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A Review of Design, Manufacturing of Grid Tied PV Inverter and Its Impact on Site Performance, Reliability and Safety

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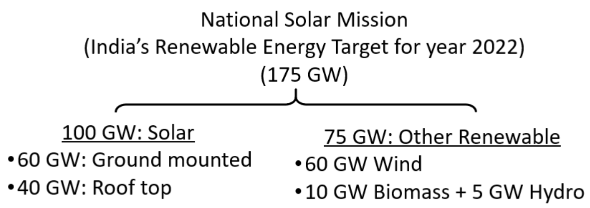
Abstract - *Rapid demand in electric power, depleting fossil fuels and global warming due to greenhouse gas emission shifting focus on renewable energy, especially on solar photovoltaic (PV) technology. PV components' decreasing prices and increasing efficiency trend is benefiting PV systems as an electricity generator. Solar inverter is a critical and one of the most important pieces of equipment in a PV solar system, but it also contributes to reliability issues mainly because of its major population of power electronics, design and manufacturing quality issues which are in-fact side effects of present cost competitive trend in solar PV industry. The aim of this paper is to present technicality and design tradeoffs to guide customer in evaluating performance, and reliability parameters of an inverter to maximize generation and increase economic life of plant. This paper focus on multi megawatt central inverters which are predominantly used in utility scale PV power plants in India.*

Key Words: Photovoltaic, Utility scale PV solar plant, Grid tied central Inverter, Performance, Reliability, Safety.

1. INTRODUCTION

PV solar power installations in India has increased due to favorable tropical climate i.e., abundant sunlight of about 300 clear and sunny days in a year and strong push from the Government of India with National Solar Mission to generate 100 GW of solar power by the year 2022.



PV based solar technology is still evolving to overcome several technical challenges to become a trusted and reliable energy provider. And key element of the solution is solar inverter, which is receiving intense attention due to their high failure rates. Design and manufacturing quality can improve the inverter performance, safety, and reliability and hence the return on investment for a PV project.

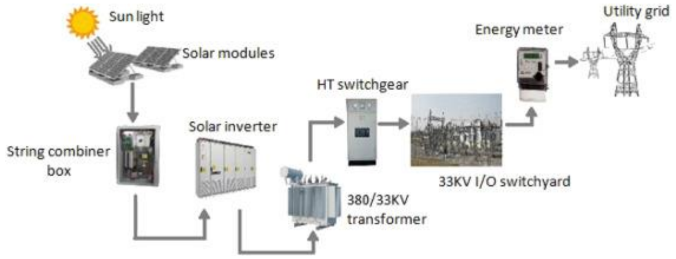


Fig-1: Constituents of a utility scale PV solar plant

2. FINANCE METRICS IN PV SOLAR PROJECTS

Continuing decline in solar tariff has made PV solar industry very cost competitive and that is one of reason there exists very few recognized inverter manufacturers globally. Higher power rated individual central inverters are cost effective (for their reduced $/kW) in utility scale power plant, but they also bring complexity in terms of design, manufacturing, operation, and maintenance perspective. So complete in and out understanding of technicality and compatibility with BOS (Balance of System) is essential for selecting a right inverter product for optimal operation of a plant.

Table -1: PV component pricing: Q1-2021

Components*	Price#	
PV Module (Poly)	22¢/Wp	16.5 INR/Wp
Central Inverter	2.0 ¢ / Wac	1.5 INR /Wac
Tariff Rates	2.7¢ / kWh	2.0 INR / kWh

*Utility scale PV plant components. #Dynamic pricing for reference only

In order to maximize the performance of a project with efficient design, operation and maintenance and to achieve guaranteed PPA (Power Purchase Agreement) parameters and increase economic life of plant, commonly used KPIs in the industry are annual energy production (AEP), performance ratio (PR) and levelized cost of energy (LCOE).

Financial analysis of a plant is performed using metrics as listed below:

2.1 Net Present Value (NPV)

NPV estimates a solar project's future value converted into today's dollars and calculated by taking the difference between the present value of cash inflows and cash outflows over a period of time. It is commonly referred to as the time value of money. A positive NPV indicates that the current value of the future cash inflows exceeds the current value of the expected future cash outflows, suggesting a profitable project for investment

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t}$$

- CFt is cash flow in the period
- n is number of periods
- t is current period
- i is discount rate

2.2 Performance Ratio (PR)

PR evaluates the efficiency of various electricity generating components and is independent of PV plant location. It compares the amount of electricity produced versus theoretical estimation. A low PR could indicate technical problems. PR value of around 80% is considered as good plant design. It is defined as ratio of measured output by theoretical calculated output, which is based on irradiation level at site, module efficiency, area occupied by PV arrays.

$$PR\,(\%) = \frac{E}{A * \eta * H}$$

- E is measured AC electrical generation (kW)
- A is effective area of the array panels (m^2)
- η is PV panel efficiency (%)
- H is site specific solar radiation on panel (kWh/m^2)

2.3 Plant Availability Factor (PAF)

PAF is a measure of the amount of time a plant is generating electricity and represents the uptime of a plant. Availability guarantee focuses on equipment reliability. It is calculated is based on generation periods and inverter running periods. Initially the availability factor for each inverter is evaluated, then depending on the number of inverters in the PV plant, the plant availability factor is evaluated. Tripping time effects the availability factor of inverter as well as the PV plant. Ongoing trend in industry demands PAF factor as ≥ 99%.

$$PAF = \frac{1}{n}\left(AF_{inveter\ 1} + AF_{inveter\ 2} + \ldots AF_{inveter\ n}\right)$$

- Availability Factor$_{inverter}$ ($AF_{inverter}$) = $\frac{\text{Running Periods x 100}}{\text{Generation Periods}}$
- Running Periods = Generation Period – Tripping
- Generation Period = End Time – Start time

2.4 Payback Period

Payback period is the time taken to recover initial cost of an investment. This period differs with selection of plant equipment and design like e.g., 1000V or 1500V dc system, type of PV modules (mono or bifacial) or module mounting design (fixed or tilt tracker) etc. This period in the industry per year adjusted for inflation, is around 6 years.

2.5 Plant Availability Factor (PAF)

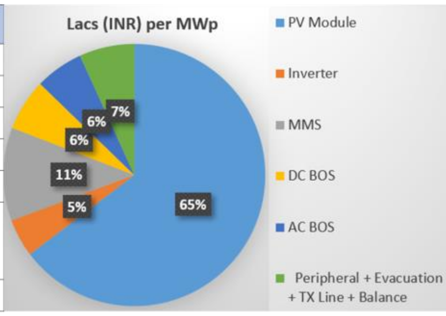
It is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis. It is regarded as the minimum constant price at which electricity must be sold in order to break even over the lifetime of the project and is calculated over the design lifetime of plant and measured in units of currency per kWH.

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}}$$

$$= \sum_{t=1}^{n} \left\{ \frac{I_t + M_t + F_t}{(1+r)^t} \right\} \div \sum_{t=1}^{n} \left\{ \frac{E_t}{(1+r)^t} \right\}$$

- I_t is investment expenditures in the year t
- M_t is operations and maintenance expenditure in the year t
- F_t is fuel expenditures in the year t
- E_t is electrical energy generated in the year t
- r is discount rate
- n is expected lifetime of system of power plant

PV Components	*Lacs per MWp
PV Module	152
Inverter	11
MMS	27
DC BOS	15
AC BOS	14
Peripheral + Evacuation + Transmission Line + Balance	16
Total in INR	235



*Based on 250MWp plant size and 25MWp block size

Fig-2: Cost breakup per MWp in a PV plant

Implementing inverters into power system extends its utilization beyond conversion dc to ac and feeding active power into grid but also supporting grid. Battery Energy Storage System (BESS) and VAR support are the ancillary services provided by plant operators to improve grid power quality and stability. These features may be monetized as incentive for plant operators.

The dc power generated from PV solar is not stable but fluctuating due to environmental conditions like varying temperature, irradiation, clouding effect etc. This is overcome by integrated battery storage system in grid tied PV inverter. BESS stores energy during off-peak hours and or during high solar irradiance and discharge during high peak demand and or during low solar irradiance. Unpredictable solar radiation is challenging to provide reliable power through PV based solar plant. Predictions of solar insolation is useful in forecasting the energy production of PV plant which is essential for plant operational efficiency and trading markets.

Abnormal grid voltage and frequency scenario is mitigated by reactive power compensation or simply VAR and frequency droop features available within inverter.

3. BASICS OF PV MODULES

Solar cell is a p-n junction made of silicon and is the basic components in a PV system. To increase voltage level the individual cells are connected in series to form a module. And to increase the current the modules are connected in parallel to form a string. Array is formed by parallel combination of strings to increase power level.

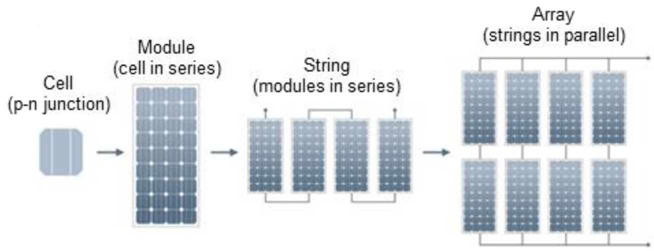
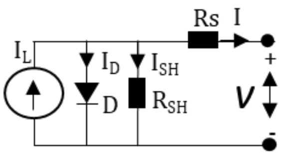


Fig-3: Components for PV array



Current equation is given by:

$$I = I_L - I_0\left\{\exp\left[\frac{V+IR_S}{nV_T}\right]-1\right\} - \frac{V+IR_S}{R_{SH}}$$

Fig-4: Single diode PV cell model and current equations

Electrical characteristics of a PV system is expressed in terms of V-I or P-V relationships and is function of irradiance and cell temperature. Module short circuit current 'Isc' is proportional to irradiation and open circuit voltage 'Voc' is inversely proportional to temperature.

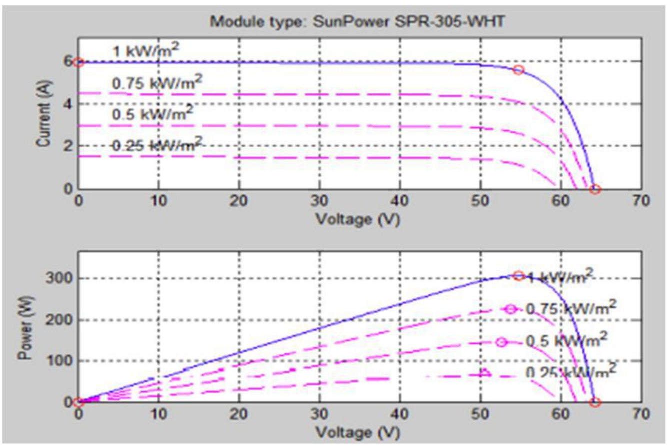


Fig-5: PV module voltage versus power and current curve

Different types of solar panels that exist, mostly fit into one of these three types as mentioned below. Each type has unique features that makes them better suited for certain solar projects.

- Monocrystalline (or simply Mono) solar panels
- Polycrystalline (or simply Poly) solar panels
- Thin film solar panels

Table -2: Characteristics of different PV modules types

Parameters	Mono Crys.	Poly Crys.	Thin film
Efficiency (light to electricity conv.)	high ~18%	low ~16%	medium ~12%
Temp. effect on efficiency	medium	low	high
Performance in hot climate	low	low	high
Performance in cold climate	high	high	high
Low radiation performance	low	low	high
Affected by shadow/ shading effect	high	high	low
Cost ($/W)	high	medium	low
Manufacturing process	complicated	simpler	simpler

Innovations taking place in module space and foreseen to dominate the market in the future is on PERC and Bi-facial technology. Bi-facial solar panel can produce additional energy yield dependent of the reflectiveness of the surface and can generate up to 25% more energy from its rear side with ideal installation conditions.

PERC (Passivated Emitter and Rear Cell) is a new technology in module aimed to achieve higher efficiency. In a standard solar cell, a portion of sunlight striking the cell exits through the back side while in PERC, with a special insulating layer between the silicon and aluminum back get trapped to increases light and produce more energy than standard cells.

4. INVERTER QUALIFICATION

Inverter is the most crucial component in a PV plant and designed to operate at rated output for 25 years but still need to be competitively priced. So, the manufacturers have to make tough cost versus reliability trade-offs. Customer need to find a compatible inverter model for their project considering various factors like technical parameter as in PPA and to meet their business financial goals. Following are critical qualification parameters customer evaluates before selecting an inverter for their project.

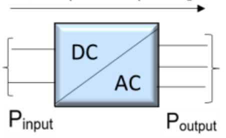
1. Technicality
   a) Power rating: kVA, kW, kVAR
   b) Technology
   c) Design margins
   d) Features: basic and addons
2. Certification: standards and compliances
3. Compatibility: with AC/ DC BOS and for rest of plant
4. Product track record (Install base)
5. Manufacturing Process: MQP, QAP
6. Reliability, availability, and maintenance (RAM) analysis
7. Guarantee and warranties
   a) Warranty (against workmanship or material)
   b) Availability (uptime) Guarantee
8. Serviceability
9. Pricing (value for money)
10. Manufacturer Bankability
11. Manufacturer qualification audit

4.1 Product Technical

a) Power Ratings

The number of inverters selected during plant design is based on plant capacity i.e., kWac fed to grid, and individual inverter power ratings (kVA, kW, kVAR). PV inverters are designed to extract the maximum available power from PV arrays and its output power depends on site specific factors like ambient temperature, altitude and inverter design factors like conversion efficiency, active-reactive power (P-Q) capability, power derating due to ambient temperature and altitude etc.

$$P_{output} = P_{input} * \eta$$



$$P_{dc\ (max)} = I_{(dc\ max)} * V_{dc\ (max\ MPPT)}$$

$$P_{ac\ (max)} = \sqrt{3} * V_{rms\ (max)} * I_{(rms\ max)} * \cos\phi$$

$$V_{rms\ (L\text{-}L)} = \frac{m_{(modulation\ index)} * V_{dc\ (MPPT)}}{\sqrt{2}}$$

It is not only the active power output capacity of inverter, but also important to know is inverter reactive power compensation capacity which is helpful to support grid stability as demanded by local grid codes. P-Q curve specifies active and reactive power capability of an inverter at specified ambient temperature and grid voltage level.

