Phase Current Control in Grid Connected Photo Voltaic Power Plants to Avoid Over voltages in Healthy Phases

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Abstract - *The present paper explains a new method to report the grid code requirements during voltage sags which necessitates unbalanced current injection, the necessity of unbalanced current injection into grid can be achieved by controlling each phase current of the three phase voltage source inverter (VSI) based on the voltage drop of the respective phases in which voltage sag or fault occurs in the Grid Connected Photovoltaic Power Plants (GCPPP).The Individual phase current control of the Voltage Source Inverter needs the calculation of the grid voltage angle of each phase and the computation of current reference of each phase to feed the current control loop which will generate voltage reference to trigger the power devices of the Voltage Source Inverter. The current reference generation consists of limitation of active current component based on reactive current required further elimination of zero sequence currents is proposed and finally re-scaling of instantaneous current references to avoid over voltages of non-faulty phases or healthy phases while preventing Grid Connected Photovoltaic Power Plants (GCPPP) from over currents is proposed. In order to validate the proposed method, a simulation model was developed using MATLAB/SIMULINK software and tested the system, the obtained results were presented here for different type of power system faults.*

Key Words: **Photo voltaic system, Grid Codes, Voltage Source Inverter (VSI), Power system faults, Phase Locked Loop (PLL), Reactive Current Control, Phase Current Limiter.**

1. INTRODUCTION

In order to safeguard the Grid Discipline certain Grid codes are imposed on Photo Voltaic (PV) Power Plants connected to grid. According to the Present Grid codes, Grid Connected Photo Voltaic Power Plants (GCPPP) need to support the Grid voltages by injecting reactive currents into grid during voltage sags.Under unbalanced voltage sags, Injection of reactive currents leads to over voltages in the non-faulty or healthy phases which have a constraint (specified ratio to Nominal Value).So we need to avoid such over voltages which necessitates the unbalanced current Injection into grid during voltage sags. These unbalanced currents can be achieved by controlling each phase current of the Voltage Source Inverter (VSI) based on voltage drop in the corresponding phase.

This report investigates for several aspects like active and reactive power studies, fault ride through, phase current control, control of Voltage Source Inverter (VSI), methods of providing current reference to VSI, support of grid voltages with the injection of reactive currents, injection of unbalanced reactive currents under unbalanced voltage sags and different control methods of providing unbalanced reactive currents under unbalanced voltage sags in the literature survey.

The reference paper [1] explains how phase current control can be achieved individually in PV system connected to grid. The reference papers [2] and [3] explains about the some research focused on active power control strategies and two methods of providing the current references for VSI's. Reference papers [4] and [5] provides about how VSI's should remain connected during voltage sags and support the grid voltages with the injection of reactive currents like as in the case of synchronous generators in conventional power plants. Reference paper [6] summarizes about the injection of balanced reactive currents to support unbalanced voltage sags may lead to over voltages in the healthy phases. In order to prevent this, new grid codes require the injection of unbalanced reactive currents during unbalanced voltage sags and for the sake of this one different control methods have been explained in the literature. A flexible voltage support method was used based on the type and severity of the voltage sags, which needs the amount of reactive power injected via positive sequence and negative sequence is controlled with an off-line control parameter were explained in [7] and [8]. An extended generalization of the above studies is presented, with that the reactive power reference and the control parameters were updated to restore the quantity of voltage drop is also presented in the paper [9].

Based on an equivalent impedance grid model, A method to set the positive sequence and negative sequence reactive power references to avoid over voltage and under voltage is described in paper [10], in which new current references were updated based on earlier reactive power reference. The paper [11] briefs about a decoupled double synchronous reference frame current controller with the capability of independently controlling the active and reactive power of the positive and negative sequences. However, the current references were regulated off-line. Paper [12] explains about new requirement for unbalanced current injection. Some research work to support the phases with unbalanced reactive power.

Since This report needs knowledge of grid voltage angle for the phase current control under unbalanced voltage sags, Phase Locked Loop (PLL) was used which is explained in paper [13]. Moreover the phase currents are defined independently, methods to prevent the controller from trying to inject a zero sequence into the grid further more rescaling the instantaneous current references is proposed to prevent over currents.

