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Edition 1.0 2019-05

TECHNICAL SPECIFICATION

Recommendations for renewable energy and hybrid systems for rural electrification –
Part 7-4: Generators – Integration of solar with other forms of power generation within hybrid power systems

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specification are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62257-7-4, which is a Technical Specification, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this Technical Specification is based on the following documents:

Draft TS	Report on voting
82/1477/DTS	82/1545A/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This part of IEC 62257 is to be used in conjunction with IEC 62257 (all parts).

A list of all parts in the IEC 62257 series, published under the general title *Recommendations for renewable energy and hybrid systems for rural electrification*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or amended.

A bilingual version of this publication may be issued at a later date.

RECOMMENDATIONS FOR RENEWABLE ENERGY AND HYBRID SYSTEMS FOR RURAL ELECTRIFICATION –

Part 7-4: Generators – Integration of solar with other forms of power generation within hybrid power systems

1 Scope

This part of IEC 62257, which is a technical specification, specifies the design and implementation of hybrid off-grid solar systems, where solar energy provides energy to a load in conjunction with other sources of energy. Such systems may or may not include an energy storage system. There are a variety of different system architectures and applications, and many ways in which these energy sources can be combined. This document distinguishes between different sorts of hybrid system applications and gives guidance on the design and integration of these systems.

It applies to single-phase and three-phase applications, and it covers situations where grid is available as an additional source of power for charging batteries and maintaining system reliability, but this document does not cover situations in which energy is fed back into a utility grid, although such systems may incidentally possess this function.

2 Normative references

The following documents are referred to in the text in such a way the some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

IEC TS 62257-7-2, *Recommendations for renewable energy and hybrid systems for rural electrification – Part 7-2: Generator set – Off-grid wind turbines* [1]

IEC TS 62257-7-3, *Recommendations for renewable energy and hybrid systems for rural electrification – Part 7-3: Generator set – Selection of generator sets for rural electrification systems*

IEC TS 62257-9-7, *Recommendations for renewable energy and hybrid systems for rural electrification – Part 9-7: Selection of inverters*

IEC 62509, *Battery charge controllers for photovoltaic systems – Performance and functioning*

IEC 62548, *Photovoltaic (PV) arrays – Design requirements*

IEC TS 62738, *Ground-mounted photovoltaic power plants – Design guidelines and recommendations*

[1] To be published.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
renewable energy
REN
energy from a source that is not depleted when used

3.2
hybrid system
multi-sources system with at least two kinds of energy generation technology

3.3
storage
storage of energy produced by one of the generators of the system in a battery

3.4
DC bus
node of the electrical system to which the DC input of the battery inverter is connected to

3.5
AC bus
node of the electrical system to which the AC output of the battery inverter is connected to

3.6
black start
process of starting an electrical power supply without relying on any other external generating source

3.7
renewable fraction
fraction of energy delivered to a load that originates from renewable power sources

4 Overview

Off-grid solar hybrid systems, where a solar energy source is combined with other sources of energy such as diesel or wind, have two primary differences in functionality compared with solar-only off-grid systems. Firstly, the intermittent nature of solar can be compensated for by making use of an additional energy source. In systems with batteries, this can help to maintain the batteries charged, and can change the way the battery bank is sized with respect to the solar resource: for example a diesel generator can be relied upon to charge the batteries if they would normally have discharged after an overcast period. Secondly, the renewable aspect of the hybrid system can reduce the fuel consumption of a system which would normally be relying solely on fuel by injecting a certain amount of renewable energy into a system which is normally sustained only by diesel generators.

5 Types of hybrid systems

5.1 General

This document makes three principal distinctions according to the primary regulator of the energy output:

a) Multi-master rotating machine dominated mini-grid systems where a diesel generator creates the grid, and to which other energy sources need to synchronize.
b) Single switched master mini-grid systems with battery banks where either the battery inverter creates the grid and the other energy sources synchronize to the battery inverter output, or the diesel generator creates the grid.
c) Multi-master inverter mini-grid where certain inverters participate in the creation of the grid alongside the diesel generator.

This list is not the comprehensive range of architectures available, and there may be subtle variations upon the architectures, for example making use of other technologies such as DC coupled gensets.

