Microgrid architectures for low voltage distributed generation

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Abstract
The high penetration of distributed generators, most of them based on renewable energy sources, is modifying the traditional structure of the electric distribution grid. If the power of distributed generators is high enough to feed the loads of a certain area, this area could be disconnected from the main grid and operate in islanded mode.

Microgrids are composed by distributed generators, energy storage devices, intelligent circuit breakers and local loads. In this paper, a review of the main microgrid architectures proposed in the literature has been carried out. The microgrid architectures are first classified regarding their AC or DC distribution buses. Besides, more complex microgrid architectures are shown. Both advantages and disadvantages of each one of the microgrid families are discussed.

Keywords
Microgrids, smart-grids, distributed generation, architectures, ac-bus, dc-bus

1. Introduction

The traditional power distribution structure (centralized generation) is formed by high-power generators (nuclear power plants, coal power plants, etc.), normally far from the consumers (cities, industries, etc.) [1]. The high penetration of distributed generators, most of them based on renewable energy sources, is modifying the traditional structure of the power distribution, leading to a more distributed generation scenario [1;2]. In a microgrid the generators are generally closer to the loads, so that a group of local loads and generators can be disconnected from the grid, operating in islanded mode [3, 4]. Energy storage devices improve the reliability of the overall system, supporting the distributed generators power capability in the cases when they can't supply the full power required by the consumers. Thus, a microgrid is a cluster formed by local loads, distributed generators and energy storage devices, with the ability to operate connected to the grid or in islanded mode [5-8] (Figure 1).

A microgrid reduces the power losses in the electric distribution network, improves the power capacity of the grid, provides local voltage and frequency regulation support, improves the reliability and reduces the CO_2 emissions [9;10]. Moreover, microgrids reduce the high investment costs required for network upgrades [6]. Therefore, it is an interesting option to increase the performance and the penetration of distributed generators. Many research projects about microgrids have been started around the world in recent years [11-13], and it is expected that microgrids for low voltage distribution networks will increase significantly in the future [new14].

The selection of the proper microgrid architecture is a critical issue that must be done carefully, since it can seriously affect the economic viability of the project. It is necessary to consider the nature of the loads, the existing and planned distributed generators, the space to place the energy storage devices, the difficulty to place new electrical lines and the existing communications, among other relevant issues [15]. Thus, for designers it is very important to have a good knowledge about the strong and the weak points of the different topologies and architectures of microgrids. For example, in the common case of existing facilities with AC loads, the most suitable option is probably an AC-microgrid, because it needs minimal modifications on the existing installations. However, for new installations other alternatives with a better performance can be considered.

This paper deals with the most common architectures of microgrids which have been shown in the recent literature. Some of those microgrids are working in commercial facilities, others in research projects. The microgrid architectures are based on either AC or DC buses, or on a combination of both, seeking the highest reliability and efficiency of the microgrid. The paper is organized as follows: in section 2 the main elements of a microgrid are described and the different alternatives are discussed, outlining their advantages and disadvantages; in section 3 the most usual microgrid architectures are presented, explaining their pros and cons, as well as the optimal application for each one of them; section 4 contains a comparative study among all the aforesaid architectures; section 5 shows some practical microgrid examples; finally, section 6 presents the main conclusions of the study.

2. Description of the typical elements of a microgrid

A microgrid is composed by the following elements: distributed generators, energy storage devices, local loads and intelligent circuit breakers. It is a part of an electric power distribution system that can be disconnected from the main grid and operate in islanded mode. The microgrid is connected to the main grid in the so called Point of Common-Coupling (PCC). Table 1 shows and describes the symbols that are used in the figures along this paper.

2.1. Distributed generators

The Institute of Electrical and Electronics Engineers (IEEE) defines distributed generation as follows: ―The generation of electricity by facilities sufficiently smaller than central generating plants as to allow interconnection at nearly any point in a power system" [16]. It is wide accepted that the power of a generator must be smaller than a few megawatts (10-50MW) to be considered as a distributed one [16;17].

The most common distributed generators are low power units (<200kW) with power electronic interfaces [14;18]. The performance of these generators must include low-noise and low-emissions characteristics, since it will be near the consumption points (residential areas, industries, etc.). Besides, it is desired that the distributed generators provide a high reliability with a low cost. Some examples of distributed generators for microgrids are: micro turbines (25-100kW), wind generators, photovoltaic generators and fuel cells. Moreover, it is important to note that the emerging Combined Heat and Power (CHP) technologies present some interesting characteristics to be used as potential microgrid generators [6;19-22]. In addition, diesel or gas generators can provide an emergency support to the microgrid improving the system reliability [23; 24].

The selection of the distributed generators for a microgrid is a complex issue. The characteristics and cost of the different technologies, and also the official grants to some renewable resources, are key factors that must be taken into consideration. In Table 2 it is shown a comparison of the cost of different generators used in microgrids, considering not only their installation, but also other issues like the operation costs and maintenance needs [25].

2.2. Energy storage devices

In a microgrid some of the generators can be based on renewable energy sources; thus, the amount of the generated power cannot be accurately controlled since it depends on uncontrollable factors like the weather (wind and sun) conditions [14;26; 27]. Energy storage devices can improve the reliability and efficiency of those generators by storing or by providing the power imbalance between the loads demand and the renewable power sources capability. In addition, it provides the energy requirements for seamless transition between grid-connected and islanded operation modes. Moreover, the energy storage devices can provide the transient differences between the source and the load power, produced by loads connection or disconnection, due to the poor dynamic response of some generators [18;28-30]. Some examples of energy storage devices are: batteries, ultracapacitors, flywheels or superconducting magnetic energy storage (SMES) [31].

Normally, the size and weight of the batteries of a microgrid are not a major issue, but it is important to provide a long storage time and a high current peak, mainly in the discharge process. Lithium-ion (Li-ion) batteries, being the preferred option in electrical vehicles, with power densities of 150-200Wh/Kg, are not the optimal choice for a microgrid because of their high cost (500-1500$/kWh). The decay of the energy stored in the lead-acid batteries is around 0.1% per hour, suitable for long-time storage; their power density varies between 30 and 40 Wh/Kg, ranging their cost between 100 to 200 $/kWh. The typical charge-discharge cycle has an efficiency of 80% and provides a service life of 1000 complete charge-discharge cycles (similar to Li-ion batteries). Thus, the lead-acid batteries are the preferred option in microgrids [32,33].

Ultracapacitors are ideally suited for the charge and discharge of large amounts of power in short periods of time (some kilowatts for a few seconds) with a large number of load-discharge cycles [34]. Flywheels are a common option to store the eventual excess of energy produced by renewable energy sources and to reuse it when the available power is low. The energy discharge time of commercial flywheel units ranges between 15 minutes and a few hours [32]. SMES can quickly provide active and reactive power to the microgrid, so that they can be used to give response to the fast transients of the microgrid. However, the energy cannot be stored for long periods of time [35].

The chosen energy storage system depends on the requirements about storage capacity, efficiency and storage time. Batteries provide the largest storage time and capacity, but with the lower efficiency and a limited capability to supply power peaks. The SMES provide a very high efficiency (> 95%) but the shortest storage time and capacity [31;36]. Ultracapacitors and flywheels can be classified between batteries and SMES. In a microgrid it is typical the use of a combination of different energy storage devices to achieve a good tradeoff among their characteristics.

