Review of Grid Interconnection Requirements and Synchronization Controllers for Dispersed Minigrids

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***Abstract*—As of 2019, the world population without electricity access is estimated to 770 million with most of these communities residing in sub-Saharan Africa. Nevertheless, between 2000 and 2019 the Indian population with electricity access has grown from 43% to 99%. Minigrids have played a major role in the efforts of increasing access to electricity in rural areas. However, interconnecting minigrids to each-other or to the main grid remains still a challenge both due to lack of clear protocols and of technically matured controllers to manage the synchronization. In this paper, a review of existing interconnection guidelines is presented and their relevance for the interconnection of minigrids is assessed. Furthermore, existing synchronization controllers are reviewed highlighting their applicability for minigrids.**

***Index Terms*— interconnection standard, minigrids, microgrids, rural electrification, synchronizing controller.**

I. INTRODUCTION

In recent years, the world population without electricity access has decreased significantly dropping to a record low 770 million in 2019 [1]. In India alone, the share of population with electricity access has increased from 43% in 2000 to 99% in 2019. The International Energy Agency (IEA) anticipates that more than 50% of the rural population currently without energy access is best supplied with electricity via minigrids. Indeed, the presence of minigrids in India has expanded significantly over the last decade due to increased involvement of private players, local banks, and the government through the Ministry of New and Renewable Energy (MNRE)'s Remote Village Electrification Programme and the Village Energy Security Programme [2]. As of 2019, according to the data gathered by the Energy Sector Management Assistance Program (ESMAP), the number of minigrids in India is estimated to be 2800.

Minigrids in rural areas 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. Another threat is the condition when the main grid or other minigrids reach the vicinity of an already existing minigrid. For example, just 6% of the minigrids in Indonesia remained in business after the main grid arrived and most village projects were abandoned [3]. This could result in lost assets and discourage investments. Thus, it is critical that the capabilities to interconnect multiple minigrids to each other and eventually to the main grid should be incorporated already in the design phase.

New methods have been recently investigated for the realization of bottom-up electrification where dispersed generation systems and other stand-alone systems are interconnected to synergize their complementarities [4]. Swarm electrification is one of such concepts aiming to drive the transition from standalone energy systems and households without energy access to a peer-to-peer microgrid [5]. In [6], it is estimated that stand-alone residential solar systems interconnected into microgrids required around 35% less generation capacity than standalone systems in order to keep the same 95% average reliability for the power supply.

The interconnection of a minigrid to other minigrids or to the main grid faces uncertainties in relation to lack of appropriate business models as well as clear technical requirements for interconnection. Nevertheless, the technical challenges and solutions for the seamless interconnections of multiple minigrids have not been given the required attention in the reviewed literature.

This paper discusses the technical challenges in association with interconnection of minigrids to each other and to the main grid. Furthermore, the paper outlines the required developments both at the level of synchronization controllers as well as implications to existing standards and guidelines.

II. CHALLENGES IN INTERCONNECTION OF MINIGRIDS

Minigrids are heterogeneous in nature since they can include different type of energy sources and generator technologies as shown in Fig. 1. For example, in Indian minigrids, generation is mostly based on diesel units or renewable generation sources as solar photovoltaic, mini/micro-hydro plants and wind turbines. Some companies are also integrating biomass/ biogas generation in minigrids to serve continuous load demand [7]. Converter interfaced

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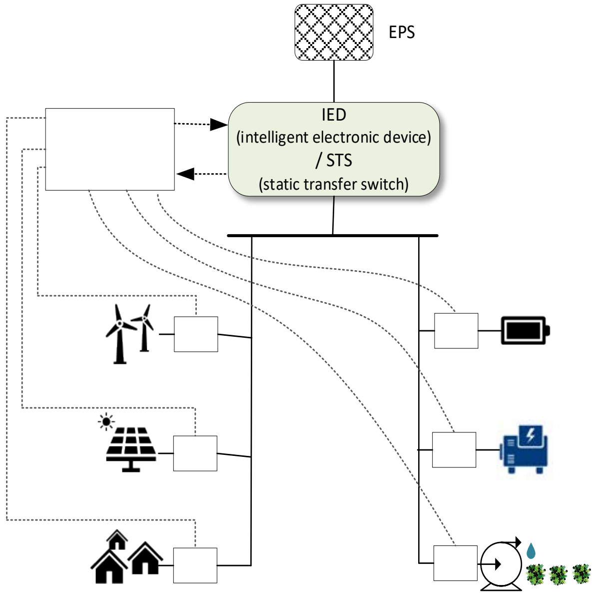

Fig. 1. Minigrid active synchronizing control scheme

generation systems connected to the main grid operate as grid-following sources since the voltage and frequency are stiffly regulated. However, with limited presence of synchronous machines and high level of solar and wind generation systems, minigrids are highly likely to be low-inertia systems. This demands that the generation systems possibly support actively the frequency and voltage regulation and offer grid-forming features [8] [9]. Hence, minigrids may be characterized by significantly different dynamic operational features. For instance, 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.