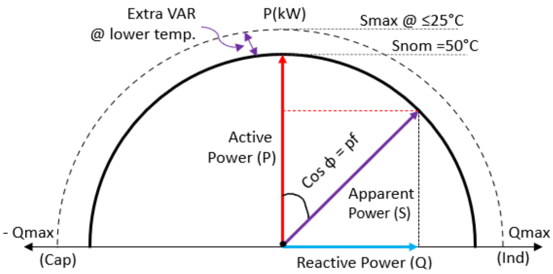


Fig -6: Typical P-Q curve representation of an inverter

Based on inverter apparent power S (kVA) and active power P (kW), reactive power compensation Q (kVAR) is calculated as:

$$Q=\sqrt{(S^2)-(P^2)} \quad \text{OR} \quad Q_{max}=\sqrt{(S^2max)-(Pdc)^2}$$

With solar panel price reducing gradually and the goal of achieving maximizing financial returns, the trend now is to size dc input power upto 50% more than nominal AC power fed to grid (i.e., dc to ac ratio =1.5). Use of module tracker (compared to fixed tilt) and bi-facial modules (compared to mono-facial) also increases dc loading factors on inverters. Higher dc loading increases available power from PV array but also has following impact on an inverter:

- Increased available short circuit current from pv array
- Increased daily operation hours and higher maintenance
- Reduced reliability and lifetime
- Increased clipping loss

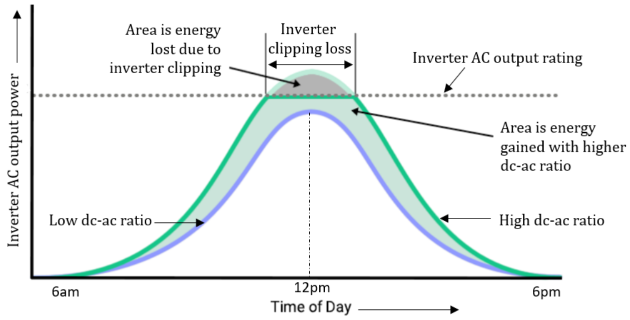


Fig -7: DC overload and clip loss in an inverter

Inverter at higher installation site altitude (normally >1000 m.) reduces output current and hence the power based on ambient temperature. This is due to the fact that air is thinner at higher elevation which decreases the cooling capacity.

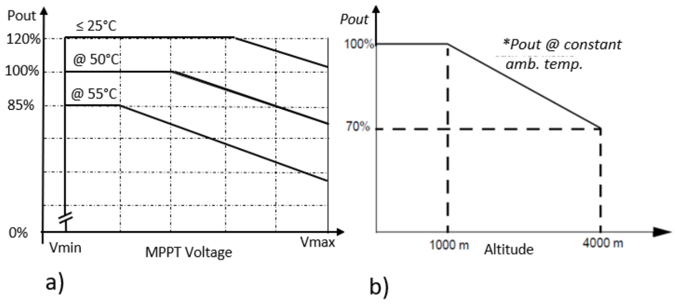


Fig -8: Typical Inverter output power versus a) ambient temperature, dc voltage and b) altitude derating curve

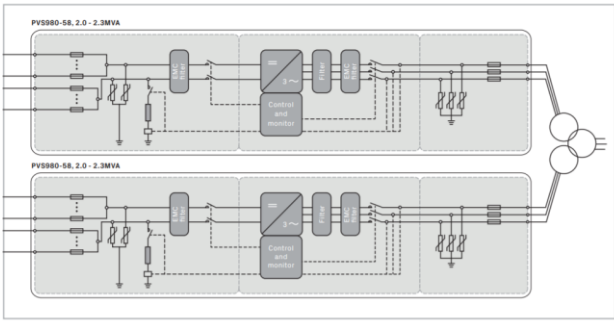
Inverter conversion efficiency (i.e., the ratio of dc input power to ac output power) is function of the input dc voltage level and ambient temperature. Lower the dc input voltage, higher the conversion efficiency due to the fact that switching loss in power switches reduces with dc voltage level. Lower the temperature, lower the heat losses and higher the efficiency.

To reduce overall plant cost of ownership or LCOE, utility-scale solar customers size higher capacity power block, which is an integration of multiple inverters with common a LV/MV transformer and MV circuit breaker. These equipments together mounted on a metal structure is called skid solution which reduces field installation cost and workmanship errors at site. Connection between the inverter and LV/MV transformer in skid is made through busduct which reduces cable loss and increases system efficiency.

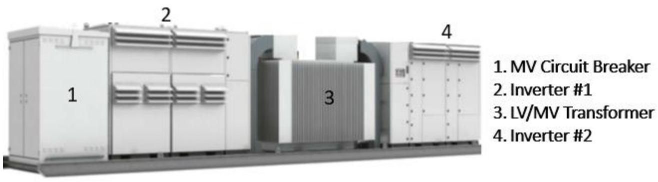
Table -3: Typical 100MWac power blocks configuration

Plant Size in MWac	100			
Individual inverter ratings in MW	1.3	2.5	3.13	5
No. of inverters	80	40	32	20
No. of Sec. windings - Per LV/MV TRF	2	2	2	2
LV/MV TRF ratings in MW	2.5	5	6.25	10
No. of LV/MV TRF	40	20	16	10
Power block size in MWac	2.5	5	6.25	10
No. of MV circuit breakers	40	20	16	10

Inverters are connected to more than two secondaries in a transformer. Four secondaries are common, but six secondaries are also available. With inverter now being developed with high power capacities like e.g., 3.125MW, 5MW etc., the transformer MVA and hence power block ratings are increasing even with reduced number of inverters and number of transformer secondary windings.



a) Single line diagram



b) Equipment details

Fig -9: a) and b) Skid solution power block with two inverters (Reference: FIMER compact skid solution)

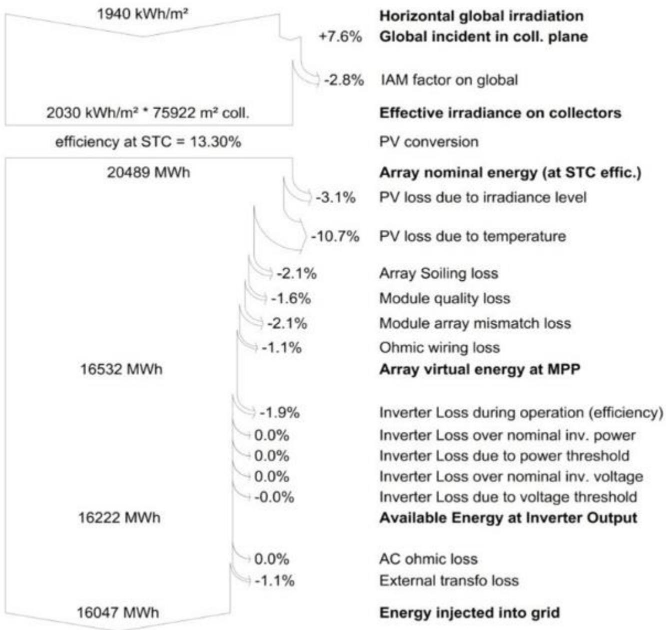
PV-Syst is the most popular and commonly used simulation software estimates the performance of the solar power plant in terms of AEP (annual energy production in kWH) and performance ratio (PR in %) representing losses at various stages of plant. The software uses .PAN file as model for PV module, and .OND file as an inverter model. PVsyst represents the loss contributed by an inverter are as tabulated below:

- **Inverter loss during operation (efficiency)** is inverter's DC to AC conversion efficiency, weighted for variance in power levels.
- **Inverter loss over nominal inverter power** is power clipping in overloading where the array produces more dc power than the maximum ac output of the inverter.
- **Inverter loss due to power threshold** is the loss of energy when the array operates below the inverter minimum power threshold.
- **Inverter loss over nominal inverter voltage** is the energy loss when the array is producing voltage below the inverter MPP voltage range.
- **Inverter loss due to voltage threshold** is the energy loss when the array is producing voltage above the inverter MPP voltage range.
- **AC and dc ohmic wiring loss** is the voltage drop due to wiring resistance and is calculated as one value for the whole system. The value is based on plant design including contribution from inverter power block size.

The Maximum Power Point Tracking (MPPT) range or window of an inverter decides how long the inverter stays connected during the day. Wider the MPPT range in an inverter, the higher the energy harvest. Higher inverter ac output voltage reduces MPPT window thus impacting energy harvest and is represented as voltage threshold loss.

An .OND (One Note Database) file contains specifications of an inverter used in the PVsyst simulation. OND file acting an inverter model in PVSyst is normally certified by third party agencies like TUV, DNV etc. to confirm the accuracy especially the efficiency, deratings with respect to data sheet parameters and type test reports.

Table -4: Typical PVSyst loss analysis in 10MW PV plant



To study impact on power system caused by PV system and by grid on solar inverter in utility scale PV plant, other forms of PV solar inverter model are used in simulation software like PSSE (Power System Simulator for Engineering), PowerFactory from DIgSILENT, PSCAD (Power System Computer Aided Design).

b) Inverter Features

In addition to basic features in an inverter, extra features (as listed below) sold by manufacturer as an optional depends upon customer requirements and compliance.

- Number of dc inputs
  - With or without dc fuse (zonal or string) protection
  - With or without dc current (zonal or string) monitoring
- Auxiliary power supply (external or inbuilt)
- Night VAR compensation feature (some make, and models has this feature as default)
- Surge protection type: type 2 or type 1+2
- Type of dc input and ac output switchgear protection type like ACB, MCCB, manual /electric operated isolator etc.
- Type of interface to LV/MV transformer: Busbar or cable connection
- Type of communication: Inverter interface with external controller like SCADA, PPC etc.

- Customer IOs (digital, analogue) types: For Inverter to interface with external customer equipment like LV/MV transformer, MV circuit breaker etc.
- Low temperature (cold weather) option (< -20°C)
- High altitude operation (>2000m altitude)

Inverter short circuit current (Isc) is limited by percentage impedance (z%) of inverter and is mostly decided by inductance value of output filter. Based on design inverter models may have one inductance (in LC filter) or two inductances (in LCL filter). Some inverter manufacturer (if their design permits) considers trade-off in passing on extra percentage of this impedance into LV/MV transformer scope or to include in inverter scope with additional cost.

For a line inductance in output filter, operating voltage, and frequency of 74μH, 690V and 50 Hz. respectively, then as per below relation, the z% and Isc calculated is 5% and 17kA respectively.

- Isc = Irated / Z%
- Z% = √3 * I * XL (Where XL = 2*π*F*L)

c) Product Design and Technology

i) DC input voltage: 1000V verses 1500V DC

The maximum dc voltage in IEC standard for LV equipment is 1500V. DC voltage of solar inverter has increased from 1000 to 1500 volts in order to achieve higher power rating with lower system cost as higher system voltage reduces number of arrays, its associated cables, combiner boxes. Higher the system voltage also contributes to reduced I^2R loss in cables. Major challenges in high voltage product design are maintaining insulation levels, creepages and clearances.

Table -5: Comparison of current per kW in 1000V and 1500V DC inverter products

Nominal AC Output Power -kW	1000	
Max. Input DC Voltage - Volts	1000	1500
Min MPPT Voltage - Volts	605	980
Max. DC Current - Amps	1653	1020
Nominal AC current - Amps	1443	875
Nominal AC Voltage - Volts	400	660
DC Current per kWac - A/kWac	1.65	1.02
AC Current per kWac - A/kWac	1.44	0.87

Sooner rather than later, 1500Vdc system can be a history and the benchmark could hit 2000Vdc technology, but, regulation and product certification may delay the adoption of this next technological phase.

ii) Inverter Bridge Topology – Three level vs Two level

Multi-level PWM topology like three level is an efficient technology in PV inverter applications, which improves quality of output voltage and current. Normally topology used in 1000V and 1500V dc inverter is two level (2L) and three level (3L) respectively. Compared to conventional two-level, the three-level topology has following advantages:

- reduced losses in magnetics contributing to increased efficiency
- reduced stress on IGBT switches
- reduced output harmonics distortion and hence the size of the magnetic components like inductor chokes
- lower dv/dt of output voltage and thus less stress on output cables and LV/MV transformer windings

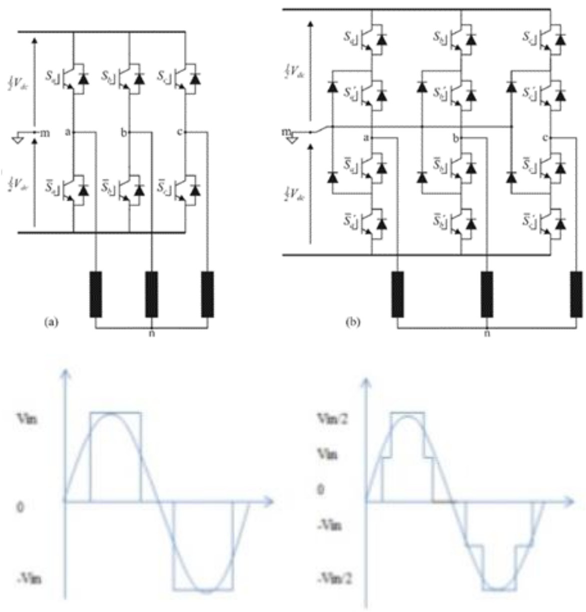


Fig -10: Two level and three level (NPC) based topology

Advanced version of 3L-NPC called active NPC (ANPC) topology is derived by adding an active switch in anti-parallel to each clamping diode. This topology performs superior to NPC in providing more zero switching states to evenly distribute IGBT losses and maintain junction temperatures.

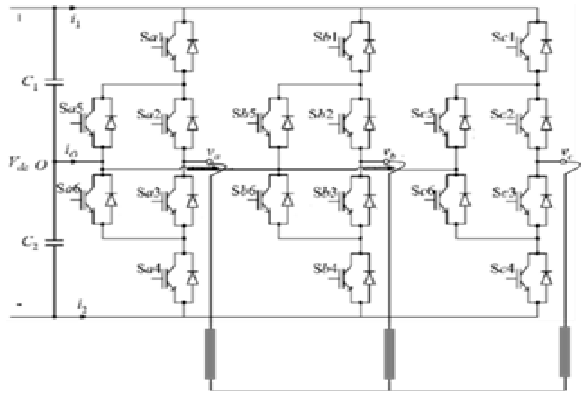


Fig -11: Three level (3L) Active NPC (ANPC) based topology

iii) Component Design Margins

For long term reliable operation and 25 years of useful life critical components of inverter like IGBTs, capacitors, cooling fans etc. are selected with enough design margin when subjected to extreme operational conditions. Design margin in critical components minimizes inverter failure rates, improves availability, and reduces Mean Time to Repair (MTTR). Considering the design stress of each critical components, it is necessary for customer to understand and evaluate design margins which decides design life of inverter.

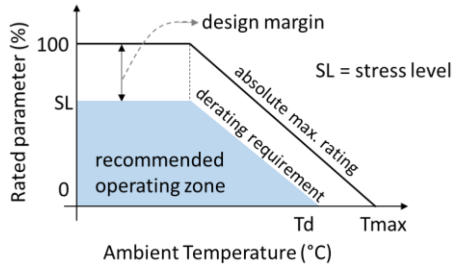


Fig -12: Component stress level and their design margins

DC bus capacitors used are normally thin film type for their relatively less degradation and longer life. Capacitor lifetime is stressed by higher operating voltage, ripple, and temperature. The peak-to-peak amplitude of voltage ripple is determined by the inverter switching frequency, PV voltage, DC capacitance, and filter inductance. As a rule of thumb, the lifetime of metallized thin film capacitors will halve every 8°C above rated operation temperature. Capacitor lifetime also shortens if inverters take part in LVRT, VAR management.