2. ACTIVE & REACTIVE CURRENT GENERATION

In order to get current references for each phase of the three phases first we need to have active and reactive current references and the respected phase angle of the grid voltages of each phase. The active current and reactive current reference are generated as follows and the phase angle is extracted from grid voltage by using phase locked loop (PLL) which will be explained in the next section.

2.1 Active Current Reference Generation

The block diagram of active current reference generation circuit is as shown in Fig. 1 below. Like as shown the amplitude of active current (i_A) is defined to regulate dc link voltage such that the difference in dc link voltage and dc reference voltage controlled by a proportional integral (PI) controller give raise the active current reference amplitude.

The dc link voltage loop is controlled by proportional integral controller equipped with an anti-windup technology that helps attain the pre-fault values very quickly after fault removal, the obtained output of PI controller is i_d^* is the active current reference in the d-q reference frame which then multiplied by a gain of Sqrt (2/3) will give the amplitude of active current (i_A).

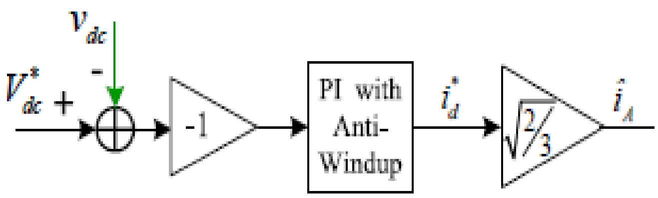

Fig. 1 Active current reference generation circuit.

2.2 Reactive Current Reference Generation

The block diagram of reactive current reference generation circuit is as shown in Fig. 2. The amplitude of reactive current of phase 'x' (i_{R-x}) are found from droop control method defined by equation (1).

$$i_{R-x} = \text{droop} \times \|de_x\| \times I_n \quad \text{with } x \in (a, b, c) \qquad \text{Eqn. (1)}$$

$$\text{For } \|de_x\| \geq 10\% \text{ of } E_{n-ph} \ \& \ \text{droop} \geq 2$$

Where $\|de_x\|$ is the amount of phase voltage drop from its nominal RMS value (E_{n-ph}), I_n is the amplitude of the nominal phase current of the inverter and droop is a constant value.

A value greater than or equal to two for droop implies that, for voltage support the injection of reactive current at the LV side of the transformer must be at least two percent of the nominal current per each percent of the voltage drop.

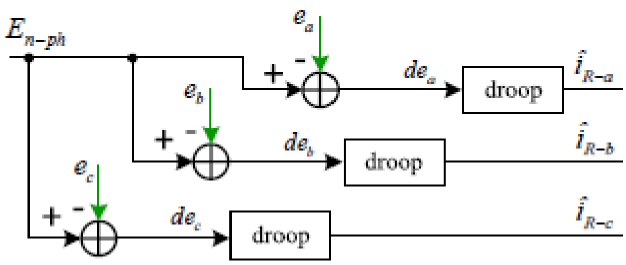

Fig. 2 Reactive current reference generation circuit.

3. CURRENT LIMITER & PHASE LOCKED LOOP (PLL)

The derived active current and reactive current references are fed to the current limiter in order to limit the active current by giving enough room to the reactive current to avoid over current in the inverter phases. For each phase one current limiter to limit active current and one PLL is used separately to extract phase angle.

3.1 Current Limiter

Under a voltage sag condition, the controller increases the active currents to maintain the power injected into the grid. At the same time, reactive current needs to be injected into the faulty phases to support the grid voltages. Consequently, the total phase currents may increase above the maximum acceptable values, which would eventually trigger the overcurrent protection. To avoid this situation, priority is given to the reactive current injection to support the grid voltages. Therefore, the amplitudes of the active currents are limited based on the reactive current required for each phase

The priority under voltage sag is to support the grid voltages with the injection of reactive currents. However, the current of each phase cannot go beyond the maximum acceptable value defined for the inverter. Therefore, in the case of overcurrent in one phase, the active current of that phase should be limited based on the current limiter defined by equation (2).

