iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 8 **Issue:** IV **Month of publication:** April 2020

DOI: http://doi.org/10.22214/ijraset.2020.4007

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue IV Apr 2020- Available at www.ijraset.com

An Overview of Grid Codes and Power Quality in Utility Connected Solar PV Power Plants

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Abstract: Electric power demand is increasing day by day due to global industrialization, improved lifestyle and rapidly growing population. Future prospect is transition to renewable energy like solar, wind, tidal etc. Solar energy is clean, green and is in abundant form in tropical countries like India. The production of solar energy is a way to diminish dependency to fossil fuels, and to mitigate global warming by lowering of greenhouse gases emission. Solar photovoltaic is a key technology in renewable energy as it is free from maintenance, noise and pollution. But photovoltaic plant output varies based environmental conditions like solar irradiance, temperature, cloud movement etc. impacting quality of power output.

This paper presents the fluctuating environmental conditions on overall power generation in PV based solar power plant. The problems related to grid stability like voltage & frequency fluctuations and relevant international standards and guidelines by Ministries and agencies in contest to India are also discussed related to grid tied PV inverters in large scale PV power plant. Impact of PWM based grid fed (central) inverters is also presented in this paper.

Keywords: Photovoltaic, Inverter, MPPT, power quality, grid codes, reactive power compensation, BESS, forecasting.

I. INTRODUCTION

The Government Of India's ambitious plan (National Solar Mission) to generate 100 GW of solar power by the year 2022 means increasing renewable power capacity and simultaneously reducing dependence on fossil fuel.

Due to advancement in technology and reduction in cost of solar cells and inverters has accelerated the adoption of solar power globally and hence the increased installed capacity of grid tied inverters in solar plants. Major concern is how the existing grid is going to cope with huge penetration of solar power. Solar energy being highly transient energy source exhibiting strong short-term and seasonal variations in their energy outputs and this intermittent nature of energy generation with grid tied inverters imposes technical challenges to the power system operation and control. Grid codes were originally developed considering synchronous generators (unidirectional power flow) but now grid integration of PWM based inverters (with capability for bi-directional power flow), utilities are presently facing major challenges of ensuring power quality, stability, reliability and safety. This has initiated the development of new standards and guidelines globally.

A. *Overview of PV Solar Plant*

Energy from the sun is received by the PV array and is converted into electrical energy which is dc in nature. This energy is converted into ac by Inverter and is synchronized with grid through step-up transformer. In this conversion process, the performance and efficiency of the PV solar plant system depends on technology of equipment used and climatic factors at installation site.

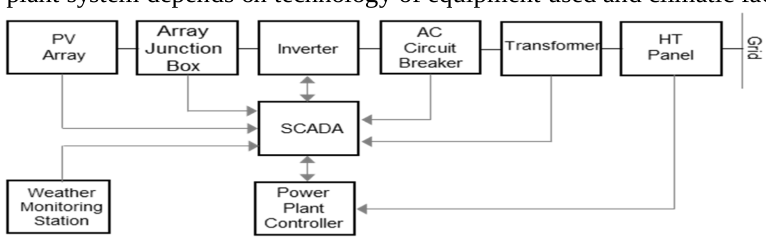

Fig. 1. Block diagram of PV power plant system

Climatic factors include solar radiation, ambient temperature, cloud movement (shading) etc. As the solar radiation keeps on changing throughout the day and seasonally, similarly the voltage, current and power output of plant varies. With the increasing solar irradiance both the open circuit voltage and the short circuit current increases. Temperature increase leads to marginal increase in current but major reduction happens in voltage. Temperature plays another major factor in determining the solar cell efficiency. Solar cell gives their best performance on cold and sunny days rather on hot and sunny weather.

II. PV ARRAY

In PV system, solar cell is the basic components and is generally a p-n junction made of silicon. Cells connected in series forms a PV module and modules connected in series forms a string to feed required dc voltage to Inverter input. An array is a combination of strings in parallel to get required plant output power.

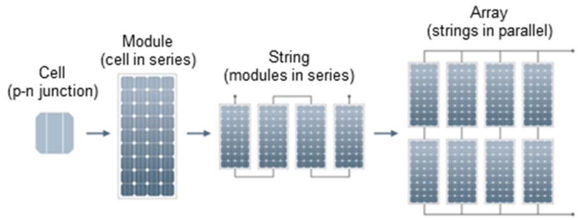

Fig. 2. Cell, Module, String, Array

The electric characteristics of a PV system is generally expressed in terms of current-voltage or power-voltage relationships of the cell. The variations in these characteristics directly depend on the irradiance received by the cell and the cell temperature. Dynamic performance of PV systems is analyzed under different weather conditions with a model which is required to convert the effect of irradiance and temperature on produced current and voltage of the PV arrays. Modelling of PV array has been done considering single diode of PV cell. The basic diagram and the equations used for modelling a solar cell is as shown below.

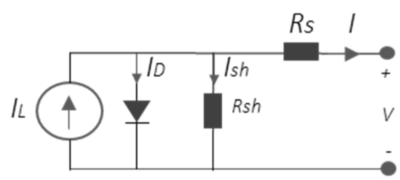

Fig. 3. Equivalent circuit for PV solar cell

From the equivalent circuit the current (I) produced by the solar cell is equal to that produced by the current source (I_L), minus that which flows through the diode (I_D), and through the shunt resistor R_{SH}.

