

Power Quality Improvement for a grid Connected Photovoltaic Power Systems by Controlling Individual Phase Currents with Fuzzy Based Controller

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Abstract: The increasing penetration of distributed power generation into the power system leads to a continuous evolution of grid interconnection requirements. Individual phase current control with the capability to avoid overvoltage in grid connected photovoltaic systems under unbalanced voltage sags is proposed to effectively meet grid code requirements for grid connected photovoltaic systems. During voltage sags grid connected photovoltaic systems should support grid voltages by inject reactive currents at grid regulations. Such injection must not allow the non-faulty phases grid voltage to go beyond 110% of their nominal value. Yet, in the non-faulty phases grid overvoltage's can occur, the currents injected into the grid are balanced by the grid connected photovoltaic system. This grid system is deal with by manipulative individual phases and injecting unbalanced currents into the grid during voltage sags. This project was verified using MATLAB/SIMULINK through simulation.

Index Terms: Photovoltaic system, power system faults, reactive current control.

I. INTRODUCTION

The control of grid-connected voltage source inverters (VSIs) under unbalanced voltage sags has been widely addressed in the technical report. Some research has focused on active power control strategies, and two methods have been Presented to provide the current references for the VSIs [1], [2],[3]. As in the case of synchronous generators in conventional power plants, VSIs should remain connected during voltage sags and support the grid voltages with the injection of reactive currents [4], [5]. This is necessary to ride-through any type of fault. The injection of balanced reactive currents to support unbalanced voltage sags may lead to overvoltage's in the nonfaulty phases [6]. To prevent this, new grid codes (GCs) require the injection of unbalanced reactive currents during unbalanced volt-age sags, and for this purpose different control methods have been proposed. In [7] and [8], a flexible voltage support method was introduced based on the type and severity of the voltage sags. For this purpose, the amount of reactive power injected via positive- and negative-sequences is controlled with an of-fline control parameter. An extended generalization of previous studies was carried out in [9], whereby the reactive power reference and the control parameters were updated in order to restore the dropped voltage amplitudes. Another study in [10]Proposed a method to set the positive- and negative-sequence reactive power references based on an equivalent impedance grid model to avoid over- and under voltages in the phases. In that paper, the new current references were updated based on the previous reactive power references. A decoupled double synchronous reference frame current controller was introduced in [11], with the capability of controlling the active and reactive power of the positive- and negative-sequences independently. However, the current references were regulated offline. Regarding the individual control of currents and voltages of the three phases, the new requirement of the European network of transmission system operators (TSOs) implies that TSOs are allowed to introduce a requirement for unbalanced current injection [12]. Few papers have studied or reported this concept to date. Some research was reported in [13] to support the phases with unbalanced reactive power. However, the method used in that paper was not universal for all types of voltage sags [14].

The objective of this project is to propose a control method based on individual control of the phase currents under un-balanced 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 in [14] 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 de-fined 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 GCPMP connected to a low-voltage (LV) programmable ac power supply.

II. CONTROL OF VOLTAGE SOURCE INVERTER.

A. Single-Phase PLL Phase Extraction for Three-Phase Systems.

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., θ_a, θ_b , and θ_c , for phase a, b , and c , respectively, as shown in Fig. 1. 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.

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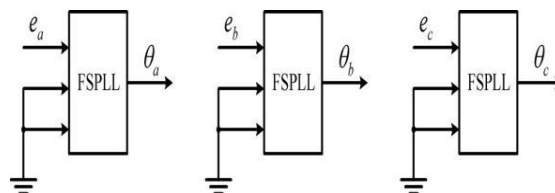


Figure. 1 Individual phase angle extraction based on the FSPLL.

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B. Generation Of 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-x}) are found from the droop control defined as

$$\hat{i}_{R-x} = droop |de_x| \hat{I}_n, \quad \text{with } x \in \{a, b, c\}$$

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

Where $|de_x|$ is the amount of phase voltage drop from its nominal rms value (E_{n-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].

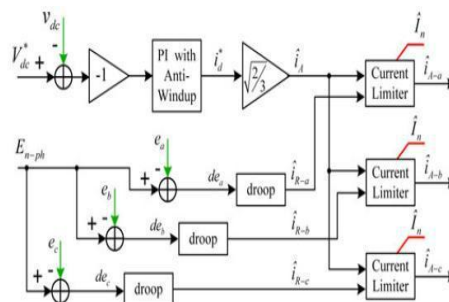


Figure.2 Control diagram for obtaining the active and reactive current references.

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 antiwindup technology that helps attain the prefault 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.