These different architectures represent different renewable fractions and spatial distributions of the power generators. A rotating machine dominated mini-grid is more suitable for applications with a low renewable fraction, where renewable energy is used to offset fuel consumption in order to increase the renewable fraction and maintain constant service,

5.2 Multi-master rotating machine dominated mini-grid

5.2.1 General

A multi-master machine dominated mini-grid is a system whereby the characteristics of the grid such as voltage and frequency are created by a fuel powered rotating machine such as a diesel generator, and to which other renewable sources synchronize.

A typical application of this is for sites with a high diesel generation set demand, such as mining. The renewable energy resource is used to offset the fuel consumption of the diesel generators somewhat, but never to completely replace them. See Figure 1.

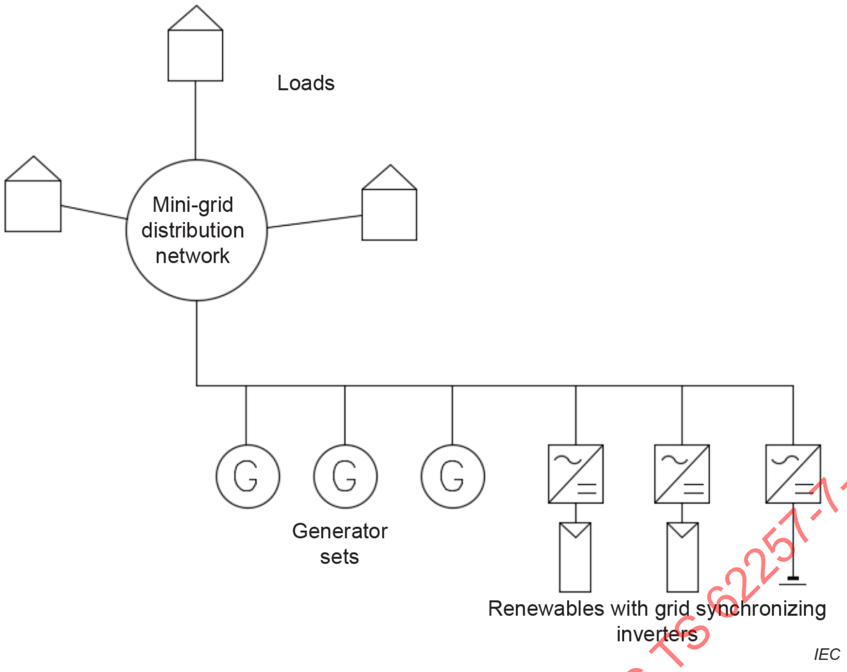

Figure 1 – Typical multi-master rotating machine dominated mini-grid architecture

5.2.2 Design

A typical arrangement is to have a diesel generator or a bank of diesel generators connected to the mini-grid distribution network, suitable sized according to the current or future predicted on-site loads. Connected in parallel to the generation sets are grid synchronizing inverters connected to a renewable energy resource, typically solar for this application. Everything is integrated together via a control mechanism, the purpose of which is ensure the correct and optimal performance of the whole system, which it does by controlling the maximum output of the inverters, and by switching diesel generators in and out according to the load being demanded.

Of particular importance is the protection of the generator sets by ensuring that under most load conditions, the generator sets are not being over-loaded or under-loaded: under-loading of a generation set can cause incomplete combustion of fuel, creating a 'wet-stacking' condition which can damage the engine. For efficient combustion the generator should typically be run at least at 40 % of its rated power but manufacturers' instructions may allow for a wider variation in power.

The other significant issue is how to maintain stability of the mini-grid in the face of rapid changes of the renewable contribution due to clouds, etc. This can be maintained by ensuring there is enough unused capacity in the generator sets (spinning reserve) that can be quickly activated in order to compensate for the drop in renewable contribution, or to integrate a small of amount of battery storage into the system.

All generating equipment shall be capable of operating at the same nominal AC voltage and frequency.

5.2.3 Design and selection of diesel generators

Detailed characteristics and design requirements for diesel generators for rural electrification, including this application, are described in IEC TS 62257-7-3.