$I = I_L - (I_D + I_{SH})$ - Similarly voltage across these elements is given by

$V_J = V + IR_S$ - By diode equ. the current through the diode Is given by

$$I_D = I_o \left\{ exp \left[\frac{V_J/n}{nVT}\right] -1 \right\}$$

On substituting the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage as given below.

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

The characteristics of a solar cell as shown in below fig. with voltage versus power and current curves is mainly dependent on radiations and temperature. Isc is proportional to Irradiation and Voc is inversely proportional to temperature. As, the temperature increases the power output decreases up to some extent even if there is good amount of radiation.

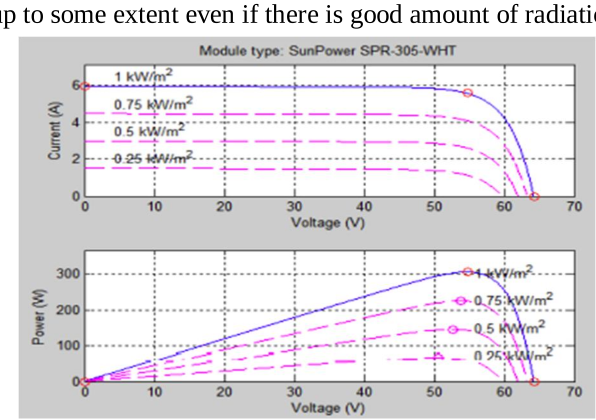

Fig. 4. I-V and P-V characteristics of solar cell

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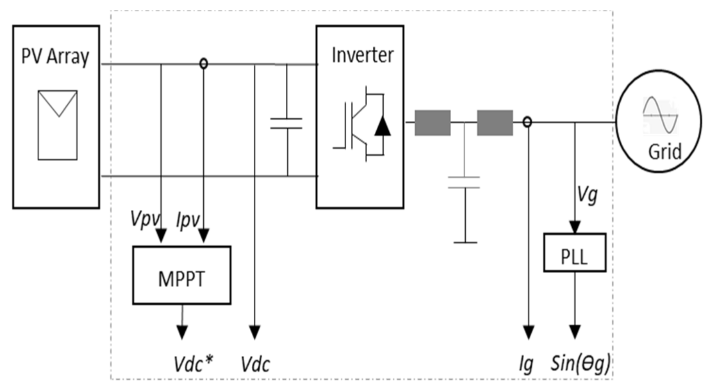
III. SOLAR INVERTER

Solar Inverter is important and critical constituent of PV solar plant. It is also referred as PV generator, distributed generator (DG), renewable energy source (RES), voltage source Inverter (VSI), or power conditioning unit (PSU) etc. but in this paper its simply called as Inverter.

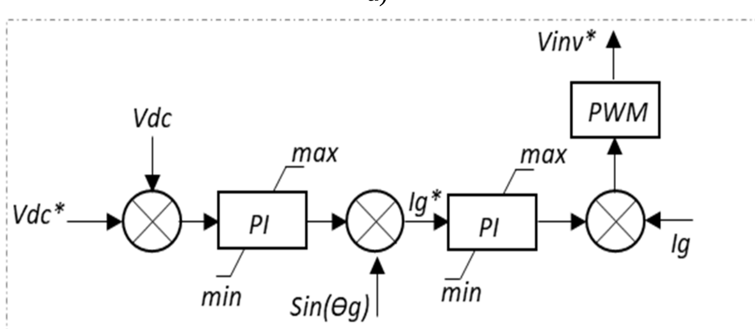
Solar Inverters differ from conventional generators in the way they produce alternating current through rapid switching of solid-state devices. Grid tied inverter produces ac voltage by switching dc voltage at high frequency using PWM. Design of inverter determines the quality of output power fed to grid. International standards like IEEE and IEC has stringent recommendations on the harmonics that can be injected into the grid and this necessitates the use of a higher order LC(L) filters. Inverter design with multi-level topology reduces EMI and harmonics output.

PV solar array has a nonlinear behavior i.e. its output varies with change in weather conditions like irradiation or temperature. Maximum power point tracker (MPPT) helps the PV array to deliver maximum power at its output and thus increases the system efficiency. The MPPT controller in inverter is based on many techniques but “Perturb and Observe” technique is used by most of the Inverter manufacturers due to its simplicity and effectiveness. Inverter also offsets its current waveform from utility by delaying in switching. This offset creates sub-cycle energy exchange between inverter dc link and grid causing either increase or decrease in grid voltage based on direction of reactive power flow.

Control structure of grid tied inverter as shown in below has three main tasks: i) MPPT, ii) Inverter control and iii) co-ordinate of active and reactive power control. MPPT aims for Vmpp at each solar irradiance and temperature according to PV curves using algorithms like perturb and observe. Inverter control performs grid synchronization, voltage modulation, dc voltage regulation and current loop. The third task delivers power demanded by PPC and controls as per PQ capability of PV generator and based on ambient temperature and solar irradiance.



a)



b)

Fig. 5. Inverter block diagram a) Power b) Control

The inverter when synchronized to grid should operate within tolerance values specified by grid codes for parameters like voltage, current etc. or else if operated outside of normal conditions may damage customer and utility equipment. Anti-islanding protection is an another important and must have safety feature built into all grid tied inverter. Islanding is the condition in which a grid tied inverter continues to power a location even though electrical grid power is no longer present and can be dangerous to utility workers. A grid tie inverter should detect islanding (loss of grid power) and switch off the inverter automatically.

