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# Zero Sequence Current Removal for Fault-ride-through a Grid Connected Distributed Generation

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*Abstract:* **— In transmission and distribution grids Voltage sags are one of the severe problems due to the high penetration of distributed generation (DG). The converter-interconnected DG system ex: solar, wind, fuel cells & mini hydal power plants, requires a fast and exact measurement of phase and frequency of fundamental grid current to produce reference current signals in order to control the converter. In case of voltage sags according to gird code the control of inverter is nothing but reactive power support. In-order to regulate the voltage in the non-faulty phases under unbalanced voltage sags is reactive current injection control by removing zero sequence from the current references. The results illustrate the capability of the developed GCPPP to ride- through the faults occurred on the grid side. The system is designed and simulated using MATLAB/ Simulink Software.**

***Index Terms*—Distributed generation, fault-ride-through, reactive current injection, voltage sag.**

## I. INTRODUCTION

The Distributed Generation is a new trend that emerges for providing electric power as required for the demand. These DG systems based on renewable energy resources such as (photo voltaic, wind energy and fuel cells) are well encouraged because of their low environmental impact and high technical advantages such as improvement in voltage levels and reduction in power losses, when these DG systems are installed in radial distribution lines. The DG systems are installed in the grid, and then the distribution system becomes an active system with both energy generation and consumption, the DG must supply locally and its working regime.

The DG systems are installed in the grid by interfacing with the power converter, (preferably the voltage source inverter) power fed from DG is converted into AC and the operation of the system is done by maintaining the DC link voltages. The control of grid-connected voltage source inverters (VSIs) under unbalanced voltage sags has been widely discussed and some research has focused on active power control strategies, is nothing but providing the current references for the VSIs.

VSIs should remain connected during voltage sags and support the grid voltages with the injection of reactive currents. This is necessary to ride-through any type of fault. The over voltages may occur in non-faulty phases due to balanced reactive current injection under un-balanced voltage sags. This can be prevented by injection of un-balanced reactive currents according to new grid codes.

The objective of this letter is to propose a control method based on individual control of the phase currents under unbalanced voltage sags. The amount of reactive current in each phase is determined based on the amount of voltage drop in that phase, which implies no reactive current injection for the non-faulty phases. Implementation of this method requires knowledge of the grid-voltage angle of each phase. For this purpose, the phase-locked loop (PLL) proposed is used. Moreover, the grid currents, including both active and reactive currents, are limited in order to protect the grid-connected photovoltaic power plants (GCPPPs) from ac over currents, addressing the fault-ride-through requirement. Since the grid currents are defined independently for each phase, two methods are proposed to prevent the controllers from trying to inject a zero-sequence into the grid. In this study, the proposed control technique was tested experimentally in a scaled-down GCPPP connected to a low-voltage (LV) programmable ac power supply.

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This paper analyses the individual phase current control under un-balanced voltage sags. Section II details the extraction of individual grid voltage phase angles and also description of current reference generation. Section III explains the methods for elimination of zero sequence from current references. Section IV details the PR controller and Fuzzy logic controller Section V shows the simulation analysis and Section VI presents the conclusion.

## II. INDIVIDUAL PHASE ANGLE EXTRACTION USINNG PLL

As the aim of the proposed method is to control the phase currents independently, it is necessary to extract the phase angle of each of the grid voltages. Therefore, the frequency-adaptive PLL is implemented based on the research in [14]. This PLL is based on the filtered-sequence PLL (FSPLL) introduced in [15]. 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. The FSPLL includes a standard synchronous reference frame PLL to obtain the angle of the extracted positive sequence. In [14], three FSPLLs were used to detect the angles of the three-phase system i.e., $\theta a$, $\theta b$, and $\theta c$, for phase *a*, *b*, and *c*, respectively, as shown in Fig.3.1. A single-phase voltage is introduced to each FSPLL, while the other inputs are set to zero as follows: $ea0 = (ea, 0, 0)$, $eb0 = (eb, 0, 0)$, and $ec0 = (ec, 0, 0)$, in which *ea*, *eb*, and *ec* are the grid voltages.