When the main grid approaches the vicinity of rural minigrids or when another minigrid emerges in the neighborhood, interconnection may become an opportunity or even a necessity. For a minigrid operated in island mode be connected with the main grid or some other nearby minigrid, they must be synchronized first. Synchronization requires that the voltages, frequencies, and phase angles for both grids are matched before they are physically connected. The synchronization controller shall orchestrate the process organizing synchronous generators, induction generators, inverter-based generators, controllable loads and storage systems within the minigrids. The integration of two heterogeneous minigrids is an even more challenging task especially if each of the two minigrids is serving an appreciable number of local loads. Hence, it is critical to define protocols for connecting and disconnecting minigrids without affecting the stability and voltage quality. Frequency oscillations and stability are reported as technical challenges faced during synchronization of microgrids with utility or other microgrids [10]. Synchronization challenges related to different generation systems are described briefly in Table I.

TABLE I
GENERATOR TYPES AND SYNCHRONIZATION CHALLENGES

Generator types	Associated systems	Synchronization
Induction generators	Wind turbines, CHPs, small hydro	Induction generators do not need to be synchronized with the grid before being interconnected.
Synchronous generators	Small hydro, diesel generator, biomass gasifier	Before synchronous generators are connected with the grid, Voltage magnitude, Voltage phase angle and frequency need to be synchronized.
Inverters	Solar PVs, some wind systems, storage elements	Needs to be inverters which can operate in both stand alone and grid -interactive mode. In this case synchronization is as simple as connecting the terminals.

III. INTERCONNECTION PROTOCOLS

Interconnection of minigrids to the main grid in the developing world is for most part a fairly recent phenomenon, and the development of best practices is still a work in progress. No international group has yet produced an agreed upon set of standard policies and procedures for interconnection [11]. The closest interconnection standard is the IEEE 1547 family of standards which has been used as reference to prepare guidelines and recommended practices in most countries. The standard is essentially developed for the interconnection of distributed generators (DGs) with the main power grid. Most of the reviewed requirements are targeting interconnection of generators to the power system and are mostly adopting the IEEE 1547 standards [12] (see Table II). There is no guideline document for interconnection of multiple minigrids and existing documents for interconnection of

TABLE II
REVIEW OF RELEVANT GRID INTERCONNECTION STANDARDS AND REQUIREMENTS.

Interconnection standard/ Requirement	Comment
IEEE 1547	Foundational document for the interconnection of distributed energy resources (DER) with the electric power system or the grid.
IEC 61727	It applies to utility-interconnected PV power systems with a rated capacity of below 10 kVA that are connected to a low-voltage (LV) utility network, and, thus, concerns the compatibility between PV systems and public networks.
IEEE 929	It was developed specifically for PV systems. It provides practical guidelines for the operation of compatible small PV systems below 10 kW when connected to a power system, covering personnel safety, the protection of equipment, power quality, and the operation of the utility system.
CEA 2007/2013/2019	Indian Central Electricity Authority (CEA): Technical standards for connectivity to the Grid.
MNRE Draft- April, 2020	Ministry of New and Renewable Energy (MNRE): Technical requirements for Photovoltaic Grid Tie Inverters to be connected to the Utility Grid in India.
EU 2016/631 (EU/Norway)	A network code on requirements for grid connection of generators.

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minigrids to the main grid are not comprehensive. The closest document available as guidebook on grid interconnection and islanded operation of minigrids power systems is published in 2013 by the Lawrence Berkeley National Laboratory [11].

IV. MINIGRID CONTROL AND SYNCHRONIZATION

Minigrids and microgrids, typically, use a hierarchical control structure that follows a top-down communication approach where the upper layer's controllers provide the lower layer controller with their respective set-points. Therefore, it has recently been proposed that this structure should be used as an attempt to standardize the control structure of microgrids [13]. The hierarchical control structure is divided into three different control layers: primary control, secondary control, and tertiary control [14], [15].

The secondary control appears on top of primary control and is responsible for removing the deviations in frequency and voltage by changing the set-points (Δf and ΔV) for the primary controllers [16], [15]. Two separate feedback loops are often used that consists of e.g., two PI controllers, as shown in Fig. 2. Here, f_{MG}, f_{ref}, V_{MG}, and V_{ref} denote the measured frequency, the reference frequency, the measured voltage, and the reference voltage for the minigrid, respectively. The secondary control can be implemented either as a centralized or as a distributed control structure [14]. 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.

