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Harmonic Analysis and Control of Grid-Connected Solar PV Inverter under Normal and LVRT Operating Modes

S. Raja Mohamed, P. Aruna Jeyanthy, D. Devaraj

Abstract*: Environmental factors and active involvement in grid-connected solar PV inverter ancillary operations may impact the quality of the current injected into the grid. The future grid-connected solar PV system with ancillary facilities (e.g., low voltage ride-through (LVRT)) will be more active and intelligent, which will degrade grid current reliability. The grid current distortions are specifically caused by the dc-link voltage variations and the modulation of pulse width (PWM) control applied to the PV inverter. This article analyzes the current harmonic distortion under the two-stage grid-connected PV system's regular (MPPT) and fault (LVRT) condition. Furthermore, a dc-link voltage variation control system for the two-stage photovoltaic (PV) inverter is presented during low voltage ride-through (LVRT) operation mode..The dc-link voltage differences are regulated under the fault condition to preserve the high modulation ratio in order to considerably mitigate the distortion rate of the grid current. Besides, the proposed system of control is designed to protect the PV inverter from the overcurrent failure under the faults to meet the modern LVRT grid codes. The conducted simulation tests have confirmed that the proposed control scheme leads to reduce a grid currents harmonics level by controlling the dc-link voltage variations.

***Keywords* : Current Harmonics, DC-link voltage variations , low voltage ride-through (LVRT), Grid –connected Solar Photovoltaic, total harmonic distortion (THD)**

I. INTRODUCTION

With an imperative demand for clean energy, it can be predicted that more photovoltaic (PV) systems will be installed in the future [1-2]. Such intensely increasing PV incorporation into the grid also threat the power system stability, reliability and power quality[3]. Consequently, specific modern grid requirements (e.g., IEEE Standard 1547-2018 [4] and IEC Standard 61727 [5]) are anticipated to be reinforced to regulate the grid-tied solar PV systems, especially in terms of power quality and ancillary services (eg, LVRT) [6]. In the future, the grid-connected PV system will be more active in various operating modes, will provide LVRT capacity in the presence of a fault on the grid, and will be equipped with a reactive power compensation function as presented in the literature [7]–[8]. However, most of LVRT enhancement schemes omit the power quality issues during their analysis. Specifically, when changing the PV system operations from normal (MPPT) to LVRT mode, it degrades the power quality with the risk of introducing resonances to the entire power system.

The control system should therefore be constructed with max imum power point tracking (MPPT) and other ancillary servi ce modes (e.g. LVRT) to comply with the LVRT grid cod-es as shown in Fig.1 [9]–[10]. The current level of distortion is one of the significant indexes of power quality for grid-tied inverter, including solar PV systems. In particular, the amount of the grid current distortion is caused by (i) variations in the DC-link voltage and (ii) the PWM pulse generation for triggering the power switches used in the PV inverter [11]. For example, both IEEE Standard 1547-2018 and IEC Standard 61727 state that grid current harmonic distortion level should be within the 5% to prevent negative impacts on other grid-connected devices. Due to the decreased grid current quality caused by the dc-link voltage variations, the LVRT operating mode will inevitably worsen the power quality at the connection point (POC). It is, therefore, worth exploring the two-stage inverter operating principles to inject the current without harmonics into the power grid network during the LVRT process.

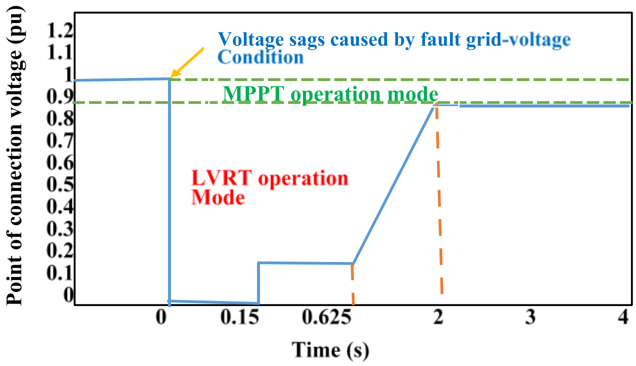

Fig.1 LVRT Code- [Country-Germany].