In general, the system shall be designed in such a way that for the typical expected loads the generator sets will avoid wet-stacking, while providing some spare capacity for spinning reserve, and so typically they need to be configured so they will operate at between 40 % to

80 % of their capacity, or values that comply with manufacturer's recommendations. When the loads on site are particularly variable, then this can be ensured by having several smaller generator sets instead of one large generator set.

It should be noted that even if there are minimum recommended loadings for the generator sets, it may be acceptable to have them running under low loadings under some circumstances if it is the only way to avoid a black-out.

5.2.4 Design and selection of renewable energy component

The design of the photovoltaic array and the installation requirements are the same as described in IEC 62548. For large scale ground mounted systems, the design requirements of IEC TS 62738 may also apply.

The design and installation requirements of the wind component are to be described in IEC TS 62257-7-2.

Because the generator sets dictate the grid conditions, it is necessary to make use of inverters that can synchronize to the grid. The characteristics of suitable inverters for this application can be found in IEC TS 62257-9-7.

The percentage contribution of renewable generation at any one time should be done so that the generator sets will continue to work within the recommended minimum and maximum loading conditions.

When there are multiple gensets, it is possible to have a greater percentage of solar penetration into the system. The higher the solar penetration, the more important it is to have effective control over their energy output. It is not recommended to have a penetration percentage of greater than 60 % renewables into this type of multi-master rotating machine dominated system.

The harmonics tolerance of the diesel generators shall be checked against the harmonics of the solar and battery inverters.

5.2.5 Design and selection of batteries

Batteries may be integrated into these systems in order to reduce or eliminate the need for maintaining spinning reserve in the gensets. The batteries are connected to the AC bus using a suitable battery inverter, as discussed in IEC TS 62257-9-7 or via a hybrid inverter on the same DC bus as the PV.

The power capacity of the battery inverters should be equal to the amount of spinning reserve to be displaced. The storage capacity should be high enough to maintain a constant power through expected generation dips, or for as long as it may take non-spinning reserve (any additional gensets for example) to start-up.

5.2.6 Control system

5.2.6.1 General

The control systems to be implemented will depend upon the expected operating mode of the gensets, and of the percentage penetration of renewables into the system.

The diesel gensets can be operated in one of two ways, or a combination of both:

- Continuous operating systems – in which all the gensets are operating all of the time, and whose output is raised or lowered via droop control. For these systems it is necessary to implement a system that can measure the power flow from the generator sets with some sort of metering, and which can measure and control the power output from the renewable energy inverters.

- On demand systems – where the load demand is met by switching gensets on and off. For these systems it is necessary to implement a system that can measure power consumption from the general power meter, which can communicate with and control the renewable energy inverters, which can measure the power output of the gensets, and which is capable of switching gensets on and off as appropriate.

5.2.6.2 Guarantee of genset minimum load

The system shall operate in such a way as to maintain a minimum load on the gensets, which shall be according to diesel generator set manufacturer's recommendations.

5.2.6.3 Protection against reverse power flux

The system shall protect the gensets against reverse power flux by limiting the power production of the renewable energy generators as required, or shutting the inverters off completely if required.

5.2.6.4 Spinning reserve guarantee

The system shall guarantee enough spinning reserve capacity in the activated gensets to cope with sudden drops in power production of the renewable energy resource. This is achieved by ensuring that enough gensets are turned on at any one time to cope with the eventuality that they may need to meet the largest likely load contingency by themselves.

In the event that batteries are coupled into the system capable of covering the drops in power production, the spinning reserve capacity requirement is not needed.

5.2.6.5 Ramp rate control

In order to soften the impact on the grid of renewable energy resources suddenly increasing in power, for example when the sun suddenly shines after a cloud has passed, the ramp rate of the inverters (the rate at which they are allowed to increase their power), should be controlled.

5.2.6.6 Reactive power control

The inverters may be capable of producing reactive power in order to support the stability of the microgrid. This may be controlled by fixing a particular power factor, by fixing a particular voltage or by simply fixing a pure amount of reactive power to produce. Dynamic power factor control may be preferred depending on the load and reactive power requirements. A technical and economic analysis should be carried out to determine whether the reactive power required should be compensated by the solar inverters or the battery inverters.