Traditionally, synchronization has been handled manually, but for minigrids that consist of several generators and inverters with different characteristics, this may become 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. Thus, the aim is first to match the voltage, frequency, and phase angle at the connection point and then close the connection switch. It is usually the secondary control layer that is responsible for synchronization.

A. Controllers for active synchronization

The secondary control layer is also responsible for the active synchronization procedure when transitioning from islanded to grid-connected mode before making the interconnection [16]. 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, a more distributed approach could also be adopted, 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 connection switch. These values are often obtained using phase-locked loops (PLL) [17]. During synchronization, the synchronization controller tries to cancel these differences by continuously adjusting the voltage and frequency control signals sent to the DGs. The voltage error is often removed using a voltage control loop similar to the one illustrated in Fig. 2. However, the main challenge is to remove the frequency and, in particular, the phase angle differences. Therefore, several different synchronization algorithms have been proposed in the research literature.

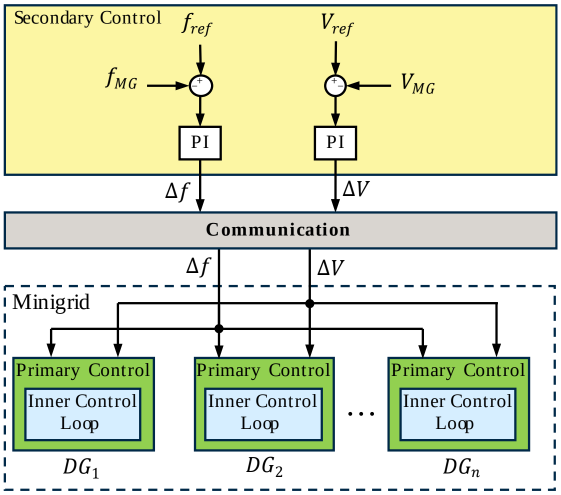

Fig. 2. Secondary control structure, adapted from [14]

In [18], a synchronization controller that closely resembled the secondary controller shown in Fig. 2 was proposed. The measured voltage V_G and frequency f_G at the main grid were used as reference values. However, to remove the differences in the phase angles, a small error term is initially added to the frequency's reference value such that:

$$f_{ref} = f_g + \varepsilon \tag{1}$$

A difference in the frequencies between the two grids will result in the phase angle error to circle between -180 and 180 degrees. Thus, the controller will simply wait until the phase angle difference becomes close to zero and then remove the frequency error term by setting ε = 0, with the objective of closely matching the voltage phasor on both sides of the PCC. The method is simple to implement as the proposed synchronization controller can closely resemble the existing secondary controller. However, it gives inconsistent results since it is difficult to remove the phase angle difference completely, and the time required for synchronization varies.

A commonly cited synchronization controller synchronization controller was given in [19] and is illustrated in Fig. 3. As in Fig. 2, 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 θ_{diff} is removed by including a third PI controller that gets activated when the frequency deviation φ is sufficiently small. The PI controller for the phase error adjusts one of the outputs from the frequency controller until the phase error has been removed. The main advantage of this approach is that it can be tailored to different types of minigrids by adjusting the different weights and filters. However, no systematic approach has been developed for selecting these weights and filters.

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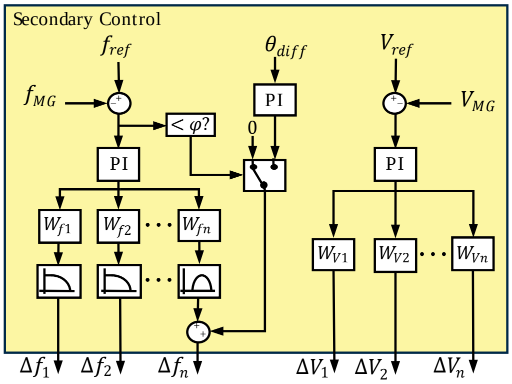

Fig. 3. Synchronization controller proposed in *[19]*

A robust controller was designed in [10], based on µ synthesis to synchronize a microgrid with the main grid. Simulations showed improved performance for the robust synchronization controller compared to the controller in [19]. However, the robust controller further increases the complexity as it requires more advanced controllers than, e.g., the PI controllers. In addition, a dynamic model of the grid is required to design the controller.