IGBTs switching at high voltage exhibits high dv/dt and gets electrically and thermally stressed. So, to ensure that these devices won't exceed maximum limits as in data sheet especially its collector -emitter voltage, collector current and junction temperature. As per leading global provider of high power IGBTs to solar inverter manufactures, the failure rate doubles with each 20°C rise in temperature. In a good designed solar inverter, the IGBTs experiences <90°C when operating full load power at 50 °C conditions. With a design rating of 150°C (as junction temperature) and in conjunction with software control and thermal management, the junction temperature rise is kept below 90°C threshold and power is fold back (de-rate) if temperature exceeds this threshold.

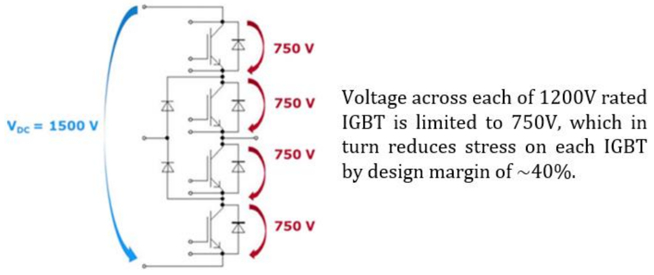


Fig -13: IGBT stress level in 1500V 3L- NPC topology

Table-6: Typical useful life predications of DC bus capacitor

Life expectancy at Vnom and at specified internal hotspot temperature	100,000 hrs. or 100,000/(8*365)=34 yrs.
Life expectancy at Vnom and at +10°C higher temp.	40,000 hrs. or 40,000 / (8*365) =13.7 yrs.
Recommended replacement is after 13 yrs. of useful life	

Table-7: Typical useful life predications of DC bus capacitor

Life expectancy at 8hrs usage/day and at 40°C	57323 hrs. or 57323 / (8/365) =20 yrs.
Life expectancy at 8hrs usage / day and at 60°C	36591 hrs. or 36591 / (8/365) =12.5 yrs.
Recommended replacement is after 12 yrs. of useful life	

iv) Thermal Management

Electrical components within inverters operates more efficiently at cooler temperatures and this helps in reducing power loss and increasing the efficiency, performance, and lifetime of an inverter. Higher dc/ac ratio causes inverter to work for longer hours resulting higher losses which calls for inverter thermal management to safeguards temperature sensitive components. Following factors are considered for efficient thermal management in an inverter:

- Component selection with better thermal margins
- Efficient cooling system with speed-controlled fans
- Software control to limit current to avoid component overheating.

Forced air cooling is simple, reliable, easy to maintain, relatively low in cost and hence is popular cooling method adopted by most of Inverter manufacturer. But air being relatively poor transport mechanism of removing heat and is not effective for large power inverter. Byproduct of air-cooled inverters is usage of large number of fans and blowers which are relatively unreliable compared to the electrical components. For this reason, high reliability design reduces fan count as much as possible.

Liquid cooled inverters use a simple low power pump and fans as the primary cooling element. Because air is a poor conductor of heat, air-cooled system, typically have a PPM (parts per MW) metric that is 5X higher than that of a liquid-cooled inverter. While liquid cooling is effective even in site located in desert but are less reliable due to more maintenance issues. Heat pipe technique combines the principles of both thermal conductivity and phase transition to effectively transfer heat.

Type of cooling system in an inverter is also based on product enclosure type. And the type of enclosure design is based on following parameters:

- withstand harsh environmental conditions like summer sunrays, winter snow /ice, desert dust etc.
- meet defined IP and arc flash safety compliance
- effective ventilation to remove internal heat
- effective in earthquake prone area and stringent seismic compliance standards

Enclosure Ingress Protection (IP) code rates the degree of protection provided by mechanical casings against intrusion, dust, accidental contact, and water. Enclosure IP is defined by IEC 60529 and as well as by NEMA standard.

Table-8: Enclosure IP definition as per IEC 60529

First number Solid intrusion (IPX_)		Second number Liquid intrusion (IP_X)	
IP	Protection	IP	Protection
0	No protection	0	No protection
1	Protection against solid objects upto 50mm	1	Protection against vertically falling water drops.
2	Protection against solid objects upto 12mm	2	Protection against direct spray of water upto 15° from vertical
3	Protection against solid objects upto 2.5mm	3	Protection against direct spray of water upto 60° from vertical
4	Protection against solid objects upto 1mm	4	Protection against water sprayed from all directions
5	Protection against dust (limited)	5	Protection against low pressure jet of water from all directions
6	Totally protected against dust	6	Protection against strong pressure jet of water from all directions
		7	Protection against strong pressure jet of water from all directions

IEC and NEMA ratings are not exactly equivalent. NEMA require additional product features and tests which are not addressed by IEC, but with some resemblance.

Table -9: IEC and NEMA comparison for enclosure IP

NEMA		IEC
1	General Purpose - Indoor	IP10
2	Drip-Proof - Indoor	IP11
3	Dust-tight, Rain-tight, Sleet-tight - Outdoor	IP54
3R	Rain-tight, Sleet Resistant- Outdoor	IP14
3S	Dust-tight, Rain-tight, Sleet-tight- Outdoor	IP54
4	Water-tight, Dust-tight, Sleet Resistant- Indoor & Outdoor	IP56
4X	Water-tight, Dust-tight, Corrosion-Resistant- Indoor & Outdoor	IP56
5	Dust-tight, Drip-Proof--Indoor	IP52
6	Occasionally Submersible, Watertight, Sleet Resistant- Indoor & Outdoor	IP67
6P	Water-tight, Sleet Resistant- Prolonged Submersion- Indoor & Outdoor	IP67
12	Dust-tight and Drip-tight- Indoor	IP52
12K	Dust-tight and Drip-tight, with Knockouts- Indoor	IP52
13	Oil-tight and Dust-tight- Indoor	IP54

Type and thickness of steel material, power coating and salt spray testing are the parameters considered for enclosure based on corrosive level atmospheric installation.

- Enclosure outer surface steel sheet material and thickness as per ASTM 304.
- Powder coating typically applied electrostatically to create a hard finish with thickness of around 80 -120µm.
- ASTM B117 is a salt spray test to check degree of corrosion resistance of materials and surface coatings.

Table -10: Environment categories based on ISO 12944-2 / ISO 9223.

Environment category	Corrosion risk	Typical location
C1	Very Low	heated buildings with clean atmospheres such as schools or offices
C2	Low	atmospheres with low levels of pollution, mostly rural areas
C3	Medium	urban and industrial atmospheres, moderate sulfur dioxide pollution, or coastal areas with low salinity
C4	High	industrial areas and coastal areas with moderate salinity
C5-I	very high (industrial)	industrial areas with high humidity and aggressive atmospheres
C5-M	very high (marine)	coastal and offshore areas with high salinity

Ambient conditions like temperature, humidity, altitude varies from site to site i.e., desert (sandy air) and seashore (salty air) for example. For outdoor installation inverters IP55 or more is preferred and based on site condition inverter manufacturers sometimes recommends customer to have canopy over inverter for additional protection of inverter from sun's heat and UV, rain and also for personal during maintenance.

4.2 Product certification: Standards and compliance

Product testing and certification process ensures that product design meet standards and performs as intended. Product is tested for applicable standards relevant to safety, performance, reliability and grid code and certificates are issued by an accredited independent organization like TUV, BV, Intertek, CSA etc. Inverter product manufacturers and customer rely on such certification including listing on the certification body's website, to assure quality to the end user and those competing suppliers are on the same level.

Refer section 10.1 for list of applicable standards and utility codes in grid tied central inverters.

4.3 Product compatibility with AC and DC BOS

It is important that the inverter selected even on merits of its design, technology, and performance is essential to be compatible enough to interface with overall plant system to operate optimally. Specifications of certain BOS equipments like LV/MV transformer, ac and dc input cables etc. are defined by inverter manufacturers. Some parameters are defined by customer based on plant design for inverter to comply like communication type to interface with external controller and number of dc fuses based on array size etc.

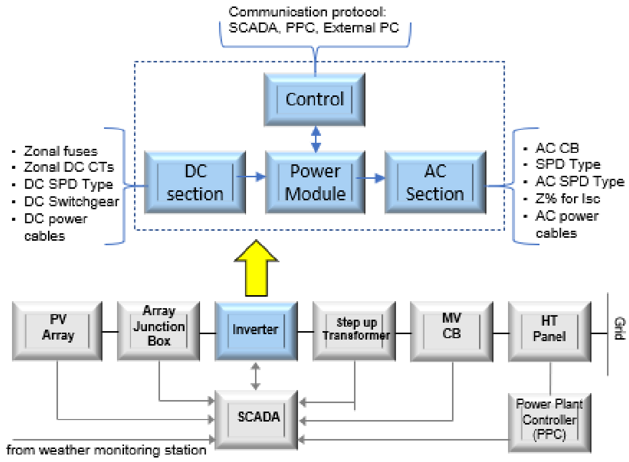


Fig -14: Inverter interface to AC and DC BOS

4.3.1 Inverter AC Output Interface

- **Inverter Transformer**

To step up inverter output voltage and sync with the grid voltage level, the transformer used are commonly called as "Inverter duty transformer" (IDT) or LV/MV transformer. Based on selected inverter model, the key parameters to be considered for the selection of inverter transformers are:

- Nominal power rating (with continuous and overloading)
- LV voltage level and frequency
- Voltage rise withstands - dv/dt (typically <1kV/µs)
- THDi harmonics pattern including dc current
- Minimum Isc impedance (typically ≥6%)
- Voltage withstand level wrt ground
- Winding connection (star /delta) and vector groups for e.g., Dy11d0 or Dy11y11 in case of three winding transformer. Normally star point of LV side is recommended to be floating in IT grounding system.

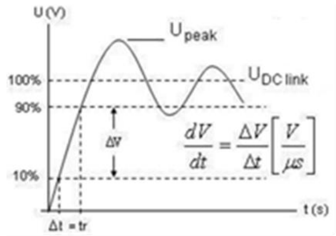
Inverter duty (LV/MV) transformer provides galvanic isolation between the PV array and the utility grid by breaking ground loops. Besides, it guarantees no DC current is injected into the grid else there exist a common-mode voltage which generates common-mode currents, which produces electromagnetic interferences, and grid current distortion. Vector sum of all three voltage in 3-phase supply should be zero which is possible in pure sine waveforms. This is not the case in PWM based inverter as its output voltage swings rapidly with switching frequency creating source of common mode voltage.

In a 3-phase transformer the primary and secondary windings are connected in different combination of star (Y), delta (Δ) and zig zag to mitigate harmonics. Delta winding in transformer reduces third order harmonics. Vector group indicates phase displacement expressed as the clock hour number. For e.g., Dyn11 transformer has delta (Δ) connected primary and a star (Y)connected secondary winding with star point (n) brought out. In Dyn11, the LV lead HV by phase shift of 30 deg (11° clock).

Table -11: Transformer vector group types

Degree	Phase relation	Connection	Degree	Phase relation	Connection
0°	In phase	Yy0, Dd0	180	Lag(180°)	Yy6, Dd6
30°	Lag(30°)	Yd1, Dy1	150	Lead150°)	Yd7, Dy7
60	Lag(-60°)	Dd2	120	Lead 50°)	Dd8
120	Lag(-20°)	Dd4	60	Lead (60°)	Dd10
150	Lag(150°)	Yd5, Dy5	30	Lead (30°)	Yd11, Dy11

Voltage spikes (dv/dt) generated by PWM based inverter results very high voltages leads to insulation damage in cables and winding in transformers. It also contributes to conducted EMI. Inverter output (LCL) filter reduces the dv/dt to acceptable limits to ~1kV per µs in LV system



Tr = time needed for voltage to rise from 10 to 90% of Vdc

Fig -15: Typical dv/dt curve

As a general rule, the voltage spike due to rate of change of voltage (dv/dt) is twice the DC bus voltage. i.e., in 690Vrms, the max voltage spike is calculated as 690*√2*2=1952V. AC interface equipments like inverter output cables, AC circuit breakers, transformers are rated to handle this higher voltage else this voltage level reduces service life for the equipment.

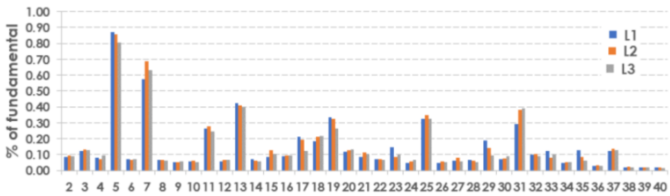


Fig -16: Typical inverter current harmonics (THDi) pattern

Total current harmonic distortion (THDi) is given by:

$$THD_i(\%) = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \dots I_n^2}}{I_1}$$

I_n = rms value of n_{th} order current
I_1 = rms value of fundamental current

RMS current for sizing cables and transformer is given by:

$$I_{rms} = I_1 * \sqrt{1 + THD_i^2}$$

- **AC Output connections**

The ac output interface of inverter to LV/MV transformer can be either through cable or bus duct, depending on current rating and inverter design. Factors to be looked for inverter output interface are, conductor type Al or Cu, its size in sq.mm, no. of runs per phase, cable insulation level (1.8/3.0 kV in 1500V and 1.1kV in 1000V dc system) and appropriate gland plates for ac cable entry from inverter transformer.

Table -12: Cable voltage grades as per IEC

Voltage grade	Phase to earth	Phase to phase
0.6/1.1kV	0.6kV	1.1kV
1.1/1.9kV*	1.1kV	1.9kV
3.8/6.6kV	3.3kV	6.6kV
*e.g., √3*1.1kV = 1.9kV		

Copper when exposed to wet or high humidity environment corrodes or oxidizes and weaken faster causing poor electrical contact and arcing at the electrical contacts. This is mitigated by tinning i.e., applying tin as base alloy over copper. Tinning gives smooth shinny surface and reduces joint electrical resistance and increases system efficiency. Flat busbars are preferred in design over circular to reduce skin effect and increase thermal dissipation. Accepted thumb rule for busbar sizing is as given below of course with positive tolerance added based by designer based on material quality, system design and ambient temperature.

- Current density for aluminum: 0.8 Amps / Sq.mm
- Current density for copper: 1.2 Amps / Sq.mm

i.e., Aluminum busbar has current-carrying capacity equal to 0.8 times of its total volume (length*breath*thickness). For example, in case of 35 sq.mm Al bus bar, current carry capacity of the. busbar is 0.8* 35 = 28 Amps.