$$i_{A\text{-}x} = \begin{cases} i_A, & \text{if } \sqrt{(i_{R\text{-}x}^2 + i_A^2)} \le i_n \\ & \text{and} \\ \sqrt{(i_n^2 - i_{R\text{-}x}^2)} & \text{if } \sqrt{(i_{R\text{-}x}^2 + i_A^2)} > i_n \end{cases} \qquad \text{Eqn. (2)}$$

Where 'x' stands for phases a, b, and c

3.2 Phase Locked Loop (PLL)

As the proposed method consists of controlling the phase currents independently, it is necessary to extract the phase angle of each phase of the grid voltages. Therefore, the frequency adaptive PLL is implemented. This PLL is based on the filtered-sequence PLL (FSPLL). The first stage of the FSPLL separates the positive sequence of the grid voltages from the negative sequence and some harmonics by means of an asynchronous d-q transformation and moving average filters (MAFs). The FSPLL includes a standard synchronous reference frame PLL (SRF-PLL) to obtain the angle of the extracted positive sequence.

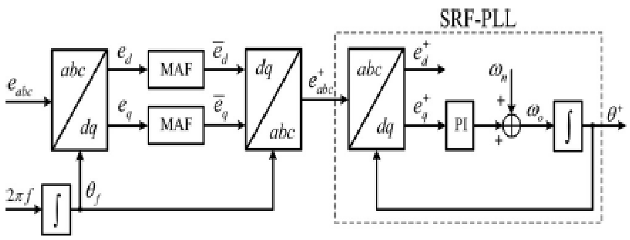

Fig. 3 Proposed FSPLL for phase angle extraction.

The block diagram of filtered sequence phase locked loop is as shown in Fig. 3. In which the given input voltage is transformed to d-q reference frame and then by using moving average filters the harmonics are eliminated later again transformed to abc reference frame, the obtained output is given as input to SRF-PLL for phase angle extraction of the corresponding phase.

Three FSPLLs were used to detect the angles of the three-phase system i.e. θ_a, θ_b, and θ_c, for phase a, b, and c, respectively, like as shown in Fig. 4. A single-phase voltage is introduced to each FSPLL, while the other inputs are set to zero as follows.

$e_{a0} = (e_a; 0; 0)$, $e_{b0} = (e_b; 0; 0)$ and $e_{c0} = (e_c; 0; 0)$, in which e_a, e_b and e_c are the grid voltages.

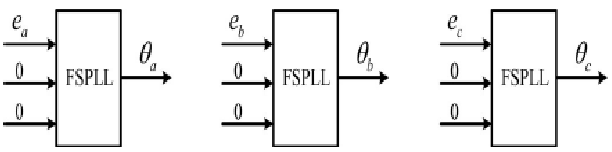

Fig. 4 Individual Phase angle Extraction based on FSPLL.

4. GENERATION OF PHASE CURRENT REFERENCE

The active current limited by using current limiter and reactive current obtained, along with phase angle extracted by using PLL are used for current reference generation of each phase like as shown in Fig. 5

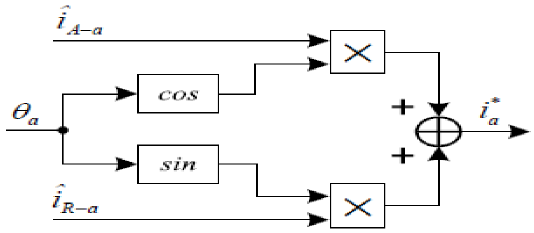

Fig. 5 Current Reference Generation for Phase 'a'.

Fig.5 shows the current reference generation for phase 'a'. Similarly the final current references for all three phases can be obtained. Which are may be as follows.

$$i_a^* = i_{A\text{-}a} \cos(\theta_a) + i_{R\text{-}a} \sin(\theta_a) \qquad \text{Eqn.(3)}$$

$$i_b^* = i_{A\text{-}b} \cos(\theta_b) + i_{R\text{-}b} \sin(\theta_b) \qquad \text{Eqn.(4)}$$

$$i_c^* = i_{A\text{-}c} \cos(\theta_c) + i_{R\text{-}c} \sin(\theta_c) \qquad \text{Eqn.(5)}$$

Here, the active and reactive current reference obtained earlier are used as the amplitudes and the phase angles extracted from phases using FSPLL are used as phase angles of the corresponding phases respectively.