2.3. Local loads

In microgrids it is possible to connect or disconnect the local loads depending of the maximum power available in both the generators and the storage devices. Thus, loads can be classified into two main groups: critical and non-critical loads [37]. Critical loads require the highest power quality and reliability, while the non-critical loads require a lower service quality. Commercial and industrial customers are usually considered as critical loads; most of residential customers can be considered as non-critical loads. The non-critical loads should be disconnected if the generated power is below the demanded value to guarantee the power supplied to the critical consumers [6;38]. Besides, the economical operating costs of the microgrid should be optimized by a suitable load management [39].

2.4. Intelligent circuit breakers

Intelligent circuit breakers are used to manage the interconnection of the distributed generators, the local loads and the grid [40]. The main circuit breaker, called Static Switch, is placed at the point of common-coupling (PCC) of the microgrid and manages the grid-connected operating mode, the islanded mode and the transition between both operating modes [41-43]. Furthermore, it is possible to use additional circuit breakers to manage the interconnection of some feeders or loads [44] like, for instance, the non-critical loads interconnection.

The typical power semiconductor used for the implementation of a static switch is a triac, like that shown in Figure 2, but some other circuits have been proposed in the literature [41;43;45]. The triac is the preferred option because it supports large overcurrents, even kilo-amps during some grid cycles [46].

3. Microgrid architectures

Microgrids can be classified into six main groups, depending on the way in which the AC and DC buses are connected. The proposed classification is as follows: AC-microgrid, DC-microgrid, hybrid AC-DC microgrid, AC-microgrid with DC-storage, DC-zonal microgrid and Solid State Transformer (SST) based microgrid. In the following, these architectures will be explained and discussed.

3.1. AC microgrid

An example of the AC microgrid architecture is shown in Figure 3. This kind is commonly known as the Consortium for Electric Reliability Technology Solutions (CERTS) architecture [14;47-50]. The AC microgrid presents one or more AC buses and any device must be connected to the microgrid by means of an AC interface, so that most of distributed generators require DC/AC power electronic interfaces [50;51]. The microgrid is connected to the grid at the Point of Common Coupling (PCC). Therefore, the whole microgrid can be a feeder from the distribution grid point of view.

The microgrid shown in Figure 3 is composed by three AC feeders; feeders 1 and 2 contain the distributed generators and the critical loads, whereas the non-critical loads are connected to the feeder 3. Each feeder contains loads, distributed generators and energy storage devices. The circuit breakers reconfigure the microgrid to adapt the generation and consumptions to any operating conditions. The static switch manages the connection of the microgrid to the distribution grid. If the quality of the electrical distribution grid is poor, then the static switch can be disconnected from the microgrid, leaving the microgrid in islanded operation mode. In [46] the limits for intentional islanding of the microgrid are defined for overvoltage (+10%), undervoltage (-20%), overfrequency (+0.5Hz), underfrequency (-0.5Hz) and overcurrent (+30%). During a grid fault, the non-critical loads are disconnected from the grid, avoiding their damage or malfunction; the static switch is opened and the critical loads are fed from both the distributed generators and the energy stored in batteries and capacitors [52].

A hierarchical control structure for microgrids has been proposed in the literature [53;54]. Four control levels are proposed: tertiary control level manages the power flows of the microgrid; the secondary control level keeps the electrical levels in the microgrid and primary control level is used to make the system stable, using fast and safe control algorithms. Besides, a level zero is defined, formed by the inner voltage and current control loops.

The most commonly used primary-level [55] control method for electronic converters feeding an AC microgrid is the droop-control algorithm [12;44;54;56-58]. This control method provides a load sharing strategy without the use of any critical communication link. Besides, it is necessary a high-level energy management control method, which takes the role of supervisor of the microgrid. There is a wide variety of energy management control methods provided in the literature [44;58-65]. The droop method deteriorates the regulation of the microgrid voltage and frequency. In [46] a maximum frequency droop of 1% at full power and a maximum voltage droop of 5% are proposed.

In the AC microgrid architecture operated in grid-connected mode, the power flows directly from the grid, avoiding any series-connected converter; this feature provides a high reliability. The feeders have the same voltage and frequency conditions as the grid, so that the loads, generators and energy storage devices must be grid-compliant. Those elements working at the grid voltage and frequency use a very mature technology, being thus highly reliable. It is worth pointing out that the existing electrical grids can be easily reconfigured to an AC microgrid scheme. The main drawback of this architecture is the large amount of complex power electronics interfaces required (inverters and back-to-back converters), so that the efficiency and reliability of the overall microgrid can be reduced. Complex electronic power converters present lower reliability than those with less components. In [66] it was studied the Mean Time Between Failures (MTBF) of different power converter topologies, having shown the MTBF value for capacitors, semiconductors and magnetic components. In general, the MTBF decreases as the complexity and the number of components of a microgrid increases. For instance, if the number of electrolytic capacitors of a power converter increases from 1 to 4 the MTBF is reduced to a third.

The AC microgrid is especially suitable for the integration of the microgrid concept into the existing facilities and, probably, will be the most common microgrid architecture in the near future.

3.2. DC microgrid

A sample of the DC microgrid architecture [67-69] is shown in Figure 4. The DC microgrid is connected through an AC/DC converter to the grid; if it is desired that the microgrid exports the excess in the generated power, this power electronic interface must be bi-directional. The DC microgrid presents a DC-bus with a regulated voltage; most distributed generators need a DC/DC or AC/DC power electronic interfaces to be connected to the bus. The AC loads require a DC/AC converter to adapt the bus voltage to the required conditions. DC loads sometimes can be connected directly to the DC bus or may need a DC/DC converter, depending on the bus voltage. To provide fast and stable load steps, some capacitors may be added to the bus without any electronic interface. Since the voltage of the DC bus is regulated by the main AC/DC converter, the DC bus voltage presents a very high quality, even under low quality distribution grids [70].

When the distribution grid fails, the microgrid must regulate itself the DC bus voltage, without the main AD/DC converter. Some control methods for this task has been developed and proposed in the literature [71-73]. Moreover, the power flow control from distributed generators and energy storage devices must take into account the available stored energy to obtain a better reliability [74].

Different types of DC microgrids have been presented in the literature [12], i.e. the monopolar, the bipolar and the homopolar type. Their architectures are similar to that shown in Figure 4, and the classification is based in the structure of the DC bus.

The DC microgrid architecture presents some advantages over the AC microgrid: a reduced number of (and simpler) power converters (DC/DC and rectifiers), the possibility to adapt the DC bus voltage to the microgrid requirements and a very high quality of the DC bus voltage, so that some DC loads can be connected directly to the DC bus. The main drawback of this architecture is the series-connected bidirectional AC/DC handling the whole power flow from/to the distribution grid, since it reduces the reliability. The MTBF parameter of a single stage inverter (full bridge) is around a 40% higher than that a double-stage one [75]. Besides, it requires a specific installation, being impossible to use the existing AC cabling and devices. Another disadvantage of the DC architecture is that AC loads can't be directly connected to the microgrid and the voltage of DC loads is not standardized. Thus, additional power stages would be needed to eventually adapt the DC bus level or to generate AC voltages.

3.3. Hybrid AC-DC microgrid

The AC-DC hybrid microgrid architecture consists in an AC microgrid with a DC sub-grid, tied together by a bidirectional AC/DC converter (Figure 5) [76-78]. Distributed generators can be connected to the AC or to the DC feeders. AC loads are connected to the AC feeder, whereas DC loads are connected to the DC feeder, using a power converter to adapt the voltage level if it is necessary. The DC sub-grid can act as a generator or a load of the AC microgrid, depending on the power balance at the DC feeder.