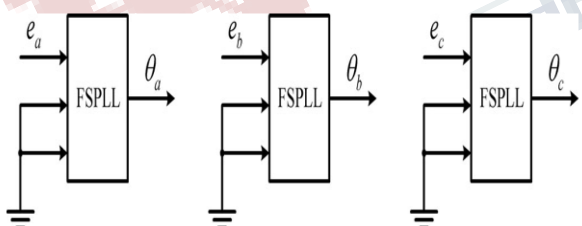


*Fig .1 Individual phase angle extraction based on the FSPLL*

## III. OBTAINING PHASE CURRENT REFERENCES

In this section, the method for obtaining the current references to feed the current control loops is presented. The amplitude of the active current ($\hat{i}A$) is defined to regulate the dc-link voltage, while the individual reactive current amplitudes ($\hat{i}R\text{-}x$) are found from the droop control defined as

$$= droop|de_x|I_n \; with \;\; x \in \{a, b, c\}$$

For $\frac{|de_x|}{E_{n-ph}} \geq 10\%$ and $droop \geq 2$

Where $|d_{ex}|$ is the amount of phase voltage drop from its nominal rms value ($En\text{-}ph$), $\hat{I}_n$ is the amplitude of the nominal phase current of the inverter, and *droop* is a constant value based on the German GCs [4]. A value ≥ 2 for *droop* implies that, for voltage support, the injection of reactive current at the LV side of the transformer must be at least 2% of the nominal current per each percent of the voltage drop [4]. The dc-link voltage loop is controlled by a proportional-integral (PI) controller equipped with an anti-wind up technology that helps attain the pre fault values very quickly after fault removal. This can be seen in the control diagram of Fig. 2. In this figure, *v*dc is the dc-link voltage, $V^*$ dc is its reference value, and $i^* d$ is the active current reference in the *dq*-reference frame.

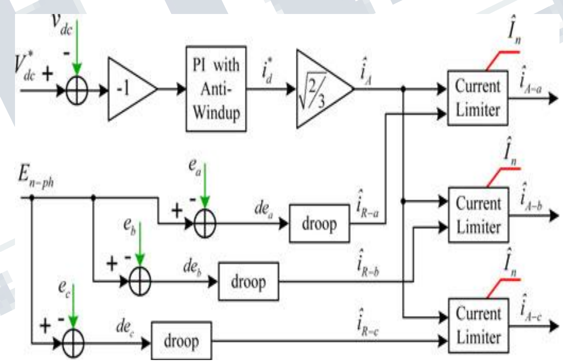


*Fig.2 Control diagram for obtaining the active and reactive current references*

***Limiting the Phase Currents:***

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 over current 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 (see Fig. 2). 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 over current in one phase, the active current of that phase should be limited. The current limiter in Fig. 2 is defined as follows:

$$i_{A-x} = \begin{cases} i_A \\ \sqrt{I_n^2 - i_{R-x}^2} \end{cases}$$

where $x$ stands for phases $a$, $b$, and $c$. The actual current reference for each phase is obtained by multiplying the amplitudes of the active and reactive currents by the cosine and sine, respectively, of the phase angle obtained from the PLLs [14]. The final current reference for each phase is achieved by adding the active and reactive current components. Fig. 3 illustrates the procedure for obtaining the current reference $i^*_a$ for phase $a$. The current references for the other phases are obtained using the same procedure.

### *B. Zero-Sequence Elimination from the Current References:*

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 a 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 () to the current references. In this case, the third component in the Clarke transformation, i.e., γ the or zero-sequence component is disregarded. As a result, the current vector will lie in the $\alpha\beta$ plane, coinciding with its projection before the zero-sequence was removed. Therefore, the $\alpha\beta$ 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:

$$i_a^{*'} = i_a^* - k_a i_0$$
$$i_b^{*'} = i_b^* - k_b i_0$$
$$i_c^{*'} = i_c^* - k_c i_0$$

where,

$i_0 = i_a^* + i_b^* + i_c^*$ and

$$k_a = k_b = k_c$$

During balanced operation, the common component *io* will be zero or very low. However, during unbalanced voltage sags, the common component may have a significant value. Consequently, after applying (3)–(7), the new references $i_a^{*'}$, $i_b^{*'}$ and $i_c^{*'}$ may differ with respect to the original values. Therefore, the reactive components of the non- faulty phases may increase, causing a voltage rise above the limits. An alternative solution to avoid this problem is explained below.

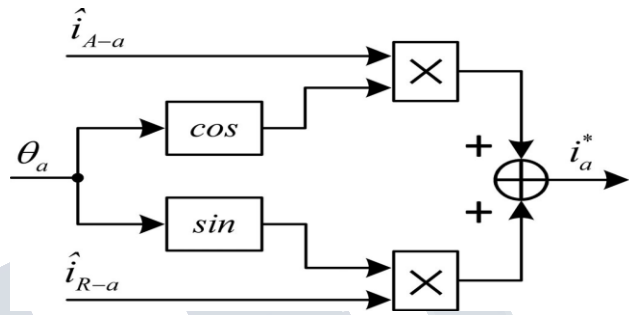


***Fig. 3. Current reference generation for phase a.***

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(s) of the phase(s) with no reactive current injection unchanged. For example, if phase $a$ is non - faulty under an unbalanced voltage sag, *ka* will be set to zero, and the zero-sequence is eliminated by changing the current references of the other phases, i.e., *kb* + *kc* = 1. In this letter, the zero-sequence elimination is divided equally between the faulty phases, i.e., *kb* = *kc* = 1⁄2.