IV. UTILITY GRID

The utility grid is basically the distribution and transmission system which transfers the electricity from the DG located away from the load. The combination of various distribution and generating substation helps in the formation of the grid and to maintain the continuous power supply economically.

The quality of power generated and delivered by the PV system should be utility compatible and hence is governed by practices and standards. Deviation from these standards represents out-of-bounds conditions and may require the PV system to sense the deviation and properly disconnect from the utility system.

One of important component of a PV power plant is a Power Plant Controller (PPC) which regulates active and reactive power output from the PV plant, such that it behaves as a single large generator. While the plant is composed of individual small generators (inverters), with each inverter performing its own energy production, the PPC coordinates the power output to provide typical large power-plant features as below;

A. Dynamic voltage and/or power factor regulation
B. Real power output curtailment when required so that it does not exceed an operator -specified limit
C. Ramp-rate control to ensure that output does not ramp up or down faster than a specified ramp-rate.
D. Frequency control to lower or increase plant output in case of over or under frequency respectively.

V. GRID CODES & STANDARD

Grid codes and standards provides technical requirements for reliable operations. Agencies all over the world has made numerous recommendations on specific requirements such that inverters-based plants must meet to provide their share of grid support. Grid code will specify the required behavior of a DG based plants during system disturbances which includes voltage control & regulation, power factor limits and reactive and real power control, response to a system fault (short-circuit), and frequency changes on the grid.

Following are the major grid codes and the standards that defines power quality in grid feed solar inverter.

1) *BDEW 2008:* is a German standard and stands for 'Bundesverband der Energie- und Wasserwirtschaft' or translated as 'German association for energy and water industries'. This standard is applicable for most DG possibilities in medium/high voltage.
2) *IEEE 1547:* Standard followed in US for 'Interconnecting Distributed Resources with Electric Power System', is meant to provide a set of criteria and requirements for the interconnection of distributed generation resources into the power grid.
3) *IEC 61727:* Photovoltaic systems – Characteristics of the utility interface standard relevant to 10 kW or smaller PV systems connected to the low-voltage grid.
4) *IEEE 519-1992:* Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. In addition to the above international standards, in contest to India, Ministries and agencies like CEA, BIS provides country related guidelines specific to all aspects of generation, transmission, distribution and supply of electricity is as discussed below;

The Central Electricity Authority (CEA) of India support Ministry of Power for forming policies in the power sector, to make technical standards & regulations, to carry out project monitoring. Grid connected PV inverter output should comply with the provisions of regulations as notified by CEA (Standard for connectivity of Distributed Generation Resources) regulation. Some of inverter related parameters notified are listed as below;

a) LVRT & HVRT
b) Reactive power control
c) Power ramp up and ramp down
d) Voltage regulations and flicker limits
e) Frequency range and PV plant response
f) Harmonics and dc current injection limits

5) *Bureau of Indian Standards (BIS):* Realizing the Indian solar market is rapidly expanding the Ministry of New and Renewable Energy (MNRE) issued guidelines to ensure quality of solar PV equipment including PV modules, inverter and batteries. The guidelines had mandated that the tests must be conducted by labs for compulsory registration with the BIS for the implementation of the order titled 'Solar Photovoltaics Systems, Devices and Component Goods Order 2017'.

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VI. POWER QUALITY ISSUES

Power quality issue is any power problem manifested in voltage, current, or frequency deviations that results in failure or malfunction of customer equipment. Sometimes power quality problems may not show the effect immediately, for e.g. the harmonic distortion may increase the aging of electrical components; without causing any immediately failure or malfunction. Major power quality issues faced by grid due to integration of solar farm based on grid tied PV based inverters are discussed below;

A. Harmonics

Harmonic is a voltage or current at a multiple of the fundamental frequency of the system, produced by the action of non-linear loads. Harmonics causes component overheating, nuisance tripping and even equipment malfunction. Total harmonic distortion (THD) and total demand distortion (TDD) are measurement levels of harmonic distortion present in power systems. THD is defined as the ratio of total harmonics to the value at fundamental frequency times.

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_n^2}}{I_1} \cdot 100\% = \frac{\sqrt{\sum_{k=2}^{n} I_k^2}}{I_1} \cdot 100\%$$

$$THD_V = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1} \cdot 100\% = \frac{\sqrt{\sum_{k=2}^{n} V_k^2}}{V_1} \cdot 100\%$$

Where In and Vn are RMS currents and voltages of the nth harmonic respectively and n = 1 is the fundamental frequency.
Total current demand distortion (TDDi)is harmonic current distortion against the full load (demand) level of the electrical system i.e. TDDi is equal to THDi at rated current output. Limits, assessments and measurement for harmonic distortion levels of VSI based grid tied solar plant are given in below standards;

Order			Current harmonics Limits (% of rated Inverter output)
IEC 61727	Odd	3-9	< 4.0%
		11 -15	< 2.0%
		17-21	< 1.5%
		23-33	< 0.6%
	Even	2-8	< 1%
		10-32	<0.5%
	TDD		< 5%
IEEE 1547	Odd	<11	4.0%
		11 -17	2.0%
		17-23	< 1.5%
		23-35	< 0.6%
		>35	0.3%
	Even	25% of odd harmonic limits	
	TDD		< 5%

IEEE 519-2014 standard discusses harmonic control in electric power systems in general. Limits for voltage and current harmonics shown in below tables are dependent on several variables defined as follows:

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

Current distortion limits for system rated 120V to 69kV

Voltage distortion limits

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

As per CEA 2013 guideline the limits of voltage harmonics, the limits of injection of current harmonics & method of harmonic measurement, shall be in accordance with the IEEE 519-2014 standards.

