Grid tied inverters for renewable energy systems – a review

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Abstract: Grid tied inverters are used to feed power produced by the renewable energy sources to the local power grid. India has a total grid interactive renewable power plant capacity of 84.39 GW, consisting of solar 31.10 GW, wind 36.93 GW, small hydro 4.61 GW and bio-power 9.94 GW. Solar and wind energy sources are most abundantly available in India and has various advantages over other energy sources but combining these two intermittent sources for the purpose of exporting the generated power through grid tied inverter has many challenging issues. In this paper, various literatures, standards and patents are reviewed to understand the function of grid tied inverters, power quality, islanding detection, overvoltage protection and safety issues. This review can help the readers in understanding the basics of the grid tied inverters and also provide information on selecting the suitable inverters for renewable energy applications.

Keywords: grid tied inverters; controllers; renewable energy; solar; wind; standards; patents; power quality.

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1 Introduction

Energy generation through renewable energy sources (RESs) gained more popularity in recent years and seems to be cost-competitive with the conventional energy generation methods. It is green energy sources and does not create any pollution to the environment. RESs are abundantly available in India and having the estimated potential of around 900 GW capacity, comprising of solar 750 GW, wind 102 GW (at 80 m mast height), bio-energy 25 GW and small hydro 20 GW (Ministry of New and Renewable Energy). India has set a goal of achieving 175 GW from renewable energy-based power plants by 2022 which includes solar 100 GW, wind 60GW, bio-power 10 GW and small hydro 5 GW (International Electrochemical Commission, IEC 61727 Standards). India has made a pledge to install 40% of power generation capacity from RESs by 2030. Figure 1 shows the details of state/UT-wise installed capacity of grid connected renewable power (Ministry of New and Renewable Energy) in India as on 30.09.2019. In X axis, state/UT is represented in numbers and in Y axis, installed renewable power plant capacity (solar, wind, bio, small hydro and total power is given in MW). Name of the state/UT w.r.t. numbers are:

1 Andhra Pradesh

2 Arunachal Pradesh

3 Assam

4 Bihar

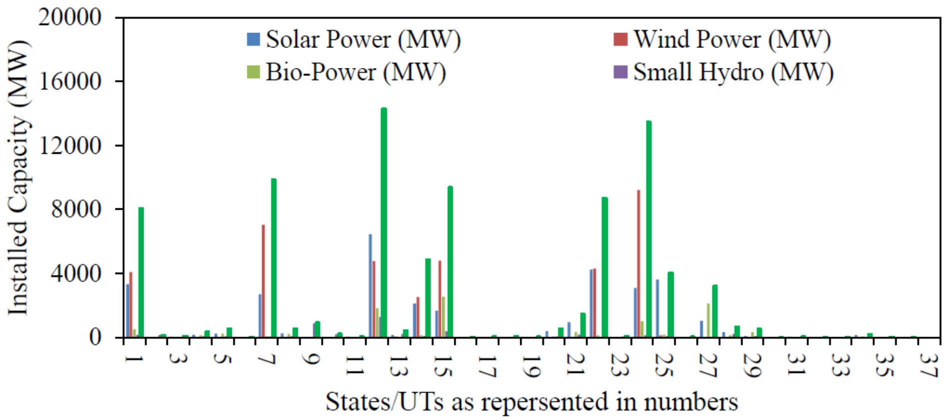
5 Chhatisgarh

6 Goa

7 Gujarat

8 Haryana
9 Himachal Pradesh
10 Jammu and Kashmir
11 Jharkhand
12 Karnataka
13 Kerala
14 Madhya Pradesh
15 Maharashtra
16 Manipur
17 Meghalaya
18 Mizoram
19 Nagaland
20 Odisha
21 Punjab
22 Rajasthan
23 Sikkim
24 Tamil Nadu
25 Telangana
26 Tripura
27 Uttar Pradesh
28 Uttarakhand
29 West Bengal
30 Andaman and Nicobar
31 Chandigarh
32 Dadar and Nagar Haveli
33 Daman and Diu
34 Delhi
35 Lakshwadeep
36 Pondicherry
37 others.

Figure 1 State/UT-wise installed capacity of grid connected renewable power in India (see online version for colours)



Most of RESs produce direct current electricity which needs to be converted into AC current and regulate the voltage levels to match with grid voltage levels. This kind of energy conversion can be obtained using an electronic inverter consisting of control and protection devices. Inverter output frequency should match with grid frequency. Main classifications of inverters are single phase inverter and three phase inverter. Single phase inverters are generally used for the load less than 10 kW and three phase inverters are used for load of 10 kW or more. A typical grid tied inverter should have insulated gate bipolar transistor (IGBT)/metal-oxide semiconductor field effect transistor (MOSFET) as switching devices; microprocessor/DSP for control. The general features of grid tied inverters are:

1 voltage (230 V for single phase and 415 V for three phase)

2 –20% and +15% for grid voltage tolerance

3 no load loss should be less than 1% of rated power

4 inverter efficiency should be more than 90%

5 total harmonic distortion (THD) should be less than 3%

6 power factor should be more than 0.9

7 output frequency should be 50 Hz

8 grid synchronisation is required when frequency deviation is observed +3 Hz or more

9 inverter should work in the temperature range –20°C to 50°C and non-condensing humidity up to 95%

10 enclosure for protection to be made as per IP-20 or IP-65.

The power factor of inverter output should be appropriate for all voltage ranges or sink of reactive power; the inverter should also have interior protection arrangement for any kind of fault arising in feeder or feeder line. Inverter should be able to operate completely automatic covering wake-up, synchronisation and shutdown.

Synchronisation is a key aspect in grid-tied systems which affect the overall performance of the renewable energy system (Mnati et al., 2018; Timbus et al., 2005; Hu and Ma, 2017). Multi-harmonic decoupling cell phase-locked loop (MHDC-PLL) is one of the fast synchronisation techniques which are used to obtain high perfection under harmonic distortions and grid disturbance scenarios. Frequency adaptive MHDC-PLL can get a fast response under high harmonic distorted grid voltages. Island discovery is another necessary function of the distributed grid-connected power systems for its safe operation (Zeng et al., 2009; Mahat et al., 2008; Zhang et al., 2007a, 2013a, 2007b; Sun and Lopes, 2004). Islanding is the condition in which a RES continues to power a location through electrical grid power is no longer present. Islanding can be very dangerous to the workers, as some circuit is still being powered, which may prevent automatic reconnection of devices. Islanding scenario should be immediately detected and disconnect from the circuit, to avoid abnormal frequencies and voltages. Islanding detection methods can be both remote and local (Li et al., 2015; Liu et al., 2010). Active detection technique like frequency shift or sliding mode frequency disturbance are introducing harmonics to the grid which affects the grid power quality, but still there will be a definite non-detection zone that needs to be addressed by suitable techniques.

With rapid increase in renewable power plants, there is an issue linked with the voltage fluctuation of the grid during power production. Voltage fluctuation can be over voltage or voltage dips due to which performance of the renewable energy system gets deteriorated (Ahmad and Loganathan, 2010). Low voltage ride through (LVRT) and high voltage ride through (HVRT) also called as fault ride through (FRT) are the crucial feature of grid tied inverter control and power converter systems (Zhou and Wang, 2002). When the voltage of the grid is dropping, renewable energy system should remain stay online in order to prevent major blackouts. LVRT is the ability of a grid tied renewable energy system to stay connected to the grid throughout a short voltage drop (a brownout) in mains or a mains failure (a blackout). HVRT enables the grid tied renewable energy systems to stay connected during temporary voltage increment scenarios. In other words, over voltage withstanding capability is known as HVRT and the capability of withstanding voltage dips is LVRT.

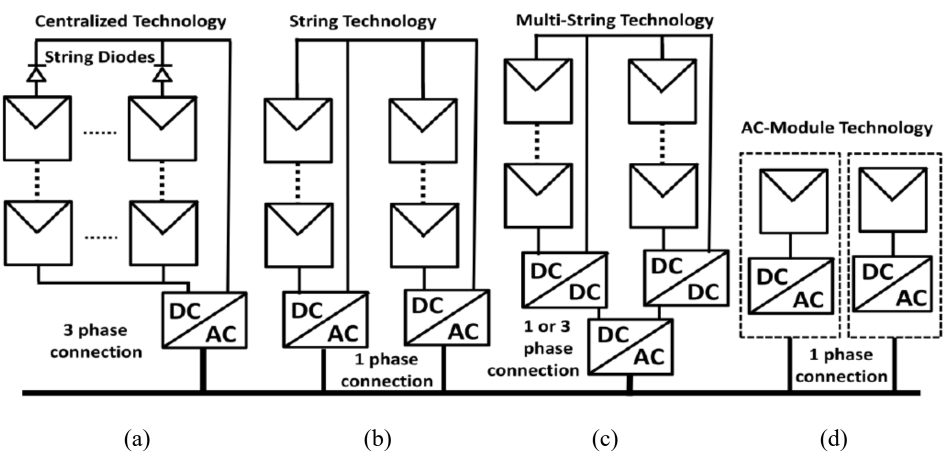
In order to address the above, in this review, various inverter technologies such as centralised, string, multi-string and AC module or microinverters, classification of inverter topologies, some standards which outlines the permissible range of various inverter parameters, some relevant patents on various controllers used in grid connected systems are discussed. This review can help the readers in understanding the basics of the grid tied inverter technologies, and also provide information on selecting the suitable inverters used in renewable energy systems.