### *C. Second Current Limiter:*

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 (*In*), a method to measure the rms value of the currents should be implemented. The following equation can be used for this:

$$i_{x-rms}^* = \sqrt{\frac{1}{T_w}\int_{t-Tw}^{t} (i_x^{*'})2\, dt}$$

in which $i_{x-rms}^*$ is the rms value of the phase current $x$, where $x$ represents the three phases ($x \in \{a, b, c\}$), and *Tw* is the window width used for the rms calculation, typically *T*/2 or *T*, *T* being the grid-voltage period (*T* =

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1/freq). The maximum current of the three phases ($i^*_{max}$) is compared with the nominal value *In*. If it exceeds *in*, all the currents are rescaled by a factor *f*rs defined as:

$$frs = \begin{cases} \dfrac{In}{i^*_{max}} & , if\ i^*_{max} > In \\ 1 & , \end{cases}$$

The final current references are set as follows:

$$i^*_{abc} = frs\, i^{*'}_{abc}$$

The proposed method for rescaling the currents is illustrated in Fig.3.4. The magnitudes indicated with the subscript "*abc*" represent the three phase magnitudes of the system, e.g., *iabc* stands for *ia*, *ib*, and *ic.*

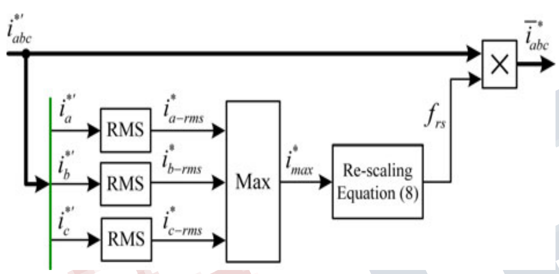


***Fig.4. Control diagram for rescaling the current references to avoid over currents.***

The process of generating the phase current references includes two limiters. The first one, shown in Fig.2, is to limit the active currents to give enough room to the required reactive current injection. The second one is based on rescaling all the current references after the zero-sequence elimination. This process is proposed here for the first time and has never been addressed in any other study.

## IV. CURRENT CONTROL LOOP

The current control is composed of two parallel loops that regulate the currents in a stationary frame. Since the control variables are sinusoidal, PR controllers were chosen, as conventional PI controllers fail to remove steady-state errors when controlling sinusoidal waveforms. The control diagram of the currents is shown in Fig.3. 5. The inputs to this control diagram are the current references obtained from (10).

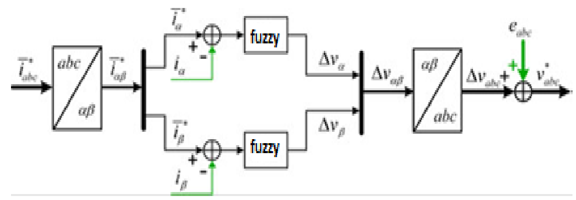


***Fig. 5. Current control loop with fuzzy controllers***

## V. SIMULATION RESULTS

The proposed control method was tested in a scaled-down GCPPP. The scheme of the GCPPP is presented in Fig. 6 and the main specifications are summarized in Table. I.

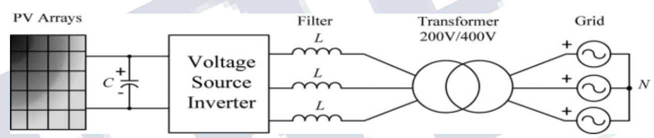


***Fig.6 Diagram of a GCPPP.***

TABLE I
EXPERIMENTAL SETUP CHARACTERISTICS

| | | | |
|---|---|---|---|
| Injected power from PV array | 2.8 kW | Transformer | 5 kVA, 400/200 V Dyn11, 50 Hz |
| Maximum operating voltage, $V_{mpp}$ | 393 V | Transformer leakage inductance (LV side), $L_{trans}$ | 0.9 mH/phase |
| DC-link capacitor, $C$ | 1100 μF | Total grid inductance, $L_g = L'_g + L_{trans}$ | 1.9 mH/phase |
| Switching frequency, $f_s$ | 10 kHz | Filter inductance, $L$ | 4 mH/phase |