B. DC current injection

The dc power of the solar panels is converted into an AC power by inverters. Besides generating AC current, inverter also inject a small DC current if inverter output is not perfectly symmetrical with respect to ground. Excessive DC current injection into an AC network can cause problems like transformer saturation, which causes additional losses and reduce transformer lifetime. DC current injection limits specified in different standards as tabulated below.

Standard	DC Current Injection Limits
IEEE 1547	0.5 % of rated output current
CEA (2013)	
IEC 61727	1% of rated output current

C. Voltage Requirements

Grid code defines voltage limits for inverters to remain connected to and disconnected from grid for safety of system. Over and under voltage limits and expected inverter response from various grid codes are as tabulated as blow.

	Voltage Range	Disconnection time in sec.
IEC 61727*	< 50%	0.10
	50% to 85%	2.00
	85% to 110%	Continue Operation
	110% to 135%	2.00
	>135%	0.05
IEEE 1547	< 50%	0.16
	50% to 88%	2.00
	88% to 110%	Continue Operation
	110% to 135%	1.0
	>120%	0.16
BDEW 2008	1.0 to 1.30	T inst. ≤ 0.1 @ network
	0.10 to 1.00	T inst. ≤ 2.7 @ network
	1.00 to 1.30	T avg. = 60 @ network
	1.00 to 1.30	T avg. = 1.5-2.4 @ TRF
	1.00 to 1.30	T avg. = 1 @ generator

*Read as trip time which refers to the time between the abnormal condition occurring and the inverter ceasing to energize the utility line.

Power and voltage levels covered in different standards are as tabulated below;

Standards	Voltage Level	Power Level
IEC 1547	-	≤ 10MVA
IEC 61727	LV (Photovoltaic)	≤ 10kVA
BDEW 2008	MV (1kV-66 kV)	No limit

D. Reactive Power Requirement

Inverter normally supports reactive power control mode by operating in any of three modes i.e. voltage set point control, power factor set point, or reactive power set point mode. The reactive power support from inverter is dynamic in nature and the upper limit of reactive power capacity is given by relation;

$$|Q| = \sqrt{S^2 - P^2} \qquad \cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}}$$

Reserve reactive power can be extracted from inverter in case positive tolerance (+10%) of grid voltage and at lower operating temp. (25°C) of Inverter as shown below.

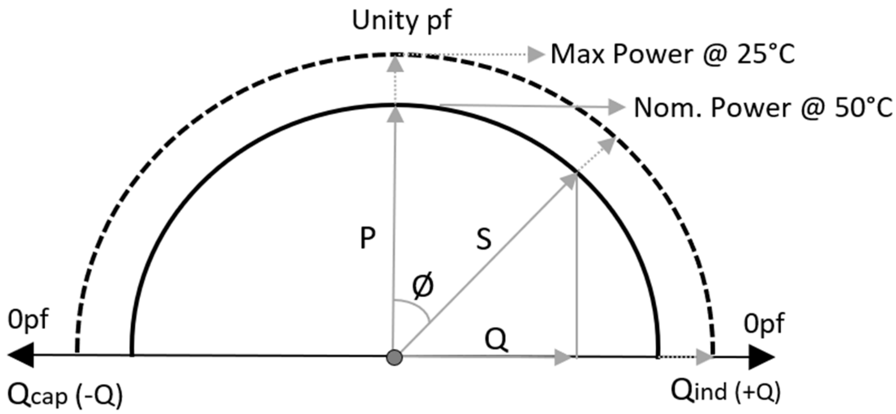

Fig. 6. Inverter PQ Curve (temperature dependent)

Inverters can operate at power factor levels less than unity and still produce 100% of real power. During cloudy skies, if solar generation drops from 100 % to 10%, the inverter can use 90% of its remaining capacity to support reactive power and enhance grid power quality. Inverters in PV system are sized to have some current capacity as reserve so that it has reactive capability at its active rated power.

E. Dynamic Voltage Support

Power feeding to the grid if subjected to sudden disconnection due to short time grid disturbances such as voltage sags or swells can possibly cause cascading tripping when demand is more than generation. Cascade tripping is the tripping of power grid due to unbalanced condition or tripping of safety devices and isolation of the part of the system to prevent damage to equipment.

To avoid this instability in the grid, regulations mandate to have Low Voltage Ride-Through (LVRT) and High Voltage Ride-Through (HVRT) capabilities. These capabilities implemented in the grid-connected inverters allows to stay connected to the grid and as well support voltage through reactive power injection during prescribed depths and durations of voltage sags and voltage swells respectively.