2 Grid tied inverters – review of literature

2.1 Inverter technologies

An overview of various available inverter technologies such as centralised technology, string technology, multi-string technology, AC module technology are shown in Figure 2. In centralised inverters, the DC source modules can be connected in series (called a string), each string generates an adequate larger voltage. In order to achieve the desired power output at higher level, the string can again be connected in parallel to get higher current through string diodes. The inverter shown in Figure 2(a), is based on centralised technology which interfaces a large number of DC source modules connected in series and parallel so that to achieve the desired three phase power output supply to the grid (IEEE Standards Association, IEEE 1547).

Figure 2 Inverter technologies, (a) centralised (b) string (c) multi-string (d) AC module



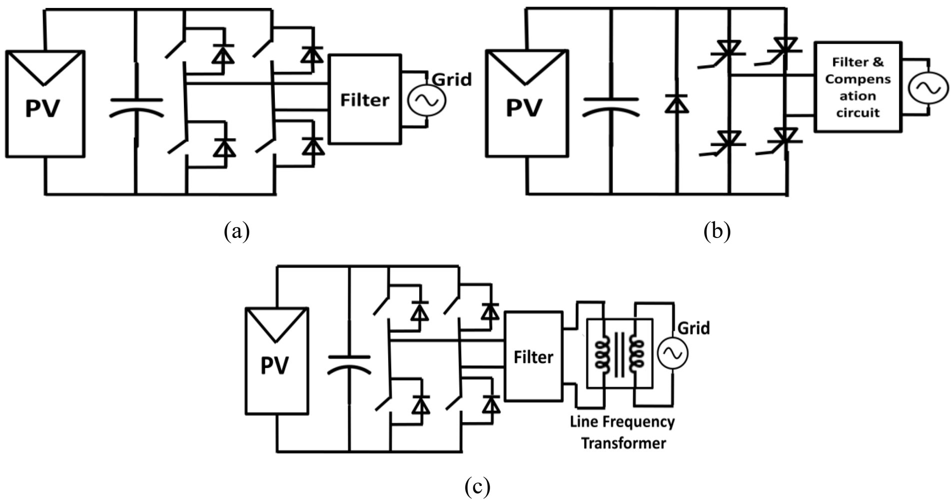
Source: Kjaer et al. (2005)

The string inverter, shown in Figure 2(b) is a smaller version of the centralised inverter where each single string of DC source modules is connected to the inverter so that to achieve the desired single phase power output supply to the grid (International Electrochemical Commission, EN 61000-3-2 Standards). The input voltage may be large enough to avoid further voltage increment. There are no losses linked with string diodes and separately maximum power point tracking (MPPT) can be applied for individual string. The multi-string inverter shown in Figure 2(c) is the further growth of the string inverter in which several strings are interfaced with their own dc-dc converter to a single dc-ac inverter (International Electrochemical Commission, EN 61000-3-2 Standards; IEEE Standards Association, IEEE 929). This kind of arrangement can be made to achieve either desired single phase or three phase power output. This is advantageous, in comparison to the centralised system, because each string can be controlled independently. The AC module as shown in Figure 2(d) is the combination of the inverter and DC source module developed for supplying power to a separate single phase electrical device (International Electrochemical Commission, EN 61000-3-2 Standards).

2.2 Central inverter technology

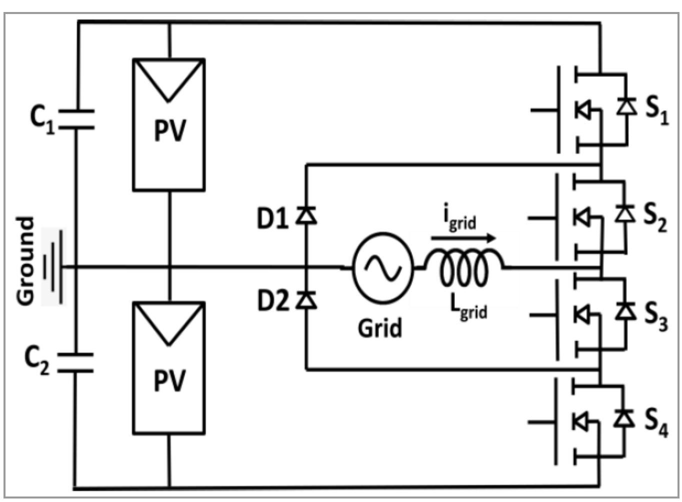
Central inverters are bulky, heavy, unreliable, uneasy to install and their efficiency are in the range of 85%–90% (Oldenkamp and de Jong, 1998). These inverters have lower power factor and higher harmonic content proportional to its output AC current (Fraunhofer Gesellschaft Institut fiir Solare Energiesysteme, 1995). In recent times, thyristors have been preferably substituted by the more advanced switching devices like power bipolar junction transistors (BJTs), power MOSFETs or IGBTs. The central inverters used in recent times are mostly self-commutated inverters (SCI). The layouts of the central inverters, with and without transformer are shown in Figures 3(a)–3(c).

Figure 3 (a) Self-commutated full bridge grid tied transformer-less inverters (b) Line-commutated transformer-less grid tied inverters (c) Self-commutated full bridge grid tied inverters with line-frequency transformer (LFT)



Source: Myrzik (2001)

Figure 4 Half-bridge diode-clamped three-level grid tied inverter



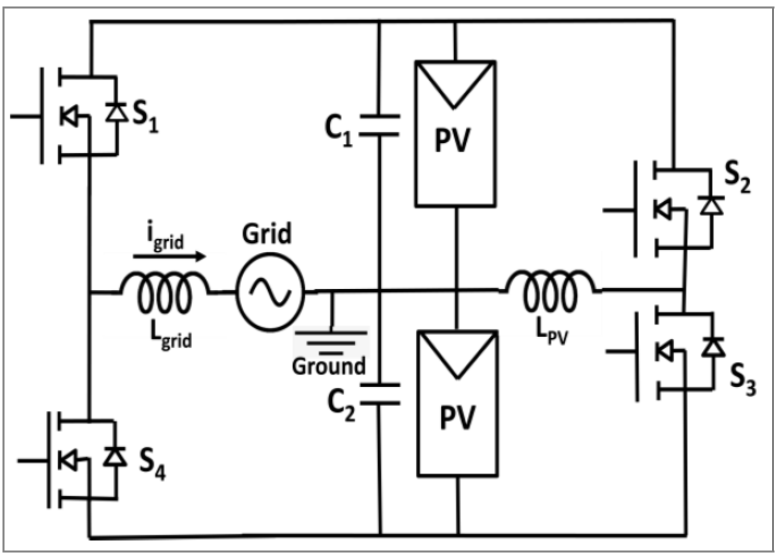
Source: IEEE Standards Association, IEEE 1547 and Kjaer and Blaabjerg (2003)

2.3 String and multi-string technology

The string and multi-string arrangements are the combination of one or multiple DC RES strings with a grid-tied inverter. The inverters can be either of single or dual-stage type with or without an embedded high frequency transformer (HFT). A classical layout of the string and multi-string half-bridge diode-clamped three level grid tied inverter is shown in Figure 4. Since, it has buck characteristic, the minimum input voltage should always be higher than the maximum grid voltage.

The inverter shown in Figure 5 is a two-level voltage source inverter (VSI), interfacing two RES. This inverter is capable of producing two-level voltage output by doubling the switching frequency to maintain same size grid inductor. Many industrial inverter techniques for central, string, multi-string, and AC module designs are discussed in the reference paper given in Sr. no. 86.