Gland plates in inverter for single core ac cable interface should be non-magnetic for e.g., aluminum. Because in single core, magnetic field around the cable heats up gland plates if made from magnetic materials like steel. In case of 3 core ac cables the gland plate can be magnetic, as all 3 phase currents are vectorially summed up and magnetic field around the cable get cancelled.

4.3.2 Inverter DC input interface

- Recommendations for dc cables input to inverter from PV array includes Al or Cu type and size in sq.mm and no. of runs per pole. Cable insulation level of 1.8/3.0kV in case of 1500V dc system and 1.1kV in case of 1000V dc system.
- Current ratings and nos. of DC input fuses within inverter is based on array junction box sizing i.e., current ratings and nos. of AJBs (array junction boxes). In case of pole grounding (either positive or negative grounding) only one ungrounded pole is protected by dc fuses within inverter. In case of floating system both polarities are protected with DC fuses.
- Zonal (string) level dc current measurement is not requirement for inverter control, but it is for plant level monitoring. Normally AJB are fitted with DC CTs. More the ability to monitor the system parameters (like zonal DC current in inverter) speeds up detection and correction of problems, increasing overall system performance and negates additional hardware cost.
- Type of SPD (type 2 or 1+2) is optional and is based DC side plant engineering.
- Each inverter manufacturer model has their standard ac and dc isolation philosophy with circuit breaker or / and contactor. Option for additional protection with lockable (LOTO) provision is based on local utility compliance and or customer requirement as per plant engineering.

4.3.3 Inverter Auxiliary Supply

Inverter auxiliary consumptions includes internal cooling, control supply for controller, contactor coils etc. This supply can be fed externally by customer or derived from inverter ac output with inbuilt stepdown (auxiliary) transformer.

As this supply is immune to grid fluctuation like LVRT, the auxiliary circuit includes buffer unit to support backup for specified duration (~20s) during grid voltage dip. If this power is supplied externally from customer UPS, surge protection device (SPD) is provided within the inverter. Manufacturer recommends type of grounding i.e., TN-S (grounded) or IT (ungrounded) to customer to comply, in case this supply is fed from inverter to customer load especially for SCADA, module tracker etc.

4.3.4 Inverter Communication Interface

Inverter has standard communication protocols like Ethernet, Modbus, PROFINET to interface with external customer controllers like SCADA and PPC. Provision in inverter for additional communication hardware for required protocols are optional and are based on customer requirement.

4.4 Product Install Base

Track record of install base (for the number of inverter units sold, commissioned and in service) indicates performance, reliability, safety issues of a similar product operating at site for specific time period. Customer likes to understand involvement and action in root cause analysis from R&D and engineering for if any repeating issues in the product at site.

Manufacturer launching a new product (NPI) in the market, must have the install base of its prototype unit, considering if any new design takes definite time (with multiple alternations) till the design gets mature. Buyer normally won't want their plant to be a lab for manufacturer (to experiment the product) until this is mutually agreed.

4.5 Manufacturing Process

In ongoing solar inverter market price trend, manufacturers are struggling to stand out from competitors to survive and hence prompting localization of components, and outsourcing manufacturing and assembly activities to sub-contractors leading to reliability issues at sites. Following are some of factor defines manufacturing process:

- Manufacturing Quality Plan (MQP)
- Manufacturing Process Quality KPIs
- Manufacturing (factory) Certifications

MQP also called as Quality Assurance Plan (QAP) is a contractual document between buyer and supplier as a commitment for delivery of product as per agreed technical specification. It covers testing and quality process of the product including sub- components manufactured (in-house and bought out). This document also includes quantum of checks during production, reference documents, acceptable norms and standards during routine checks and factory acceptance test (FAT) as per ISO 2859. This standard is acceptance sampling system for inspection in terms of the acceptance quality limit (AQL).

FAT is performed as per mutually agreed MQP to assure that the equipment meets all the contractual requirements and any issues if any can be addressed before product is dispatched to customer site and thus saves time and money over fixing issues at site.

Fig -17: FAT process parameters

Incoming quality checks (IQC) of raw material for production avoids potentially non-conformity, prior to moving it to the production or assembly line. Inspection is done on parts in accordance with customer purchase order, drawings and standards and other relevant documents. Statistical analysis is the preferred method of performing inspection. In some cases, inspection may be omitted for non-critical parts or if supplier is certified vendor. List of critical components normally considered for inspection are IGBT, Inductor chokes, DC link capacitors, busbars, switchgears, fuses, transducers (CTs), fans, electronic boards etc.

Manufacturing quality process is the guarantee for good product quality and to understand how effective the process performs is to measure its KPIs. Some of commonly used KPI are First Pass Yield (FPY), On Time Delivery (OTD) and Defects per Unit (DPU).

FPY measures the percentage of product made correctly without any rework activity while OTD indicates the rate of finished product produced (delivered) in time. DPU identifies the number of defects per manufactured unit. A defect is an occurrence of non-conformance to customer requirements and it is possible for a single product to have multiple defects.

- $FPY\ (\%) = \frac{\text{Nos. units produced without defects}}{\text{Total nos. of units produced}}$
- $DPU\ (\%) = \frac{\text{Total nos. of defects}}{\text{Total nos. of units}}$
- $OTD\ (\%) = \frac{\text{No. of units produced on-time}}{\text{Total nos. of units}}$

Traceability in manufacturing is an activity of collecting and managing information regarding what has been done in manufacturing processes from acceptance of raw materials, assembly process and shipment of products. If in case of product quality problem occurs, traceability record helps the manufacturer to takes effective measures promptly by recall, repair or replace of damaged parts of the products.

Factory (process) certification plays a key role to be a global player in the marketplace, to maintain consistency and quality of a product, process, or service across the nations. Usually, inverter manufacturer certifies for 'Design, manufacture, supply and service' of the inverter product'. ISO, UL, CE are few agencies in place for this type of certifications. Certification issued is by independent certification bodies but accredited by the IAF (The International Accreditation Forum) member to be internationally recognized. Some reputed and global certifying bodies are TUV Nord, DNV GL BV, etc.

International Organization for Standardization (ISO) ensures that products and services are safe, reliable and of good quality. Some of the necessary ISO standards applicable for inverter manufacturers are:

ISO 9001 specifies requirements for a quality management system (QMS) in an organization to demonstrate the ability to consistently provide products and services that meet statutory and regulatory requirements.

Manufacturer documents its QMS to clearly and concisely identify their processes, procedures and work instructions in order to explain and control how it meets the requirements of ISO 9001:2015.

- *A **process** states what needs to be done and why.*
- *A **procedure** states how the process needs to be done.*
- *A **work instruction** explains how to carry-out the procedure.*

Standard Operating Procedure (SOPs) are top-level documents that tell employees which actions to take under various circumstances and Work Instructions (WI) describe those actions in detail. WI ensures that the manufacturing processes are consistent, timely and repeatable. Work instructions narrows to an individual task within an SOP.

ISO 14001 sets out the requirements for an environmental management system (EMS) which helps organization to improve their environmental performance through more efficient use of resources and reduction of waste.

ISO 45001 specifies requirements for an occupational health and safety (OH&S) management system, which provide a structured framework for ensuring a safe and healthy workplace thus preventing injury and ill-health.

The UL certification is a North American product certification from Underwriter Laboratories (UL) shows that the product in question is tested to meets US and Canadian safety standards. UL audit includes inspection of UL rated inverter components, verify that the manufacturer has the required test equipment and are functioning properly and are calibrated at least once annually. Review the manufacturer's records to assure that the tests (relevant to routine safety and grid abnormality tests as in UL 1741, IEEE 1547, UL 62109) are being conducted and appropriate action is taken with respect to failures and rejections.

CE Mark is a symbol affixed to products before it is sold to European market, indicating that the product meets all the requirements of the relevant recognized European harmonized performance and safety standards.

4.6 RAM Analysis

RAM refers to reliability, availability, and maintainability. It addresses the weakest link in a product which helps to improve the overall product reliability.

Reliability is the probability of a product, that will perform its intended function adequately for a specified period of time. It defines the failure frequency and determines the uptime patterns.

Availability is the percentage of uptime over the time horizon and is determined by reliability and maintainability.

Maintainability describes how soon a unit can be repaired, which determines the downtime patterns.

Failure Mode and Effects Analysis (FMEA) is one of several tools to conduct RAM analysis. It is a methodology aimed in organizations to anticipate failure during the design stage by identifying all of the possible failures in a design or manufacturing process. It focuses on the risk assessment detection, elimination, and/or mitigation of critical risk events. Two types of FMEA are:

- Design Failure Mode Effects Analysis (DFMEA)
- Process Failure Mode Effects Analysis (PFMEA).

DFMEA helps to analyze potential failures of a product design whereas PFMEA helps to analyze potential failures of a particular process during manufacturing. Risk Priority Number (RPN) is a numerical assessment of the risk priority level in failure mode analysis. It is product of severity of failure mode, potential of failure occurrence and capability of failure detection and each is ranked on a scale of 1 to 10.

RPN = Severity x Occurrence x Detection

Root Cause Analysis (RCA) is problem-solving process and is an integral part of continuous improvement used to identify the root causes of a fault. FMEA is a proactive method i.e., looks ahead to what could happen while RCA i.e., analyzing a root cause of a problem occurred is reactive. Commonly used tools for root cause analysis are Pareto Chart, 5-Whys Analysis, Fishbone Diagram, 8D (eight disciplines), Failure Mode and Effects Analysis, DMAIC (Define, Measure, Analyze, Improve, and Control (DMAIC) etc.

4.7 Guarantee and Warranties

i. Warranty Against Workmanship or Materials

Manufacturer guarantees the product for a period after delivery from factory (Ex–Works), is free from any defects related to the components or manufacturing process, which may prevent the normal operation, installation, and maintenance under proper conditions. Normally inverter comes with a standard 5-year workmanship warranty and is extendable with typically 2- or 3-year increments.

Extended warranty from inverter manufacturer protects against unforeseen costs from issues that may arise over the life of plant. This future-proof assurance provides added confidence to financiers, developers, and utilities as it includes coverage of spares, remote and onsite diagnostic, and repair services. Independently verified MTBF product data also serves beneficial to customer over purchasing extended warrantees from inverter manufacturer.

ii. Availability (Uptime) Guarantee

Availability is defined as the percentage of time a product is able to produce electricity and this guarantee is based on the inverter not providing power due to inverter failure.

Inverter manufacturers offer uptime and guaranteed availability for their product as a part of service package in service level agreement (SLA) by capturing data from years of field operation, to take the mean time between failures and other reliability statistics. Based on service contract if availably goes below over a specified timeframe the manufacturer will pay or accrue a credit for the customer at a fixed rate either per kWh lost (based on solar irradiance) or at a flat rate per kWac (based on time down) that would have been delivered if the inverter was fully functional. Exceptions for this calculation not counting as downtime includes, external grid events, maintenance that requires a shutdown of the inverters etc.

With ongoing trends in industry, inverter manufacturers offer ≥ 99% annual availability guarantee. Manufacturer costs critical spares and recommend customer preventative maintenance plan with scheduled inspections, checks and measurements in inverter to support this guaranteed uptime.

4.8 Serviceability

It is critical to customer to understand the importance of after sale service support from the product manufacturer to attend repair or replacements during breakdown and maintain high uptime throughout lifecycle of the product.

Region wise warehouse (for spares) availability, competency and team size of service engineers are some of serviceability factors considered. Large-scale utility customers prefer advanced monitoring and diagnose software installed in inverters where manufacturer can remotely monitor, diagnose, and troubleshoot inverter (even on dedicated smartphone apps) and reduce dependency on maintenance staff and services. Common KPIs covered in service level agreement (SLA) are:

- **Acknowledgement time** also called reaction time is the time between detecting the problem (receipt or noticing of alarm/fault) at site and its acknowledgement by the manufacturer or its Authorized Service Provider (ASP) to deliver solution and /or dispatch a technician to site.
- **Intervention time** is the time the manufacturer takes to reach the site from the moment of acknowledgement. This time assesses the capacity of the manufacturer, how fast they can mobilize the service team and be on site.
- **Response time** is the sum of acknowledgement and intervention time. Minimum response times are guaranteed on the basis of fault classes classified on the basis of the unavailable power and the consequent potential loss of energy generation.
- **Resolution time** or repair time is the time to resolve the fault starting from the moment of reaching the site. This time is generally not guaranteed, because resolution often does not depend totally on the service contract.

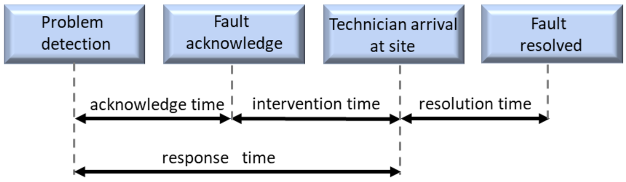


Fig -18: Key service deliverable KPIs

4.9 Pricing

Inverter price depends on state of art design, technology, ratings, add-on features, warranties, and volume of purchase. Manufacturer that demonstrates, or the buyer perceive, that the product quality is higher than similar competing product often support premium pricing. Inverter manufactures incorporates the cost of anticipated repair or replacements if any extended warranty period into their pricing structure. Inverter installation cost and plant BOS cost due to selected inverter also matters to customer on inverter pricing.

Market for utility scale solar projects in India is dominated by central inverters. 'The bigger, the better' seems to be the mantra-owing to the reason that inverter price depends on its power capacity. Each year, the National Renewable Energy Lab performs a cost benchmark

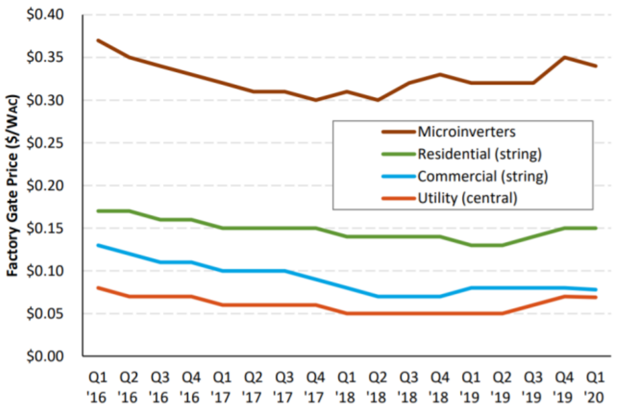


Fig -19: Solar inverter pricing (Q1- 2020 NREL Report)

4.10 Bankability

The bankability (i.e., financial health) of the supplier and hence their credibility is very important for investors. Considering utility-scale projects are expected to deliver 25 years of energy production, and investor making huge investment ensures, the key component suppliers like inverter manufacturing company is around for the life of the plant to support the project in terms of service and availability of replacement parts and secure project financing. As supplier bankability improves, financing risk is reduced, and this leads to lower financing costs and greater viability of projects.