1) *Fault Ride-Through (FRT):* FRT capability is requirement of grid code which specifies a voltage-against-time profile and the values for the profile parameters are to be defined by the responsible transmission system operator. LVRT and HVRT specifies capacities of Inverter to remain connected to grid during and following grid fault including participating in dynamic voltage control.

a) *Low Voltage Ride-Through (LVRT):* When grid voltage drops below the preset low voltage threshold while the inverter remains online, the event is called a low voltage ride-through. This functionality avoids an unintentional disconnection of feed in power or network collapse (blackout). The inverter must be connected during symmetrical and unsymmetrical voltage sags for duration based on specific grid code. As per CEA guideline the inverter shall remain connected to the grid when voltage at the interconnection point on any or all phases dips up to the level as shown by voltage and time bound curve;

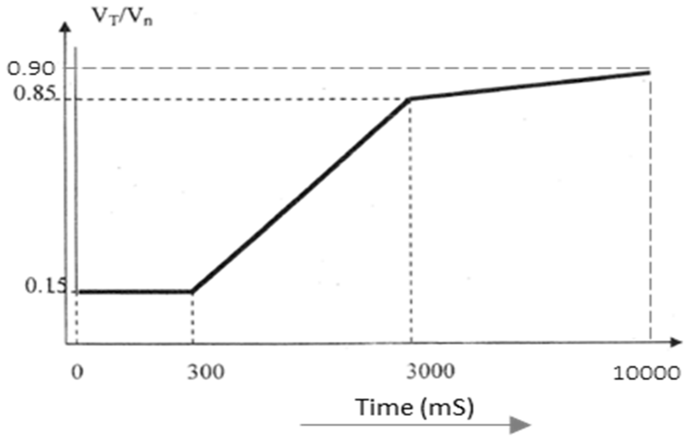

Fig.7. LVRT curve as per CEA (2013)

The ratio of the actual voltage (Vr) to the nominal system voltage (Vn) at the interconnection point during the voltage dip, the individual inverter shall generate active power in proportion to the retained voltage. Provided further that during the voltage dip, the generating station shall maximize supply of reactive current till the time voltage starts recovering or for 300ms, which ever time is lower.

As per BDEW curve shown below if voltage drops with values above the borderline 1 must not lead to instability or to the dis-connection of the generating plant from the network. If the voltage drops at values above the borderline 2 and below the borderline 1, generating units shall pass through the fault without disconnecting from the network. Below the borderline 2, a short-time disconnection of the generating plant may be carried out in any case.

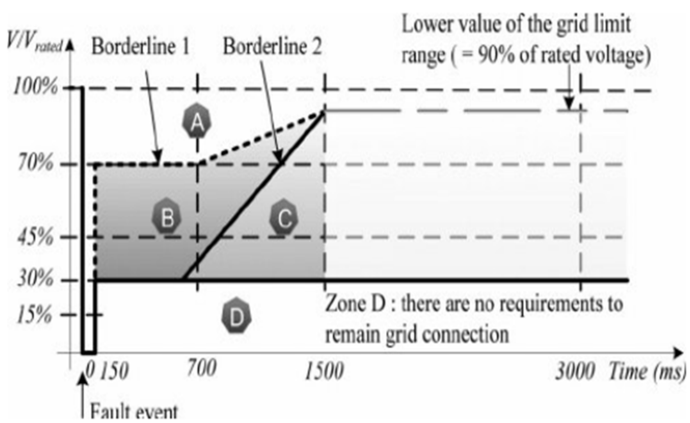

Fig. 8. LVRT curve as per BDEW

A new standard IEC 62910:2015 provides a test procedure for evaluating the performance of Low LVRT functions in inverters used in utility-interconnected PV systems.

b) High Voltage Ride-Through (HVRT): As per CEA guideline the inverter shall remain connected to the grid when voltage at the interconnection point, on any or all phases (symmetrical or asymmetrical overvoltage conditions) rises above the specified values given below for specified time;

Over voltage (pu)	Minimum time to remain connected (Seconds)
$1.30 < V$	0 Sec (Instantaneous trip)
$1.30 \geq V > 1.20$	0.2 Sec
$1.20 \geq V > 1.10$	2 Sec
$V \leq 1.10$	Continuous

F. Active and Reactive Power Control

Active power generated and injected at unity power factor into the grid only depends on solar radiation, and therefore cannot be controlled. With increasing penetration level of solar PV inverters, sudden change in active power generation due to partial shading results in poor voltage regulation. To address these issues, various grid codes like IEEE 1547, BDEW etc. allows inverters to actively participate in voltage support whenever it is necessary and provide reactive power compensation by reducing active current in favor of reactive current supply.

The dependence of the additional reactive current on the voltage deviation is a proportional gain K, called the 'K-factor'. K factor determines that the current increase from nominal current will be K times the depth of the voltage dip. Normally K-factor of solar power generating units is 2 or higher.

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

According BDEW, during voltage dip the Inverter should inject reactive current as shown in below figure.