Figure 5 Utility interactive solar photovoltaic (PV) two levels VSI with generation control circuit (GCC)

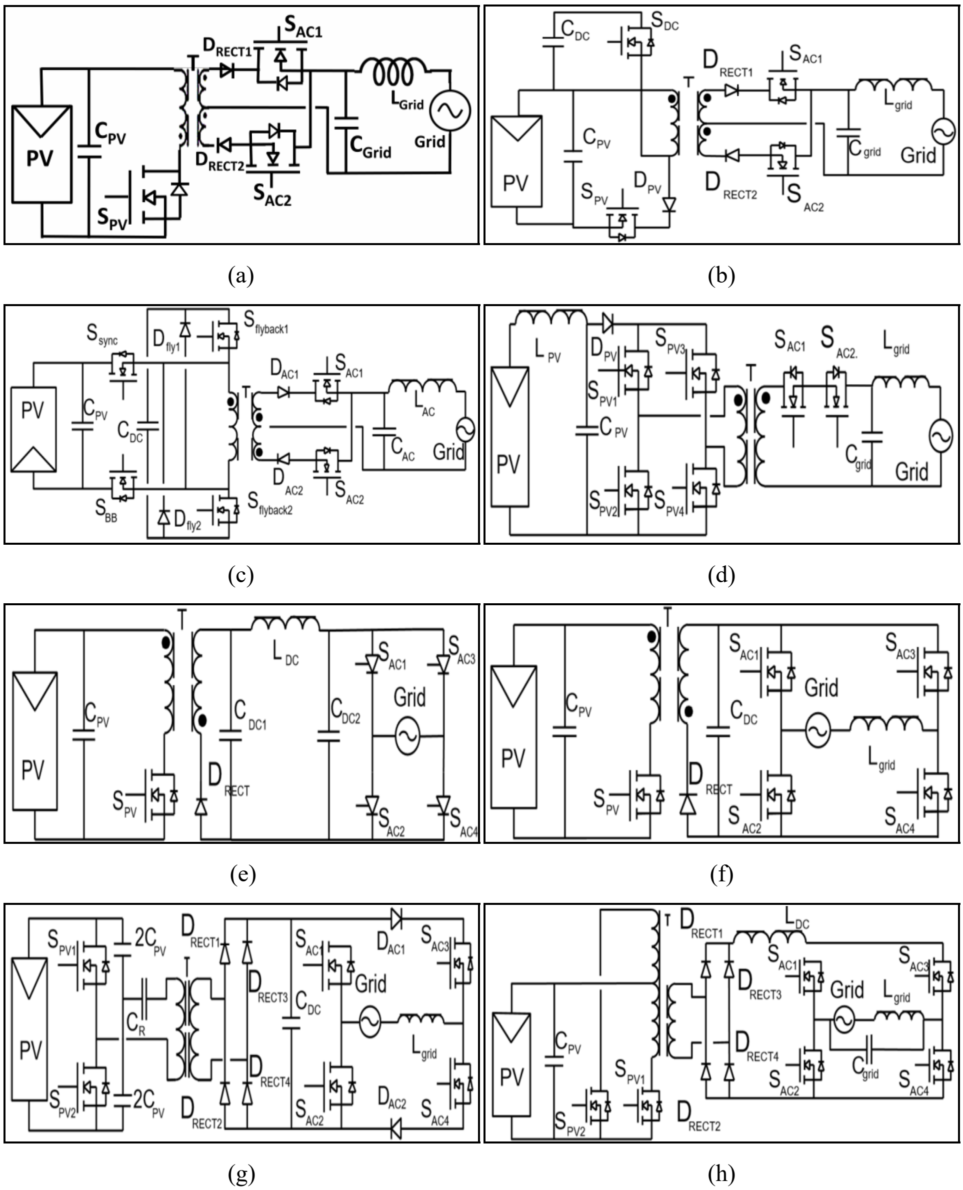


Source: Nagao and Harada (1997) and Mekhilef et al. (2000)

2.4 AC module technology

The AC module technology is the union of one RES module with a grid tied inverter. The mismatch losses between RES modules does not happen here, since there is only one RES and it also helps in optimal adjustment between the RES and the inverter by using independent MPPT. It has possibility of a simple and convenient enlarging of the system, because of its simple modular structure. It is a plug and play device. The users those who are not understanding of electrical installation procedure can also use this. This AC module inverters can be of the dual-stage category with an embedded HFT. Figures 6(a)–6(h) shows the layout of some of the AC module inverters.

Figure 6 Layout of some of the ac module inverters, (a) flyback-type inverter (b) flyback and buck-boost inverter (c) modified Shimizu inverter (d) dual-transistor flyback-inverter (e) flyback converter along with a line-frequency dc-ac unfolding inverter (f) flyback converter along with a PWM dc-ac inverter (g) series-resonant converter along with an high frequency inverter in grid side (h) Mastervolt Soladin 120 plug-and-play inverter



Source: Meinhardt and Cramer (2000), Calais and Agelidis (1998), Myrzik and Calais (2003), Kjaer et al. (2002), Haeberlin (2001), Meinhardt and Cramer (2001), Oldenkamp and de Jong (1998), Lindgren (1999) and Shimizu et al. (2002)

Table 1 Critical electrical parameter of some of AC module inverters

Fig. no.	5(a)	5(b)	5(c)	5(d)	5(e)	5(f)	5(g)	5(h)
Ref. no.	Meinhardt and Cramer (2000)	Calais and Agelidis (1998)	Myrzik and Calais (2003)	Kjaer et al. (2002)	Haeberlin (2001)	Meinhardt and Cramer (2001), Oldenkamp and de Jong (1998)	Lindgren (1999)	Shimizu et al. (2002)
Nominal power (in W)	100	105	160	160	150	100	110	90
Grid voltage (in V)	230	85	230	100	120	210	230	230
Input voltage (in V)	48	35	28	-	44	30	30	24–40
Efficiency (%)	96 M	-	82 E/87 M	-	-	-	87 N	91 E, 93 M
Power factor	0.95	-	-	-	-	-	-	0.99
THD (%)	-	< 5	-	-	-	-	-	-

The topology shown in Figure 6(a) is a 100 W flyback type inverter. This is designed using one single-transistor flyback converter along with a centre-tapped transformer (Meinhardt and Cramer, 2000). The topology shown in Figure 6(b) is a 105 W flyback and buck-boost type inverter. The requirement for a large decoupling capacitor is nullified by introducing a buck-boost converter into the flyback converter (Calais and Agelidis, 1998). The inverter shown in Figure 6(c) is modified Shimizu inverter (Myrzik and Calais, 2003), which is an improved version of the earlier technology. In order to overcome the problem of overvoltage, one-transistor flyback converter is replaced with a dual-transistor flyback converter. In this inverter the polarity of the DC source module is interchanged.

The layout shown in Figure 6(d) is a dual transistor flyback inverter (Kjaer et al., 2002), consisting of 160 W buck-boost inverter. In this inverter, a little amount of energy can be accumulated in the leakage inductance. The topology shown in Figure 6(e) is a 150 W flyback dc-dc converter together with a line-frequency dc-ac unfolding inverter (Haeberlin, 2001). The inverter shown in Figure 6(f) is a 100 W flyback dc-dc converter together with a PWM dc-ac inverter (Meinhardt and Cramer, 2001; Oldenkamp and de Jong, 1998). The inverter in Figure 6(g) is based on a 110 W series-resonant converter with a high frequency inverter towards the grid (Lindgren, 1999). The commercially available Mastervolt Soladin 120 inverter is shown in Figure 6(h), which is a plug and play inverter (Shimizu et al., 2002). The information of the critical electrical parameters of AC module inverters such as nominal power (W), grid voltage, input voltage, efficiency [maximum efficiency (M)/European efficiency (E)/nominal condition efficiency (N)], power factor and THD (%) are given in Table 1.

From Table 1, we can understand that the nominal power varies from 90–160 W, grid voltage 85–230 V, input voltage (from PV to inverter) 24–48 V, efficiency 82%–96%, power factor varies from 0.95 to 0.99 and THD is less than 5% is given for flyback type buck-boost inverter with high power decoupling. Most of the AC module inverters are not having the information about THD. It is required that all the inverters designed to connect in grid tied should have voltage and current harmonics within the specified range as per IEEE 519 (2014) as given in Table 5 and Table 6.

2.5 Classifications of inverter topologies

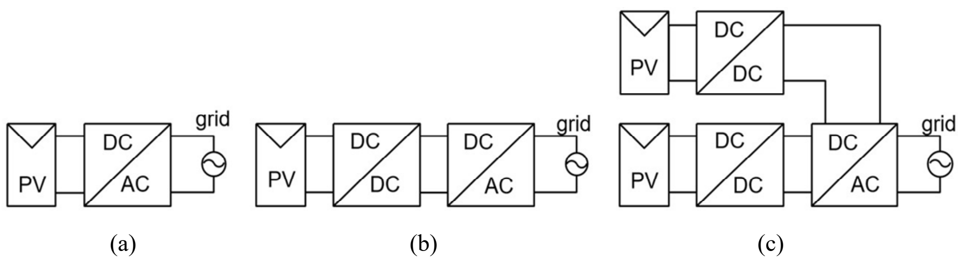
The inverter topologies can be classified based on the number of power processing stages, place of power decoupling capacitors, transformer whether it is connected or not, and the type of grid interface. Three different categories of inverters on the basis of number of power processing stages are shown in Figures 7(a)–7(c). They are single RES, or multiple RES connected in series or parallel. Figure 7(a), shows a single power processing stage that manages the MPPT, voltage enhancement and grid current handling. Figure 7(b) represents dual power processing inverter in which dc-dc converter is controlling MPPT and the dc-ac inverter manages the current being injected to the grid. Voltage enhancement process introduced in both stages. In two stage inverter given in Figure 7(c), each DC power source module or string is joined to a dc-dc converter which is linked to a single dc-ac inverter.