Competition among inverter brands and reduced tariffs in PV solar market has caused numerous acquisitions and exits in recent times and hence there are very few (tier 1) inverter companies surviving globally. The best warranty does not matter if the manufacturer is not around to back it up.

4.11 Supplier Qualification Audit

It is challenging for a inverter manufacturer to keep consistency in material grade, type used and their seamless integration of mechanical and electrical components, change in sub-venders and skilled manpower time to time at factory as they are the main cause for variation in maintaining the consistency of manufacturing process and quality. Hence manufacturers are on their toes to offer cost-effective product.

This qualification process assesses manufacturer reliability, capability, capacity, and credentials. Customer expects that inverter product manufactured and delivered must perform defect free for its specified design life. This audit supports customer to have diligence to check control and consistency of design and manufacturing process.

Some of qualification parameters includes, manufacturing company organization, its mission, factory capacity & experience, licenses, certificates, production line, manufacturing process, machineries, and equipments, quality control plan, vendor management program, engineering process & design change control management, resolution of customer (site) complaints. As a part of the qualification audit, customer provides audit scores to manufacturers.

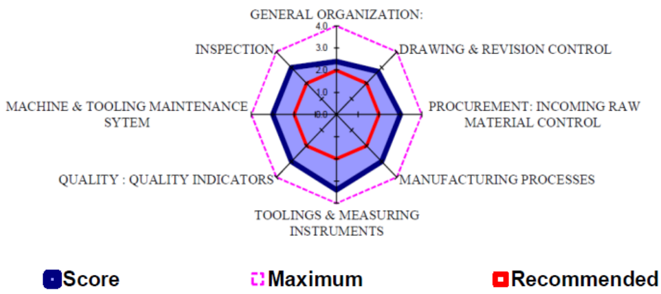


Fig -20: Typical graphical representation of audit score

5. INVERTER FUNCTIONALITY

Solar inverters produce alternating current with PWM technique i.e., high frequency chopping dc voltage with IGBTs. This rapid switching generates high dv/dt and di/dt and hence electromagnetic interference (EMI) noise from inverter. Multi-level topology and higher order LCL filters in inverter determines the quality of output fed to grid to comply to standards like IEEE, IEC, and local grid codes.

Solar inverter in process of performing its main task of converting dc to ac power, has three other important tasks:

- **MPPT Control**

Inverter input dc power is not all time constant as PV solar array is nonlinear i.e., varies with change in weather conditions like irradiation and temperature. Maximum power point tracker (MPPT) controller algorithm controls dc input voltage and current to provide maximum dc power and thus improves the system efficiency. The MPPT control algorithm in inverter is based on many techniques but Perturb and Observe (P&O) is used by most of the inverter manufacturers due to its simplicity and effectiveness.

- **Inverter control and protection**

Inverter control performs grid synchronization, voltage modulation, dc voltage regulation and current loop control. Inverter when synchronized to grid delivers active or reactive power based on PPC reference. Protection within inverter is set based on internal and external faults and as per specified grid codes. Internal ac fuses and ac breakers restrict damage to inverter. Input dc fuses protect the inverter dc circuit and dc input cables in case of short-circuit scenario. Inverter protects itself against thermal overload by power foldback or de-rating output power generation.

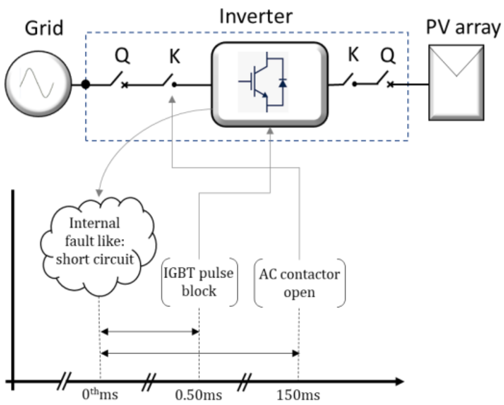


Fig -21: Typical inverter response in event of grid fault

- **Active and reactive power control**

Inverter delivers active and reactive power as demanded by PPC and as per inverter P-Q capability based on grid voltage, ambient temperature, and solar irradiance. Inverter synchronized to grid, offsets its current waveform from utility by delaying switching which creates sub-cycle energy exchange between inverter dc link and grid. This causes increase or decrease in grid voltage based on direction of reactive power flow.

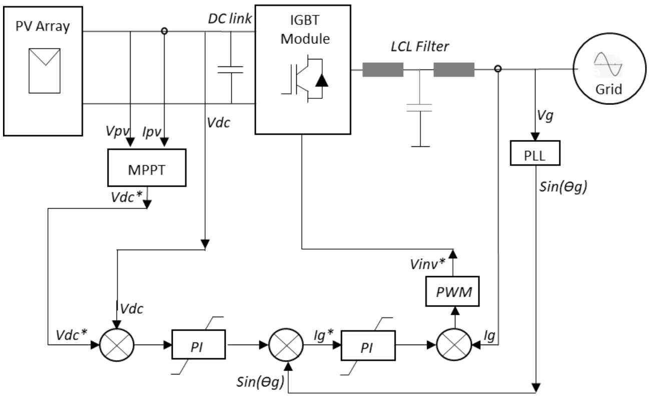
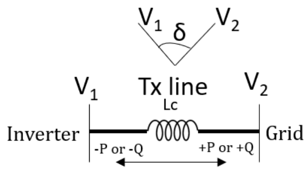


Fig 22: Inverter block diagram: Power and Control

According to the theory of instantaneous power, the reactive and active power of inverter can be regulated by changing the amplitude and the phase of inverter output voltage. The active and the reactive power compensation are realized simultaneously. The reactive power compensation feature improves the utilization factor of the inverter during non-sunshine hours or at night, to support grid voltage stabilization.

PV inverter runs in current control mode where active (Id) and reactive (Iq) current are constantly controlled. Under normal operation only active power is drawn from PV array and injected into grid. During grid fault i.e., when voltage dips, grid requires PV inverter to inject reactive power (Iq ά voltage dip) to support grid voltage. The active power (P) and reactive power (Q) flowing between the inverter and the grid is obtained by means of a phase analysis and is expressed as;



Case **- Inverter operation**
P > 0 (+P) - supply active power
P < 0 (-P) - absorb reactive power
Q > 0 (+Q) - supply reactive power
Q < 0 (-Q) - absorb reactive power

- Active power flow is determined by power angle δ
- Reactive power is determined by voltage magnitude IV_1I and IV_2I

$$P = \frac{V_1 * V_2 * \sin\delta}{2\Pi F L_C}$$

$$Q = \frac{V_1^2}{2\Pi F L_C} - \frac{V_1 * V_2 * \cos\delta}{2\Pi F L_C}$$

- V1 is inverter terminal voltage
- V2 is voltage on electric grid
- Lc is coupling inductance
- Phase difference between V1 and V2
- F is system frequency

Inverter also supports reactive power generation according to the defined curves such as Q(U), Q(P), and cosϕ (P). In Q(U) control mode, reactive power generated by the inverter depends on the grid voltage whereas in Q(P) control mode, the reactive power generated by the inverter is function of active power. In cosϕ (P) control mode, the reactive power generated by the inverter depends on the active power.

Historically, utilities were asked generators to disconnect from grid during abnormal voltage abnormality. But now inverters acting as distributed generators can easily control VAR or change PF through switching topology and can quickly become capacitive or inductive i.e., source and sink reactive power, the utilities are now asking inverters to keep connected during grid fault and support grid to stabilize with VAR control feature.

Centralized power stations often require power to be transmitted over long distances. But reactive power which is essential to stabilize gird is difficult to transport over long distance. So solar inverters acting as distributed generators (DG) installed close to the load, generates and absorbs reactive power to support grid stability.

6. Inverter Design CTQs

Design of an inverter product is measured in CTQs (critical to quality) parameters. Considering on-going market trends, typical CTQs considered by inverter product manufacturer are as listed below:

- Modularity:
  -Redundant design to reduce downtime
- Utilization:
  -Overload ≥ 120%
  -High DC / AC ratio ≥1.5
- Conversion efficiency:

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- η_{max} >99%
- η_{euro} ≥98.8%

- Auxiliary power consumption:
  -Less than 0.5% of Pnom
- Thermal Performance
  -More than 55°C and upto 60°C
- Availability
  -More than 99.5%
- Footprint
  -Reduced weight ≤ 1.5 Kg/kW
  -High power density ≤5 m3 /MWac
- BOM cost (standard)
  ≤10 lac INR (or 13.5 k$) per MWac
- High reliability with better design margins in terms of MTBF
- Reduced MTTR with direct accessibility and reduced replacement time for critical components.

7. PERFORMANCE

Conversion efficiency and cooling are the two most important factors decides PV inverter performance which is dependent on design of power electronics (IGBTs) switching circuit and thermal management.

Next generation power electronic devices like IGBTs with Silicon Carbide (SiC) technology has increased power conversion efficiency compared to conventional silicon (Si) devices. SiC based power devices switch faster, operate at much higher switching frequencies and temperatures, managing the same level of power as Si devices but at approximately half the size. This enables dramatic increase in power density and allows simpler cooling design and fewer parts, thus a smaller and more compact inverter footprint.

7.1 Inverter Efficiency

Losses in inverter are due to factors like conversion loss, losses associated with magnetics, copper, and self-consumption. Inverters in process of converting dc to ac power, produces loss also called conversion loss due to heat generating during IGBT switching. This loss decides inverter conversion efficiency. For e.g., a 1 MW inverter with 98% conversion efficiency mean it has 2% or 20-kW loss. For a given inverter design, efficiency depends on ambient temperature and DC voltage level. Efficiency is more at minimum MPPT voltage due to reduced PWM switching losses. Manufacturer specify efficiency at minimum MPPT voltage level and standard operating temperature around 25°C as per design. Conversion efficiency is not a fixed number but a curve which fluctuates with the input power or voltage. Commonly measured efficiencies are: Euro, CEC and Peak or max efficiency.

Practically inverter operates at its peak efficiency only for a small period of the day. And this is why the weighted efficiencies like Euro (European) and CEC (California Energy Commission) have been developed to indicate how an inverter might perform throughout the day. Euro and CEC efficiencies differs on loading levels and based on climatic conditions in Europe region (for Euro) and California including US south-west regions (for CEC) respectively.

Table -13: Euro and CEC efficiency weightage table

Euro Efficiency						
% Loading	5	10	20	30	50	100
weight in pu	0.03	0.06	0.13	0.1	0.48	0.2
CEC Efficiency						
% Loading	10	20	30	50	75	100
weight in pu	0.04	0.05	0.12	0.21	0.53	0.05

Table -14: Typical efficiency values at different DC voltage levels and loading points

Output %	5%	10%	20%	25%	30%	50%	75%	100 %
Vmin	97.02	98.26	98.8	98.8	98.82	98.75	98.54	98.29
Vnom	96.26	97.79	98.4	98.48	98.51	98.47	98.28	98.0
Vmax	95.7	97.56	98.26	98.36	98.4	98.37	98.18	97.93

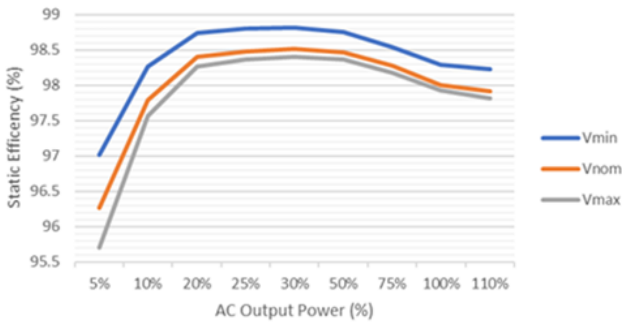


Fig -23: Efficiency curve at different dc voltage levels

Based on efficiency at different loading (at min MPPT) and weightages as in above tables, the Euro and CEC efficiencies are calculated as below:

Euro Efficiency
= 0.03 x 97.02 + 0.06 x 98.26 + 0.13 x 98.74 + 0.1 x 98.82 + 0.48 x98.75 + 0.2 x 98.29 = 98.58%

CEC Efficiency
= 0.04 x98.26 + 0.05 x98.74 + 0.12 x 98.82 + 0.21 x 98.75 + 0.53 x 98.54 + 0.05 x 98.29 = 98.60%

Peak (Max) efficiency = 98.75% -> 98.8%

As per IEC 61683, the worst accuracy of the conversion efficiency is given as: Max deviation = $\pm 0.2 * (1 - \eta) * \eta$%. So, for η_{max} of 98.5%, the worst accuracy is ±0.3%. This is below the tolerance value of measuring instrument like precision power analyzer Yokogawa WT3000 which is < ±0.2%.

7.2 Thermal Management

The performance and lifetime of an inverter depend on its operating temperature. Hence better thermal management is very essential for entering the next era of PV inverter. The most heat generating components with-in an Inverter are:

- IGBT modules
- Inductor chokes
- Aux. internal transformers

- Control supply (SMPS) units
- Current carrying busbars also contributes to some extent

The operating temperature of components selected is normally more than the temperature experienced within enclosure. Considering there exists temperature difference (ΔT) between the ambient and the anticipated product enclosure, together with the volume of air, the amount of heat that can be removed from the enclosure can be determined. The thermal design of a product begins with the method of determining the cooling method. The selection of cooling methods is based on the heat flow density, temperature rise, reliability, size, weight, and cost. Most popular cooling technique includes (forced) air cooling, liquid cooling, heat pipes system.

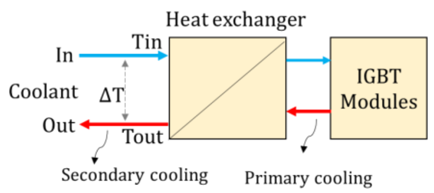
In forced cooling, the fans are always used with filters to reduce the dust entering the enclosure. As a thumb rule, a filter reduces the airflow by about one third. Therefore, when selecting the fan size, the free flow CFM should be three times the required air flow rate to provide sufficient cooling. In forced air-cooling method, the fan capacity selected to remove the amount of heat with the given temperature differential is calculated as per below relation:

$$CFM = Q / (Cp * r * Dt) \quad or$$

$$CFM = (1760 * Q \text{ in kW}) / (Dt\ °C) \quad \text{...for constant Sp. heat \& density}$$

- *CFM = volume over time in cubic feet per minute (ft^3/min)*
- *Q = heat transfer (kW)*
- *Cp = specific heat of air*
- *r = density*
- *Dt = change in temperature in °C*

Air is relatively a poor transport medium of removing heat and is not so effective for large power equipments. Hence alternative coolant medium like liquid cooling, heat pipes is adopted. In liquid cooling, the required coolant flow rate is calculated as per relation shown below:



$$\text{Flow rate in } m^3/hr. = \left[\frac{Pkw}{(Tout - Tin) * (\rho Cp/3600)} \right]$$

- Tin = inlet temperature in °C
- Tout = outlet temperature °C
- Pkw = heat loss in kW
- ρ = specific gravity in kg/m^3
- Cp= specific heat in J/kg/K

Forced air cooling is simple, reliable, easy to maintain, relatively low in cost and hence is popular cooling method. Liquid cooling is effective even in site located in desert but is less reliable due to more maintenance issues. Heat pipe works on the principles of both thermal conductivity and phase transition to effectively transfer heat between two solid interfaces. Heat pipes technology delivers the performance of water cooling with use of air cooling. It contains no mechanical moving parts and typically require no maintenance which makes the inverter suitable for outdoor utility-scale PV plants.