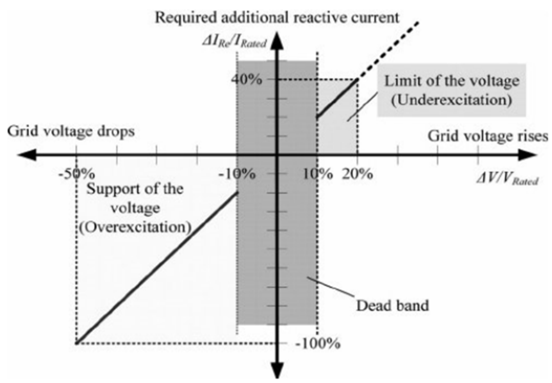

Fig. 9. Reactive current injection from Inverter during balanced network fault

1) *Reactive Power Compensation:* Reactive power management is an essential part of how voltage levels are controlled in electric power system. The process of absorbing and injecting reactive power is known as reactive power compensation. The inverter regulates the voltage at its PCC by controlling the amount of reactive power that is injected or absorbed from the power system. When the system voltage is high, the inverter absorbs reactive power (inductive mode), while the it generates and injects reactive power into the system when the system voltage is low (capacitive mode). The inverter adjusts the real-time relationship between real and reactive power to enhance grid stability whereas conventional generator does not. Utilities are understanding this benefit of solar inverter that can automatically match grid voltage, while at the same time independently change its power factor to improve grid stability. Additionally, inverters act as a Static VAR Compensators, with its built-in capacitor and inductor to regulate voltage during rapid changes in generation or load, even at night when not generating real power.

G. Night VAR Compensation

Inverters in PV plant do not produce any real power output in absence of irradiation from sun but supports to control reactive power, power factor correction and voltage control during night-time or non- sunshine hours. The PV inverters do absorb little active power from the grid during sun free hours to compensate inverter internal losses and regulate the DC bus voltage and to keep it within limits and operate the inverters in VAR mode. This eventually extends the utilization of PV inverters beyond active power generation and helps improving grid stability.

H. Voltage Unbalance

During phase in-balance grid fault, operator requires inverter to respond to sudden increase in negative sequence voltage with fast negative sequence reactive current output to improve phase voltage symmetry.

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.

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I. Flicker

Voltage flicker is rapid change in voltage that distorts normal sinusoidal voltage waveform. Such distortion results in PV based solar plant due to fluctuation of the output power as a result of variations in solar irradiance caused by the movement of clouds. Inverters are not allowed to introduce significant voltage flicker on utility grid as measured at PCC. Magnitude of the flicker depends upon the stiffness of the grid which involves voltage level, distance from the substation, size of the substation transformer and electrical design of plant.

The two important parameters constrained in grid code are the short-term flicker severity (PST) which is typically measured over a 10-minute period and the long-term flicker severity (PLT) which is typically measured over a 2-hour period. The PST values are calculated as follows:

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

Where Ψi is the weighting coefficient of the ith percentile exceedance flicker level (Pi). PST is measured in per units. PST value of 1.0 pu being the threshold of human perceptibility. The PLT value can be derived from the PST using the below formula:

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

Voltage flicker limits specified as per IEC 61727 states that the operation of the PV system should not cause voltage flicker in excess of limits stated in the relevant sections of IEC 61000-3-3 for systems <16 A or IEC 61000-3-5 for systems with ≥ 16 A.

Short term (10 minutes)	$P_{st} \leq 0.35$
Long term (2 hours)	$P_{lt} \leq 0.25$

IEEE 1547 specifies the flicker, caused by the solar plant at the grid connection point, must be within the limits as in by IEEE 519-1992, IEC 61000.4.15, IEC 61000.21

J. Frequency Requirements

Inverter response for frequency regulation requirement for various grid codes is as shown in below table.

	Freq. in Hz.	Disconnection / clearance time
*BDEW-2008	47.5 to 51.5	Continuous operation
	< 47.5	Instantaneous trip within 0.2s
	> 51.5	
**IEC 1547	> 60.5	Instantaneous trip within 0.16s
	<59.8 to 57.0 Adj. setpoint	Instantaneous trip within 0.16 to 300s
	<57.0	Instantaneous trip within 0.16s

* ** For Inverter > 30 kW, default clearing times

CEA-2013	Freq. Hz.	Inverter operation
	47.5 to 52	Continuous operation
	49.5 to 50.5	Operation at rated power output

1) *Primary frequency response (PFR):* Primary frequency response is similar to droop characteristic of governor used in conventional generators. Normally droop is set to 5% (default), meaning 100% change in power output for 5% frequency deviation. All grid tied inverters in operation must reduce their active power output when system frequency deviates as per droop characteristic recommended by standard. Active power reduces with gradient of 40% per Hz of available capacity as shown in below power vs frequency curve of inverter as per BDEW 2008.