This architecture combines the advantages of AC and DC microgrids. There is a direct connection to the grid, thus presenting a high reliability; the AC feeder allows using the existing equipment; the DC feeder allows the use of a reduced number of simpler converters. Moreover, some DC loads can be connected directly to the DC feeder, without the need of any power converter. This microgrid architecture is suitable for installations with critical loads (at the DC feeder) in combination with more robust loads (at the AC feeder).

3.4. AC microgrid with DC storage

To improve the flexibility of the AC microgrid it is possible to place the energy storage devices at a separate DC bus [79], while the distributed generators and the AC loads are placed at a conventional AC bus. The interconnection with the grid is done by means of a static switch, which manages the transition from islanded to grid-connected operating modes and vice versa. This architecture is called AC microgrid with DC storage [6]. An example of this configuration is shown in Figure 6. Generators and loads can be grouped at a single feeder or distributed at different ones. The energy storage devices are placed in a separate DC bus and an AC/DC bidirectional power electronic interface is used to connect each energy storage device [79].

Since it is easier and more robust to connect in parallel several energy storage devices to a DC bus, this architecture groups this devices all together and, consequently, the microgrid sees a global and single energy storage system. The performance of this microgrid architecture is similar to the hybrid AC-DC one, with an easier management of the energy storage. However, the energy storage must be centralized at any physical point of the microgrid, so that this microgrid architecture can be useful in facilities with a centralized storage of energy, i.e. a residential area with communitarian energy services.

3.5. DC-zonal microgrid

In the DC-zonal microgrid several DC feeders are connected to the main AC bus through centralized bidirectional AC/DC converters [67;80]. A block diagram of this architecture is shown in Figure 7. Distributed generators and loads are connected to the DC feeders with the suitable power electronic interface. In this architecture the DC feeders can provide different voltage levels, improving the performance of the microgrid.

This architecture provides the same advantages and disadvantages as the DC microgrid, but the DC-zonal microgrid allows different DC bus voltages and management techniques at each feeder. The main drawback of this architecture is the increased complexity because of the interconnection between feeders. This microgrid can be suitable for facilities where the highest voltage quality and reliability is required.

3.6. Solid State Transformer based microgrid

In this kind of architecture the grid frequency transformer is replaced by a solid state transformer (SST). The SST can use a high frequency transformer, reducing both the size and weight with regard to grid frequency transformers, and provides AC and DC feeders to the microgrid. Also, the SST manages the power flow between the feeders and the grid [81]. AC loads are connected directly to the AC feeder, and DC loads are connected to the DC feeder [67;82]. It is preferred that distributed generators become connected to the DC feeder, since the electronic interfaces and the control algorithm are more simple and robust. A scheme of this architecture is shown in Figure 8.

The SST is a single-input dual-output power converter [67;81;82] with a structure shown in Figure 9. The first stage is an AC/DC converter, which provides a constant voltage and manages the current flow with the grid; next, a DC/DC converter adapts the voltage level to the required by the DC loads; the last stage is a DC/AC converter that generates the high quality voltage of the microgrid AC feeder.

The SST based microgrid architecture has the following advantages: very high quality energy, simple electronic interfaces, simple connection of DC loads, compatibility with AC grid loads and robust management of energy storage devices. Its main disadvantage is the solid state transformer, since it is a series-connected power converter, which reduces the reliability and efficiency of the system. That efficiency reduction may be compensated by the small number of power converters connected to the feeders.

4. Microgrid architectures at a glance

In order to get a better performance understanding of the architectures presented in this paper, it is interesting to compare them by using the following criteria:

- Series connected power converters: a series connected power interface provides a high quality in the voltage of the microgrid and easy management of the power flow, but degrades its reliability, since the probability of failure is increased. A failure of this device affects the whole microgrid.

- Grid-compliant devices: A grid-compliant device is designed to run under the usual working conditions of the grid, i.e. with voltage and frequency drifts, voltage distortion, voltage sags, flicker and voltage disruption.

- Possibility of reconfiguration of existing facilities: the wires, protection and switching devices in AC and DC microgrids have different characteristics. In an AC microgrid the existing devices in a traditional facility can be reused and minimal modifications need to be done, consequently, the reconfiguration to a microgrid is simple.

- Required number of power electronic interfaces: it is very common to need a power electronic converter to connect any device to a microgrid, adapting the voltage level and frequency between the device and the microgrid. In AC feeders the most common power interfaces are the DC/AC (inverters) to connect the distributed generators. AC/DC (rectifier) interfaces are needed to feed the DC loads, whereas bidirectional AC/DC converters are used for interfacing the energy storage devices. In DC feeders the most common power interfaces are the DC/DC converters to connect the distributed generators, energy storage devices and some DC loads. Some DC/AC converters are needed to connect AC loads. The lower the required number of power electronic interfaces, the higher the reliability and the efficiency of the microgrid.

- The reliability of a power electronic converter improves as its complexity is reduced. Therefore, the simplest power electronic interfaces provide the highest reliability, being preferred to be integrated in a microgrid.

- Quality of the energy in the microgrid: voltage and frequency deviations, voltage distortion, voltage sags, flicker and voltage disruptions can degrade the quality of the energy supplied to the consumers in a microgrid. When a microgrid is connected directly (through a static switch) to the grid, the energy quality is that of the distribution grid. If the loads require a higher power quality, it is possible to use a power electronic converter to generate the AC voltage of the microgrid, thus accurately controlling the quality of the energy.

- Easy management of the energy storage: the energy storage devices in a microgrid must be managed accordingly to a certain strategy, e.g. seeking to keep the same charge level in all the battery banks on stream. The complexity of the energy management depends on the type of power electronic interface and on the required communication links. When all devices are placed close to each other and the interfaces are DC/DC converters, the management is easier than when DC/AC interfaces are needed or when large distance communications are required.

In Table 3 it is shown a comparative analysis between the proposed architectures by using the previously defined criteria.

5. A few experimental microgrids

Some microgrids are being used in experimental facilities, providing performance data under real working conditions. An extensive review of existing microgrids can be found in [6], which is focused on the physical system and the microgrid control structure. Some of them are briefly described in the following. References for additional information have been included.

The AC microgrid architecture is the most commonly found in the experimental facilities, but some other like the AC microgrid with DC storage or the Solid State transformer based microgrid can be found. The other architectures are rarely used today, since they require deeper modifications in the facilities and the existing equipment, but it is expected than in the future they become the usual ones.

The CERTS project (USA) [25;47;49] is one of the most complete experimental projects. This microgrid is based in the AC microgrid architecture. Different types of distributed generators are connected and tested, providing both heat and power to the microgrid. Several experiments combine different generators and loads. The data obtained from those experiments is published online in the web of the CERTS consortium [83].

The BC Hydro Boston Bar (Canada) [6] uses the AC microgrid architecture without storage units, connected to the grid through a 69/25kV substation. A pair of hydro power generators feed the loads during the grid outages, during periods between 12 and 20 hours. The peak power capacity of this microgrid is 3 MW. During an islanding event the loads are connected or disconnected depending on the water level.

The UW microgrid test bed (USA) [6;84] is an AC microgrid that was implemented to research about control issues of the microgrids, specially with the integration of diesel generators in AC microgrids. The frequency droop programmed in this microgrid is around 3Hz. In islanded mode the behavior is stable, but in grid-connected mode some problems with the reactive power flow have been reported.