In Figure 8, two types of single and multiple stage inverters are shown based on different locations of the power decoupling capacitor. Capacitor should be kept in parallel with RES for single stage inverters. For multistage inverters, capacitor should be either placed in parallel with the RES sources or in the dc link. The size of the decoupling capacitor can be calculated (Martins and Demonti, 2002) using the below equation (1):

$$C = \frac{P_{PV}}{2.w_{grid}.U_C.u_C} \tag{1}$$

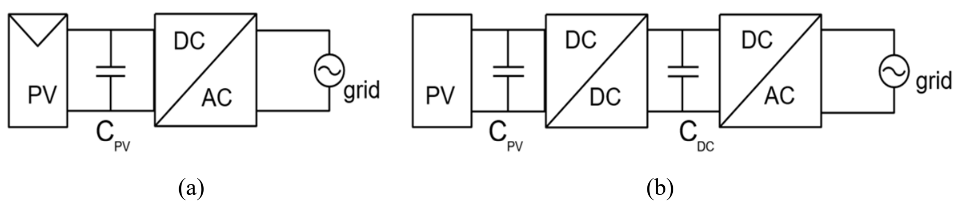
where P_{PV} is the nominal voltage for RES, w_{grid} is the frequency of the grid, U_C is the mean voltage across the capacitor, and u_C is the amplitude of the ripple.

Figure 7 (a) Single stage power processing inverter (b) Dual power processing inverter (c) Dual stage inverter



Source: Martins and Demonti (2002)

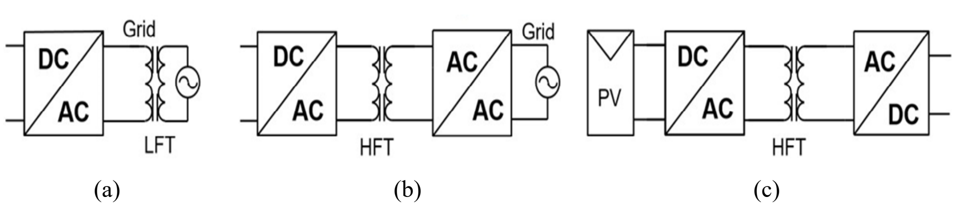
Figure 8 (a) Capacitor in parallel with the single stage inverter (b) Capacitor in the dc link between two stages of the inverter



Source: Martins and Demonti (2002)

Some inverters used high-frequency dc-dc converter or dc-ac inverter with transformer, others uses LFT in grid side and some inverters do not comprises of any kinds of transformer, as shown in Figures 9(a)–9(c). The LFT removes the problem associated with injection of dc currents into the grid, but it is not getting attracted because of its bulky size, weight and price.

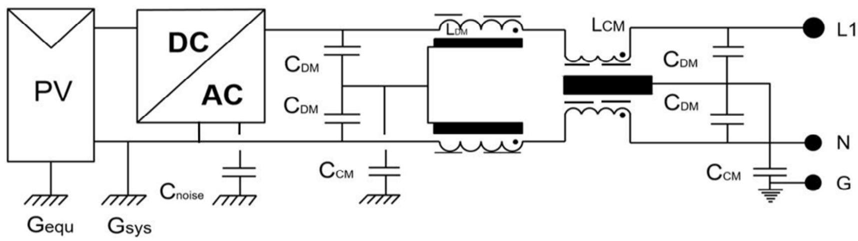
Figure 9 (a) LFT is in between the inverter and the grid (b) HFT in an HF-link grid-tied ac/ac inverter (c) HFT in a dc-link dc-dc converter



Source: IEEE Standards Association, IEEE 1547 and Martins and Demonti (2001)

A few transformer-less high input voltage topologies are available which can be grounded at both input as well as output as shown in Figure 10. It has single phase common mode (CM) and differential mode (DM) electromagnetic interference filters.

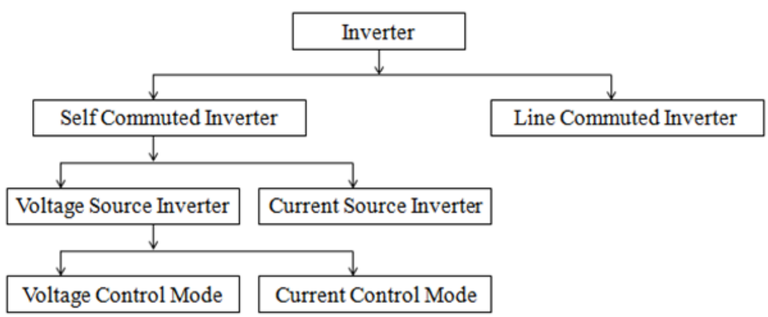
Figure 10 Transformer less high input voltage inverter



Source: Martins and Demonti (2002)

A grid-tied system should have, appropriate phase, frequency, and voltage magnitude of the three-phase AC output signal, which is required for the quick and appropriate synchronisation with the grid. The inverter can be classified on the basis of turn-on and turn-off behaviours (commutation), which are called as the line-commutated inverters (LCI) and the SCI. LCI inverters depend on the circuit parameters and the switches operate on the basis of the polarity or direction of the current movement. However, SCI inverters function with full control over the turn-on and turn-off process of switching components. The two major categories of inverters can be further divided into various subcategories based on power electronics as shown in Figure 11.

Figure 11 Power electronics-based inverters

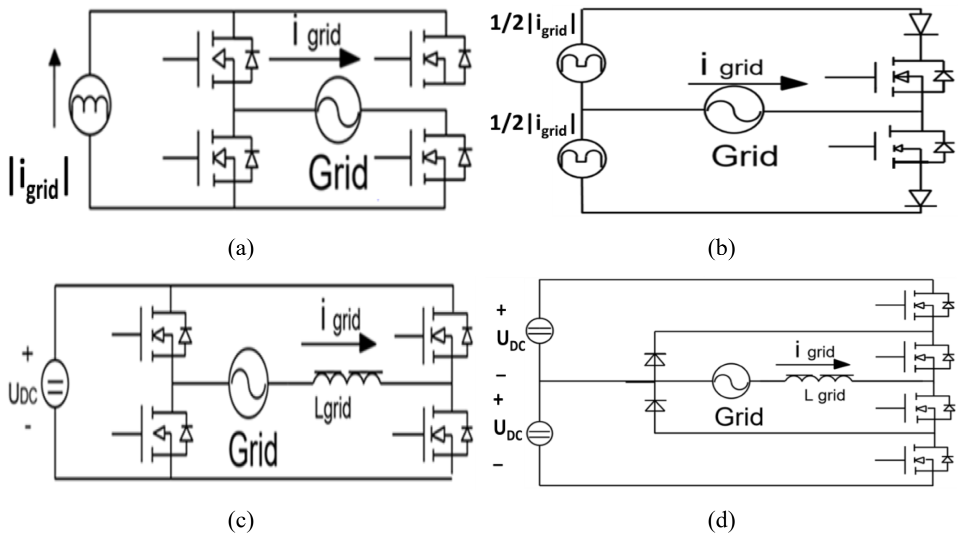


Source: IEEE Standards Association, IEEE 519

The inverter topologies as shown in Figures 12(a)–12(b) are line-frequency commutated current-source inverters (CSIs). The topology shown in Figure 12(c) is a standard full-bridge three-level VSI, capable of creating a sinusoidal current by applying the positive/negative dc-link or zero voltage to the grid inductor. The topology shown in Figure 12(d) is a half-bridge diode clamped three-level VSI capable of creating, 3, 5, 7 distinct voltages across the grid and inductor.

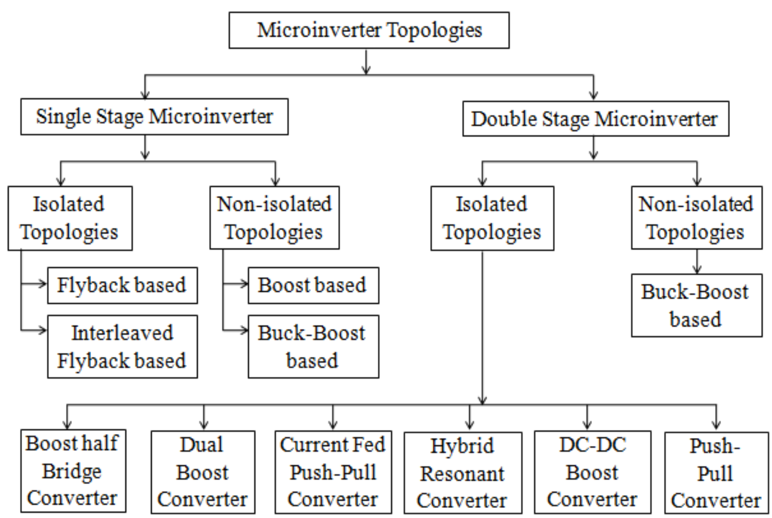
Mainly, the AC module inverters, i.e., microinverter topologies are classified in various categories. The classification of microinverter topologies are given in Figure 13. The summary of specifications of some of the studied microinverters is given in Table 2.