However, each country have their own grid (LVRT) codes. This paper taken well known Germany grid LVRT code for the investigation.

Having regard to the above factors, this paper describes first the setup of the two-stage solar PV system and then provides the dc-link voltage control approach to reduce the harmonics of the current injected into the grid. At the same time ensure secure operation during LVRT operation. Finally, the Matlab simulation confirmed the suggested analytical statement.

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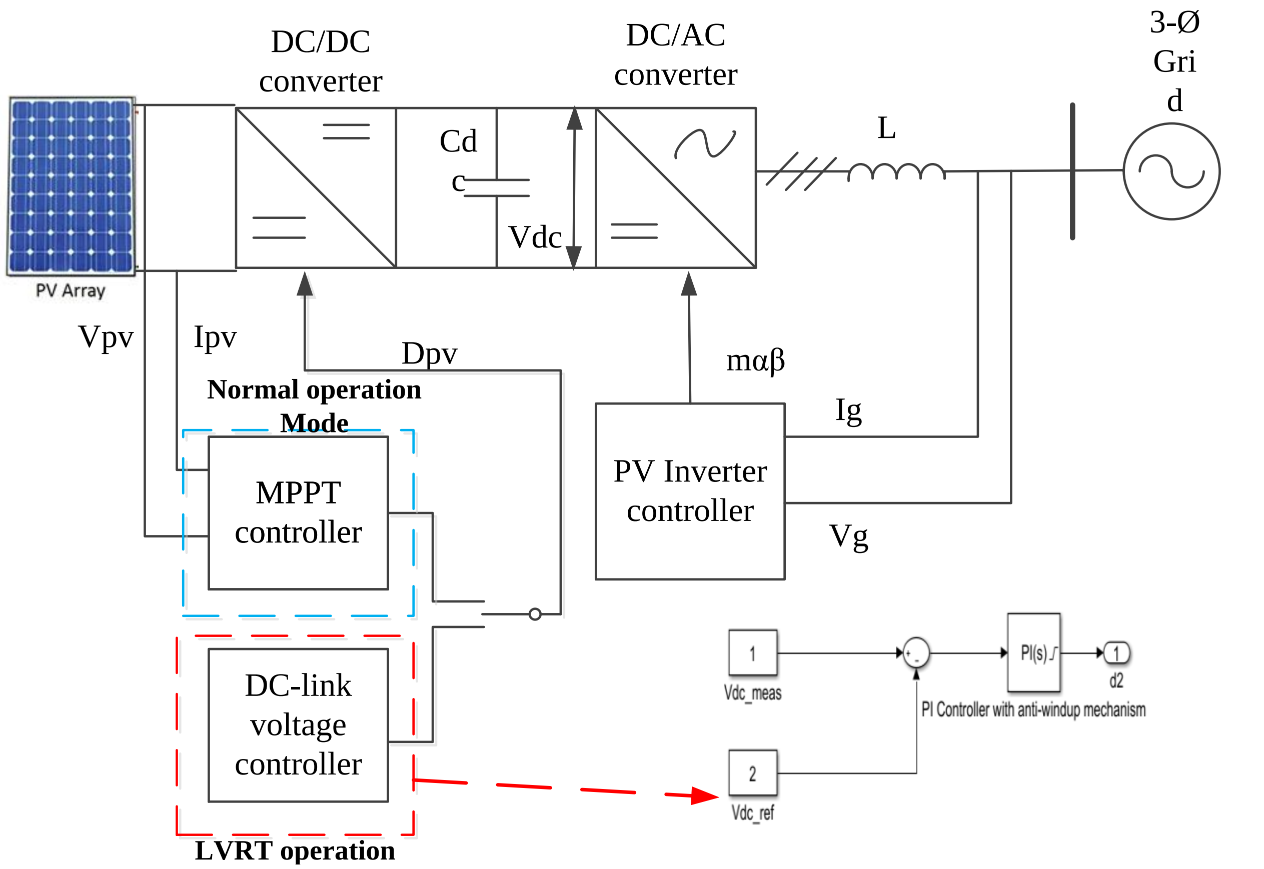


Fig.2 Study system with controllers.

