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A Review of Low Voltage Ride-Through Capability Techniques for Photovoltaic Power Plant Systems

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Abstract**— *the very hot development and increasing demand of photovoltaic power system has shown green light to the application of solar (PV) power generation system in the transmission and distribution grid connected system. This development of photovoltaic power system makes go to the low voltage ride through (LVRT) techniques, which is very important and one of the major problems in grid connected systems in recent years. This paper represents an overview of LVRT techniques for PV generation systems, based on the current control, fault detection, dc-link voltage control and grid synchronization under different voltage dip operation conditions and solutions are also discussed as well, and at the end LVRT requirements in different grid codes for PV Power Plant are explained.***

Keywords— Photovoltaic System, LVRT logic, MATLAB, SIMULINK.

INTRODUCTION

In recent years, growing grid connected converters, to improve performances during regular and irregular grid connected operation situations, is a very important fashion everywhere in the world, in particular inside the area of renewable energy conversion. For example, application of low voltage ride through (LVRT) in wind turbine and photovoltaic generations, in lots of nations because of the growth in capability and penetration stage of solar energy (PV) systems.

To keep inverters to be connected to the grid to improve voltage profile and increase reactive power without exceeding current generation to help the grid connected systems for the duration of various fault conditions is common LVRT requirements of PV power plants. The LVRT necessities are properly common and widely extent in distinctive feature of its advantages in frequency stability and voltage recovery etc. The LVRT requirements and standards such as limit curves for the voltage and reactive power requirements are different in every country. However, this paper is proposed based on the advantages to the grid regarding the concern about grid tied inverters, resulting in lots of issues and challenges in terms of inverter design and operational procedures. The major problem, for instance is that grid-tied inverters need to remain stable and control overcurrent to improve reactive power requirements and voltage profile.

This paper presents, different techniques of LVRT capability of PV power system and some challenges as faults detection, power balance, etc. Hence, the following overview content is regarding to these problems, with the equivalent solutions. Few techniques to improve LVRT logic performances according to the grid condition, like Enhanced Phase-Locked Loop (EPLL) [13], Synchronous Reference Frame with Low pass filter (LSRF) [12], Moving Average Filter (MAF) [14], Decoupled Double Synchronous Reference Frame (DDSRF) [11]. Here complete designed and detailed structure of these techniques are not demonstrated, but their brief overall performance and LVRT logic are discussed.

LVRT TECHNIQUES

2.1 The first Proposed (LVRT Logic) Technique. [1]

The efficient logic is developed based totally on two conditions: The first one is transient short circuit condition while the second one is voltage sag condition. Fig (1) displays the selected LVRT logic flow chart on the way to decide the functioning of the proposed study. In this case 0.08 sec is the predefined time for the inverter to be disconnected from the system due to transient short circuit fault. Even the fault insists after it. Reactive power will be injected into the system for the predefined time (0.15 Sec in this case), when the voltage sag is sensed. During reactive power injection, inverter pulses is going to be blocked. If the voltage sag persists to remain even after specified time, the PV system will be isolated from the nearby grid.