1. 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. There-fore, 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:

$$\hat{i}_{A-x} = \begin{cases} \hat{i}_A, & \text{if } \sqrt{\hat{i}_{R-x}^2 + \hat{i}_A^2} \leq \hat{I}_n \text{ and} \\ \sqrt{\hat{I}_n^2 - \hat{i}_{R-x}^2}, & \text{if } \sqrt{\hat{i}_{R-x}^2 + \hat{i}_A^2} > \hat{I}_n \end{cases} \quad (2)$$

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].

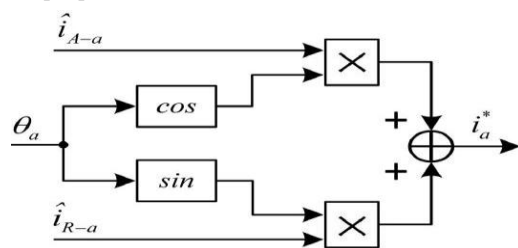


Figure.3 Current reference generation for phase a .

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.

2. 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 ($abc/\alpha\beta$) to the current references. In this case, the third component in the Clarke transformation, i.e., the γ 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.

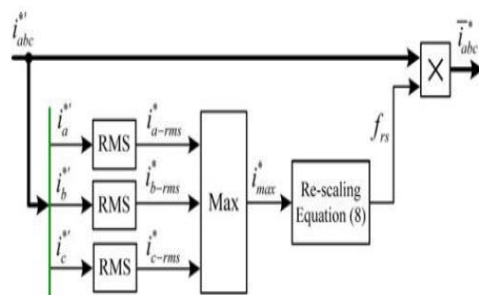


Figure. 4 Control diagram for rescaling the current references to avoid overcurrents

$$i_a^{*'} = i_a^* - k_a i_0 \tag{3}$$

$$i_b^{*'} = i_b^* - k_b i_0 \tag{4}$$

$$i_c^{*'} = i_c^* - k_c i_0 \tag{5}$$

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: Where

$$i_0 = i_a^* + i_b^* + i_c^* \text{ and} \tag{6}$$

$$k_a = k_b = k_c = 1/3. \tag{7}$$

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 (3)–(7), the new references $i_a^{*'}, i_b^{*'},$ and may differ with respect to the original values. Therefore, the reactive components of the nonfaulty phases may increase, causing a voltage rise above the limits. An alternative solution to avoid this problem is explained below.

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 nonfaulty 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 letter, the zero-sequence elimination is divided equally between the faulty phases, i.e., $k_b = k_c = 1/2$.

3. Second Current Limiter

Once the zero-sequence component is removed from the current references, the amplitudes of the currents change, which may produce overcurrents. To limit the phase currents at or below the maximum value (I_n), a method to measure the rms value of the currents should be implemented. The following equation can be used for this:

$$i_{x-rms}^* = \sqrt{\frac{1}{T_w} \int_{t-T_w}^t (i_x^{*'})^2 dt} \tag{8}$$

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 T_w is the window width used for therms calculation, typically $T/2$ or T , T being the grid-voltage period ($T = 1/\text{freq}$). 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 rescaled by a factor f_{rs} defined as

$$f_{rs} = \begin{cases} \frac{I_n}{i_{max}^*}, & \text{if } i_{max}^* > I_n \\ 1, & \text{if } i_{max}^* \leq I_n. \end{cases} \tag{9}$$

The final current references are set as follows:

$$\bar{i}_{abc}^* = f_{rs} i_{abc}^{*'} \tag{10}$$

The proposed method for rescaling the currents is illustrated in Fig. 4. The magnitudes indicated with the subscript “ abc ” represent the three phase magnitudes of the system, e.g., i_{abc} stands for $i_a, i_b,$ and i_c . 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.

C. CURRENT CONTROL LOOP

The current control is composed of two parallel loops that regulate the currents in a stationary frame. Conventional PI controllers are usually used in grid-connected photovoltaic power plants. These PI controllers suffer from two major drawbacks; steady-state errors in case of sinusoidal reference signals besides their limited disturbance rejection capability. To overcome these shortcomings proportional-resonant (PR) and fuzzy-logic controllers are investigated.

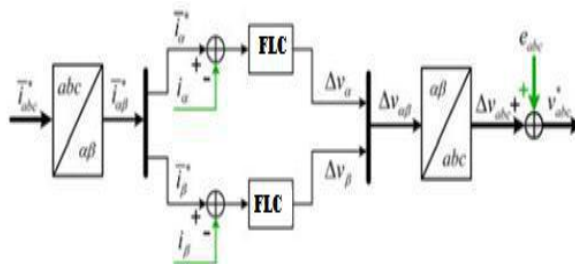


Figure: 5 Current control loop with fuzzy logic controllers (FLC).