II. TWO-STAGE GRID-TIED PV SYSTEM

Fig.2 illustrates the scheme to be described. The first phase of the system consists of PV modules and a boost converter, which increases the comparatively low voltage of the solar PV system into an appropriate value. The second phase consists of an inductor (L) filter linked to the grid by a three-phase three-level inverter. Maximum energy point tracker (MPPT) incremental conductance (IC) is introduced on the boost converter to extract maximum energy from solar PV under different metrological situations. The suggested control approach comprises of MPPT and DC-link voltage controllers linked to a boost converter, respectively supplied to the gate pulse under normal and fault circumstances (LVRT mode).

III. OUTPUT CURRENT HARMONICS ANALYSIS

The primary causes of PV inverter harmonics are disturbance of grid voltage, switch harmonics, variability of DC-link voltage owing to MPPT etc. This paper analyzes the harmonic in PV inverter owing to the difference of capacitor DC-link voltage in MPPT mode and suggests the DC-link voltage control approach to mitigate the harmonics of grid current. The closed-form treatment of the feedback current harmonic distortion can be derived from the concept of ' harmonic impedance. '.

This concept focuses on the approved linear method and it is considered in this study to examine the harmonic range under distinct levels of power. It is possible to obtain the harmonic impedance by calculating the gain at the harmonic frequency of a closed-loop transfer function based on equ (1). This impedance offers an easy measure of a current regulatory scheme's harmonic sensitivity [12]. One of the important cause of harmonic impedance changes is the DC voltage variation. It is possible to calculate the complete harmonic element of the PV inverter output current Ih using equ (2).

$$I_o = \frac{G_{PI}\, G_{pwm} G_{inv} G_f}{1+G_{PI} G_{pwm} G_{inv} G_f} I_{ref} - \frac{G_f}{1+G_{PI}\, G_{pwm} G_{inv} G_f} V_g \qquad (1)$$

$$I_h = V_h / Z_h \qquad (2)$$

A. Grid voltage alteration

The inverter current harmonics are caused by the voltage difference between the grid voltage (Vg) and inverter output voltage(Vinv) Always, field measurement data's show that the grid voltage have the harmonics, its level depends upon the location and types of load used. It is varies from application to applications, However most case lower order harmonics found , which is hard to remove like higher order harmonics. In literatures, different methods are proposed and tested under various condition to reduce the grid voltage harmonics. [13]-[14].

The Equ (3)-(4) shows the grid current harmonics and grid side harmonic impedance It is clear from In equ (3) current harmonics are due to the manipulation of the grid voltage

$$I_{\_g\ harmonics} = \frac{G_f}{1 + G_{pi}G_{pwm}G_{inv}G_f} V_{g\_harmonics} \tag{3}$$

$$Z_{g_{harmonics}} = \left| \frac{1 + G_n G_{pwm} G_{inv} G_f}{G_f} \right| \tag{4}$$

where Gpi, G_{PWM}, Ginv and Gf are the transfer functions for the PI controller, PWM, inverter and filter, correspondingly.

B. DC-Link Voltage Variation: MPPT and LVRT Modes

In the two stages grid-connected PV system (Fig. 2) can not assume DC-link voltage as a constant [15]. Since it is coupled in the high voltage side of the inverter. In this topology, to minimize the decoupling capacitor, a higher voltage ripple can be presented across a DC-link. Therefore, the hypothesis of steady DC-link voltage is not true. This variation does not affect harmonic sources on the basis of equ (1 But the inverter transfer function G_{inv} will change, which will also change the harmonic impedance. The voltage at MPP equal to VDC reduces as the energy produced by the photovoltaic scheme reduces, I–V curve [15-16]. When a fault happens on the grid, the grid voltage drops at the link point (POC) bus terminals from the normal level, which makes the power imbalance on inverter input and grid sides. Due to the power imbalance, dc-link voltage variations increases sharply, which triggers the overcurrent protection device of the inverter that gets disconnect from the grid. Under the LVRT grid code as shown in Fig.1, PV inverter must be connected with the grid during a certain level of voltage sag on the specified time (minimum 150 ms). The DC-link voltage fluctuation control scheme is presented in [17] to improve the grid-tied two-stage PV system LVRT capacity. However, the harmonics analysis has not been carried out during the LVRT mode.