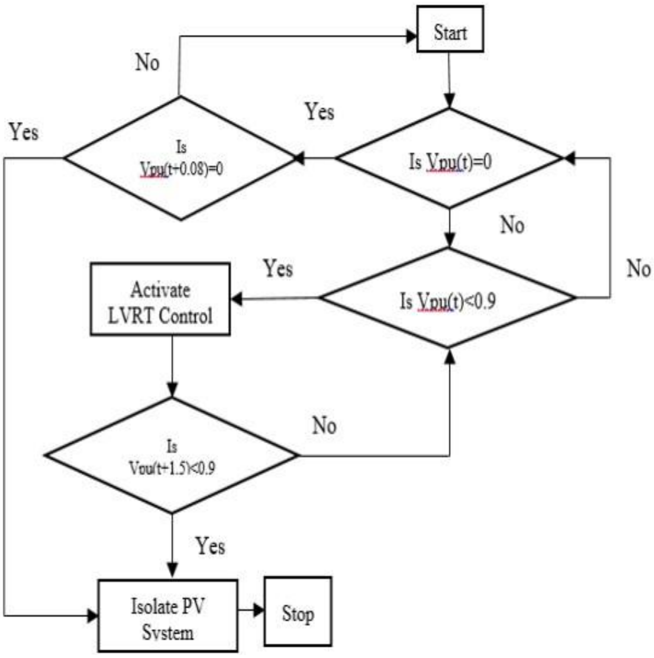

Fig.1 Flowchart of basic LVRT Characteristic Implementation

The proposed study fruitfully improves LVRT capability of traditional PV systems. The mitigation of voltage sag is distinguished achievement. Embedding reactive power injection device with already installed PV inverter will enhance the local grid stability and protection. The approach is beneficial within the cases where full-fledged LVRT associated grid codes cannot be implemented because of obstacles in hardware. [1]

2.2 The second technique [2], presents a novel control strategy for single-phase two stage grid-connected photovoltaic systems. During grid-fault period, Dc-link voltage is flexibly regulated with different stages of two-stage system to decrease voltage variant. When current injected to the grid, constant peak current strategy is followed to keep away from triggering over-current protection. Active and reactive output currents decoupling regulated with 2^{nd} order generalized integrator (SOGI)-primarily based PLL algorithm while the quantity of reactive power delivered for grid improvement depends on sag depth of grid voltage. The following aspects have been shown in the form of simulation

2.2.1 DC-link voltage remains stable during sag period. Active power regained, once grid fault is cleared and Dc-link voltage variation is decreased.

2.2.2 SOGI-PLL followed in this paper has specified benefits over other PLLs (like inverse Park PLL) in reaction rapidity and detection correctness, as a result enhancing the capability of LVRT whilst applied in DPGS.

2.2.3 Active and reactive current that is required is equipped without exceeding the control limit with constant peak current strategy.
Amplitude of active current of grid connected inverter lies within the energy generated by using Photovoltaic array in MPPT mode. For the functions of no longer triggering over-current protection, constant peak current strategy is delivered here. Amplitude of current injected to the grid is kept to be stored constant, commonly the nominal value, during LVRT due to usage of this strategy. Current stands for nominal value and limits value of grid current, respectively. With the assumption sag depth continues to be constant in a short duration of time. [2]

2.3 The third technique [3] delivers an enhanced PV based grid connected with power storage system that DG power conversion unit remains interconnected to grid even during fault conditions and Maximum Power Point Tracking (MPPT). This LVRT has been done by means of controlling voltage at DC link capacitor. The voltage variations at the DC link capacitor is able to be kept in the desired limits using bidirectional DC/DC converter. So the proposed system implements LVRT minus compromising efficiency of photovoltaic system. It also helps the grid by way of sending active power for the duration of faults also. The suggested system implements Low Voltage Ride Through using battery energy storage system (BESS) connected to DC link through a bidirectional DC/DC converter and then to the grid via a circuit breaker control. Over voltage appears across DC link during fault condition and the controller senses the fault appearance and operates bidirectional DC/DC converter in buck mode and sends extra charge at DC link to charge the battery through bidirectional DC/DC converter. Controller operates bidirectional DC/DC converter in boost mode while the voltage across DC link is lower than required voltage, and the DC link becomes charged from the battery. [3]

2.4 The forth technique [4] takes a look at a predictive-based control model strategy for grid-tied Z- source inverters (ZSIs) for PV systems with LVRT capability. The proposed system follows two operation modes:
2.4.1 Normal grid condition mode
2.4.2 Grid fault condition mode.
The maximum accessible power from the PV panels is injected into the grid in normal mode and for ancillary services, reactive power compensation as a power conditioning unit can be supplied from DG system to central ac grid. In case of grid faults, the proposed system adjustments the performance of reactive power injection into the grid for LVRT operation consistent with the grid necessities. Hence, the suggested controller for ZSI is deliberating each as power exceptional problems and reactive power injection underneath abnormal grid conditions. The effects of the proposed system exhibit fast dynamic response, small tracking error in steady-state, simple control scheme and eliminate the necessities of multi–nested loop of classical controller.
The proposed system has rapid dynamic reaction in different solar irradiance or grid reactive power requirement in keeping with LVRT operation. The system has been switched between LVRT and MPPT modes of operations effortlessly.
Some experiments have been performed to affirm the overall implementation of the proposed system.
Suggested Predictive Model Control System Modelling
This part gives the predictive modelling of the PV side impedance and the grid- side filter. The dynamic model of the grid side filter is given by