5. ZERO SEQUENCE ELIMINATION

Since the currents of the three phases are regulated independently, the sum of the three currents may not be zero. This would mean circulation of a zero-sequence current component through the ground. This cannot happen if the ground circuit is open. Furthermore, if the ground circuit offers low impedance, circulation of this current may not be a desired situation. Therefore, this zero-sequence should be removed from the current references. This can be achieved by applying the Clarke transformation (abc/αβ) to the current references. In this case, the third component in the Clarke transformation, i.e. the γ or zero sequence components, is disregarded. As a result, the current vector will lie in the αβ plane, coinciding with its projection before the zero-sequence was removed. Therefore, the αβ components of the reference currents will be preserved.

An equivalent way of removing the zero-sequence is changing the current references of each phase by subtracting one third of the common current component from each of them, as follows.

$$i_a^{*'} = i_a^* - K_a i_0, \qquad \text{Eqn. (6)}$$

$$i_b^{*'} = i_b^* - K_b i_0, \qquad \text{Eqn. (7)}$$

$i_c^{*'} = i_c^{*} - K_c i_0$, Eqn. (8)

Where $i_0 = i_a^{*} + i_b^{*} + i_c^{*}$ Eqn. (9)

And

$K_a = K_b = K_c = 1/3$ Eqn. (10)

During balanced operation, the common component i_0 will be zero or very low. However, during unbalanced voltage sags, the common component may have a significant value. Consequently, after applying from Eqn. (6) to Eqn. (10), the new references $i_a^{*'}$, $i_b^{*'}$ and $i_c^{*'}$ may differ with respect to the original values. Therefore, the reactive components of the healthy or non-faulty phases may increase, causing a voltage rise above the limits. An alternative solution to avoid this problem is as explained follows.

The proposed solution is based on changing the current references depending on the activation of the reactive current injection for each phase, keeping the reference of the phase with no reactive current injection unchanged. For example, if phase a is healthy or non-faulty under an unbalanced voltage sag, k_a will be set to zero and the zero-sequence is eliminated by changing the current references of the other phases, i.e. $k_b + k_c = 1$. In this case, the zero-sequence elimination is divided equally between the faulty phases, i.e. kb = kc = 1/2.

6. RESCALING THE CURRENT REFERENCES

Once the zero-sequence component is removed from the current references, the amplitudes of the currents change, which may produce over currents. To limit the phase currents at or below the maximum value (I_n), the RMS value of the three phase current references after zero sequence elimination is obtained and later on the maximum value of those RMS values of the current references is identified. The maximum current of the three phases (i^{*}_{max}) is compared with the nominal value I_n. If it exceeds I_n, all the currents are re-scaled by a factor f_{rs} defined as follows.

$$f_{rs} = \begin{cases} I_n / i^{*}_{max} & \text{if } i^{*}_{max} > I_n \\ 1 & \text{if } i^{*}_{max} \leq I_n \end{cases} \qquad \text{Eqn. (11)}$$

The ultimate final current references to feed the current control loop can be obtained according to the following equation shown by Eqn. (12)

$$\bar{i}^{*}_{abc} = f_{rs} \times i^{*'}_{abc} \qquad \text{Eqn. (12)}$$

7. CURRENT CONTROL LOOP

The Ultimate current references that are obtained from Eqn. (12) are given as input to the current control loop as shown in Fig. 6. The Input given to the current control loop is transformed to Stationary reference frame (αβ) by applying Clarke transformation.

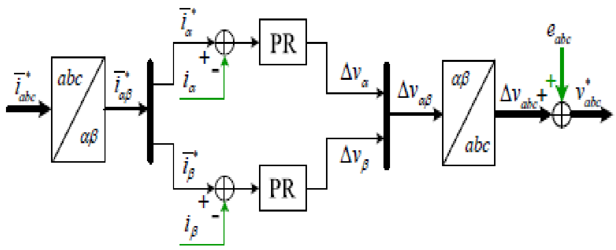

Fig. 6 Current Control Loop consisting of PR controllers.