Figure 12 (a)–(b) Line-commutated CSI switching (c)–(d) Self-commutated VSI switching



Source: Lohner et al. (1996)

Figure 13 Microinverter topologies classification



Source: Alluhaybi et al. (2019)

From Table 2, it can be articulated that for the listed micro-inverters power varies from 50 to 500 W, efficiency varies from 85% to 99%, switching frequency varies from 9.6 to 600 kHz, number of active switch varies from 2 to 9, number of discrete diode varies from 0 to 8, switching can be hard or soft, decupling capacitor capacitance varies from 15 to 11,000 μF, THD varies from 0%–5%, life-time can be short or long, and cost can be low/moderate/high.

Table 2 Summary of specifications of some microinverters from the studied literatures

Description	*Single stage*			
	Non-isolated		*Isolated*	
	B	*BB*	*F*	*IF*
References	Shimizu et al. (2002), Martins and Demonti (2002), Martins and Demonti (2001), IEEE Standards Association, IEEE 519	Lohner et al. (1996), Alluhaybi et al. (2019), Caceres and Barbi (1999), Fang and Ma (2010), Ribeiro et al. (2010), Soleimani et al. (2017), Jain and Agarwal (2007), Abdel-Rahim et al. (2010), Vazquez et al. (1999), Kusakawa et al. (2001), Tang et al. (2014)	Patel and Agarwal (2009), Chamarthi et al. (2015), Kumar and Sensarma (2017, 2018), Wang (2004), Gautam and Sensarma (2017), Kasa et al. (2005a), Hu et al. (2013), Shimizu et al. (2006), Hirao et al. (2005)	Kjaer and Blaabjerg (2003), Hu et al. (2012), Hasan et al. (2016), Sukesh et al. (2014)
Power (W)	100–500	50–500	55–300	200–250
Efficiency (%)	90–97.5	87–96.5	70–90.6	94.1–95.7
Sw. frq. (kHz)	30–100	10–70	9.6–100	70–600
NAS	4	4–8	3–6	6–8
NDD	0–3	0–8	2–5	2
Switching hard/soft	Hard	Hard/soft	Hard/soft	Hard/soft
DCC (μF)	-	2,000–10,000	15–5,000	5,600–11,000
DG	No	Yes/no	-	-
THD (%)	0–4.74	0–5	0–5	0–4
Lifetime	Short	Short	Short/long	Short
Cost	L	L/M	M/H	H

Description	*Double stage*						
	Non-isolated	*Isolated*					
	BB	*B*	*DB*	*CFPP*	*HR*	*DDB*	*PP*
References	Kasa et al. (2005b), Mukherjee et al. (2013), Zhang et al. (2013b), Edwin et al. (2014)	Gao et al. (2014)	Kim et al. (2013)	Chomsuwan et al. (2002)	Abdel-Rahim et al. (2011)	Yu et al. (2010), Chen et al. (2015)	Jiang et al. (2012a), Chiu et al. (2013)
Power (W)	170–300	210	230	250	300	400–500	100–500
Efficiency (%)	85–99*	95.6	92.18	-	97.5	85–96.2	-
Sw. frq. (kHz)	10–30	21.6	-	50–100	100	20–50	20–50
NAS	5–6	6	7	2	5	4–6	8–9
NDD	2–6	2	3	2	2	4	5–6
Switching hard/soft	Hard	Hard	Hard	Soft	Soft	Soft	Hard
DCC(μF)	-	18	33	-	-	36–50	20–50
DG	No	-	-	-	-	-	-
THD (%)	4.5	0–2.87	-	-	-	2.5–3.8	-
Lifetime	Long	Long	Long	Long	Long	Long	Long
Cost	M/H	H	H	H	H	M/H	H

Notes: *Efficiency reported for inverter only.
Where B is boost, BB is buck boost, F is flyback, IF is inter leaved flyback, DB is dual boost, CFPP is current fed push pull, HR is hybrid resonant, DDB is DC/DC boost, PP is push pull, L is low, M is moderate, H is high, NDD is no. of discrete diode, NAS is no. of active switch, DCC is decoupling capacitor and DG is dual grounding.

It can be articulated that both transformer-based and transformer-less single stage micro-inverters are advantageous to double stage topologies due to its simplicity, compactness, and relatively high efficiency. It seems that isolated single-stage topologies exhibit potential for micro-inverter design, especially in connection with the criteria for renewable energy systems like galvanic isolation and for high power factor in the output power.

However, most important parameters for the future developments of micro-inverters can be as higher efficiency, higher power density and low cost. Based on this study, it can be articulated said that non-isolated single-stage micro-inverters can be preferred over other micro-inverter topologies due to its low weight, compactness, less losses, lower cost, high integration and comparatively higher efficiency.

3 Grid tied inverters – review on standards

The charge controller/MPPT components used in the inverter should qualify environmental tests as per IEC 60068-2 or equivalent BIS standards. The junction boxes/enclosures should be as per IP 65 for outdoor, IP 54 for indoor and also as per IEC 529 specifications. There are several standards like IEC 60364-7-712, IEC 61727, IEC 61683, IEC 62093, IEC 62116, IEC 62446 and UL 1741 which can be referred for interconnected PV inverters, installations in buildings, utility interfaces, efficiency measurement, documentations, tests and inspection and use in independent renewable power systems. The inverters should satisfy with applicable IEC or equivalent BIS standard for efficiency measurements and environmental tests (IEC 61683, IS 61683, IEC 60068-2). Inverter technical parameter details as per EN 61000-3-2 (Meinhardt and Mutschler, 1995), IEC 61727 (International Electrochemical Commission, IEC 61727 Standards), IEEE 1547 (Mastervolt, http://www.mastervolt.com/sunmaster), and IEEE 929 (Shimizu et al., 2001) standards are given in Table 3.

From Table 3, it can be said that the even harmonics should not exceed 30% of the odd harmonics, maximum current THD should be less than 5% and DC current injection should not surpass 1% of the rated output current. The inverter should have electrical safety features. It should have over current protection, DC surge protection, lightning protection, ingress protection, labelling of PV system equipment, electrical quality, DC power injection, harmonic injection, and phase imbalance (or unbalance). The inverter should sense abnormal voltage and respond to it and trip time should be within the range. The trip time range is given in Table 4. Whenever there is a deviation from the specified percentage of the nominal voltage, inverter must detect abnormal voltage and respond appropriately.

High voltage systems can have maximum up to 2.0% THD which is caused by HVDC terminal whose effects will have attenuated at places in the network at which future users may be connected. The voltage and current distortion limit as per IEEE 519 (2014) is given in Table 5 and Table 6, respectively.

Even harmonics are limited to 25% of the odd harmonic limits. The individual voltage harmonic should not exceed 5% and total voltage harmonic distortion should not surpass 8%.

The concerned IEC 61000 sections for electromagnetic compatibility comprising voltage fluctuation and flicker are shown in Table 7.

Table 3 Details about inverter parameter ranges as per standards

Issues	*EN 61000-3-2*	*IEC 61727*	*IEEE 1547*	*IEEE 929*
Nominal power	3.7 kW	10 kW	30 kW	< 500 kW
Harmonic currents (order-h) limits	(3), 2.30 A	(3–9), 4.0%	(2–10), 4.0%	(3–9), 4.0%
	(5), 1.14 A	(11–15), 2.0%	(11–16), 2.0%	(11–15), 2.0%
	(7), 0.77 A	(17–21), 1.5%	(17–22), 1.5%	(17–21), 1.5%
	(9), 0.40 A	(23–33), 0.6%	(23–34), 0.6%	(23–33), 0.6%
	(11), 10.33 A		(> 35), 0.3%	
	(13), 0.21 A			
	(15–39), 2.25 A			
	Even harmonics ~ 30% of odd harmonics	Even harmonics < 25% of odd harmonics	Even harmonics < 25% of odd harmonics	-
Max. current THD	-	5%	5%	5% of the fundamental
Power factor at 50% rated power	-	0.90	-	
DC current injection	< 0.22 A corresponds to a 50 W half wave rectifier	< 1% of rated output current	< 1% of rated output current	≤ 0.5% of the rated output current
Voltage range for normal operation	-	85%–110% (196 V–253 V)	88%–110% (97 V–121 V)	88%–110%
Frequency range for normal operation	-	50 ± 1 Hz	59.3 Hz to 60.5 Hz	59.3–60.5 Hz