$$\frac{d}{dt} i_L(t) = \frac{1}{L}(v_i(t) - (v_g(t) - i_L(t)R_{esr})\ldots \text{(1)}$$

$$\frac{d}{dt} v_C(t) = \frac{d}{dt}(v_g(t) = \frac{1}{C}(i_L(t) - i_g(t)) \ldots \text{(2)}$$

Where
(t): Inductor current,
(t) : Output voltage of the inverter,
(t) : AC grid voltage,
L and C: filter's inductance and capacitance, $_{esr}$: Equivalent series resistance of the inductor.
Through the making use of the Euler forward approximation method to (1) and (2), the discretised models of (1).
$(k + 1) = \frac{T_s}{L}(v(k) - v_g(k) - i_L(k)R_{esr}) +(k)$ …(3)
$(k + 1) = \frac{T_s}{C}(i_L(k) - i_g(k)) + v_C(k)$… (4)
And (2) are found as
WhereT_s: sampling length. One of the important traits of ZSI is its shoot-thru mode for bendy boosting of the input (PV) voltage. In this mode, both switches in a single leg of the inverter are concurrently grew to become ON.

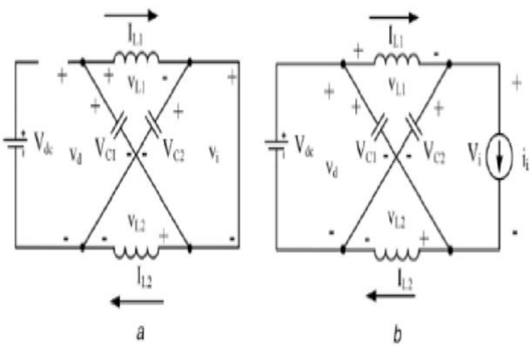

Fig. 2 (A) Equivalent Circuit In Shoot-Through Mode, (B) Equivalent Circuit Inside The Non-Shoot Through Mode.

$$\frac{x_\beta(s)}{x(s)} = \frac{x\omega^2}{s^2+x\omega s+\omega^2)}\ldots \text{(5)}$$

Where χ: damping factor, ω: fundamental frequency

Harmonics that are not closed to the fundamental frequency can be filtered by SOGI. The fundamental component from signals related to harmonic components can effectively be extracted through this way. Therefore, using SOGI as the grid voltage $v_g(t)$ and grid current $i_g(t)$ is shown as

$(t) = V_g \sin(\omega t)$… (6)
$(t) = I_g \sin(\omega t + \varphi)$ … (7)
$(t) = V_g \sin(\omega t + \pi/2)$ … (8)
$i_g(t) = I_g \sin(\omega t + \varphi + \pi/2)$ …(9)
The predictive equations for the active and reactive power is determined as
$(k + 1) = (k) - \omega T_s(k) + \frac{2T_s}{L}(v_g{}^2 - v_{g\alpha}(k)v_{i\alpha}(k) - v_{g\beta}(k)v_{i\beta}(k))$… (10)

$(k + 1) = (k) + \omega\, T_s(k) - {}_2{}^{T}{}_{L}\underline{s}(v_{g\beta}(k) - v_{i\alpha}(k)v_{g\alpha}(k)v_{i\beta}(k))\ldots$ (11)

This system is working for overnight operation of PV sources in DGs with reactive power compensation capability as ancillary provider from DG to central grid. [4]