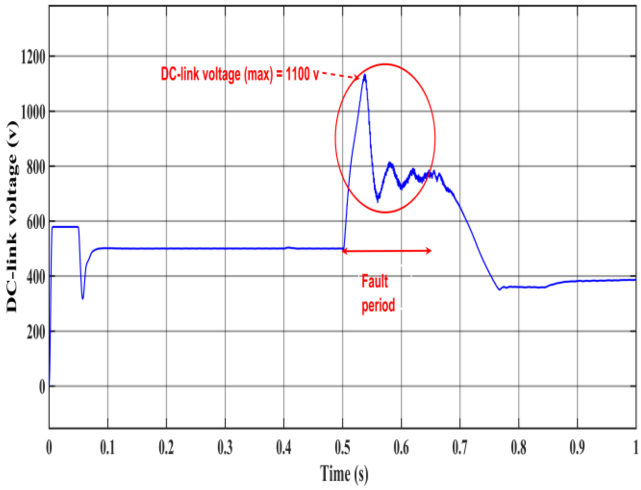
IV. RESULTS AND DISCUSSIONS

The proposed control strategy is evaluated in a 100-kW solar PV array system linked to a 25-kV grid provided on the Matlab website [18]. The fault is created at t = 0.5 s and after 0.15 s is eliminated. Total simulation time is 1s. Simulations are conducted under two cases: (i) with MPPT control (ii) Proposed Control scheme. The PV array and DC-link voltage controller (i.e., PI controller) parameters are shown in Table 1. The solar PV system performance during the fault shown in Appendix –A (Fig.5).

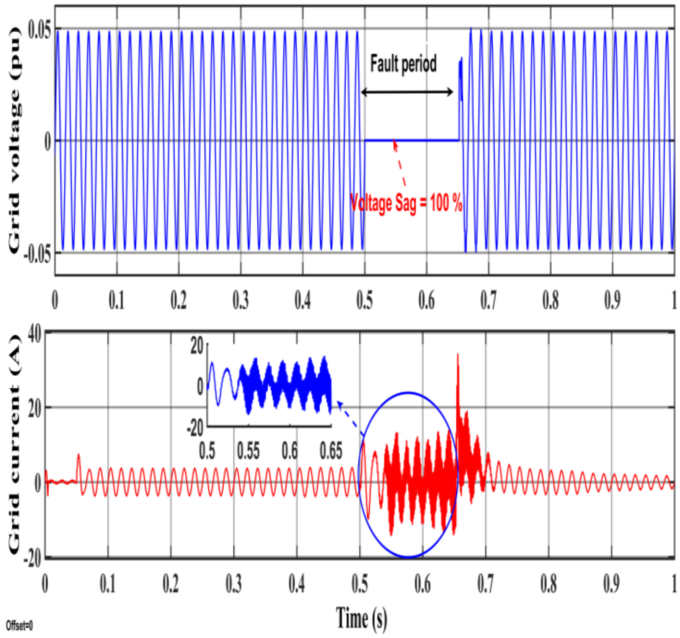
It can be observed from Fig.3 (a)-(c), that under the symmetrical fault (3-LG), the system working in MPPT operation mode induces a harmonic (i.e., THD = 19.51%) in the grid current due to high dc-link voltage variations.