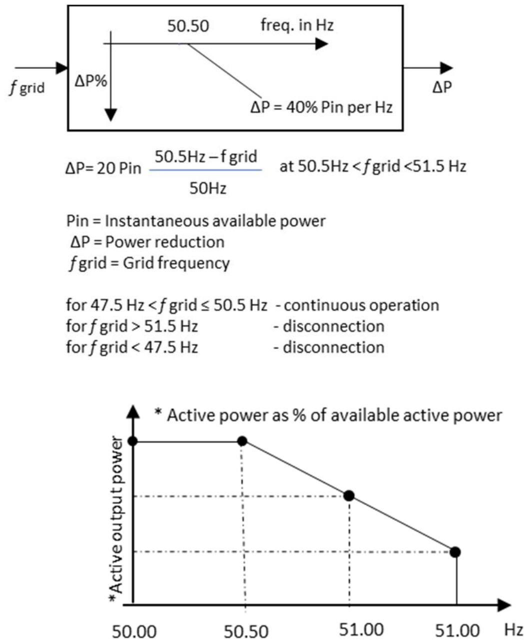

Fig. 10. Frequency versus Inverter power curve

K. Ramp rate

Grid tied inverter based solar plant control system during startup, shut down and normal operation should be capable of controlling ramp rate of its active power set by specific grid code. From grid stability point of view some grid codes define power ramp rate i.e. for example if power feed to grid is suddenly resumed after fault clearance, the inverter out power is ramped up until original power value is achieved.

Grid-connected solar PV inverter integrated with battery energy storage system (BESS) helps in ramp rate control. The BESS controls ramp rate of PV based inverter power plant output such that when output power of the plant decreases faster than ramp rate, BESS supplies power to grid so that power received by grid decreases only with ramp rate limit.

CEA (Technical Standards for Construction of Electrical Plant and Electric Lines) Regulations, 2013 states that for frequency regulation requirements, during disturbance, in case of BESS integrated PV plant, when system frequency fall below 49.7Hz, the system should act immediately within 1s and should be maintained for at least 10min. After 10^{th} minute the real power frequency response should not decrease at ramp rate higher than 10% of maximum AC active power capacity per minute. It also specifies that PV plant shall be able to control rate of change of power output at rate not more than ±10% per minute independent of metrological condition. Accepted ramp rate control tolerance shall be ±10%.

L. Anti-islanding

Anti-islanding protection is an important and must have safety feature built into all grid tied inverter. Islanding is the condition in which a grid tied inverter continues to power a location even though electrical grid power is no longer present and can be dangerous to utility workers. A grid tie inverter should detect islanding (loss of grid power) and switch off the inverter automatically.

Generation during the islanding has no longer under utility control may damage customer and utility equipment if operates outside of normal voltage and frequency conditions. To satisfy this concerns, utility interconnected PV inverters have implemented islanding detection and prevention (also called anti-islanding) technique. Anti-islanding capability detects when system operates in an island and disconnects it from grid. According to IEEE 1547 and IEC 62116:2014 the inverter on formation of an island must be de-energized within two seconds or meets the requirements of local codes.

M. Reconnection Time

In case of grid fault (for e.g. may be due to abnormal grid voltage or frequency) Inverter trips and disconnects from the grid. And the time Inverter required to reconnect to the grid once the normal operation conditions are detected is called reconnection time and its value is in between 20 to 300s. The IEEE1547 standard, specifies a reconnection delay typically fixed or may be adjustable for up to five minutes (300s).

VII. BIS STANDARDS

BIS specified standards for PV inverters and their relevance to IEC standards is as tabulated below;

BIS	Description	IEC equivalent
IS 16221 (Part 1): 2016	Safety of power converters for use in photovoltaic power systems - general requirements	IEC 62109-1: 2010
IS 16221 (Part 2): 2015	Safety of power converters for use in solar photovoltaic power systems – Particular requirements for inverters	IEC 62109-2: 2011
IS 16169: 2014	Test procedure of islanding prevention measures for utility-interconnected photovoltaic inverters	IEC 62116: 2008

VIII. ONGOING LATEST TRENDS

Battery Energy Storage System (BESS) is one of the latest trends in PV solar. The unpredictable solar radiation and fluctuating weather condition is challenging to provide reliable power through PV based solar system. To overcome this concern the grid-connected solar PV is integrated with battery storage system. BESS stores energy during off-peak hours and or during high solar irradiance and discharge during high peak demand.

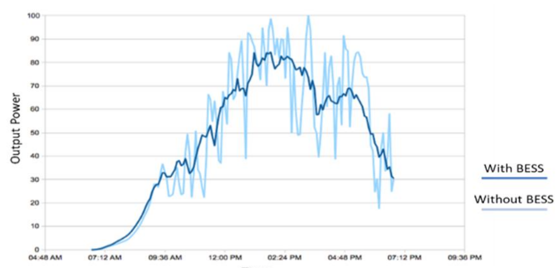

Fig. 11. Power fluctuation profile with and without BESS

BESS improves negative impacts of PV solar based power generation and helps smoothing the output i.e. voltage and frequency control, ramp support and demand response. The BESS controls ramp rate of PV based inverter power plant output such that when output power of the plant decreases faster than ramp rate, BESS supplies power to grid so that power received by grid decreases only with ramp rate limit. BESS are normally connected along with grid tied solar power generation as shown below figure.

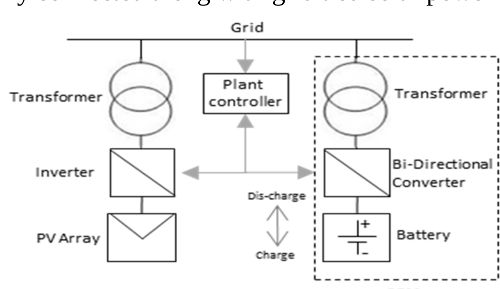

Fig. 12. Block diagram for BESS in PV solar plant

Forecasting is another technique when used with BESS supports the grid operators to address the load-balancing needs. The unpredictability of intermittent solar energy constitutes reliability challenges for utilities whose goal is to match electricity supply to consumer demands across centralized grid. As a result, forecasting techniques have obtained importance. The forecasted generation from the solar station is by prediction climatic and meteorological conditions, i.e. amount of irradiation, the position of the sun in the sky, the duration of daylight, cloudiness, precipitation, etc.