The Bronsbergen Holiday Park microgrid (Netherland) [85] is an AC microgrid consisting in 208 holiday homes. The generators are 108 roof fitted photovoltaic modules, with a peak capacity of 315 kW, connected to the grid at 10 kV. The microgrid is equipped with a centralized energy storage based on two battery banks.

The residential microgrid of Am Steinweg Stutensee (Germany) [86] was built for testing purposes, feeding 101 apartments with a peak power of 150 kW. The architecture is a four-wire three-phase AC microgrid, connected to the 20 kV grid. There are placed different kinds of generators: Combined Heat and Power (CHP) (28 kW of electric power), several photovoltaic facilities (35 kW peak) and a lead-acid battery bank of 880 Ah (100 kW peak).

The microgrid system at the National Technical University of Athens (Greece) [6] is based in the AC architecture connected to a low-voltage grid. A pair of photovoltaic generators (Total power 1.2 kW) and a wind turbine (1 kW) power the microgrid. The energy storage is formed by a battery bank of 4.5 kW peak, and some controllable loads are used to test the behavior of this architecture.

The Hachinohe project (Japan) [88] is connected in a private distribution line. The system is composed by a gas engine system (510 kW), PV systems (total power 130 kW) and small wind generators (20 kW). Four schools and other installations are connected to the distribution line. It is an AC microgrid with a single feeder connected to the grid through a by-pass switch.

Kythons Island microgrid (Greece) [87] delivers power to 12 houses. The generators are a photovoltaic plant of 10 kW and a 5 kW diesel generator. The energy storage is formed by a 53 kWh battery bank. In this island there is no grid connection, so the microgrid works all the time in islanded mode. The architecture of this microgrid is the AC microgrid with DC storage.

In the University of Manchester (UK) [6] is installed the 20 kVA microgrid/flywheel energy storage laboratory prototype [6]. This microgrid is based in the AC microgrid with DC storage architecture. The generator is a synchronous machine moved by an induction motor. The storage is a 20 kW flywheel connected to the main feeder by means of an inverter. The microgrid is connected to the low voltage grid by means of a by-pass switch.

The CEI RICERCA DER test microgrid (Italy) [87] is a research project of 800 kVA, based on a Solid State Transformer architecture, with different types of generators (photovoltaic, solar thermal, CHP, different battery technologies, flywheels…) connected to the grid by means of a Solid-State Transformer without DC bus, thus, all the agents of the microgrid are connected to the same feeder, which is linked to the 23 kV grid by means of an AC/AC converter and a transformer.

6. Conclusions

In this paper a review of microgrid architectures has been presented. The architectures under consideration are the AC-microgrid, DC-microgrid, Hybrid AC-DC microgrid, AC-microgrid with DC storage, DC-zonal microgrid and solid state transformer based microgrid.

The AC topologies connected to the grid through a static switch (AC-microgrid and AC-microgrid with DC storage) are the most reliable ones, since in the grid-connected mode the consumers are connected directly to the electric grid. Moreover, the existing AC facilities can be easily reconfigured to implement these microgrid architectures only with a few modifications of their components, being it possible to reuse the existing AC loads.

The reliability is also affected by the number of power electronic interfaces and their complexity. The hybrid AC-DC microgrid and the SST based microgrid present the simplest and lowest number of power electronic interfaces, since the distributed generators, energy storage devices and loads can be connected to the AC or DC feeders, depending on their characteristics and, therefore, the power electronic interface device is simple or not needed.

If a high power quality is required by the microgrid loads, the voltage of the microgrid must be generated by power electronic converters. From this point of view, the preferred microgrid architectures could be AC (SST based microgrid) or DC (DC-microgrid, DC-zonal microgrid). In these architectures a power electronic converter connects the grid to the microgrid, minimizing the effect of the grid disturbances and providing the needed power quality level.

The management of the energy storage devices in a microgrid is an issue of great importance, since the charge level must be maximized and balanced between the different devices. Sometimes, the distance between the storage devices is large, becoming the communication between them a problematic issue. Moreover, in AC buses the management of the energy storage devices becomes more complicated. Thus, the DC-microgrid, DC-zonal microgrid and the SST based microgrid provide an easy management of the stored energy, whereas the AC-microgrid with DC-storage provides the simplest management, since the energy storage is grouped and connected to a DC bus.

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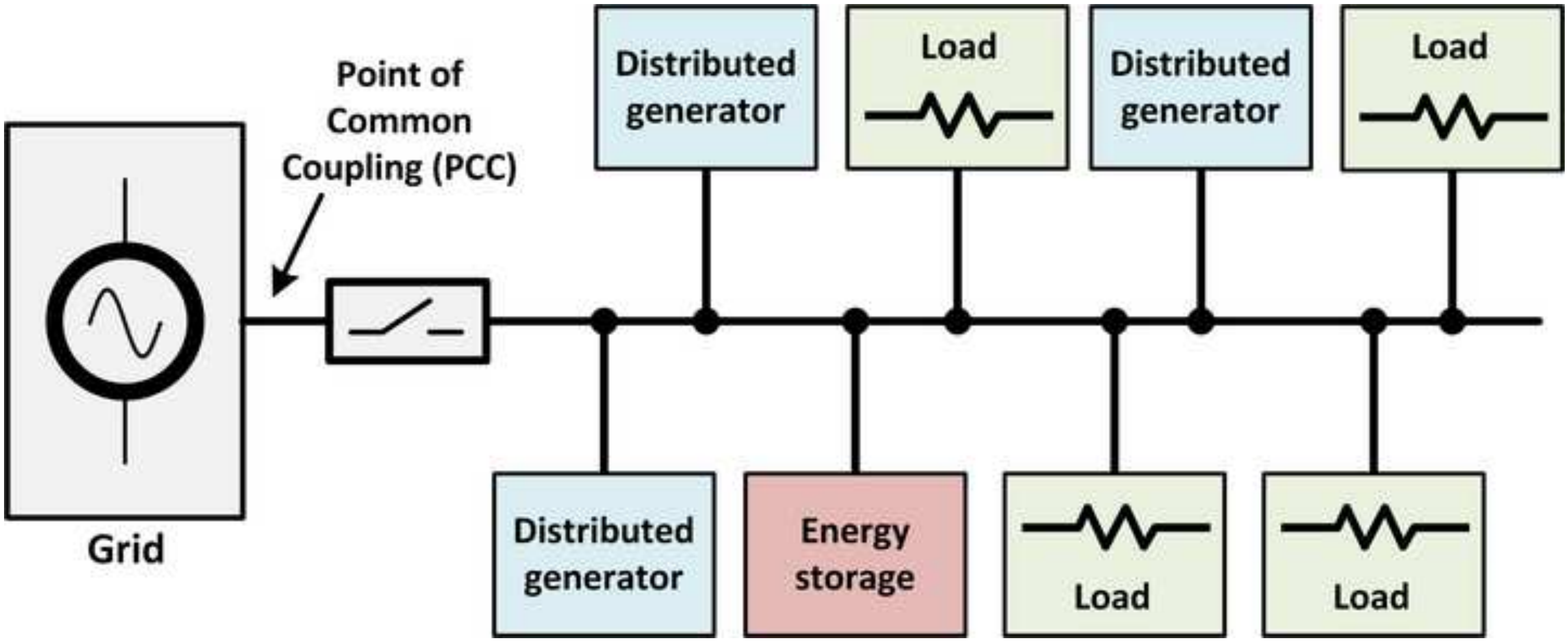