Table 4 Trip time in response to abnormal voltages

IEC 61727		*IEEE 929-2000*	
Grid voltage (at interconnection)	*Maximum trip time*	*Voltage (at point of common coupling)*	*Max. trip time*
V < 50% of $V_{Nominal}$	0.1 seconds	V < 50%	6 cycles
50% ≤ V < 85%	2.0 seconds	50% ≤ V < 88%	120 cycles
85% ≤ V ≤ 110%	Continuous	88% < V ≤ 110%	No operation
110% < V < 135%	2.0 seconds	110% < V < 137%	120 cycles
135% ≤ V	0.05 seconds	137% ≤ V	2 cycles

Source: International Electrochemical Commission, IEC 61727 Standards and Shimizu et al. (2001)

Table 5 Voltage distortion limits as per IEEE 519 (2014)

Bus voltage (V) at PCC	*Individual harmonic*	*Total harmonic distortion (THD)*
V ≤ 1.0 kV	5.0%	8.0%
1 kV < V ≤ 69 kV	3.0%	5.0%
69 kV < V ≤ 161 kV	1.5%	2.5%
V > 161 kV	1.0%	1.5%

Source: Shimizu et al. (2003)

Table 6 Current distortion limits as per IEEE 519 (2014)

Maximum harmonic current distortion in percentage of IL						
Individual harmonic order (odd harmonic)						
ISC/IL	*< 11*	*11 ≤ h < 17*	*17 ≤ h < 23*	*12 ≤ h < 35*	*35 ≤ h*	*TDD*
< 20	4	2	1.5	0.6	0.3	5
20 < 50	7	3.5	2.5	1	0.5	8
50 < 100	10	4.5	4	1.5	0.7	12
100 < 1,000	12	5.5	5	2	1	15.5
> 1,000	15	7	6	2.5	1.4	20

Source: Shimizu et al. (2003)

Table 7 IEC standards and scope for electromagnetic compatibility, including flicker

Standard	*Description*	*Scope*
IEC 61000-3-2	Harmonics	Inverter < 16 A AC current per phase
IEC 61000-3-3	Voltage fluctuation and flicker	
IEC 61000-3-12	Harmonics	Inverter > 16 A and < 75 A AC current per phase
IEC 61000-3-11	Voltage fluctuation and flicker	
IEC 61000-3-4	Harmonics	Inverter > 75 A AC current per phase
IEC 61000-3-5	Voltage fluctuation and flicker	

Source: Kouro et al. (2015)

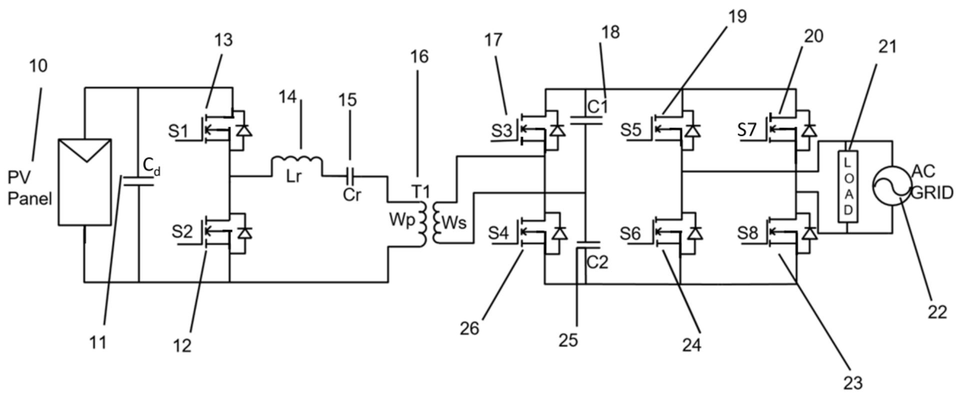
From Table 7, it can be said that the IEC 61000 standards, relevant sections can be referred for understanding about harmonics, voltage fluctuation and flicker limits of the inverters.

4 Grid tied inverters – review on patents

One of the method and system for a low cost bi-directional grid connected PV micro-inverter was patented by Indian Institute of Technology, Mumbai and got an International Publication Number (WO 2014/192014 A2). This invention presents the micro-inverter topology which converts the DC voltage output from the solar panel in an AC voltage. A low cost bi-directional micro-inverter capable of supplying bi-directional flow of power between a load and power sources is shown in Figure 14. It has a cascade connection of a decoupling capacitor, a half-bridge switching stage design, a series interlinking of inductor and capacitor as resonant tank circuit, a HFT, filter capacitors and a low frequency switching network comprising of switches in a full bridge arrangement (Madhuwanti, 2014).

Maximum power can be extracted from RESs by controlling electrical power creation from RE sources, operating dc-ac inverter at highest efficiency in the absence of maximum power point as well, dc-ac inverter input can vary over a range of isolation and temperature, to provide dynamic reactive capability for reliable operation and to achieve grid code requirements by varying reactive power dynamically using suitable power control circuits (Porter et al., 2019a). By the use of suitable converters, inverter circuitry, power converter functionality and inverter sweet spot converter control circuitry, the losses other than wire transmission loss can be avoided and efficiencies of 99.2% or more can be achieved (Porter et al., 2016, 2019b).

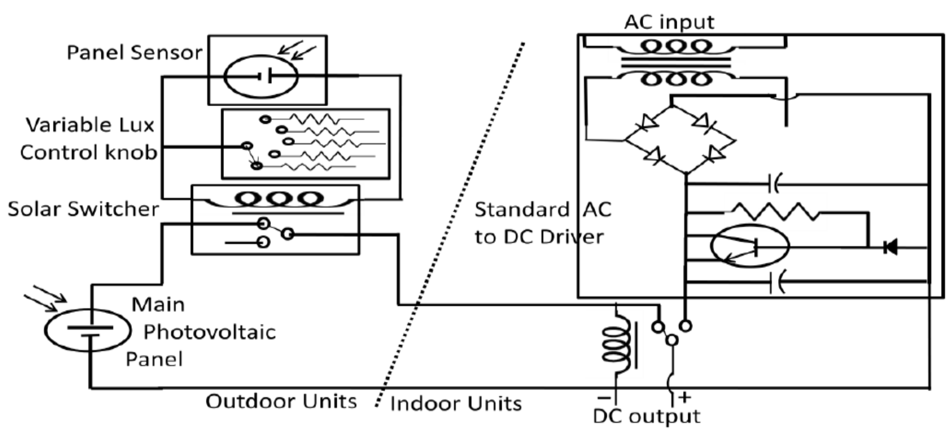
Figure 14 Bi-directional grid tied micro-inverter for SPV system (WO 2014/192014 A2)



Source: Madhuwanti (2014)

One of the devices for generating electricity by harnessing solar energy and method was patented by Ghosh (2015), West Bengal. This patent relates to a device for continuous indoor/outdoor illumination. Figure 15 shows a device for continuous indoor/outdoor lighting using DC power from solar panels to drive LED lights.

Figure 15 Circuit layout for grid tied inverter for SPV system (US 2015/0189705 A)



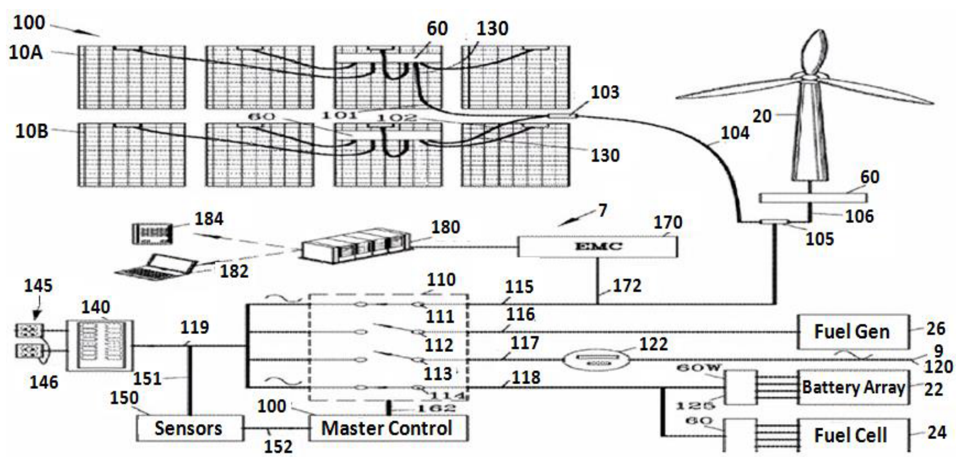
Source: Ghosh (2015)

An auto grid or PV power selector was developed using two relay switches, where one relay switch will toggle on/off in case of low solar irradiance availability and the first relay will trigger the second relay switch for powering the LEDs be selecting any one power from grid or solar (Ghosh, 2015). This device enables complete indoor/outdoor lighting by using from solar panel directly only. LED lights were used in this, which works on DC. The prototype device developed invention employs two 300 milliamp 12 V relay switches in an innovative arrangement which triggers automatically based on ambient light conditions.