2.5 The fifth technique [5] studies the stability improvement during day and night by the usage of solar photovoltaic farm inverter as a static compensator (STATCOM) to alter voltage at the point of connection. The solar photovoltaic farm commonly generates real power for the period of days but keeps remaining inactive during nights. The proposed PV solar system running as a STATCOM is referred to as PV_STATCOM. This scheme shows the usage of total capacity of inverter for the duration of night and the remaining after real power production all through day for carrying out different STATCOM operations. MATLAB/SIMULINK is used for the whole system modelling and analysis single machine system having midpoint connected PVSTATCOM. Additionally almost maximum use of a photovoltaic solar farm as a STATCOM that's inactive during night and simulated using MATLAB/Simulink is presented here. Through this scheme solar Photovoltaic farm operation is offered as a generator during day period and voltage regulation in the transmission line has been done via closed loop control scheme. Similarly, this new idea is inexpensive than the traditional devices which they used to attain the same reason like FACTS devices and does not need more upkeep. This PV_STATCOM within the subject of PV-solar gives upward push to new opportunities to earn profit inside the night and daylight at the side of the sale of active power in the course of the day.

System Description

This scheme is the single bus system that PV STATCOM is connected in the middle of the transmission line. The transmission line segments TL1, TL2 shown in fig below, are represented as lumped circuit. The real power to be injected from the distributed generators to the grid relies upon the level of solar insolation, temperature and so on. Here the proposed grid connected PV-STATCOM as voltage regulator and the DC-Link capacitor is sized in this type of manner that it reduces the DC side distortions. At night the PVSTATCOM is running and the PV arrays are disconnected from the inverter. To preserve the DC-link capacitor voltage, an amount of active power is taken from the grid. [5]

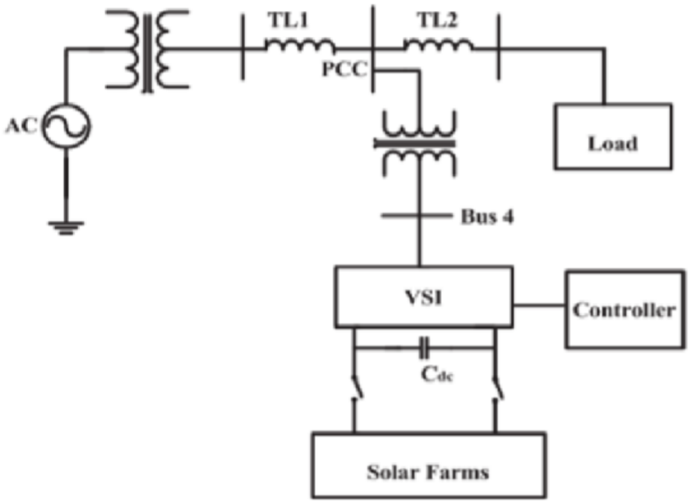

Fig.3 Single Line Diagram of PV- STATCOM System

2.6 The sixth technique [6] as a part of the overall fault ride through (FRT) necessities shows low voltage ride through (LVRT) capability of a three-phase-four- wire grid tied PV inverter. In this paper necessary adjustments to manage including positive sequence (PS), negative sequence (NS) and zero sequence (ZS) separation, a phase locked-loop (PLL) as well as voltage sustenance via reactive current as well as stress factors to the hardware has been identified and the standard system has been described. For all forms of LVRT, unique detection methods for transient variant of the grid voltages, sequence separation techniques, a stable PLL to reap the PS for orientation functions of the reactive current required for voltage support that needs to be carried out. Extra sequence compensation is needed except PI controller in dq0 reference frame. Despite the fact that the PV power limits itself, extra stress is also created at the DC link capacitors by way of oscillation at some stage in unsymmetrical grid faults and in the course of the absence of a booster stage on the semiconductors through switching complete current on the carried out open circuit voltage of the photovoltaic system. [6]

2.7 The seventh technique [7] offers a control method to keep the dc-link voltage of PV system constant in the course of Low Voltage Rid through (LVRT). Through this study changing the operation point on the I/V curve of the PV cell from the maximum power point to another point has been done and the active power output of the PV is reduced from the maximum to the specified value. This control strategy enables the PV system to generate reactive power to support the grid during fault. This enables the grid to maintain voltage stability. Also, reactive power can be delivered by the PV system during fault without the use of a DC-Chopper to protect the system and to keep the DC-link voltage constant. This causes a reduction in the general cost of the PV system. The proposed LVRT control of the PV system which is used here consists of two parts: 1. Active Power Control includes two PI controllers and 2. Reactive Power Control. The aim of this mode is to make the active power injected to the grid equal to the active power generated by the PV system to keep at the DC-link voltage constant and keeps power balance at the two sides of the DC link. [7]