5.2.6.7 Load control

An optional control mechanism is for the control system to have the ability to switch on and off certain loads on site, in order to stop the system from overloading, or in order to maintain the genset minimum load and spinning reserve requirements. For example, it is possible to install some 'dump loads', resistive loads whose sole purpose is to ensure that the genset is working at its minimum operating capacity.

5.3 Single switched master mini-grid

5.3.1 General

In this application, the grid conditions are normally formed by battery inverters. Under certain conditions (for example when battery capacity is low) the grid forming battery inverters can be switched out and the generator sets can be switched in, under which circumstance the generator sets then dictate the grid conditions.

Renewable energy sources may be integrated onto the DC side of the battery inverters, the DC bus, or onto the AC bus, and in the latter case they need to be capable of synchronizing to the grid conditions. See Figure 2.

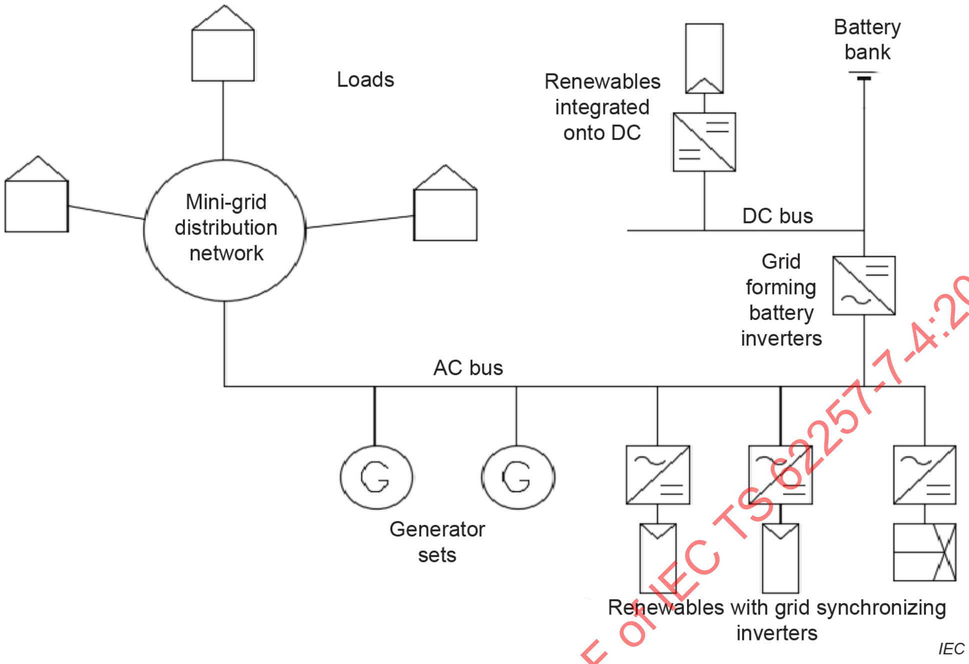

Figure 2 – Single switched master mini-grid architecture

5.3.2 Design

A typical arrangement is to have a battery bank connected to grid-forming bi-directional inverters, which sends energy onto an AC bus. Other energy sources may be coupled onto this AC bus, such as renewable energy generators with grid synchronizing inverters and generator sets. The sequence of operations is as follows:

- Under normal operation the battery inverters create the conditions of the mini-grid, frequency and voltage. The renewable energy resources are either DC coupled (generating into the DC side of the battery inverters), or AC coupled (generating into the AC side of the battery inverters). Diesel gensets are AC coupled but remain disconnected. The renewable energy component can be used to supply the loads and to charge the batteries.
- When the demand from the mini-grid is higher than the battery inverter and renewable energy sources can provide, or when the batteries become very discharged, then the diesel generators are switched on, and the renewable energy sources are generally switched off. The power from the gensets can then be used to meet the demands from the grid and to charge the batteries.
- In some cases, grid may be available, and this may also be used to meet high demand on site or charge the batteries in a similar way to the generator sets.