8. INVERTER RELIABILITY

"Product Reliability is defined as the probability that a product will perform its required function, subjected to stated conditions, for a specific period of time". Product reliability is quantified in MTBF (Mean Time Between Failures) for repairable components and MTTF (Mean Time to Failure) for non-repairable components.

Performance guarantees and longer warrantees of PV products is the need the industry. Inverter is considered as a weak link in PV systems, and very few inverter manufactures provide a warranty beyond 5 years. As project paybacks are typically more than 5 years, customers push inverter manufacturers to demonstrate higher product reliability. Reliability for solar inverter increases with reduced parts count, number of wired connections and increased design safety margins on its critical components.

Reliability (R) is given by R=e(-λt). As an example, for failure rate (λ) of 0.5%, reliability for one year (or probability of inverter not failing within one year) is 0.995 or 99.5%. For 10 years, this will be 95.1%. Another parameter used to check failure frequency is the mean time between failures (MTBF) and is given by MTBF = (1/ failure rate). In this case for a failure rate of 0.5 %, the expected time between failures is 1/0.005 = 200 inverter-years.

Reliability in terms of MTBF is given by R= e-t/MTBF

Failure Rate (λ̃) is defined as the frequency with which an engineered system fails as defined by reliability engineering. It is the most common metric for measuring the reliability of inverters. The failure rate over time follows a curve that looks like a bathtub which has three zones: Infant mortality, useful life and wear out.

Equation exponential modelling of the bathtub curve is given by: P(t) = e-t/MTBF

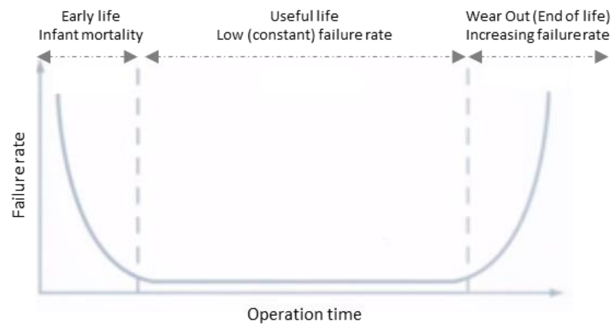


Fig -24: Typical bathtub curve of a product

Infant mortality rate refers to the rate of inverter failure based on design, manufacturing, shipping, installation and operating at the initial phase. After stabilization, the product enters into its useful life. In this phase the product matures, and the failure rate becomes nearly constant. This is common time frame for making reliability predictions. As components begin to fatigue or wear out, failure occur at increasing rates and MTBFs calculated in this phase is no longer applicable.

MTBF is the inverse of the failure rate. It is a statistical measure and cannot predict (accurately) failure on any single unit or sample but on a lot. Low component count is considered as most fundamental rule of design for reliability and the reliability of a system is the product of the reliabilities of all the individual components. For e.g. if each component has an annual reliability of 99.99 percent means, there is only a 0.01% chance of failing in a year.

MTBF = 1/ (sum of all the part failure rates)

For MTBF of 250,000 hours, and operating time of 5 years (43,800 hours), the probability that the product will work for time 't' without failure is given by:

P(t) = e-t/MTBF = e-43800/250000 = 0.8392

which means that there is an 83.9% probability that the product will operate for the 5 years without a failure, or 83.9% of the units in the field will still be working at the 5-year point.

Cooling and thermal management plays an important role in design for improved reliability, as the operation life of product drops by half for every 10°C rise. If MTBF of a product is calculated at lower temperature say 25°C, and it is operated at higher temperature say 55°C. then product MTBF at 55°C will be one eighth.

Reliability testing is a critical component of inverter product development and production for performance to maintain near perfect uptime. For a truly reliable product, quality begins at the design table. Quality control ensures, prior to assembly each component is individually inspected to confirm there is no manufacturing quality defects.

9. SAFETY

Solar Inverter as a product may resemble to normal PWM based variable frequency drive (VFD), but it is important to recognize that it also acts as a generator. Electricity comes from two sources in a solar inverter i.e., from the utility grid and solar PV array. Even when main AC circuit breaker is shut off, the PV system will continue to supply power, and this requires extra caution on safety of personal during operation, service, and maintenance. Voltage surge and arc flash are other major incident occurrences in PV plants as most of the power equipment are exposed to outdoor installation, high dc/ac ratio and high voltage (1500V) system.

9.1 Integral Isolation Safety

Based on design and applicable compliance, an inverter consists of protection mechanism like circuit breakers, contactors and fuses at its dc input and ac output circuit. To facilitate repair and maintenance safety, a separate (exterior to inverter) isolation may require even if one such is included within the inverter.

The dc isolator meant for inverter maintenance work does not completely isolate the input dc conductor from PV array, but that particular compartment within inverter remains exposed to dc voltage. External array junction boxes must have breaker, or a separate disconnector box installed to isolate the PV array from the inverter.

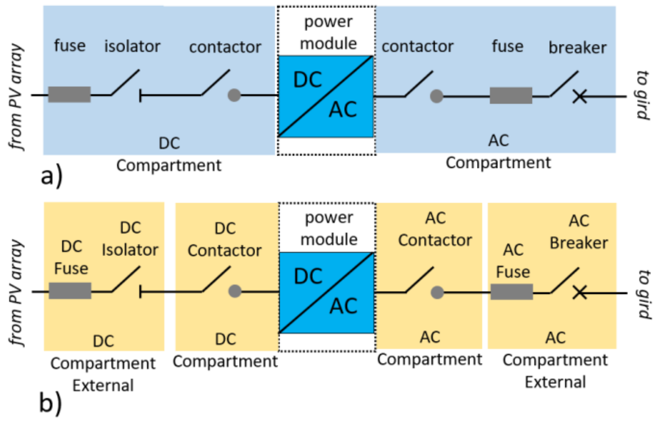


Fig -25: Inverter cubicle a) without and b) with isolation

Input dc (zonal) fuses within inverter are meant for fast protection response from short circuit energy and eventually from fire fed by the PV arrays. The dc input fuse is of gPV type and are sized based on PV array design. Thumb rule for sizing dc fuse is 1.56 times short circuit current (Isc) and 1.20 times module open circuit voltage (Voc) as safety factors.

$$I_{rated} = \frac{Isc \times 1.56}{Kf}$$

- (Kf is the temp. de-rating coefficient)

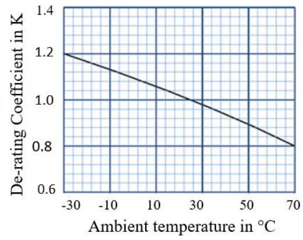


Fig -26: Typical de-rating chart for dc string fuses

AC side protection in inverter is based manufacturer design, fault level, and local grid code compliance which is accomplished usually with fuse (type aR), switchgear like molded case circuit breaker (MCCB) or Air circuit breaker (ACB). Some design has ac contactors and /or manual isolators as well.

Table -15: Utilization category of different fuses as per IEC

Utilisation Category	Appplication (Characteristic)
gPV	Full range breaking capacity fuse protection of PV modules and cables against the inverse over-currents in the photovoltaic application
gG	Full range breaking capacity fuse for general application, mainly used for cable and line protection.
aM	Partial range breaking capacity fuse for the short circuit protection of motor circuits.
gR	Full range breaking capacity fuse for the protection of semiconductor devices (quicker than gS).
gS	Full range breaking capacity fuse for the protection of semiconductor devices for increased line utilisation. Combines gR and gG performance.
aR	Partial range breaking capacity fuse for the short circuit protection of semiconductor devices.
gTr	Full range breaking capacity fuse for transformer protection, rated in transformer apparent power (kVA) instead of rated current (A).
gM	Full range breaking capacity fuse for motor circuit protection, dual rated (widely used in the UK, Australia and South Africa.
gN	North American general application fuse, mainly for cable and line protection.
gD	North American general application time-delay fuse, mainly for motor circuit protection.
Note: The 1st lower-case letter indicates the breaking range of fuse i.e 'g' = full-range and 'a' = partial-range breaking capacity. The 2nd, upper-case letter indicates the characteristic.	

9.2 Surge Voltage Protection

Lightning arrestors and surge protection devices are essential to safeguard critical and expensive equipments in solar PV plants as most of equipment like PV modules, inverter, transformer, power cables etc. are exposed to open sky, and hence prone to get damaged due to voltage surge during lightning. Usually, lightning arrestors protects PV array and high-power upstream evacuation transformers while SPDs protect inverters.

SPD connected between line to line and line to ground conductors, routes transient currents to the ground, thus protecting the equipment from damage from over voltage. SPDs can be of metal oxide varistors (MOVs) or gas discharge tubes (GDT) and both has limited lifetime and can handle finite number of surge events. GDT type has high current handling capacity compared to MOV.

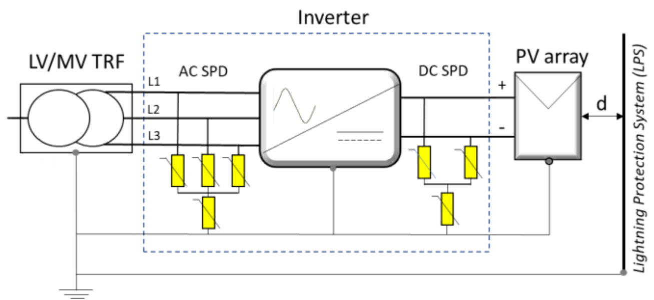


Fig -27: AC and DC SPD types in PV inverter

Types of SPDs within inverter are selected based on PV plant engineering i.e., for direct or indirect lightning strike, sizing of lightning arrestors and earthing system. SPD selection is defined by IEC 61643-12, IEC 62305-4, EN 50539-12:2013.

SPD are categorized as Type 1, 2 and 3 based on duration of impulse current handling capacity. IEC 62305-1 and -6 (2006) specify two current impulse waveforms referred as 10/350 ls and 8/20 ls in terms of their rise time and half peak width.

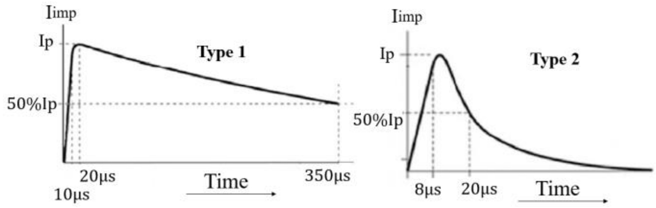


Fig -28: Impulse current waveforms in Type 1 and 2 SPDs

Table -16: Current handling capacity of different SPD types

Type	Protection against	Current handling capacity
1	Direct lightning strokes	10/350 µs
2	Indirect lightning strokes	8/20 µs
1+2	Direct + Indirect lightning strokes	Combination of 10/350µs and 8/20 µs

9.3 Arc Flash

Arc flash is a type of electrical fault that results when electric current flows through an air gap between conductors due to breakdown of an insulating medium causing extreme amounts of light (arc flash). This creates a hazardous condition that vaporize metal, and even destroy equipment, causing significant hazard to anyone in the vicinity.

Arching in ac system tend to self-extinguish as the voltage alternates polarity constantly, passing through 0 volts 100 times in 50Hz frequency. While intensity of arc flash in dc is more severe as dc voltage remains at a continuous (zero frequency) and due to presence of discharge energy in dc link capacitors.

Three main aspects of system design contribute to the arc fault risk in utility scale PV plant are high dc voltage, current and large geographic distribution of dc wiring. Consequences of an arc flash are fatalities among personnel and damage of equipments. The most common cause of arc faults is insulation failure due to defective or aging material, loose connections, dust, moisture, vermin, and human error such as touching wrong surface or a tool slipping and touching live conductors. Appropriate creepage and clearance in design plays an important role to avoid arc flash incidents.

Dedicated arc flash vent provided in an inverter enclosure and sometimes enclosure doors itself acts as resistance to arc from personal hazards. Hence inverters are not recommended to operate with open doors. AC and DC power cable entry ports are major source of arc flash in outdoor installation, as there are more changes of foreign objects entering through if glands are not sealed appropriately. Use of lead through for cable entering to inverter keeps enclosure IP intact.

Fig -29: Cable lead-throughs (Fimer: PVS 980 inverter)

Of many different arc flash energy calculation techniques, the most relying is on voltage, current, radiated energy, or a combination of these. For e.g. consider a 690-volt phase-to-phase system with fault current of 20 kA. In absence of any arc protection if, the fault lasts for 200ms. before the overcurrent protection clears it, arc flash energy released is ~3MJ which corresponds roughly to a stick of dynamite and is calculated as per below formula:

Energy = voltage x current x time … Joules
i.e., 690V x 20,000A x 0.2 s = 27,60,000 ~ 3MJ

IEEE 1584-2002 (Guide for Performing Arc Flash Hazard Calculations) provides standard guide for performing arc flash calculations and it also does not exclude the use of alternative calculation methods. Furthermore, NFPA 70E Article 130.3(B)(1) requires an arc flash hazard analysis be performed.

9.4 Ground Fault

The presence of undetected ground fault can result in arcing and fire in an inverter. The source of ground faults can be within the inverter or in externally connected dc or ac circuit. Based on the grounding system, ground fault is detected by the insulation resistance (IR) and pole grounding circuit incorporated within the inverter.

PV system is exposed to potential-induced degradation (PID) effect which is linked mostly to negative potential with respect to ground. This effect is accelerated by high dc voltage, temperatures, and humidity. The phenomenon is not immediately noticeable, rather it develops over time. Grounding the negative dc pole on the inverter mitigates this problem of accelerated performance degradation. Frameless PV module reduces the probability of PID because of no or very less leakage current in absence of metal frame. Frameless modules are with double glass, higher weight, and costs more, hence not always economical for all projects.

In case of ground fault at positive pole or at ac output, inverter detects the fault by measuring flow of leakage current through pole grounding circuit. Inverter interrupt excess current by opening the pole grounding contactor.