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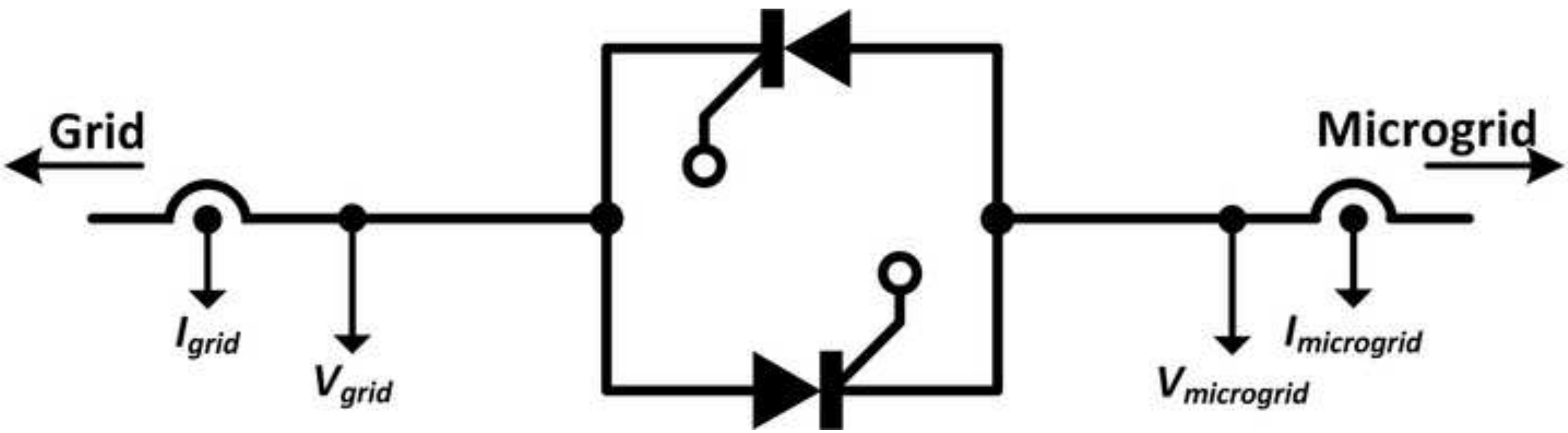

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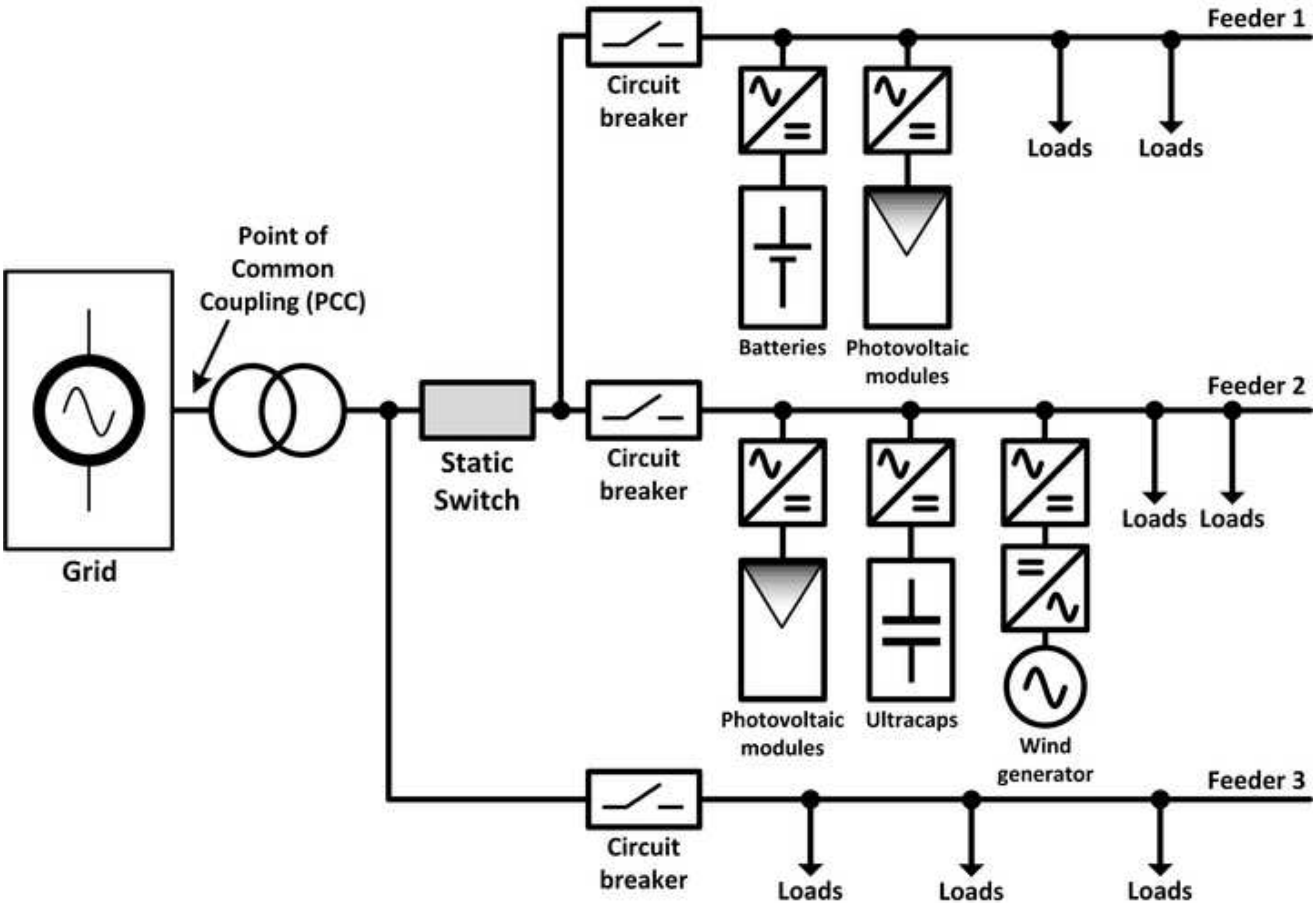