Table. I Test system parameters

System	Parameters
PI-controller of DC-DC converter	Kp = 0.0001; Ki = 1
PV generation system	Power Capcity100 kW DC-linkvoltage/Capacitor-500 V/ 12000µF Switching frequency 5 kHz Inverter voltage 260 V/ 50 Hz Set-up transformer 260V/230kV, 100 kVA
Three-phase Grid	25-kV feeder . 120 KV Transmission line



(a)



(b)

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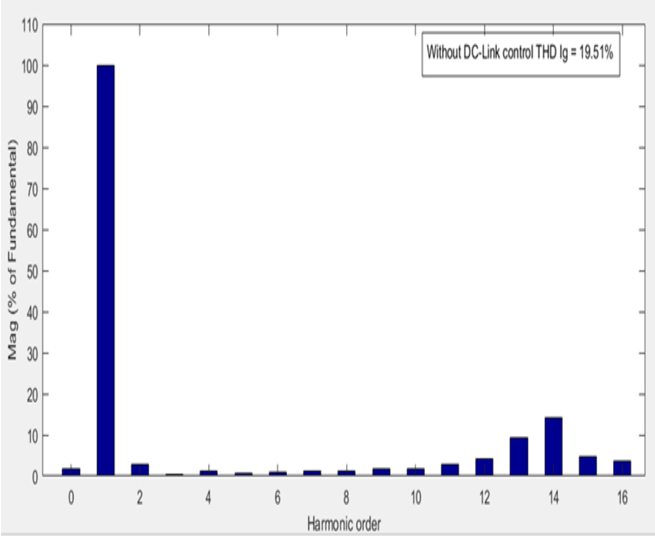
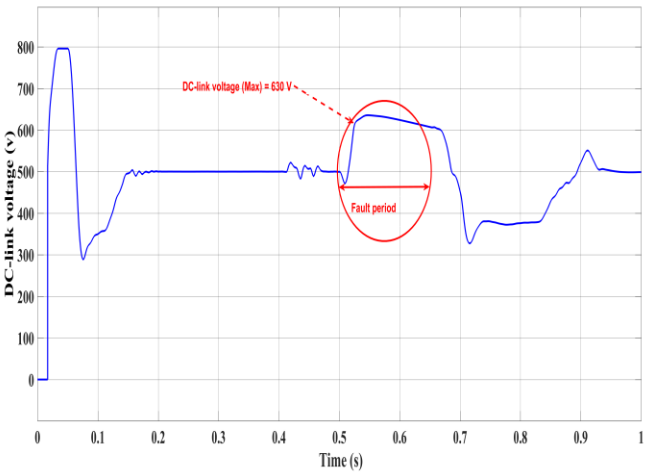


(c)

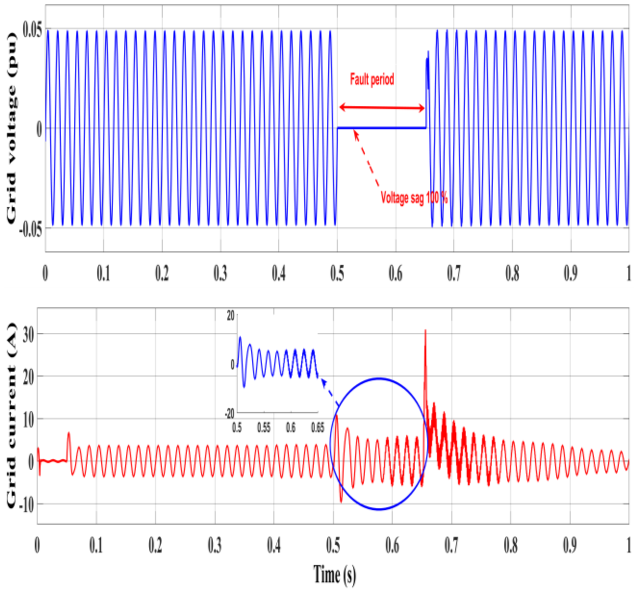
Fig. 3.Without proposed control (MPPT mode): (a) DC-link capacitor voltage (b) Power grid voltage and current (c) Grid current harmonics (% THD)

Alternatively, as presented in Fig.4 (a)-(c), when voltage sag occurs on the POC, DC -link voltage control is enabled and the system injects reactive power according to the grid codes, although the amplitude of the grid current is maintained almost constant in order to avoid inverter disconnection from the grid due to inverter-over current triggering device. In addition, the suggested control system decreases the dc-link voltage differences in this situation, which decreases the harmonic injection into the grid.