The Current Control Loop is consisting of two parallel loops with PR controllers that regulate the currents in a stationary frame. As shown in the Fig. 6, the reference values i_α, i_β are obtained from grid voltages by transforming them into stationary reference frame (αβ) by means of Clarke Transformation. Since the control variables are sinusoidal, PR controllers were chosen, as conventional proportional-integral (PI) controllers fail to remove steady-state errors when controlling sinusoidal waveforms. The regulated signal in the form of voltages are again converted back into the 'abc' reference by means of inverse Clarke transformation, the obtained signals in addition with earlier grid voltages measured can be given as input to the pulse generator to generate required pulses to VSI.

8. GCPPP SYSTEM

The block diagram of the Grid Connected Photo Voltaic Power Plants (GCPPP) system is as shown in Fig. 7, The Simulink model of the GCPPP system is developed by using the MATLAB/SIMULINK software for validation purpose of proposed method. The Typical parameters used in the Simulation model are summarized in Table-1.

The Simulation model of GCPPP system is shown in Fig. 8. In the figure fault is located at the grid side or high voltage side of the transformer and tested the model with different types of Line to Ground (LG) and double Line to Ground (LLG) faults, the performance of the model is found satisfactory and the results are presented in next section for one LG and one LLG faults respectively.

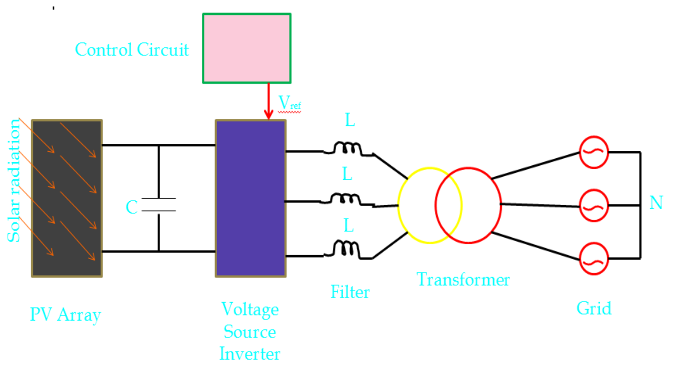

Fig. 7 Block diagram of GCPPP System.

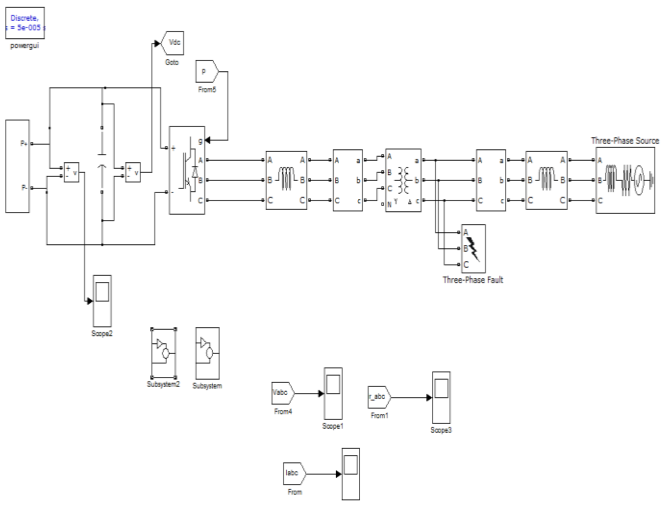

Fig. 8 Simulation model of GCPPP System.

Table-1: Parameters used in GCPPP Simulation model.