Now a days there are cloud based platforms (like GE's 'Predix') which does performance monitoring and maintenance of all equipment across the plant with aim of zero downtime. With such technology, solar plant is able to switch from scheduled to predictive maintenance, minimizing the downtime and labor costs.

IX. CONCLUSION

This paper provides overview on today's significant share of renewables especially PV solar and associated power quality issues which are becoming increasingly important in the grid connected PV generation system.

Unpredictability of intermittent solar energy results in un-stability & unreliability challenges for utilities.

Grid tied inverters are beneficial to the utility grid and help to correct the power quality on the grid while still maximizing real power generation and supporting in stability, reliability and safety of grid. Design of inverter is also most important to ensure quality of power output and safety. PV solar power generators must comply with grid codes which sets limits on the power quality and safety. Grid code guarantees the safe and reliable operation. Integration of solar PV and battery energy storage systems into the grid benefits voltage stability through dynamic VAR support, and frequency regulation via droop control response.

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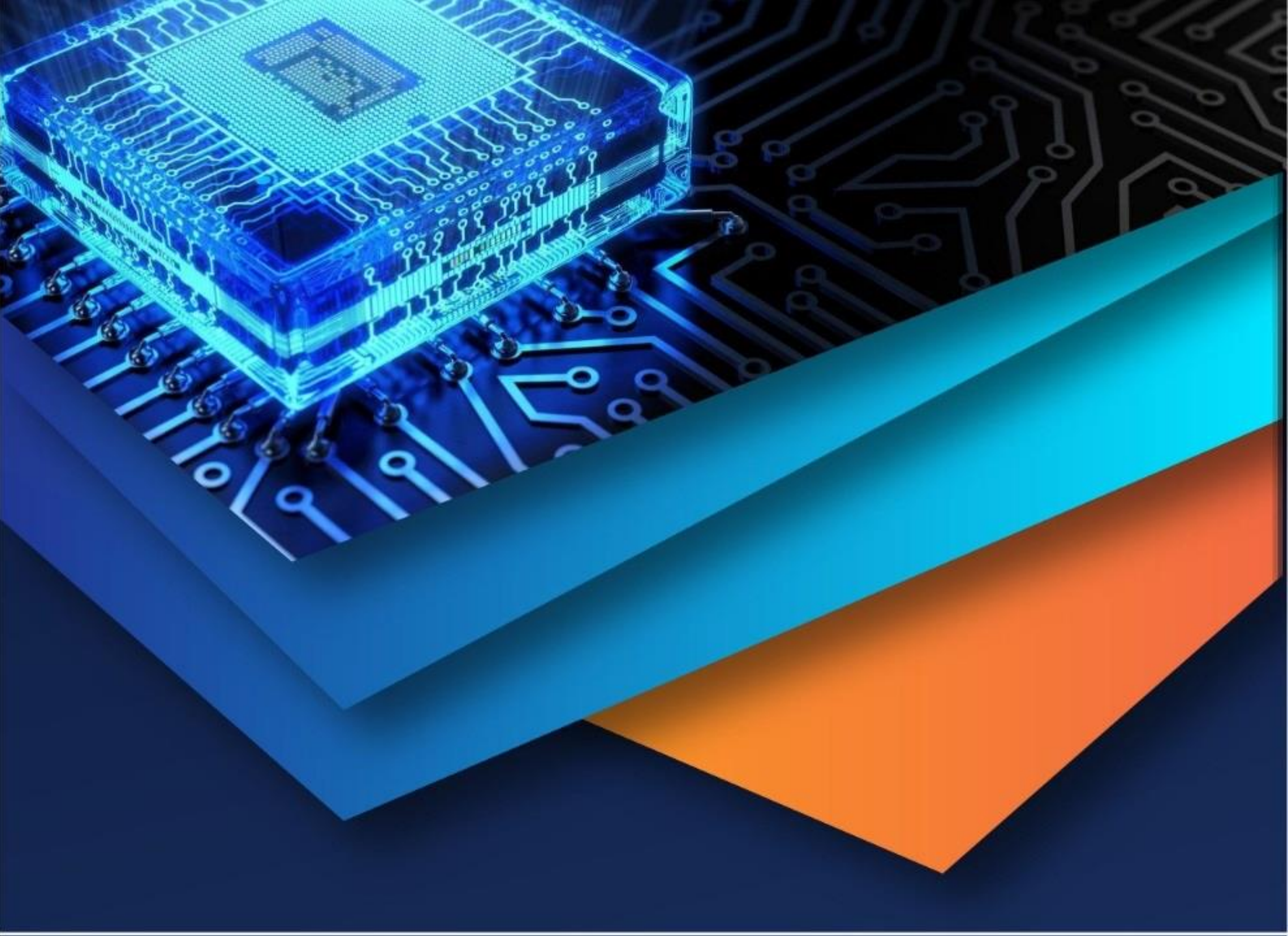

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