Prior to selecting the equipment, the end-use load application should be fully understood, including time-of-day use profiles, and a detailed study of the on-site renewable energy resources should be carried out, including anticipation of future load growth. Simulations may then be carried out in order to determine the behaviour of the system, and cost-benefit analyses should be performed in order to determine the best combination of equipment.

All AC coupled generating equipment shall be capable of operating at the same nominal AC voltage and frequency.

5.3.3 Design and selection of diesel generators

Detailed characteristics and design requirements for diesel generators for rural electrification, including this application, are described in IEC TS 62257-7-3.

In general, the system shall be designed in such a way so that in the event that the battery inverters are not able to meet the system demand, the diesel generators are able to meet the entire site demand. Generator sets shall avoid wet-stacking, and so they should be sized so that under expected loads they are providing at least 40 % of their capacity, unless a manufacturer's recommendation says otherwise. When the loads on site are particularly variable, then this might be ensured by having several smaller generator sets instead of one large generator set.

In some cases, a diesel generator is present only to boost battery voltage after a lengthy period of inclement weather. In these cases, a manual on-off switch may suffice to control when the generator is turned on. If automated starting and stopping of the diesel generator is needed, it may be controlled via the hybrid system control system, or it may be equipped with a remote starter. Start-up time should be considered to allow buffer time for the generator to start operating before the batteries are fully depleted and the system shuts down.

5.3.4 Design and selection of renewable energy component

The design and installation requirements of the photovoltaic component are described in IEC 62548. For large scale ground mounted systems, the design requirements of IEC TS 62738 may also apply.

The design and installation requirements of the wind component are to be described in IEC TS 62257-7-2.

The peak power sizing of the renewable energy generators depends upon a site dependent technical and economic analysis, taking into account the percentage of time the system owner wants to be using the genset compared to the cost of the equipment. Wind and solar energy often peak at different times throughout 24 h and seasonal cycles. Depending upon the location, combining wind and solar may help smooth the energy production profile at a given location and reduce further the dependency on fuel for the genset.

5.3.5 Design and selection of batteries

DC coupled renewable energy resources need to be connected to the batteries via a suitable charge controller, in order to protect the batteries. The charge controllers should conform to IEC 62509.

The characteristics for suitable bi-directional battery inverters and inverters for AC coupled renewable energy sources are covered in IEC TS 62257-9-7.

The bi-directional battery inverters shall be sized in such a way that they are able to meet the normal load demands of the site without any contribution from renewables, diesel generation or grid, with care taken over peak power loads, and with a view to how loads may increase in the future.

The usable battery capacity needs to be large enough to maintain the loads running throughout the desired autonomy time. A number of hours of autonomy are chosen to take into account the eventuality that there is no or limited renewable energy resource for a period of time in which the batteries need to keep the system running.

In order to guarantee quality of supply, hybrid systems do not need to be designed with as many hours of autonomy as pure renewable energy and battery systems, but the lower the number of hours of autonomy chosen, the more frequently the gensets will be needed in order to maintain supply. A minimum and maximum state of charge shall be set through the control system, which will depend upon the technology of the batteries, the overall battery management system, and any need to maintain a reserve in the event of generation set failure.

A detailed site dependent technical and economic analysis should be carried out in order to determine the ideal sizing of the battery bank, with special consideration taken over the recommended depth of discharge for the technology being used, battery life, battery degradation, the ambient temperature in which the batteries will be operating with any cooling needs taken into consideration, the time in which it will take them to discharge and the battery condition at end of life.

5.3.6 System control

5.3.6.1 General

The system needs to be controlled in such a way as to maintain the health of the energy storage system, maintain the quality of the micro-grid, and maximize the use of renewable energy resources. It needs to be able to switch in and out the diesel generator or grid as required in order to maintain security of energy supply and to keep the batteries charged. Control methods can be via direct communication, reliant on good measurement of loads and devices and high speed communication links, or via droop methods that rely on changes in frequency to coordinate the operation of various devices, and which do not require separate communication channels. (Note that frequency control may not be suitable where a system shall be connected to the main utility grid in the future as droop control may not be possible once connected to an external grid).