Parameter	Value	Parameter	Value
Maximum Operating Voltage of Solar Panel (V_{mpp})	393 Volts	Transformer Ratings	5 KVA, 400/200 V, Dyn11, 50 Hz
DC Link Capacitance (C)	1100 µF	Filter Inductance (L)	4 mH/Phase
Switching Frequency (f_s)	10 kHz	Grid Inductance (Lg)	1.9 mH/Phase

9. SIMULATION RESULTS OF GCPPP SYSTEM

The Simulation results of the GCPPP system for a line to ground (LG) voltage sag with 100% voltage drop in phase 'a' imposed at grid side or high voltage side of Dyn11 transformer are as shown in Fig. 9(a) to 9(c). the fault transition takes place at 0.2 sec to 0.4 sec during the total simulation time of 0.6 sec starting from 0.

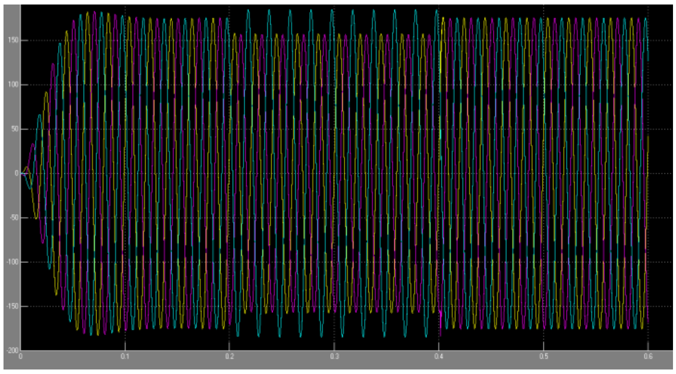

Fig. 9(a) Grid voltages at the LV side of the transformer.

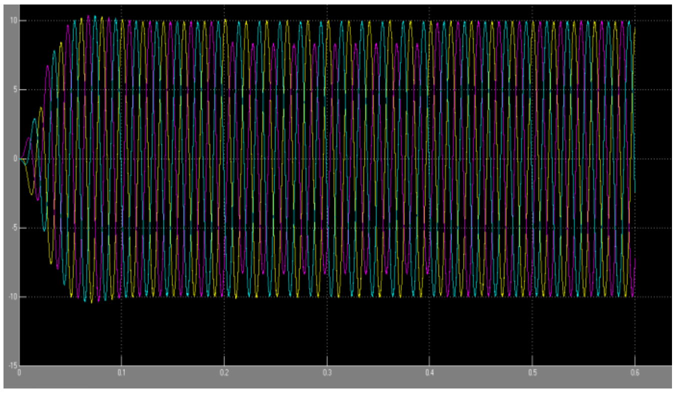

Fig. 9(b) Output currents at the LV side of the transformer.

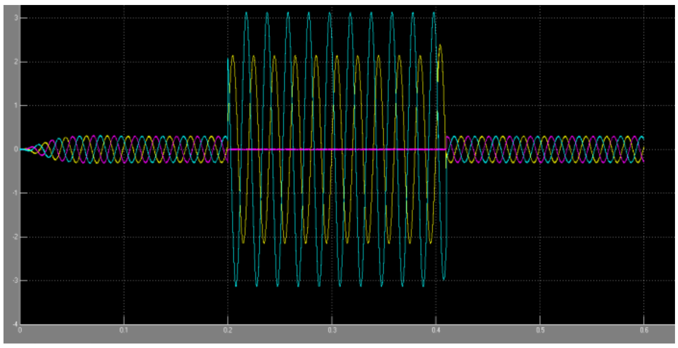

Fig. 9(c) Generated reactive current references.

Since the transformer is of Dyn11, the LG fault imposed on the grid side is transformed to Inverter side on two phases and avoids the over voltage in the healthy or non-faulty phases. Also limits the phase currents other than the faulted phase to their nominal values.

The Simulation results of the GCPPP system for a Double line to ground (LLG) voltage sag with 100% voltage drop in phase 'a' and phase 'b' imposed at grid side or high voltage side of Dyn11 transformer are as shown in Fig. 10(a) to 10(c). The fault transition takes place at 0.2 sec to 0.4 sec during the total simulation time of 0.6 sec starting from 0.