Proportional-resonant (PR) controllers were introduced in to overcome the shortcomings of the stationary-frame PI controllers as well as the complexity related to the synchronous-frame controllers. PR controllers transform the DC compensation network into an equivalent AC network, providing a theoretical infinite gain in a narrow bandwidth that is centred at a predefined resonance frequency and hence eliminating the steady state error at that frequency and allowing outstanding tracking behavior with sinusoidal reference signals. Fuzzy logic-based controllers have recently gained large acceptance in many applications due to their robust performance and good dynamic response. The marvel of fuzzy logic is that it facilitates computation with words rather than with numbers and does not necessitate a detailed model of the plant to be controlled.

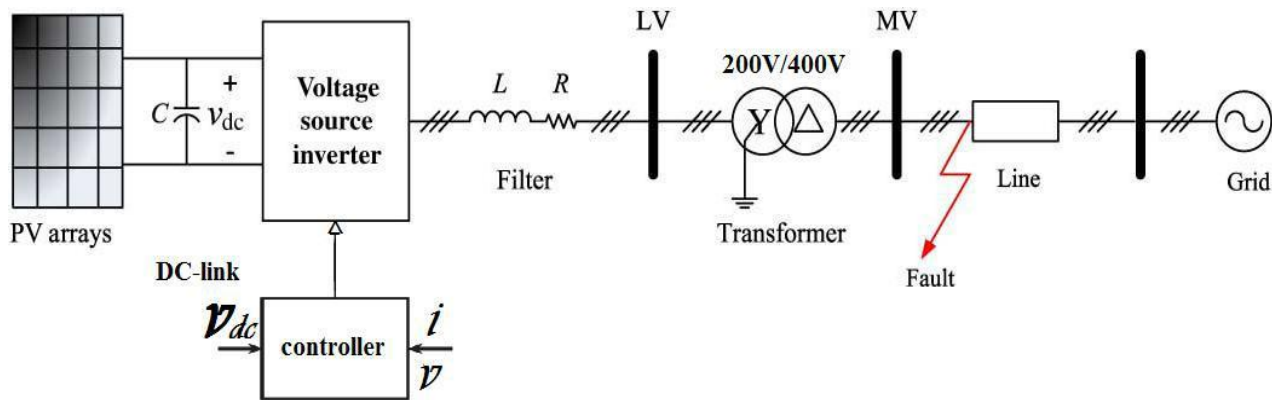


Fig: 6 Diagram of a GCPPP

III. 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.

PR and Fuzzy controllers are used to regulate the output current of a inverter in order to achieve a unity power factor. The system shown in Fig.7 is simulated in MATLAB/Simulink with the help of SimPowerSystems toolbox. The controllers are compared with respect to the three performance parameters:

- Steady-state error (i.e. resulting degradation of power factor)
- Transient response
- Total Harmonic Distortion (THD)

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 μ F	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

In normal operation, the dc-link voltage is regulated by the inverter. However, under voltage sag, some modifications should be implemented in order to keep the GCPPP grid-connected. The proposed method tries to match the power generated by the PV modules with the power injected into the grid while trying to keep the dc-link voltage constant.