An interface for renewable energy system was patented by Della Sera and Kravitz, Technology Research Corporation, Clearwater, FL (USA) (US 2014/0266289 A1). This patent shows an improved interface for renewable energy systems by interconnecting multiple power sources such as PV panels, wind turbines, standby generators, etc. Further, this apparatus can be used for mapping and identifying a performance and fault in a solar panel array, microinverters, status and data circuit for storing values.

Figure 16 shows a better interfacing of RESs with the grid using multi-channel micro-inverter having unique heat dissipation, unique mountings, and provisions for remote communication. This system is capable of automatic switching between, on-grid operation, off-grid operation and emergency power operation. Fault detection in SPV systems, performance monitoring, etc. can also be done using this interfacing system (Della Sera and Kravitz, 2014).

Figure 16 Interface for renewable energy system (US 2014/0266289 A1)

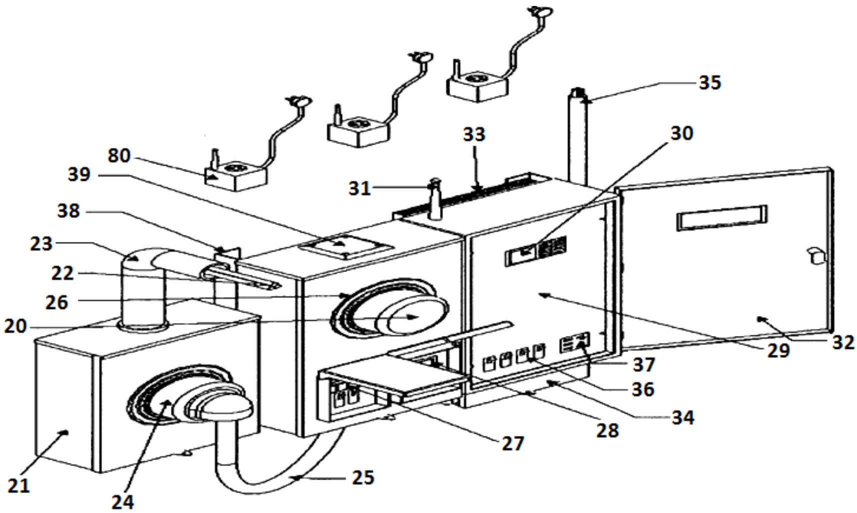


Source: Della Sera and Kravitz (2014)

A system and method for single plug-in attachment of a high voltage intelligent for renewable energy system with wireless smart load management system was patented by Mathiowetz (2011), Minnetonka, US 2011/0004357A1. This invention can improve the integration and management of renewable energy systems.

A high voltage intelligent grid-tied controller for renewable energy systems with wireless smart load side power management system is shown in Figure 17. It can be used for efficient power management in renewable energy systems, to be used in home or small business places. It provides low cost, installation and management of the electric energy generation from solar panels, wind turbines, hydrocarbon fuelled generators, fuel cells or energy storage for future electric automobiles with smart energy management system. It also have wireless controllers, which can be connected with the key appliances like motors, pumps, for monitoring real time load continuously with proper energy management (Mathiowetz, 2011).

Figure 17 Grid-connected controller with wireless smart load management system (US 2011/0004357A1)

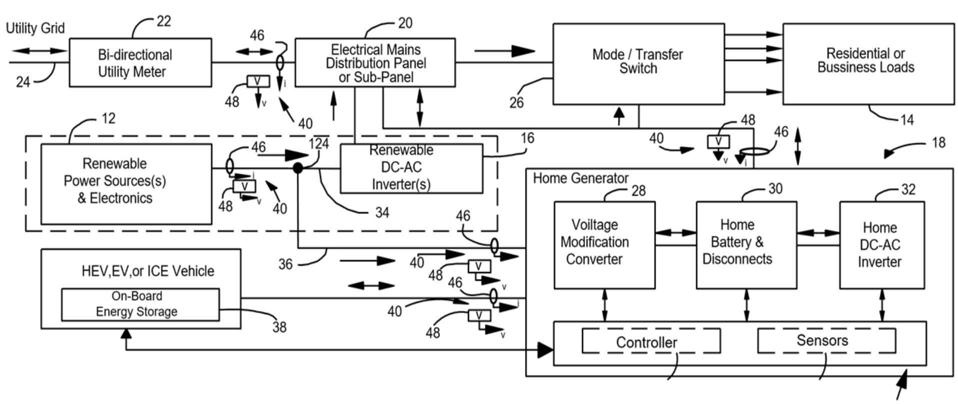


Source: Mathiowetz (2011)

A renewable energy system with integrated home power was patented by King (2017), King Electric Vehicles Inc., Schenectady, NY, US 9,559,521 B1. This patented system includes a grid-tied RES and home power supply system.

Figure 18 shows the system connected to the RESs along with the power supply system having a voltage modification circuit, one energy storage device, and an inverter to supply AC power output to the distribution panel. A bi-directional energy meter was used to measures a net flow of AC power output from the first and second inverters and the grid power taken for supplying to the load based on power requirement of the load, and a controller which controls the flow of power in the power supply system (King, 2017).

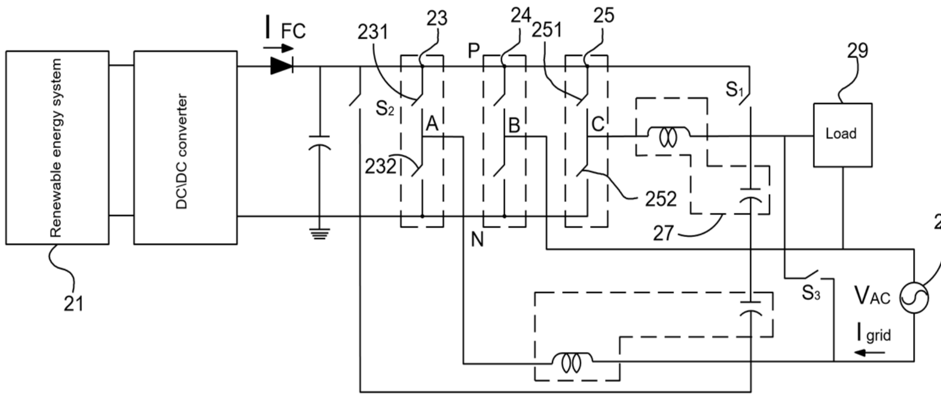
Figure 18 Renewable energy system with integrated home power (US 9,559,521 B1)



Source: King (2017)

A device for managing single-phase power for renewable energy system was patented by Su et al. (2010), Industries Technology Research Institute, US 7,714,463 B2. This patented device is shown in Figure 19.

Figure 19 Device for controlling single-phase power conditioner (US 7,714,463 B2)



Source: Su et al. (2010)

This device comprises of a power supply system to provide alternating current, a renewable energy system, a DC-DC converter, a grid-tied power conditioner for transforming voltage levels of the AC power and DC power, a controller for issuing control signals for controlling the grid-tied power conditioner and a load which can consume electricity (Su et al., 2010). The primary objective of the invention was to provide a control device for a single phase power conditioner for a RE system so that it can be tied with the utility system to provide electricity when the utility system functions normally, otherwise the load consumes transferred power when one of the utility system and the renewable energy system does not provide electricity. The power conditioner of this invention provides better efficiency and output voltage waveform.

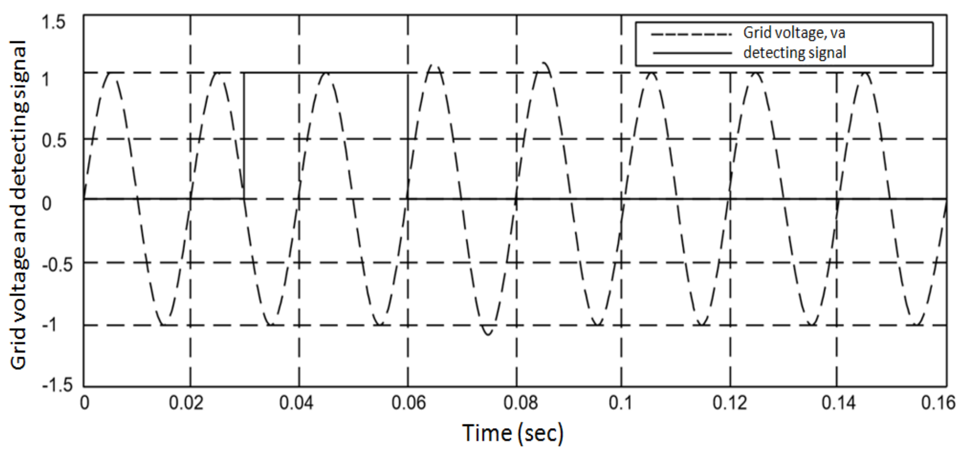
5 Various controllers for the grid-connected renewable energy system

The controllers which are used in grid tied renewable energy systems are mainly classified as linear controllers, nonlinear controllers, robust controllers, adaptive controllers, predictive controllers and intelligent controllers. Further, they can be divided in subcategories as classical controllers, proportional resonant (PR) controllers, linear quadratic Gaussian (LQG) controllers, sliding mode controllers (SMC), partial feedback linearisation (PFL) controllers, hysteresis controllers, H-infinity (H∞) controllers, Mu-synthesis controllers, deadbeat controllers (DB), model predictive controller (MPC), NN controllers, repetitive controllers (RC), fuzzy logic controllers (FLCs) and autonomous controllers. The brief details about different controllers are given below.