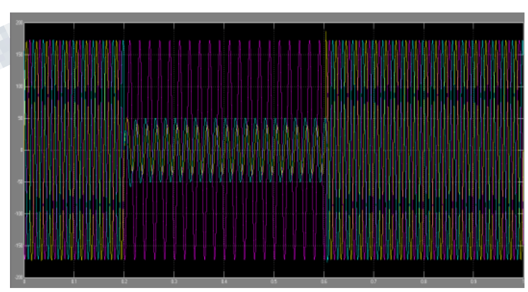

***Fig.7 Grid voltages at the LV side of the transformer***

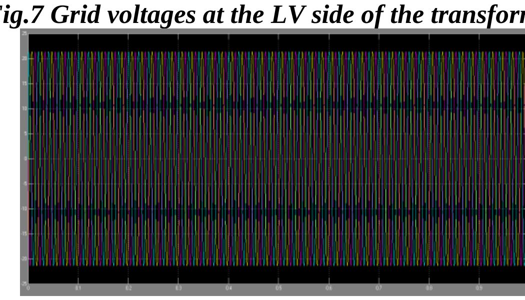

***Fig.8. output currents at the LV side***

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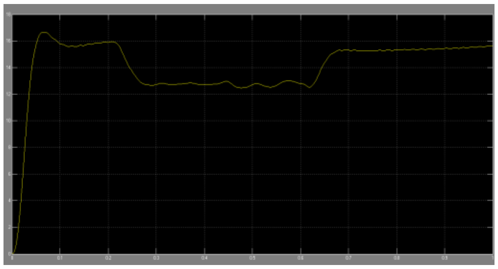

*Fig.9. generated reactive current references*

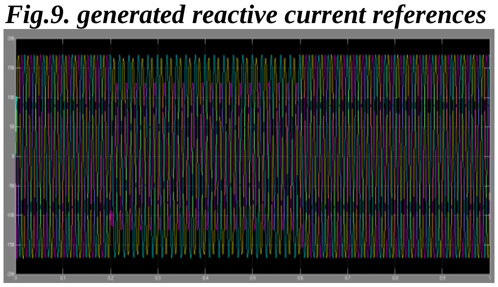

*Fig.10. Grid voltages at the LV side of the transformer.*

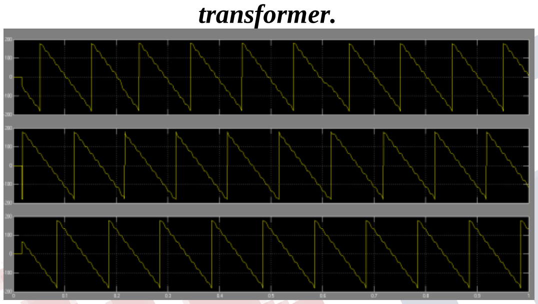

*Fig.11. Detected angles of phase a, b and c.*

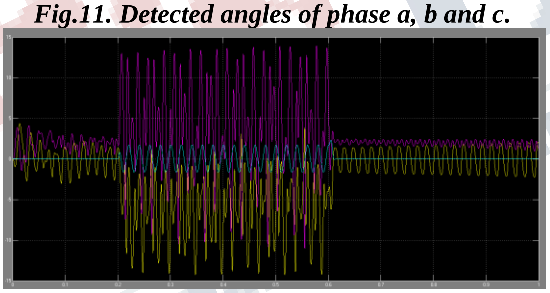

*Fig.12. Generated reactive current references*

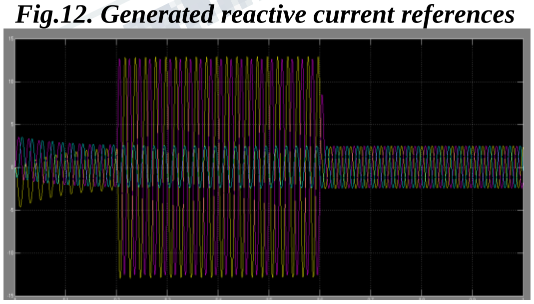

*Fig 13. output currents at the LV side*

## CONCLUSION

In this paper, to protect the non-faulty phases of grid from overvoltage a new control strategy based on individual control of the 3 phases of a grid connected distributed generation has been proposed and which is done by independent control of reactive currents injected into the grid. Based on the amount of voltage drop in each phase the reactive currents are determined separately. Depending on the required amount of reactive currents the active current references of each phase is needed to be limited. In this paper, by using fuzzy controller two solutions for removing the zero-sequence component which is necessary in 3-Ø system from the current references generated have been proposed. Another method for rescaling the instantaneous current references to avoid producing over voltages and over currents in the non-faulty phases in the grid connected distributed generation has also been proposed. This proposed control method has been tested using fuzzy controller on a scaled-down laboratory prototype operating with a “weak” grid.

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