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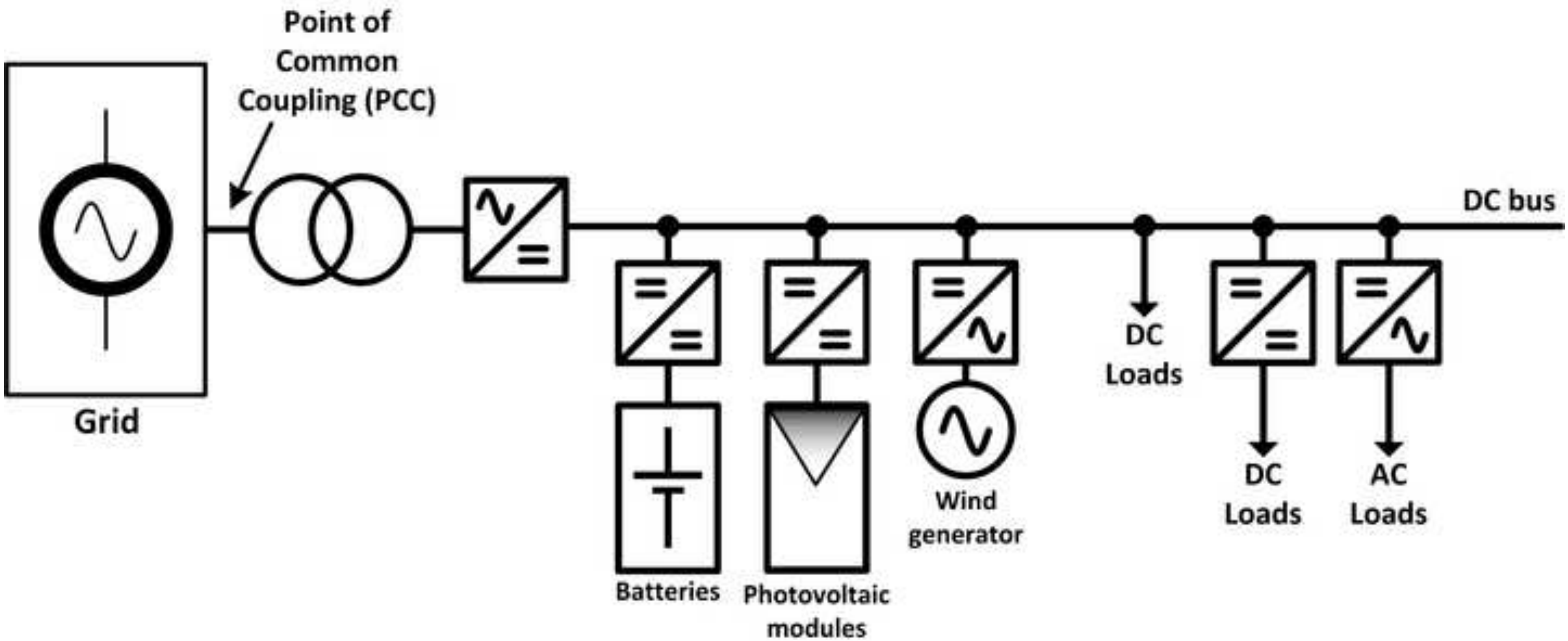

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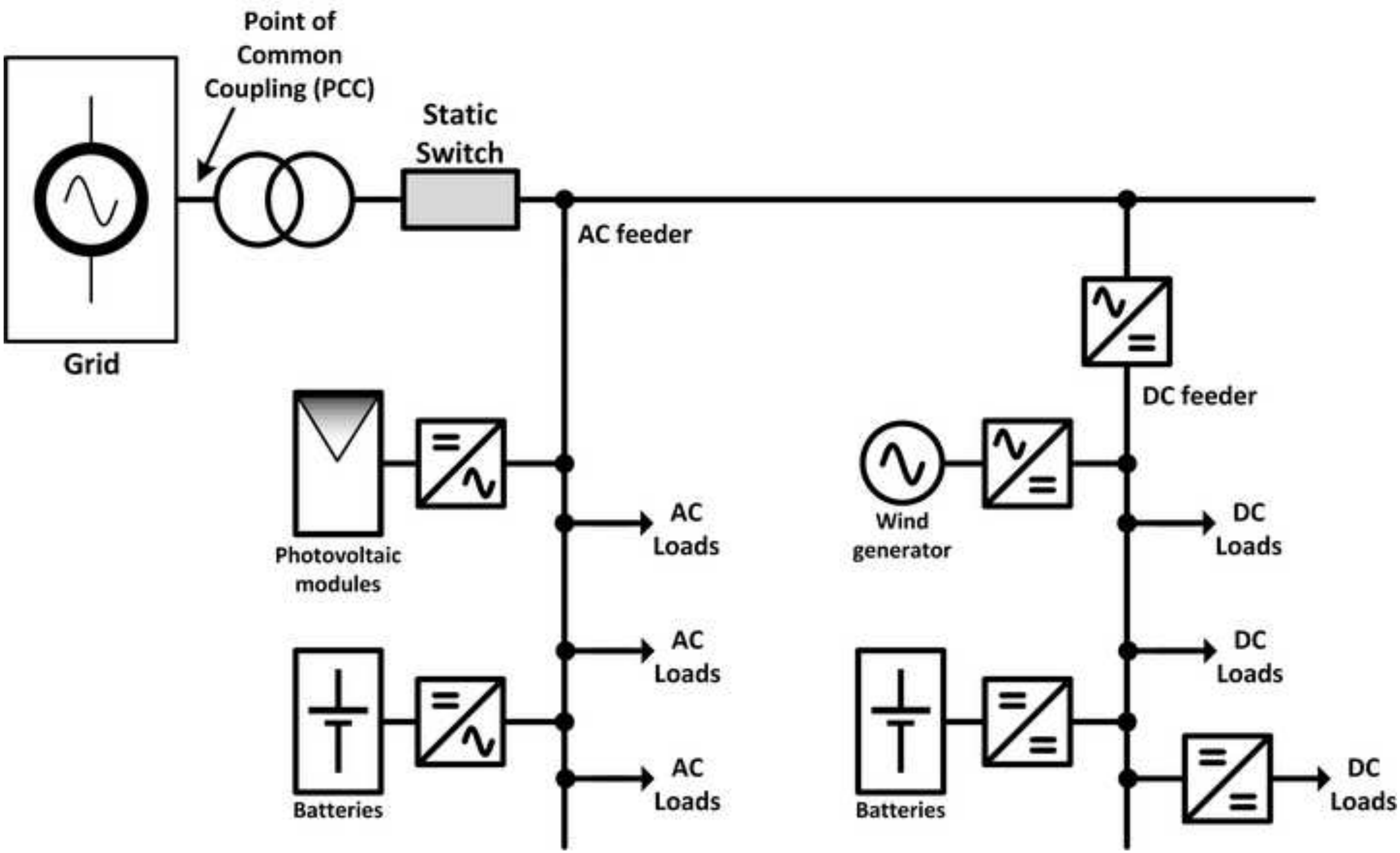