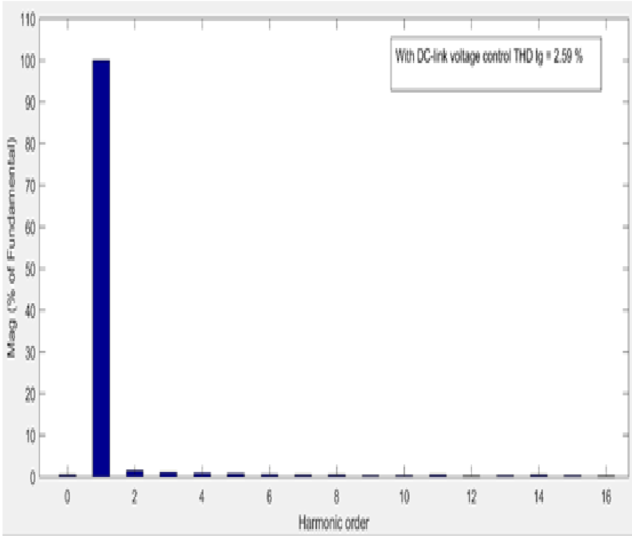
Total harmonic distortion (THD) can be noted in this case is 2.59%, which is within the IEEE-519 standard limit (Maximum THD = 5%). From the results, it is observed that if harmonic quantities need to be lowered at low power stages, the power system engineers should concentrate on reducing harmonic distortion by controlling differences in the DC-link voltage.



(a)



(b)



(C)

Fig. 4. With proposed control (DC-link voltage mode). (a) DC-link capacitor voltage (b) power grid voltage and Grid current (c) Grid current harmonics (% THD)

V. Conclusion

This work proposed a novel LVRT strategy for regulating the DC-link voltage for the two-stage PV inverter. The simulation results show that the during the fault condition, the system move from MPPT mode to LVRT mode by the proposed control system current harmonics are under IEEE 517 harmonics level standard (2.5%), at the same time without proposed control the harmonics level is 19.5%. MATLAB/Simulink simulations results revealed the increased efficiency of the proposed control solution and decreased the total harmonic distortion (THD) of the grid current, which is increase the power quality of the interconnected system.

APPENDIX

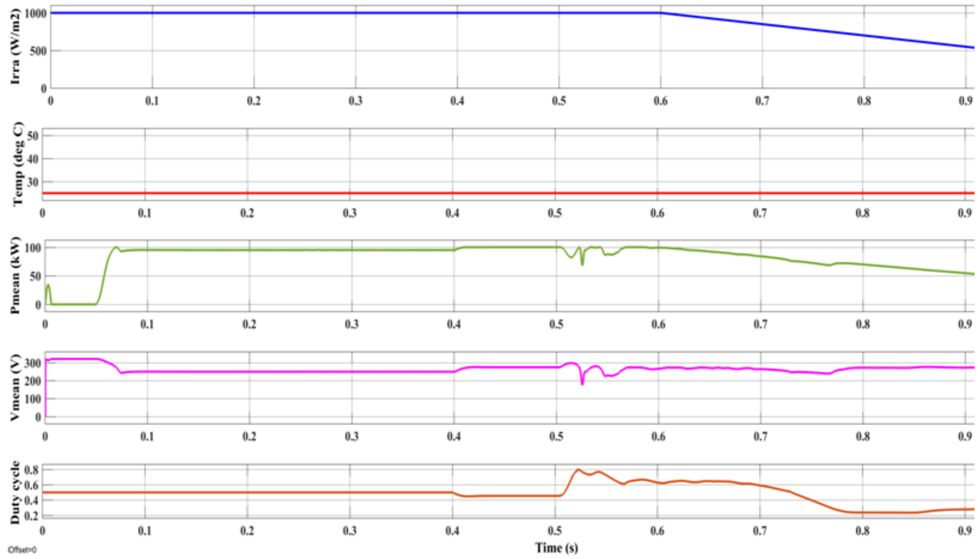


Fig. 5 Solar PV system parameters.

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