection of minigrids or microgrids. Such synchronization controller is illustrated in Figure 5.5. The aim of a synchronization controller is first to match the voltage, frequency, and phase angle at the connection point and then close the switch when the differences have been reduced to an acceptable level. The secondary control layer is usually responsible for the active synchronization procedure. Typically, a master-slave approach is used, where a single DG is responsible for setting the voltage and frequency of the minigrid and with the remaining DGs operating in grid-following mode. However, there is also possibility to use a more coordinated approach where multiple DGs are responsible for the synchronization. Nevertheless, both approaches require measurements of the voltages, frequencies, and phase angles on both sides of the switch are available. Usually, these values are obtained using phase-locked loops (PLL) [12].

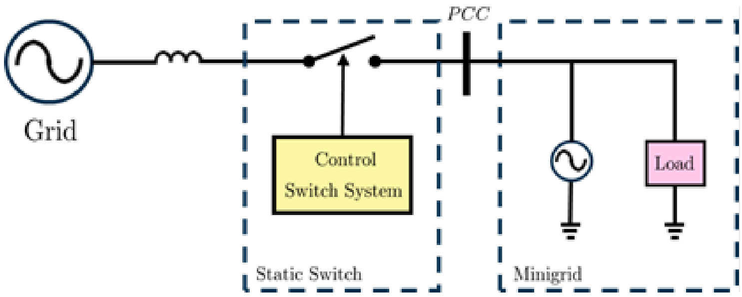

Figure 5.5 - Representative synchronization control structure for a minigrid

PLLs have widely been used for many different industrial applications due to their robustness, effectiveness, and simplicity. A PLL typically consists of a closed-loop feedback control system that generates a signal with the same phase and frequency as a reference signal. The traditional PLL structure consists of three main blocks, a voltage-controlled oscillator, a low-pass filter, and a phase detector. For grid applications, and in particular 3-phase networks, a synchronous reference frame PLL (SRF-PLL) is commonly used, which is illustrated in Figure 5.6.

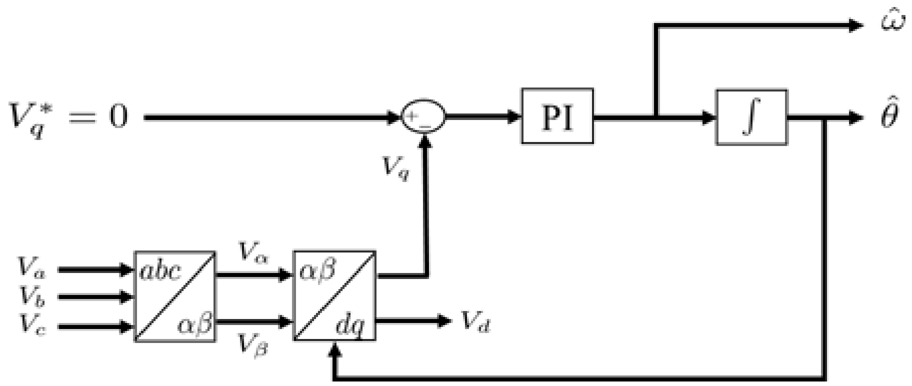

Figure 5.6 - Synchronous reference frame PLL

As previously mentioned, the synchronization control is commonly done by the secondary control layer using a minigrid central controller (MGCC). The MGCC receives information about the voltages, frequencies at both sides of the connection point and computes the phase angle difference. During synchronization, the MGCC tries to remove these differences by adjusting the voltage and frequency set-points sent to the DGs. Several different synchronization algorithms have been proposed in the research literature. A structure similar to Figure 5.3 is often used, where two PI controllers are used to remove the voltage and frequency differences by using their measurements as reference values. However, the main challenge is to remove the difference in the phase angles.

In [16], a synchronization controller that was similar to the secondary controller shown in Figure 5.3 was proposed. The measured voltage and frequency at the main grid were used as reference values. However, to remove the differences in the phase angles, a small error term was added to the frequency's reference value. A small error in the frequencies between the minigrid and the main grid will result in the phase angle error to circle between -π and π. Thus, the controller can simply wait until the phase angle difference becomes close to zero and then remove the frequency error term, hoping to closely match the voltage phasor on both sides of the PCC. The method is very simple to implement as the proposed synchronization controller closely resembles the typical secondary controller. However, it gives inconsistent results since it is very difficult to remove the phase angle difference completely, and the time required for synchronization will vary.