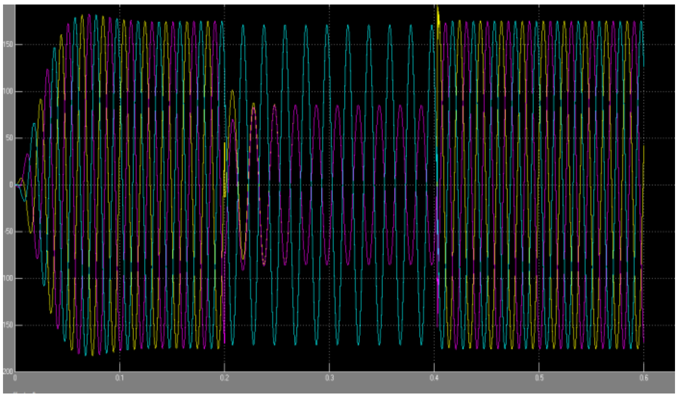

Fig. 10(a) Grid voltages at the LV side of the transformer.

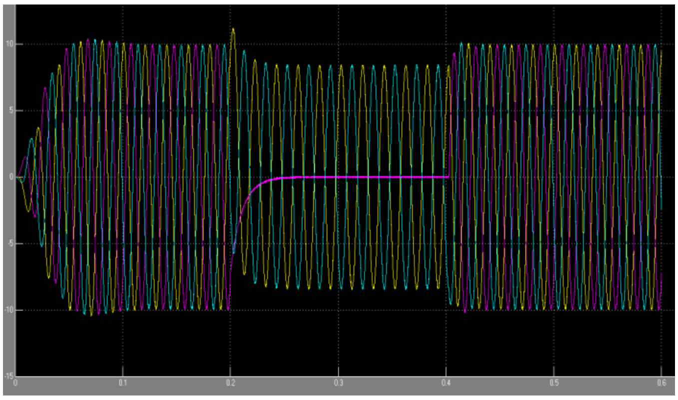

Fig. 10(b) Output currents at the LV side of the transformer.

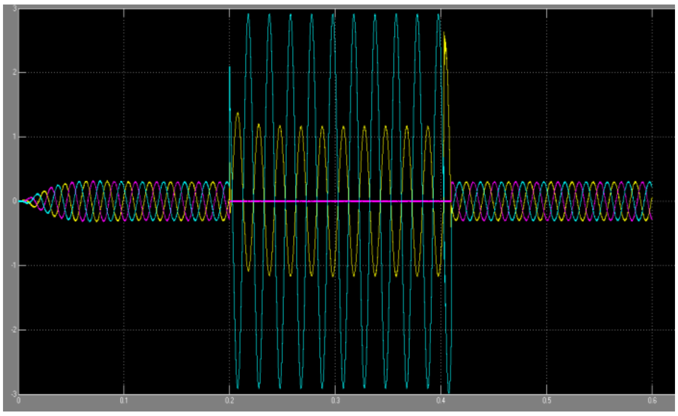

Fig. 10(c) Generated reactive current references.

Since the transformer is of Dyn11, the LLG fault imposed on the grid side is transformed to Inverter side on two phases and reduces the magnitude of voltages and further increases voltage sag, avoids the over voltage in the healthy or non-faulty phases. Also limits the phase currents other than the faulted phase to their nominal values.

10. CONCLUSIONS

In the present paper, a new control method of phase current control of Voltage Source Inverter (VSI), based on reactive current injection into grid for Grid connected Photovoltaic Power Plants (GCPPP) has been proposed to effectively meet grid code requirements under unbalanced voltage sags. In order to support the grid voltages in GCPPP systems during voltage sags, the phase currents are derived separately based on the voltage drop in corresponding phase respectively, which in turn protects the Healthy or non-faulty phases from over voltage production. During the process of phase current control, each phase current of the VSI should be limited to the nominal value of inverter current such that the active current is predicted depends on the reactive currents needs to support grid voltages. Since the independent phase current control is carried on, the presence of zero sequence components must be eliminated in a three phase system. Finally rescaling of current references is also proposed to avoid over voltages in healthy phases while preventing the GCPPP system from over current protection. The proposed control technique has been verified with Simulation model developed by using MATLAB/SIMULINK software and the results were presented for LG and LLG voltage sags.

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