Linear controllers are designed in such a way that it obeys superposition principle, and it is suitable for linear systems. PID, PI, PD and proportional controllers are classical controllers. PR controllers can be used for enhancing converter reference tracking performance and to remove few shortcomings of PI controller (Castilla et al., 2013; Shen et al., 2010; Huerta et al., 2012; Busada etr al., 2012). LQG controllers optimise the mean of quadratic criteria. It also uses Kalman filter (Komurcugil, 2012). Both the LQR and Kalman filter can be designed and computed separately. These types of controllers are appropriate for both time-variant as well as time-in variant systems.

Nonlinear controllers show very good operation in comparison with the basic controllers (Niroomand and Karshenas, 2011). The performance of SMC is dependent on a sliding surface which is difficult to locate a legitimate. Its performance is also dependent on the sampling time. SMC faces distortion if an inadequate sampling time is chosen, it also tracks variable reference, which causes chattering and degrade the overall efficiency of the renewable energy system. PFL controllers work on feedback linearisation technique. A robust controller is useful, when there is a concern of uncertainties. Multivariable system problems can be resolved by H-infinity techniques (Ouchen et al., 2016a). In predictive controllers, the future behaviour of controlled parameters is predicted by using system model, based on predefined optimisation criteria to obtain the optimal actuation and it can be easily implemented. In DB, the dynamic response of the system is controlled by the differential equation which is derived from the deadbeat control theory (Tan et al., 2012). Intelligent controllers obtain automation using the imitation of biological intelligence. RC is one of the intelligent controllers whose basic idea is derived from the internal model (Zhao et al., 2016; Lin et al., 2016). FLC is one of the intelligent controller in which the knowledge of smart human being is defined and implemented to control the dynamics of the system. The signal detection for grid voltage increase in FLC is shown in Figure 20.

Figure 20 Signal detection for grid voltage increase in FLC



Source: Hannan et al. (2013)

Table 8 comprehensively summarises the some important controllers based on modulation, controller parameter, filter, phase, etc. as reported in the literatures as per the references shown in Table 8.

From Table 8, it can be articulated that the controllers used in grid connected renewable energy systems are either single phase or three phase type; they have PWM, SVM, SPWM, VLUT or SVPWM modulation; voltage, current or power as control parameters and LCL, LC or L as filters.

Table 8 Main features of some of the proposed controllers in the studied literatures

Controller	*Phase 1Ø/3Ø*	*Modulation*	*Control parameter*	*Filter*	*References*
Classic	1Ø/3Ø	PWM, SVM, SPWM, VLUT	V, P, C	LCL, LC, L	Miret et al. (2013), Liu et al. (2014), Li et al. (2013), Ebadi et al. (2014), Samui and Samantaray (2013), Yuan et al. (2002), Miret et al. (2009), Chilipi et al. (2016), Radwan and Mohamed (2016)
Adaptive	1Ø/3Ø	SPWM, PWM, SVPWM	V, C, P	LCL, LC, L	Eren et al. (2015), Sun et al. (2014), Do et al. (2013), Jung et al. (2014), Jorge et al. (2013)
Deadbeat	1Ø/3Ø	PWM, SVM, SVPWM	C, V	LCL, LC, L	Moreno et al. (2009), Huerta et al. (2010), Mattavelli (2005), Zeng and Chang (2008)
Adaptive, repetitive	1Ø/3Ø	SVM, SPWM	C	LC, L	Espí et al. (2011), Guo et al. (2014)
Adaptive, MPC	3Ø	SVM	C	LCL	Ahmed et al. (2011)
Classic, PR	1Ø/3Ø	PWM, SVPWM, SPWM	C	LCL, L	Xu et al. (2014), Geng et al. (2011), Lee and Hu (2011), Bao et al. (2014)
PR	1Ø/3Ø	SVM, PWM	V, C	LCL	Camacho et al. (2013), Castilla et al. (2008, 2013), Shen et al. (2010)
LQG	3Ø	PWM	C	LCL	Huerta et al. (2012)
PR, LQG	3Ø	SVPWM	C	L	Busada et al. (2012)
SMC, fuzzy	1Ø	PWM	V	LC	Komurcugil (2012)
SMC	3Ø	PWM	C	L	Kumar et al. (2016)
PFL	3Ø	PWM	V, P	LCL	Mahmud et al. (2014)
Hysteresis	1Ø	PWM	C	L	Ho et al. (2009)
Hysteresis, MPC	3Ø	PWM	C	LCL	Zhang et al. (2016)
H∞, repetitive	3Ø	PWM	C	LC	Hornik and Zhong (2011)
H∞	3Ø	PWM	C	LC	Yang et al. (2010)
Predictive	3Ø	SVM	V	LC	Lim et al. (2014)
Fuzzy, predictive	3Ø	PWM	P	L	Ouchen et al. (2016a)
SMC, predictive	3Ø	PWM	P	L	Ouchen et al. (2016b)
Adaptive, deadbeat	3Ø	PWM	C	L	Mohamed and El-Saadany (2007)
Deadbeat, repetitive	3Ø	PWM	V	LC	Niroomand and Karshenas (2011)
MPC	3Ø	PWM, SVPWM, SVM	V, C, P	LCL, LC, L	Tan et al. (2012), Mariethozand and Morari (2009), Rodríguez et al. (2007), Lee et al. (2012), Sathiyanarayanan and Mishra (2016)
Classic, repetitive	3Ø	PWM, SVM	V, C, P	LC, L	Bojoi et al. (2011), De Almeida et al. (2014), Nazir et al. (2014)
Repetitive	1Ø/3Ø	PWM, SPWM	V, C	LC	Liu and Wang (2015), Jiang et al. (2012b)
RC	1Ø	PWM	C	LCL	Zhao et al. (2016)
Fuzzy, NN	3Ø	PWM	P	L	Lin et al. (2016)
Classic, NN	3Ø	PWM	P	L	Kyoungsoo and Rahman (1998)
Classic, hysteresis	1Ø	PWM	V, C	LC	Yao and Xiao (2013)
Autonomous	3Ø	PWM	V, C, P	LCL	Wang et al. (2014)

Note: Where PWM – pulse width modulation, SVM – space vector modulation, SPWM – sine pulse width modulation, VLUT – voltage look up table-based modulation, SVPWM – space vector pulse width modulation, V – voltage, C – current, P – power, LCL – inductor capacitor inductor, LC – inductor capacitor and L – inductor.

6 Selection of grid tied inverters

The selection of grid tied inverters can be done on the basis of specific requirements of users. 20–30 years ago, the efficiency of renewable energy systems was very low, they were expensive to install and its applications were not fully developed. There were no selection and safety requirements imposed by the government, state electricity board and electric companies. Today, with an advancement of power electronic technologies, the regulations and requirements for the renewable energy systems are being standardised. Two types of requirements and guidelines should be considered for selection of inverters, i.e., performance requirements (efficiency, power density) and legal regulations.

7 Conclusions

In this review paper, the information collected from the literatures, standards, patents on grid tied inverters used for renewable energy systems are discussed to understand the inverter technologies, classification of inverter topologies, specifications for non-isolated, isolated single stage and double stage micro-invertors and various converters for grid connected RES. Information about, nominal power, harmonic contents, % of THD, power factor, voltage range, frequency range was reported. The power quality, injection of DC current into the grid, detection of islanding operation and system grounding was highlighted. The installed capacity of various grid interactive renewable power systems was presented. The role of power decoupling between the modules and the grid was discussed. The historical development of inverter was discussed with a classification of the inverters, number of power processing stages, type of power decoupling between the module and the grid. AC module inverters, i.e., micro-inverters are preferred in recent times, in comparison with large centralised inverters. If several strings are to be connected to the grid, then multi-sting concept seems to be preferred. HFT avoids resonance, and grounding in both input and output terminals also avoids resonance in current main paths. Efficiency, power density, leakage current reduction, manufacturing and installation cost, galvanic isolation, anti-islanding detection, and ideal features for grid-connected inverters are considered as an important parameter in choosing a grid tied inverter for renewable energy systems.

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