2.8 The eighth technique [8] presents modelling and control strategies of a large scale grid connected PV system in depth that can support the low voltage ride through capability of DC primarily based photovoltaic power plant. It should be cited that grid side inverter plays a crucial role in low voltage ride through and consequently, overvoltage and under voltage tripping of DC link of the grid tied inverter should be prevented, if viable. This paper efforts to include DC link over and under voltage protection in the control loop without increasing average cost of protective device. It is observed that under the coordinated control scheme DC link over voltage can be saved within specified amount without any extra cost. It is also discovered that DC-link under voltage tripping condition can be prevented using the proposed study.

Suggested System

A five MW PV plant model system of a grid connected consists of two PV units each connected to separate DC-DC boost converter is discussed in this paper.

A three phase voltage source inverter (VSI) and DC link capacitor are connected to deliver sinusoidal current to the grid and maintain constant DC voltage at the DC link. Eventually, a Δ-Y (Y grounded) transformer is also connected to integrate the system to the grid.

In this proposed system, grid voltage is discussed and used to adjust the duty ratio command signal when grid side voltage goes under a certain value. Hence, the controller sets the reference duty ratio to zero or decreases it based totally on the severity of the grid fault. In this manner, duty ratio can be used a lot precisely compare to the case while no protection is implemented. The controller consequently forces the PV module to ship power toward the DC-link in a controlled manner. Subsequently, DC link voltage can be minimized. In order to avoid that, all the integral controller of the voltage source inverter is reset when the DC link voltage goes under a certain threshold value. Therefore the proposed controller can be carried out without problems without incorporating extensive modification in the control system and extra circuit elements are now not required. [8]

2.9 The ninth technique illustrates a multi-mode operation for the 3- phase PV power plant with Low Voltage Ride through (LVRT) capability is proposed. Active power from the PV arrays continuously extracted by boost converter for the duration of LVRT and maximum power point tracking (MPPT) can be quickly observed while the grid fault is cleared through this proposed multi-mode operation strategy. Additionally, the multichannel boost converter with interleaved operation can increase power conversion efficiency even as reducing the input current ripple. However, maximum reactive power below rated current amplitude can be supplied by the maximum current limitation control (MCLC) of the 3- phase inverter all through the voltage sag duration.

Operational Principles

During LVRT operation, when the inverter allows active output power smaller than its present output power, the maximum power point tracking function needs to be abandoned and input power of the interleaved boost converter should be reduced to maintain power flow balance and avoid the circuit damage. With a purpose to achieve power flow control in the course of LVRT in addition to shorten the MPPT recovery duration after the grid fault is cleared, a multi-mode operation strategy is presented. The PV power system can be operated inside the MPPT mode, the constant power control (CPC) mode, and the short -circuit current (SCC) mode based on the amount of the generated PV power plant and the specified maximum active output power of the inverter.

2.9.1 The MPPT Mode

The range of the three phase inverter voltage is ninety% to fifty% of its normal value, however the present active output power of the 3- phase inverter is less than the acceptable maximum value, Pinv, max, as given below, and the boost converter can remain its MPPT operation to reap the maximum power from the PV array.

Therefore, input reference current Ipv, ref of the boost converter keeps constant and equals to its maximum power point (MPP), Impp, under normal operation.

$I_{pv,} = I_{mpp}$ (1)

$P_{cmd} = P_{mpp}$ (2)

$Qcmd = \sqrt{(S_{inv,max},^2 - P_{mpp},^2}$ (3)

And also it should be cited that the dc-link voltage can be controlled by way of the 3phase inverter below the MPP Mode.

2.9.2 The CPC Mode

Once the output power of the 3-phase inverter is not less than the acceptable maximum value, Pinv, max, the maximum power point tracking function of the boost converter should be abandoned. Under this condition, the most effective and simple way is to turn off the switches of the boost converter and deactivate the energy harvesting from PV arrays.