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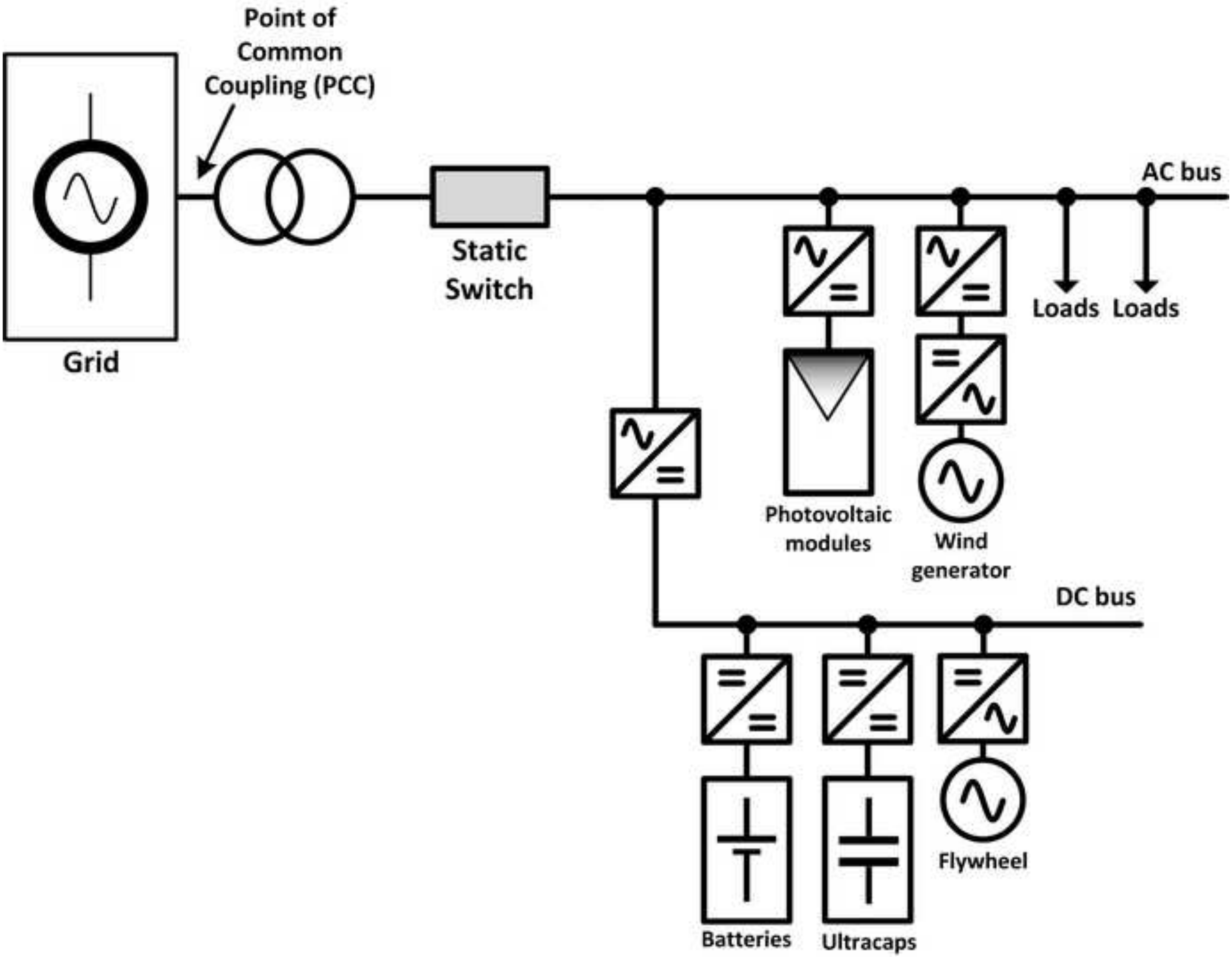

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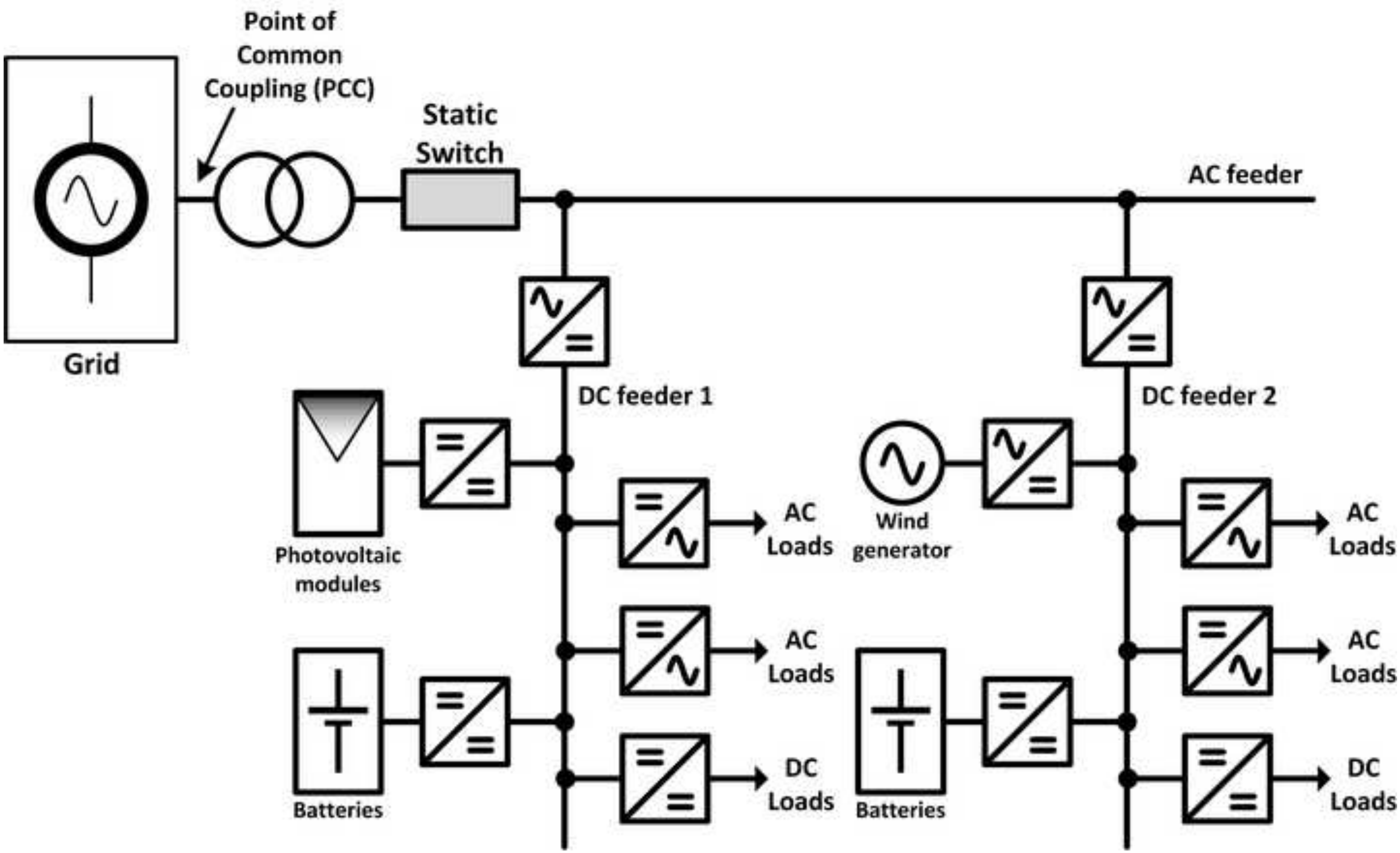