5.3.6.2 Throttling of solar production

When batteries are fully charged, and the solar production is greater than the load being demanded the system should be able to reduce the solar production so that the AC bus voltages do not exceed specifications. Control of renewable energy production can also protect diesel generators from reverse current flow.

Monitoring and communication can be set up in order to control the inverters. Alternatively, some battery inverters can slightly shift the frequency of the grid: the grid-synchronizing solar inverters detect this shift, taking it as a signal to reduce their power output.

5.3.6.3 Protection of gensets from overload

When the genset is activated, it is providing power to the loads as well as to the batteries via the bi-directional inverter/charger. The system shall be capable of limiting the amount of current being asked from the genset. The typical way of achieving this is to react to generator droop: if the system senses that the frequency from the gensets is dropping because it is reaching maximum load, then it will lower the amount of charging current being demanded from the batteries. Forced activation of the gensets shall be programmed to ensure operation is initiated fortnightly in the case that the load level does not require the gensets to operate regularly.

5.3.6.4 Prioritizing energy source

The system may be configured to prioritize different energy sources depending upon time-of day or upon measured conditions and energy demand. Real-time weather forecasting might be implemented in order to predict moments of low solar or wind, and give time for generators to start up.

5.3.6.5 Activation of dump loads

As an alternative to throttling renewable energy production, it is possible to switch on dump loads. For example, with wind power, when the power being produced is in excess to the demand, a resistive load can be turned on in order to consume that power, and keep the grid within healthy parameters.

5.3.6.6 Protection of batteries

The system shall be designed in such a way as to protect the energy storage system within its particular operating limits and where possible to operate the storage in such a way to maximise its useful service life. This can be achieved by programming regular charging of the batteries by the genset. It can also be controlled through disconnecting of non-essential loads if needed.

5.3.6.7 Load sharing

Renewable energy inverters may be switched into the system by either sharing the load equally amongst all the inverters, or in a 'team mode', by switching inverters in successively, adding more members to the team as load increases. Team mode is a good way to reduce inverter wear, and to maximize the conversion efficiency of the system, since inverter efficiency curves typically are more favourable under higher loading conditions.

5.3.6.8 Grid forming master transition

When the grid-forming energy source is changed, for example to the genset or to grid, then it is important to make the transition with as little impact upon mini-grid as possible. In order to transition from grid-forming inverter to genset, the inverter shall change voltage and phase to match the new master, and then close a transfer switch to connect the new master to the microgrid. In order to transition from genset back to the grid forming inverters, the process is the same, with the inverter matching the phase and voltage of the master and then transitioning, except in the event of an unexpected shutdown, in which case the battery inverters need to black start the system.

5.4 Multi-master inverter dominated mini-grid

5.4.1 General

In this situation, a mixture of rotating machine generation sets, renewable energy inverters and battery inverters feed into a mini-grid, but all are capable of contributing to the creation of the grid, i.e. various technologies act together as the grid formers. This solution is particularly applicable to decentralized solutions, with various energy generation technologies spread throughout a comparatively large site. See Figure 3.

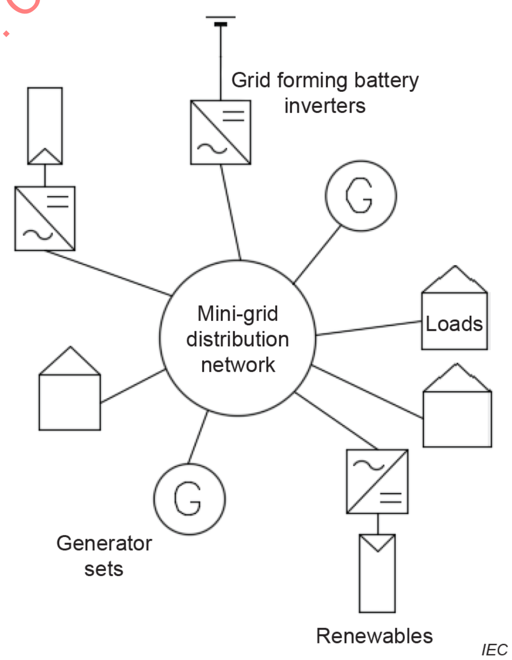

Figure 3 – Multi-master inverter dominated mini-grid architecture