Another approach that was primarily designed for droop based DGs was suggested by [17]. Here, the frequency, voltage, and phase are controlled sequentially where at first the measured frequency is sent directly to the droop controllers and used as the nominal value. Secondly, the voltage is controlled, followed by the control of the phase angles using two separate PI controllers. However, instead of having correction terms of the voltage and frequency as outputs from the PI controllers, active and reactive power set-points are used and sent to the droop controllers.

One of the most popular proposed synchronization control methods was given in [18], where different signals are sent to the different DGs. As in Figure 5.3, two separate PI controllers are used, with the inputs being the differences between the actual and desired values of the frequency and voltage. However, instead of using the same control output for all DGs, the outputs can be weighted and filtered differently for the different DGs. The phase error is removed by adding an additional PI controller that gets activated when the frequency deviation is sufficiently small. The PI controller for the phase error adjusts the signal of one of the outputs from the frequency controller until the phase error has been removed. This approach's main advantage is that it can be tailored to different types of minigrids by adjusting the different weights and designing the filters. However, determining how to choose these weights and filters can be challenging, and there is no systematic approach for doing so. Furthermore, this approach also introduces an additional control loop to remove the phase error, which further adds some complexity. Therefore, it would be preferable to have a synchronization controller that closely resembles the existing secondary controller.

To avoid adding unnecessary complexity to the secondary control layer, the synchronization controller by [19] is proposed. This control structure was originally developed for virtual synchronous machines but can also be used to synchronize minigrids. In this approach, a very similar control structures can be used for both the synchronization and when the minigrid is operating in island mode. The synchronization controller is almost identical to the secondary controller shown in Figure 5.3, with the reference values being the measured frequency and voltage from the main grid. The phase error is removed by multiplying the phase difference with a proportional gain and then adding it to the error for the frequency controller. An illustration of the proposed synchronization control structure is shown in Figure 5.7, where it is compared to the secondary controller when it is being operated in island mode. As can be seen from the figure, only a proportional gain needs to be added when going from island mode to synchronization. Therefore, assuming that the existing MGCC is working and tuned appropriately, then the proposed synchronization controller should also be relatively easy to implement and tune.

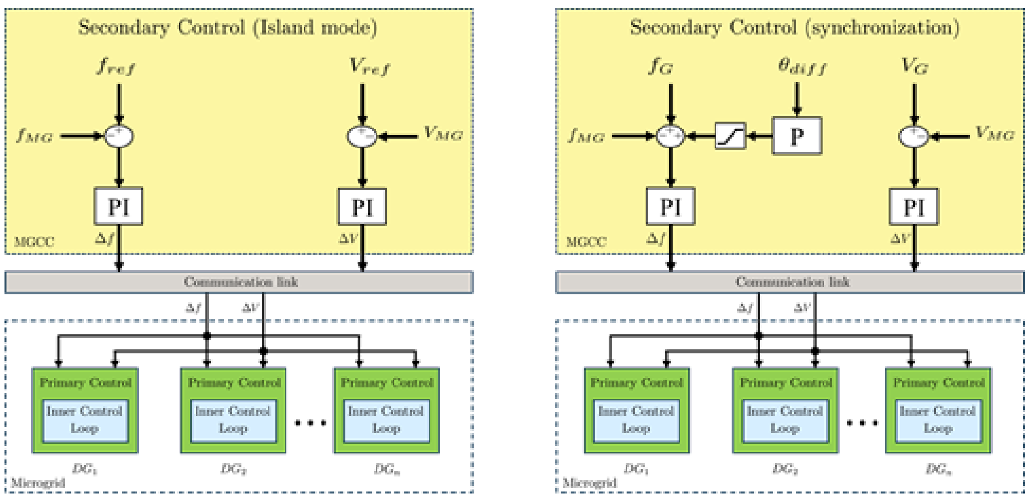

Figure 5.7 - Comparison of the secondary controller in island mode and the proposed synchronization controller

6 Conclusions

This report brings out the status of microgrids/minigrids in India, different players involved while outlining the challenges for successful operation. As the prime objective of the project is to develop protocols for integrated operation of different minigrids/microgrids in Indian context, different existing minigrids/microgrids are explored to suit the requirement of investigations. In this process, an option is identified while keeping it open for adaptability to experiment at laboratory scale, considering the exigencies during experimentations. In addition, the report also describes different operation/control philosophies for stable and reliable operation of interconnected as well as islanded microgrid which will be further developed investigated in the process of achieving the defined project objectives.

7 References

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