In other words, to continuously carry the solar energy to the grid in addition to shorten the MPPT response time after the grid fault is cleared, the CPC Mode comes in the picture. Throughout this operation, the DC-link voltage should be controlled via the front- end interleaved boost converter and the input reference current is decreased to keep balanced power flow. Consequently, a current reference, Ipv, ref of the boost converter is derived as:

$I_{pv,ref} = I_{vp} \times \frac{P_{in,max}}{P_{pv}}$ …(4)

Where Ipv: input current

Ppv: input power
Pinv,max: maximum permissible power of the 3- phase inverter.
However, the dc-bus voltage cannot remain stable below the CPC mode because of the unpredictable power losses of the converter. Therefore, an improved current for the boost converter to maintain a stable dc-bus voltage is commended.

$If \quad V_{dc} > V_{dc}$, then $\quad I_{pv,ref}{}' = I_{pv,ref} - \Delta I_{pv}$

$Else\ If \quad V_{dc} > V_{dc},$, then $\quad I_{pv,ref}{}' = I_{pv,ref} + \Delta I_{pv}$

$Otherwise \quad I_{pv,ref}{}' = I_{pv,ref}$

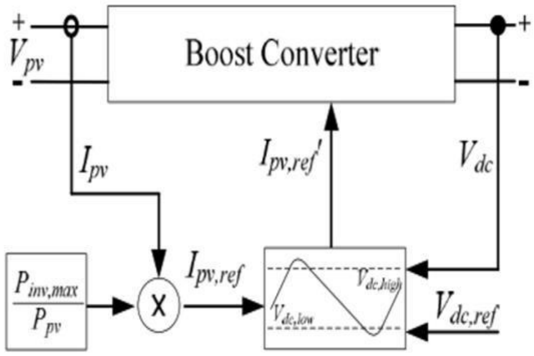

Fig. 4 The Current Control Diagram of The CPC Mode

Finally, the reactive power is given as below

$P_{cmd} = P_{inv,}$ … (5)

$Q_{cmd} = \sqrt{S_{inv,max,}{}^2 - P_{inv,max,}{}^2}$ …(6)

2.9.3 The SCC Mode

Fig. 4 suggests a typical I-V curve of the PV array to show the SCC Mode. Once grid fault is cleared, to increase the MPPT speed, the SCC Mode is presented. The main switches of boost converter are completely turned on to extract the short -circuit current thus the PV array is operated at point A. With the SCC Mode, the boost converter will start to carry out the MPPT function from point A rather than point B once the grid fault is cleared.

According to the Fig. 5, the current difference, between Isc and Impp, ∆I1 is very less than, the current difference between the Point B and the Impp, ∆I2. The proposed SCC Mode can rapidly achieve the MPP with the identical current perturbation. Through this Mode, the short -circuit current, Isc, is equal to the input reference current, Ipv, ref, of boost converter as shown in below.

$Ipv,ref = Isc$

It should be said that the short -circuit current is limited by means of the PV array and the complete grid- connected duration of the LVRT code is

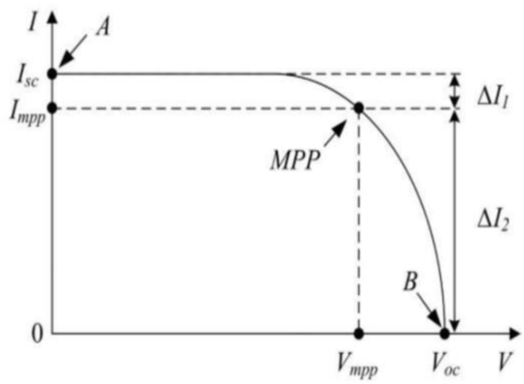

Fig.5 The Typical I_V Curve of The PV Array

2.10 The tenth technique [10] presents

LVRT capability of 3 mainstream single – phase transformer less PV inverters under grid faults. In this paper control techniques with reactive power injection are also mentioned. Full-bridge inverter with bipolar modulation has been selected for the inverter. The full -bridge inverter with DC bypass and the Highly Efficient and Reliable Inverter Concept (HERIC). Control strategy of transformer less PV inverters during faults, normally the control strategy carried out a single- phase grid connected system consists of two cascaded loops.