Synchronization controllers for droop based DGs have been proposed in [20] and [21]. In [20], only the frequency and phase were synchronized using the control structure shown in Fig. 4. The PI controller eliminates the phase difference θ_{diff} by adjusting the active power set-points ΔP for the droop controllers. The droop P-f controller is given by:

$$f = f^* + m\left(P^* - P + \Delta P\right) \tag{2}$$

where m is the droop gain and P is the measured active power. P^*, and f^* are the nominal values for the active power and frequency, respectively. The values for P^* and f^* are kept constant during the synchronization process in [20]. However, in [21], f^* is replaced with the main grid measurement f_G to better react to changes in the main grid frequency. In addition, a second control loop for V-Q droop controllers is added in [21] to remove any voltage difference.

For inverter-based DGs, the synchronization controller can be designed to directly modify the PWM signals generated for the inverter [22], [23]. As a result, it is possible to achieve much faster synchronization with very little frequency and voltage oscillations. However, these approaches have been developed for minigrids that only consist of inverter-based DGs. Therefore, they cannot be generalized, e.g., to controlling synchronous generators, nor is it clear how these synchronization controllers will perform in minigrids with higher inertia.

V. CONSIDERATIONS ON THE SYNCHRONIZATION PROCESS

To interconnect multiple minigrids with each other or the main grid, it is crucial that synchronization can be achieved seamlessly and reliably. Therefore, it is important to implement appropriate synchronization controllers that give a robust performance and ensure the grid stability. Several control structures for active synchronization have been proposed in the research literature. However, they only consider synchronization when trying to re-connect a single minigrid to the main grid.

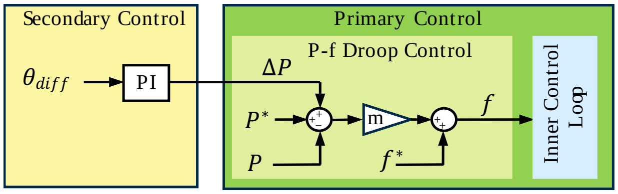

Fig. 4. Synchronization control for droop based DGs

The inertia and the rated power of a minigrid can be expected to be relatively insignificant compared to the main grid. This implies that the main grid behaves as a stiff voltage source with regards to the frequency since the minigrid has practically no effect on the grid dynamics. The voltage at the connection point to the minigrid may vary depending on the impedance connecting the minigrid to the main grid. In case of a low connection impedance the voltage will be largely unaffected and be stiff while for higher connecting impedance the voltage will experience variations depending on the power exchanged between the minigrid and the grid. In these conditions the connection of a minigrid to an external grid is equivalent to the connection to a stiff voltage source and the dynamics are rather decoupled. Moreover, the synchronization process needs to account solely on the characteristics of the minigrid. This effectively simplifies the process of the synchronization and the design and the tuning of the controllers.

When connecting two minigrids the conditions are more diversified and more options for the synchronization can be considered. Indeed, since the frequency in the minigrids will be less steady than for a main grid the synchronization process is less straightforward. Another aspect to be considered is the stability of the operation of the combined system composed by the two minigrids. In presence of a large disproportion between ratings or inertia values the conditions resemble the conditions of connection to a main grid. Indeed, the minigrid with the larger power and inertia will be dominant and act similarly to a stiff voltage source since the effect of the other minigrid would be minor. The case of two or more minigrids with comparable inertia poses more challenges for ensuring stability and acceptable transient conditions after the connection.

For low inertia minigrids that use only inverter-based DGs, it is possible to use different synchronization controllers than minigrids containing synchronous generators. Nevertheless, since most of today's minigrids consist of both inverter-based DGs and rotating machines, it would be preferable to use synchronization controllers that can be possibly generalized for all types of minigrids. Ideally, the synchronization controller should also closely resemble the existing secondary controller to reduce the complexity of the resulting control structure. Besides control structure selection, the controllers need to be tuned appropriately. However, despite that controller tuning can arguably be considered more important than control structure selection, there is a clear lack of literature on this topic for synchronization controllers. Therefore, it is important to develop systematic approaches for

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selecting the tuning parameters that can be used for different minigrids.

VI. CONCLUSIONS

Minigrids are playing and are expected to play an essential role in the electrification of rural areas and in providing electricity access where not available yet while a main grid is not reachable in the proximity. However, in order to encourage investments and optimize the use of resources, it is relevant to consider how to preserve the value of the minigrid infrastructure when a connection to a main grid will become available or how to benefit from the possibility to interconnect multiple minigrids. However, the synchronization process is not defined in standards yet. This paper presented a brief review of interconnection standards that could serve as a basis for minigrid interconnection. Moreover, the paper provides a review on synchronization schemes proposed in literature and general consideration on their use and on their main benefits and disadvantages.

The authors plan to compare the performance of existing synchronisation controllers on a numerical model of rural microgrids as further work. This will serve as a basis to recommend feasible implementations for an Indian context.

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