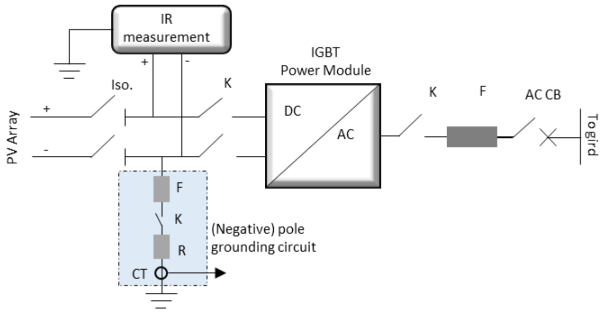


Fig – 30: Typical IR measurement and pole grounding circuit

Ground fault in floating system or in an ungrounded array is detected by measuring insulation resistance between positive and negative pole with protective earthing (PE). The measuring time is determined by the system leakage capacitances and insulation resistance value.

PWM based PV inverter, reflects switching frequency to the dc bus, producing leakage currents which in turn flows through the frame and the stray capacitances of PV modules. This forms a resonant circuit with the PV modules, inverter ac filter elements, and grid impedance. Capacitance value depend on weather, PV topology, PWM pattern, metallic frame material, and passive filter element values in an inverter.

As per IEC 62109-2, leakage current is limited to10mA rms per kVA of rated inverter power.

Table -17: ground fault detection current as per UL 1741

Inverter DC rating	Max. Ground Fault Current
0-25 kW	1 Amp.
25-50 kW	2 Amps.
50-100 kW	3 Amps.
100-250 kW	4 Amps.
>250 kW	5 Amps.

According to the IEC 62109-2 safety standard, the IR measurement between the DC and PE is performed before the inverter (IGBT pulsing) is started and pole grounding circuit is off. Pole grounding circuit comes into picture only after IR check is performed. Normally negative pole grounding system has both IR and pole grounding current measurement units while floating system has only IR measurement.

10. TESTING

Inverter testing is an exhaustive process. Tests conducted on a product at various stages from design till dispatch and at site to ensure to perform operations as designed. Different types of tests are as listed below.

1. Type Test
2. Routine Test
3. Factory Acceptance Test (FAT)
4. Site Acceptance Test (SAT)

10.1 Type Test

Type test also known as compliance test determines if a product complies with and tested for applicable standard relevant to safety, performance, reliability, and grid codes. Type testing essentially means running a design of the product through a series of tests and then future product that is built to the same or very similar design can be considered to comply with the same requirements and if tested in the same way would also pass the test. Listed below are different type tests applicable to utility scale grid tied PV inverters:

IEC 62109-1 (2010): Safety of power converters for use in photovoltaic power systems –Part 1: General requirements. This standard covers mainly the following:

- Temperature limits
- Electrical ratings
- Protection against electric shock and fire hazards
- Protection against fault and short circuit conditions
- Environmental requirements like pollution degree rating.

IEC 62109-2 (2010): Safety of power converters for use in photovoltaic power systems–Part 2: Particular requirements for inverters. This standard covers the array insulation resistance detection for inverters for ungrounded and functionally grounded system.

IEC 60068-1: Environmental testing. This test ensures that the product availability is maintained over a long lifetime at specified extreme temperature and humidity variations. Applicable parts covered in this standard are:

- Part 2-1:2007– Test A: cold
- Part 2- 2:2007– Test B: dry heat
- Part 2-14: 2009 – Test N: change of temperature
- Part 2-30: Tests – Test Db: damp heat, cyclic

IEC 60529-2004: Degrees of Protection Provided by Enclosures (IP Code). This standard classifies the degrees of protection provided by electrical enclosures basically for the protection of persons against access to hazardous parts, protection of equipment against the ingress of solid foreign objects and the ingress of water.

IEC 61000-6-2 (2016): Electromagnetic compatibility (EMC)– Part 6-2: Generic standards – Immunity standard for industrial environments. This standard ensures that the product shall continue to operate normally as intended without degradation of performance due to electromagnetic disturbances generated by external equipment or environment. This standard covers mainly the:

- Radiated immunity
- Conducted immunity
- Electrostatic discharge immunity
- Surge immunity
- PFMF (Power Frequency Magnetic Field) immunity
- EFT (Electrical Fast Transient) immunity

IEC 61000-6-4 (2006 and 2010): Electromagnetic compatibility (EMC) – Part 6-4: Generic standards– Emission standard for industrial environments. This standard ensures that the disturbance generated by product operating normally in industrial locations do not exceed a level that could prevent other equipments in vicinity from operating as intended. This standard cover:

- Radiated emission
- Conducted emission

IEC 61683 (1999): Photovoltaic systems – Power conditioners–Procedure for measuring efficiency. Purpose of this standard is to provide the means to evaluate the efficiency of solar inverter by a direct measurement of input and output power during factory testing. Measurements includes Euro, CEC, and Max. efficiencies. It also measures no load and standby losses, ripple and distortions in inverter input and output voltage and currents.

EN 50530-2010: Overall efficiency of grid connected photovoltaic inverters. This European standard provides a procedure for the measurement of the static and dynamic efficiencies of the maximum power point tracking (MPPT) of grid-connected PV inverters. Based on the static MPPT efficiency and conversion efficiency, the overall inverter efficiency is calculated, and dynamic MPPT efficiency is indicated separately.

IEC 62116 (2014): Utility-interconnected photovoltaic inverters – Test procedure of islanding prevention measures. The standard ensures that the inverter in operation and synchronized to grid, should isolate from grid within 2s during loss of grid voltage and frequency. Islanding is a scenario in which a grid tied inverter continues to feed power even though electrical grid power is no longer present which can be dangerous to utility workers.

Bureau of Indian Standards (BIS): To ensure quality of solar PV equipment like modules, inverter, and batteries, MNRE has issued guidelines titled 'Solar Photovoltaics Systems, Devices and Component Goods Order 2017'. PV inverters to register with the BIS for following tests:

- **IS 16221 (Part 1): 2016 -** Safety of power converters for use in PV power systems - general requirements. IEC equivalent for this standard is IEC 62109-1
- **IS 16221 (Part 2): 2015 -** Safety of power converters for use in solar PV power systems – Particular requirements for inverters. IEC equivalent for this standard is IEC 62109-2.
- **IS 16169: 2014 -** Test procedure of islanding prevention measures for utility interconnected PV inverters. IEC equivalent for this standard is IEC 62116:2008.

BDEW-2008 (Germany specific): Guideline for generating plants connected to the medium-voltage network.

CEA-2019 (India specific): Central Electricity Authority (Technical Standards for Connectivity to the Grid) Regulations, 2019.

IEEE 1547-2003 (UL specific): Standard for Interconnecting Distributed Resources with Electric Power Systems

UL 1741 -2010: (UL specific): Standard for safety for of inverters, converters, controllers, and interconnection system equipment for use with distributed energy resources. Safety includes anti-islanding requirement.

IEC 61727 (2004): Photovoltaic (PV) systems – Characteristics of the utility interface.

Following are protections normally included in the above grid codes:

- Abnormal voltage and frequency (OV, UV, OF, UF)
- Low and high voltage ride though (LVRT)
- High voltage ride though (HVRT)
- Anti-islanding protection
- Voltage regulation
- Frequency droop
- Harmonics (THDi and THDv)
- DC current injection
- Reconnection delay time
- Ramp time
- Flicker

10.2 Routine Test

Routine tests are performed at the manufacturers' works place to reveal if any faults in material or construction on each individual product manufactured. This ensures that the product manufactured is in accordance with the proto build on which the type tests have been passed. Manufacturer declares successful completion of the routine test on producing routine test certificate (RTC). This test does not confirm the reliability of the product.

10.3 FAT (Factory Acceptance Test)

This test is performed at factory and witnessed by customer or customer nominated third-party inspector (TPI). The FAT verifies the equipment is built and operates in accordance with the agreed design specifications documents like GTP (Guaranteed Technical Particular) and MQP. Tests covered during FAT as per MQP includes material quality, characteristics, stage inspection and manufacturing process, routine tests, packing material and process, review of documentation like type and routine test reports of the product and its components including bought out items.

10.4 Site Acceptance Test (SAT)

The tests which are not feasible to perform during FAT at factory, are performed at site and those are mostly related to inverter when connected to Point of Common Coupling (PCC). And this includes tests like active power controllability and reactive power control modes: voltage control, reactive power control and power factor control.

Below is the list and details of tests which are part of type, routine and /or FAT.

- **Safety Test**

To comply to safety standards, the product must pass safety tests such as the high voltage (HV), insulation resistance (IR), and earth bonding test. Ambient temperature and humidity influence the insulation resistance, so HV and IR test readings are unreliable if taken at different temperatures. Thumb rule is that for every 10°C temperature rise, halves the resistance.

Earth (or ground) bonding test ensures all the ground points in a product under test are well connected between each other, and to the mains ground so that the product does not cause an electric shock from insulation failure. As per UL 62109-1 the impedance measured between ground and touch point ≤1mΩ when applied test current is 10 A for ≥2s.

Insulation resistance (IR) test ensures effectiveness of insulation between mutual circuits and ground. High voltage (HV) test also called as dielectric voltage or voltage withstand test ensures leakage current is less than the specified limit when the applied HV for a duration of 1s to the device under test. As per IEC 62109-1, the test voltage in 1500V system is calculated as 2700V by below relation:

Vtest= {1200+(system voltage)} :- interpolation permitted.

- **Functional test**

This test is performed at low (auxiliary or control) voltage level. It includes operation and feedback of auxiliary and control circuits like fans, heaters, lamps, contactors. It also includes protection logic to check inverter response during critical faults and warnings. The faults are normally simulated by changing threshold parameters in firmware.

- **Nominal Power Test**

This test is performed to ensure the inverter under test operates at rated output power and current under application of applied nominal voltage and the measured values complies to the product technical specifications.

Normally a manufacturer has inverter as DUT (device under test) and dc source connected in back-to-back configuration. The ac output of the inverter is fed back into the dc source, allowing power recycling and the power system to supply only the losses relevant to transformer, dc source, DUT and interconnecting cable. The dc source emulates PV array for dc power variations i.e. dc voltage due to temperature variation and dc current during irradiations changes.

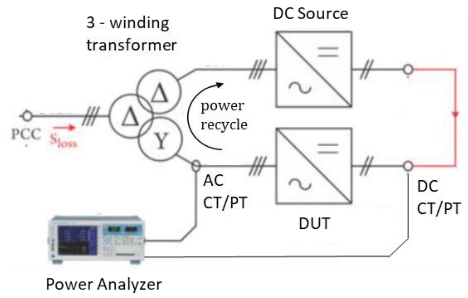


Fig -31: Back-to-back testing of inverter under test

- **Calibration test**

This test confirms that the inverter parameters like voltage, current and power measured by inbuilt inverter controller is within acceptable limits when measured with external (calibrated) measuring instrument like power analyzer.

Fig.- 18: Instrument accuracy limits as per IECEE OD-5014, Edition 1.1 2019-06

Parameters	Range	Accuracy limits
Voltage ≤1000V	≤1kHz	±1.5%
Voltage ≤1000V	≥1kHz ≤ 5kHz	±2%
Voltage >1000V	Dc ≤20kHz	±3%

Current >5A	Dc ≤60kHz	±1.5%
Power Factor	50/60Hz	±0.05
Frequency	<10kHz	±0.2%

The IEC 61000-4-30 Class A standard defines the measurement methods, time aggregation, accuracy, and evaluation, for each power quality parameter to obtain reliable, repeatable, and comparable results. IEC 6100-4-30 Class A standardizes the measurements of voltage and current magnitudes, power frequency, Flicker, current and voltage harmonics.

Transducers used within inverter like CT and PT accurately measures the electrical power, while temperature sensors like PT100 decides thermal performance and protection from over-temperature. The important factors in selecting the transducers are

- Accuracy: closeness of measured to standard value
- Linearity: measurements consistency over the range
- Response time: how fast measurement is performed

- **Sleep and wakeup mode test**

This test checks at what minimum input dc voltage and power level inverter goes to sleep mode (i.e. stops generating power simulating night or non-sunshine scenario) and wakes up from sleep mode to fed power to grid. Minimum MPPT voltage specified in product specification is calculated as: (√2*Vrms) +Vd+ Vm] .... volts

Where Vrms is grid voltage, Vd is voltage drop across output LCL filter and across semiconductor devices in power module and Vm is modulation index usually ≤1.

Wake up voltage is normally >120% of min. MPPT voltage. In sleep mode, if dc voltage is equal to wake up voltage, the inverter starts generating the power based on dc power availability after a pre-defined delay time which is programable and is normally around 5min.

- **Burn-In (Heat Run) Test**

Purpose of this test is to ensure that temperatures rise of critical components within inverter like IGBTs, filter chokes, mains busbar, fuses, controller, and electronics boards are within the safe limit. The test is performed normally for 8 hrs. or till temperature stabilization subject to manufacturer test facility. This test also ensures that power connection such as the bolted joints are appropriately torqued during the manufacturing.

Manufacturers burn-tests every inverter that rolls off their line as per their standard process or as request from customer during production or on offered units during FAT. This test detects weak link in an inverter that may not exhibit symptoms during early stage of operation. By exposing these weak points in the factory, the site issues can be proactively addressed.

- **Harmonics and DC current Injection Measurement**

PWM topology, switching frequency, modulation index and output LCL filter design ensure that inverter limits the current and voltage harmonic generation to comply specific grid codes.

Table -19: IEEE 519-2014 limits for Voltage and current THD

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \le 1.0$ kV	5.0	8.0
1 kV < $V \le 69$ kV	3.0	5.0
69 kV < $V \le 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

DC current or zero frequency component injected by inverter into transformer winding causes magnetic saturation increasing losses within transformer due to temperature rise.

Table-20: Grid codes for dc current injection limits.

Standard	DC Current Injection Limits
IEEE 1547/CEA 2019	0.5 % of rated output current
IEC 61727	1% of rated output current

IEEE P2800 is a draft (expected publication Q2-2021) standard for interconnection and Interoperability of inverter-based resources (IBR) interconnecting with transmission network. The scope of this standard is to develop technical minimum capability and performance requirements for IBRs including IBRs' ride-through capability, reactive power (voltage) control, active power (frequency) control, power quality, protection etc.

- **Inverter Response for Abnormal Grid**

In case of grid abnormality, inverter responses accordingly to grid codes as set in firmware parameters. Inverter response may be instantaneous or delayed trip, output power derating or reactive compensation support. Abnormal grid includes under and over voltage, under and over frequency, phase loss, unbalance etc. Local utility specifies disconnection time or how inverter should behave during the grid abnormality.