2.10.1 An internal current control loop, which is the responsible of inverter current protection and the power quality issues,
2.10.2 An outer voltage control loop, in such a way that grid voltage is controlled to generate preferred current references for the internal control loop.

Current Control Loop

The controller is selected here as the inner current controller is the PR+HC controller, offers a great performance in terms of harmonic rejection. Compared to the conventional PI-based controller in the synchronous rotating reference frame, in the PR+HC controller there is no need for quadrature signal generator and dq-currents decoupling.

$$G_i(s) = k_p + k_r \frac{s}{s^2+\omega_0} + \sum_{h=3,5,7} \left(\frac{k_{rh}s}{s^2+(h\omega_0 r)^2}\right) \ldots (1)$$

Voltage Control Loop

For the outer voltage control loop, it gives the system operation conditions and then it generates a current reference, which is ultimately applied in the internal current control loop. Because of the advantages of simple implementation and delay-free property, the SOGI system is adopted in this paper in line with the benchmarking outcomes presented.

The mentioned tests cleared that, although the HERIC inverter is the greatest candidate in terms of efficiency, it is not very unique probably in case of voltage sag and the other two topologies provide reactive current during LVRT. [10]

GRID CONNECTED REQUIREMENT FOR (LVRT) PV SYSTEM

PV generating units require to operate in variety across the rated voltage and frequency to be archived at the Point of Common Coupling, so the PV plant needs to maximize the output power, using (MPPT) methods. These needs are Fault Ride through Capability regarding to LVRT and HVRT, active and reactive power limitation when the fault occurs through absorbing or injecting reactive current to support Point of Common Coupling. [15]

3.1 Comparison of various grid codes concerning Fault Ride through Capability

In this section LVRT requirements in the form of table and figure has been shown.

TABLE 1

LVRT REQUIREMENTS IN INTERNATONAL GRID CODES

GC Country	During Fault		After Fault	
	Vmin (%)	Tmax (S)	Vmin (%)	Tmax (S)
Germany	0.0	0.15	90	1.5
Italy	0.0	0.2	86	1.5
Spain	20	0.5	80	1.0
Australia	0.0	0.45	80	0.45
USA	15	0.625	90	3
Denmark	25	0.14	75	0.75
Japan>2016	30	1.0	80	1.0
Japan<2016	30	1.0	80	0.45

Table.1 [15] explains the LVRT requirement enforced by Italian, German, Spanish, USA, Japanese, and Australian GCs concerning to PV penetration and Danish GC concerning with wind farm and also can be used for PV system.

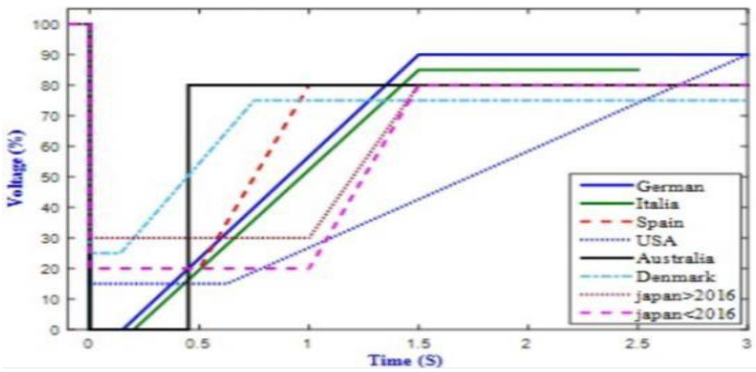

Fig.6 Comparison of LVRT Requirement At Various GCs

Figure.6 shows the LVRT requirements according to various grid codes countries.

CONCLUSION

This paper provides an overview of LVRT capability techniques that effectively improve LVRT capabilities of PV power plant systems based on the analysis of some new updated grid codes with LVRT needs, the techniques to resolve fault detection, current control, power balance, etc. The voltage sag mitigation is prominent accomplishment and it can be claimed from the selected paper results that the LVRT capability of grid-connected PV power plants can be further enhanced using the represented control strategies. By this way, we can add the PV power systems to the grid stability and reliability, which represents a better challenge to the grid connected system and LVRT requirements in different grid codes for PV system is briefly explained.

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