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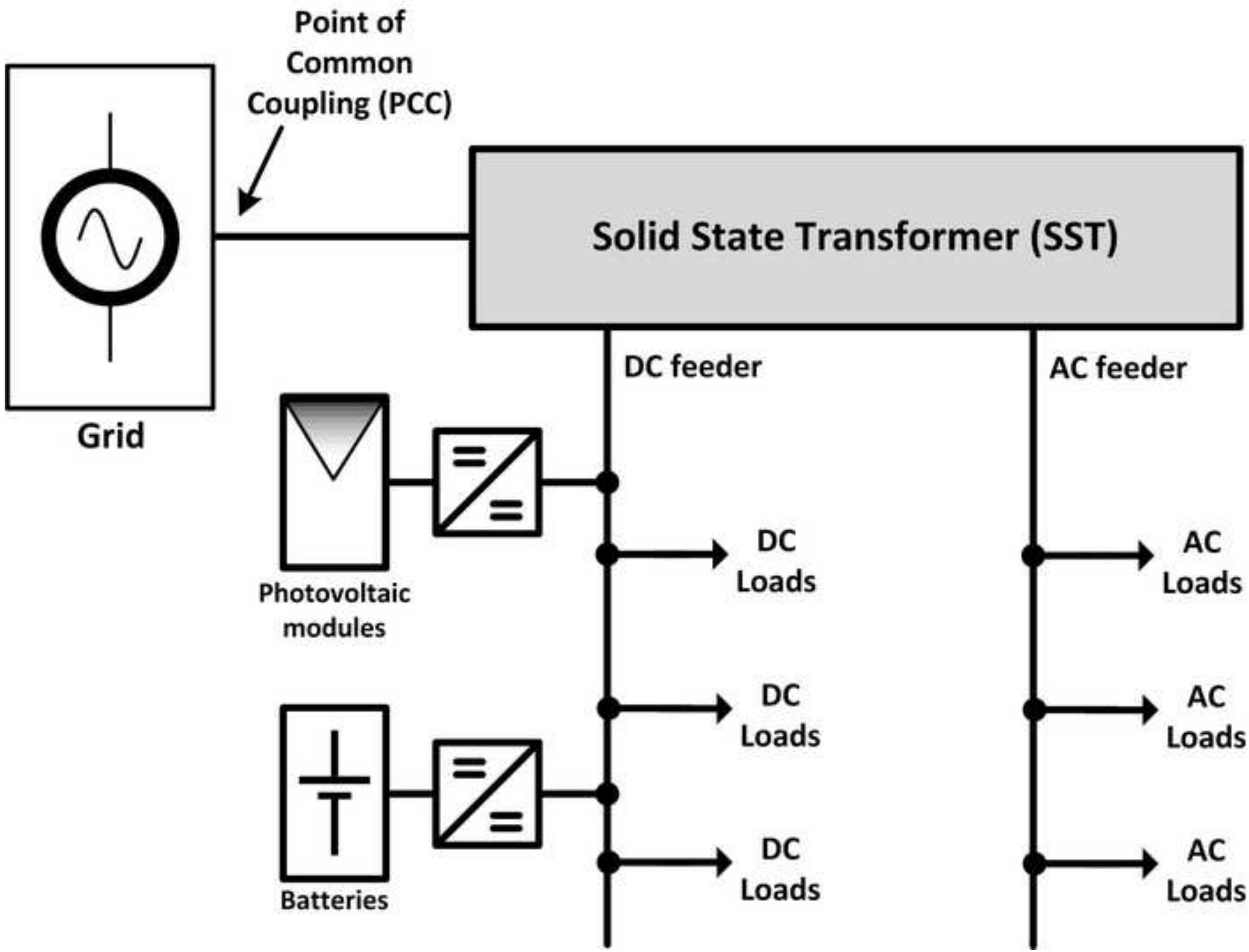

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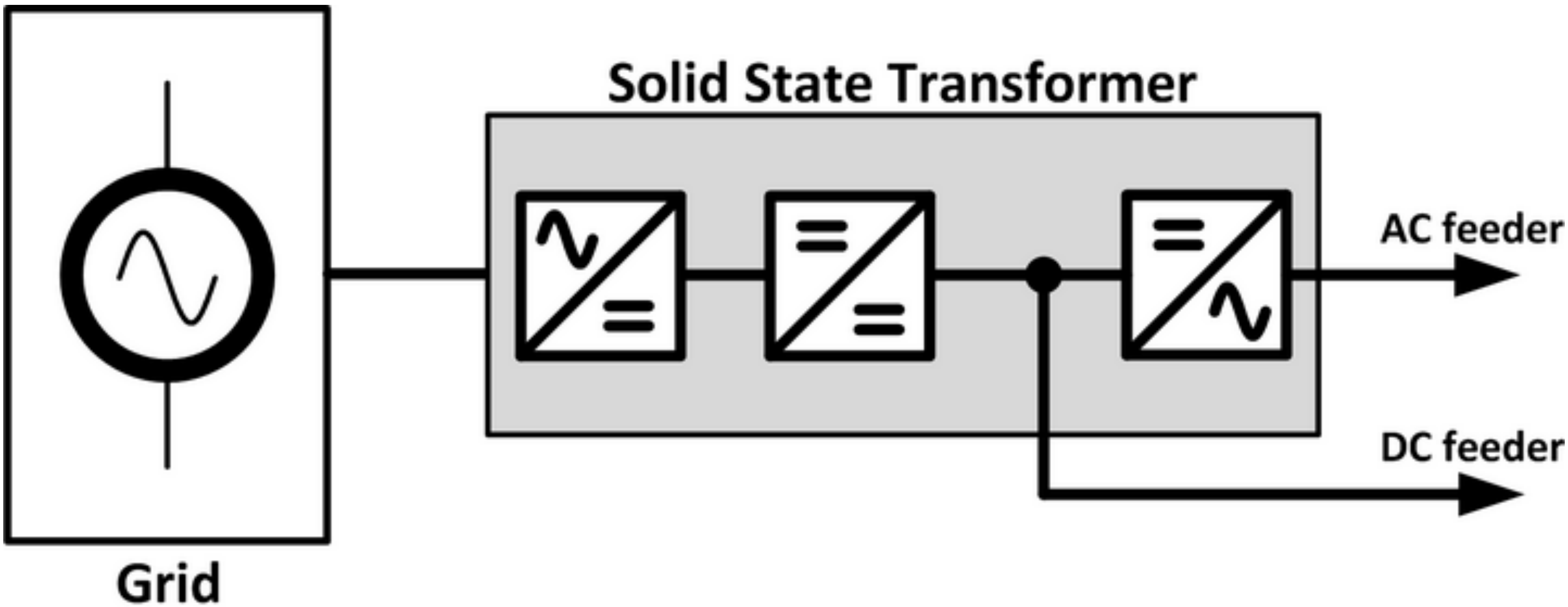


Table 1

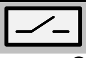
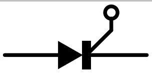
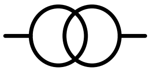
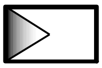
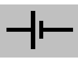
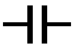
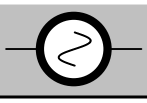
Symbol	Description
	Circuit breaker
	Thyristor
	Current sensor
	Transformer
	AC/DC converter (rectifier)
	DC/DC converter
	DC/AC converter (inverter)
	Photovoltaic module
	Batteries
	Capacitor
	Electrical grid

Table 2

	Power (kW)	Cost ($/kW)	Operation & Maintenance cost	Lifetime (years)
Diesel backup generator	5-500	700	26.5 $/kW/year + 0.000033 $/kWh	12.5
Gas backup generators	50-500	950	26.5 $/kW/year + 0.000033 $/kWh	12.5
Wind generators	10	6055	5.7 $/kW/year	12.5
Small photovoltaic generator	5	8650	14.3 $/kW/year	20
Big photovoltaic generator	50-500	6675	3.93 $/kW/year	20
Fuel cells	1-2000	5000	0.035 $/kWh	5-10

Table 3

	AC microgrid	DC microgrid	Hybrid AC-DC microgrid	AC microgrid with DC storage	DC-zonal microgrid	SST based microgrid
Series connected power converters	No	Yes	No	No	Yes	Yes
Grid-compliant devices	Yes	No	Yes	Yes	No	Yes
Possibility of reconfiguration of existing facilities	Yes	No	With a few modifications	Yes	No	With a few modifications
Required number of power electronic interfaces	High	Medium	Very low	Low	Medium	Very low
Complexity of the required power electronic interfaces	Complex	Simple	Simple	Simple	Simple	Simple
Quality of the energy in the microgrid	Low	High	Medium	Low	High	Very high
Easy management of the energy storage	No	Yes	No	Yes	Yes	Yes

Captions