Table-21: Grid codes for abnormal voltage and frequency

IEC 61727	
Voltage Range in %	**Disconnection time in sec.**
< 50%	0.10
50% to 85%	2.00
85% to 110%	Continue Operation
110% to 135%	2.00
>135%	0.05
IEEE 1547	
Voltage Range in %	**Disconnection time in sec.**

< 50%	0.16
50% to 88%	2.00
88% to 110%	Continue Operation
110% to 120%	1.0
>120%	0.16
BDEW-2008	
Frequency in Hz.	**Disconnection / clearance time**
47.5 to 51.2	Continuous operation (no trip)
< 47.5	Instantaneous trip within 0.2s
> 51.5	
IEEE 1547	
Frequency in Hz.	**Disconnection / clearance time**
> 60.5	Instantaneous trip within 0.16s
<59.8 to 57.0 Adj.	Inst. trip within 0.16 -300s
<57.0	Instantaneous trip within 0.16s
CEA -2019	
Frequency in Hz.	**Inverter operation**
47.5 to 52	Continuous operation (no trip)
49.5 to 50.5	Operation at rated output power

- **Grid Shutdown and Reconnection Delay**

The grid shutdown test ensures that the inverter in operation and synchronized to grid, gets isolated from grid within specified time (which is normally <2s) during loss of grid voltage and frequency. This test also ensures that inverter does not produce high voltage spikes (i.e.,> √2 times of nominal grid voltage) when it disconnects from the grid.

The time required for inverter to reconnect once the gird resumes back is called the reconnection time and is typically ≥60s. IEEE 1547 specifies a reconnection delay adjustable up to five minutes (300s).

- **Voltage Regulation**

This test checks how inverter compensates grid over or under voltage by feeding inductive or capacitive reactive current respectively into the grid as specified by appropriate grid code. The ratio of additional reactive current (ΔI) requirement to support change in voltage (ΔV) is given by 'K-factor, which is normally 2 or more.

$K = \Delta I / \Delta V$ | ΔI = resulting current increase during fault in pu
ΔV = depth of voltage dip during grid fault in pu

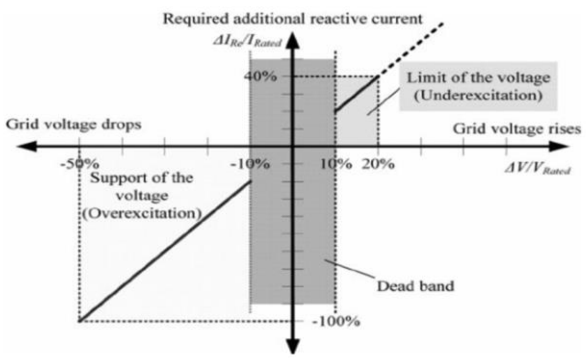


Fig -32: Reactive current injection during voltage regulation

Short time grid disturbances due to voltage sags or swells cause cascading tripping when demand is more than generation. To avoid this, grid codes mandate dynamic voltage support in terms of Low Voltage Ride-Through (LVRT) and High Voltage Ride-Through (HVRT) capabilities in inverter. This capability keeps inverter connected to the grid and support voltage through reactive power injection.

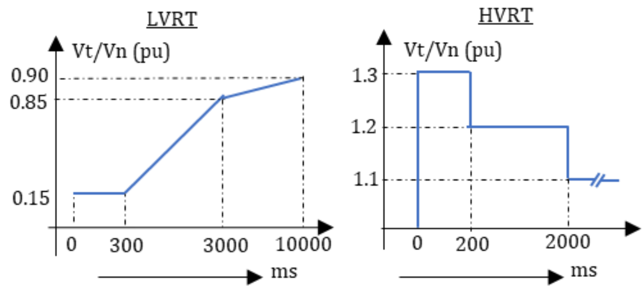
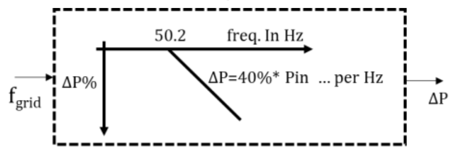


Fig -33: LVRT and HVRT curve as per CEA- 2019

- **Frequency Droop**

This test checks how inverter compensates grid over frequency by reducing its active output power feeding to grid as specified by appropriate grid code.



$$\Delta P = 20\, P_{in} \frac{50.2Hz - f_{grid}}{50Hz} \quad \text{at } 50.2Hz < f_{grid} < 51.5Hz$$

Pin = Instantaneous available power
ΔP = Power reduction
f grid = Grid frequency

for 47.5 Hz < *f* grid ≤ 50.2 Hz - continuous operation
for *f* grid > 51.5 Hz - disconnection
for *f* grid < 47.5 Hz - disconnection

Fig -34: Frequency droop curve as per BDEW

- **Ramp Test**

This test checks inverter's active power ramp specific to grid code during startup and shutdown. The PCC controls plant ramp rate set by utility operator as per grid code which is important from grid stability.

- **Voltage (Phase) Imbalance**

Voltage unbalance is a condition in which the three-phase voltages differ in amplitude or displace from 120° phase relationship, or both. The degree of unbalance is defined by the ratio of the negative sequence voltage component to the positive sequence component. According to the EN 50160:2010 and the IEC 61000-2-2 standards, the voltage unbalance, or the negative phase sequence component of the supply voltage shall be within the range of 0 to 2% of the positive phase sequence component.

During un-balanced fault like line-to-line fault, inverter responds to sudden increase in negative sequence voltage by injecting fast negative sequence current output to improve phase symmetry.

- **Flicker**

Fluctuation in inverter output voltage is a result of variations in solar irradiance caused by the movement of clouds which creates voltage flicker that distorts nominal voltage waveform of utility network. Magnitude of flicker not only depends on inverter output at PCC (point of common coupling) but also on the stiffness of the grid, which is function of voltage level, cable distance from the substation, substation transformer ratings and plant electrical design.

Parameters considered in grid code are the short-term flicker severity (PST) and long-term flicker severity (PLT). PST is measured in per units over a 10-minute period and the PLT is measured in per units over a 2-hour period. As per IEC 61727, the PST and PLT values should not exceed the limits stated in the relevant sections of IEC 61000-3-5 for LV systems and for current ≥ 16 A.

$$PST = \sqrt{\Psi_{0.1}P_{0.1} + \Psi_1 P_1 + \Psi_3 P_3 + \Psi_{10}P_{10} + \Psi_{50}P_{50}}$$

$$PLT = \sqrt[3]{\left(PST^3/12\right)}$$

Where, Ψi is the weighting coefficient of the i[th] percentile exceedance flicker level (Pi).

Flicker measured in power analyzer is as per IEC 61400-4-15 and limits as specified in IEC61000-3-5 is as tabulated below.

Short-term (10 min) flicker emission limit: $P_{ST} \leq 1$	Long-term (2 hrs.) flicker emission limit: $P_{LT} \leq 0.65$

- **MPPT Efficiency Test**

In case of PV inverter both the conversion and MPPT efficiencies contributes the pay-back time and the profitability of grid-connected PV systems. The behavior and efficiency of the MPPT can be analyzed in both static and dynamic conditions. The static MPPT efficiency describes the ability of the MPPT to find and hold the MPP under constant environmental conditions (i.e., solar irradiance and cell-temperature) whereas the dynamic MPPT efficiency describes the ability in tracking the MPP in case of variable conditions.

In dynamic conditions the MPP and hence its efficiency is normally analyzed using staircase or trapezoidal irradiance profile. Slow MPP tracking reduces the MPP efficiency.

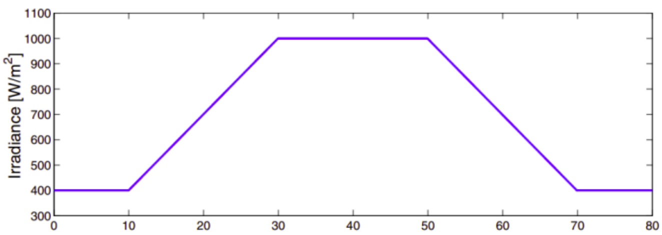


Fig -35: Dynamic MPPT testing with trapezoidal irradiance profile

- **Communication Check**

Establishing communication and checking exchange of signals like commands, references and setpoints between inverter and external customer controller like PPC, SCADA is performed during a FAT.

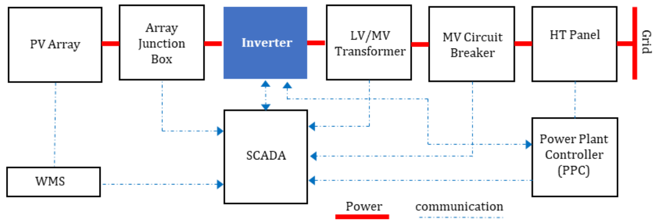


Fig -36: Inverter communication with AC and DC BOS

In most cases, even in absence of hardware controller, the test is performed with ModScan simulator. ModScan operates as a Modbus master and allows to access and change data points in a connected slave device using the RTU mode.

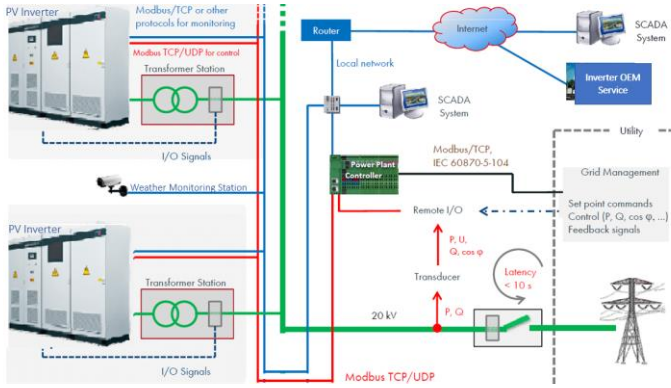


Fig -37: Typical communication protocols in a PV plant

11. Participants of PPA and Their Role in PV Solar Plant

Generating companies (GENCOs) invites tenders for setting up PV plants where interested developers' bids. GENCO signs a Power Purchase Agreement (PPA) with the developers, and then a Power sale Agreement (PSA) with the distributor companies (DISCOM) to sell the power to the consumers. PPA is a financial agreement made between power producer and customer power purchaser.

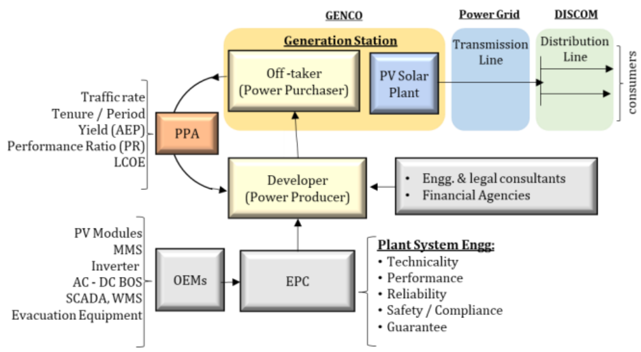


Fig -38: Participants of PPA and their role in PV plant

- Federal power generators (GENCOs) in India are:

- NTPC (National Thermal Power Corporation Limited)

- NLC (Neyveli Lignite Corporation Limited)
- NHPC (National Hydroelectric Power Corporation)
- THDC (Tehri Hydro Development Corporation Limited)
- NEEPCO (North East Electric & Power Corporation Ltd.)
- SJVNL (Satluj Jal Vidyut Nigam Ltd.)

- Federal power transmitter in India is Power Grid Corporation of India Ltd. (PGCL). PGCL is a CTU (Central Transmission Utility) engages in power transmission business with the responsibility for planning, implementation, operation, and maintenance of inter-state transmission system (ISTS).
- Independent Power Producers (IPPs) are private entities or developers who own and or operate plant to generate electricity and sell it to a utility. Reputed Indian IPPs are Tata Power, ReNew Power, Adani etc.
- Power Distributor companies (DISCOMs) participates in transmission and distribution of power.
- (SECI) is a Central Public Sector Undertaking (CPSU) company under the administrative control of the MNRE, to facilitate the implementation of national solar mission into solar project development on turnkey basis for several PSUs.
- CEA specifies technical guidelines for building the solar plant and CERC (Central Electricity Regulatory Commission) regulates electricity traffic of GENCO.
- Load Dispatch Centre (LDC): Operation of each of regional grids is handled by the regional load dispatch centers (RLDC). The state grids are managed and operated by state load dispatch center (SLDC). National Load Dispatch Centre (NLDC) schedules and dispatch electricity across various regions and also coordinates cross-border energy exchanges.
- Electricity Regulatory Commission (ERC): Tariff regulation and grant of connectivity is governed by regulations issued by the Central Electricity Regulatory Commission (CERC) and the respective State Electricity Regulatory Commission (SERC).

12. CONCLUSIONS

Globally utility scale solar PV installation is growing at exponential rate and at a same time record-low power purchase agreement (PPA) tariff is intensifying scrutiny of project budgets. This is forcing PV inverter manufacturer for price cuts and take conservative call on design cost versus product life. This tradeoff impacts design, manufacturing quality and in turn on-site performance of the product. Considering the ongoing site issues in inverter, it is important for customer to emphasis on product design factors like performance reliability safety factors.

ABBREVIATIONS

- ASTM - American Society for Testing and Materials.
- CISPR - Comité International Spécial des Perturbations Radio, (The International Special Committee for Radio Protection)
- CSA - Canadian Standards Association
- IEC - The International Electrotechnical Commission
- IEEE - Institute of Electrical and Electronics Engineers.
- NEMA - The National Electrical Manufacturers Association
- TUV- Technischer Überwachungsverein (Technical Inspection Association)

REFERENCES

(1) National Renewable Energy Laboratory: Q4 2019/Q1 2020 Solar Industry Update by David Feldman, Robert Margolis, May 28, 2020.

(2) Availability factor of a PV power plant: evaluation based on generation and inverter running periods, by Nallapaneni Manoj Kumar, Srikar Dasari Jagathpally Bhagwan Reddyc. International Scientific Conference "Environmental and Climate Technologies", CONECT 2018.

(3) Photovoltaic Inverter Reliability Assessment. Adarsh Nagarajan, Ramanathan Thiagarajan, Ingrid Repins, and Peter Hacke National Renewable Energy Laboratory, Technical Report NREL/TP-5D00-74462 October 2019

(4) Aiming for grid parity on utility-scale solar applications Industry Application IA08303004E Effective September 2012.

(5) An Overview of Grid Codes and Power Quality in Utility Connected Solar PV Power Plants, by Kiran Dhandale, Dr. Bhaskar, International Journal for Research in Applied Science & Engineering Technology, Volume 8 Issue IV Apr 2020.

(6) Active and Reactive Power Strategies with Peak Current Limitation for Distributed Generation Inverters During Unbalanced Grid Faults, By Antonio Camacho, Miguel Castilla, Jaume Miret, Angel Borrell and Luis Garc´a de Vicu˜a, IEEE Transactions on industrial electronics, 2014.

(7) Research on Inverter Integrated Reactive Power Control Strategy in the Grid-Connected PV Systems, by Hua Li, Che Wen, Kuei-Hsiang Chao, and Ling-Ling Li. Energies 2017, 10, 912; doi:10.3390/en10070912.