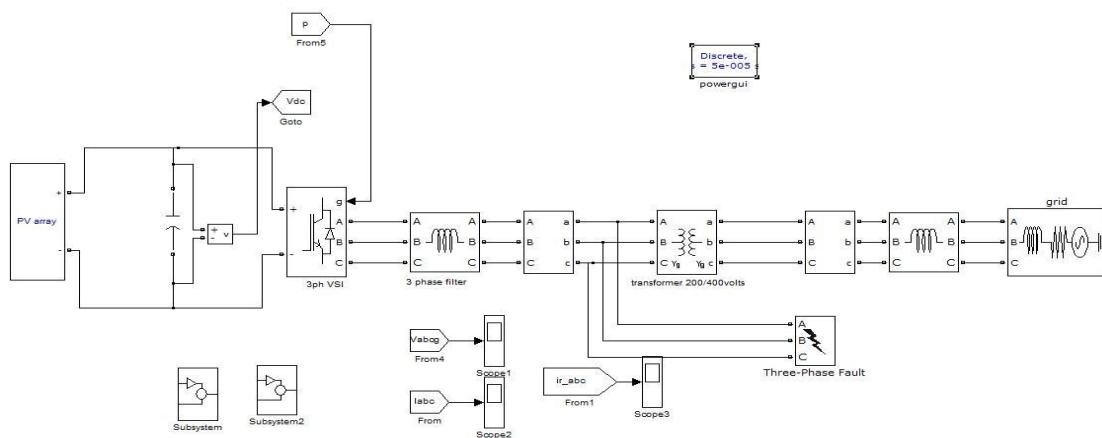


Figure.7 simulation block diagram of GCPPPs

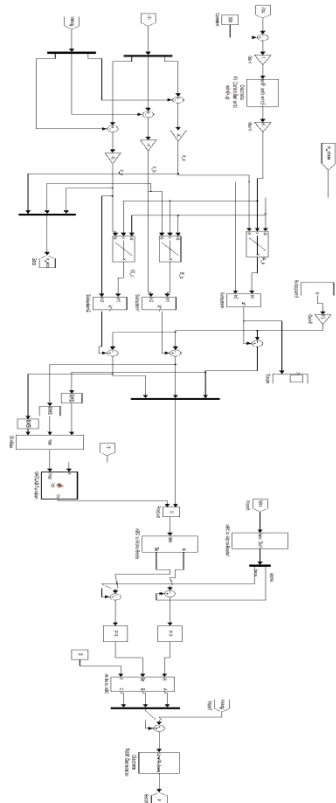


Fig: 8 simulation diagram of PR controller Subsystem1)

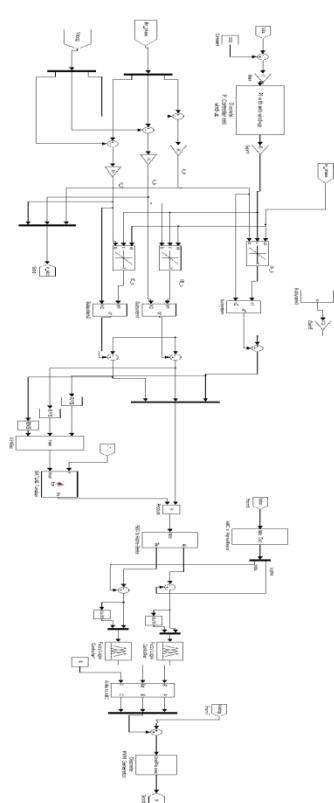


Fig: 9 simulation diagram of fuzzy controller Subsystem1)

Experimental results were obtained by connecting the scaled-down GCPPP to the laboratory “weak” grid. First, balanced currents were injected. In this case, the lowest line-to-line voltage was considered for the droop control. This implies the injection of balanced reactive currents into all three phases. Let us consider voltage sag as a fault. The detailed control method under balanced currents can be found in [17]. Fig. 10 and 11 shows the results obtained under a line-to-line ground (LLG) voltage sag with 100% voltage drop in phase *a* and phase *b* imposed at the grid side of the transformer. The voltage magnitudes are scaled down by a factor of 20 to be able to show them on the oscilloscope.

As demonstrated, the injection of balanced reactive currents under unbalanced voltage sag leads to voltage rise in the nonfaulty phase. Fig 6.5 and 6.6 shows Performance of conventional and proposed control methods under 100% LLG voltage sag at the grid side of the transformer respectively.

Both the performance outputs looking are same but the total harmonic distortion (THD) was reduced in proposed control system.

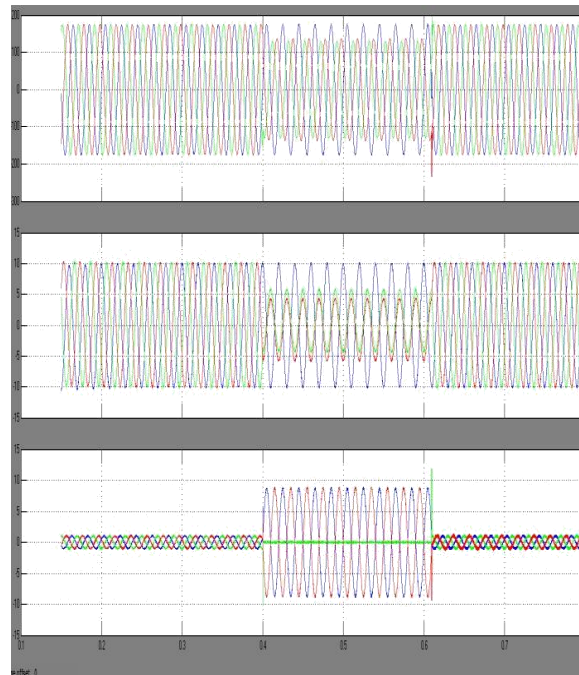


Fig: 10 Performance of the conventional control method under a 100% LLG voltage sag at the grid side of the transformer. From top to bottom: Grid voltages at the LV side of the transformer, output currents at the LV side, and reactive current references

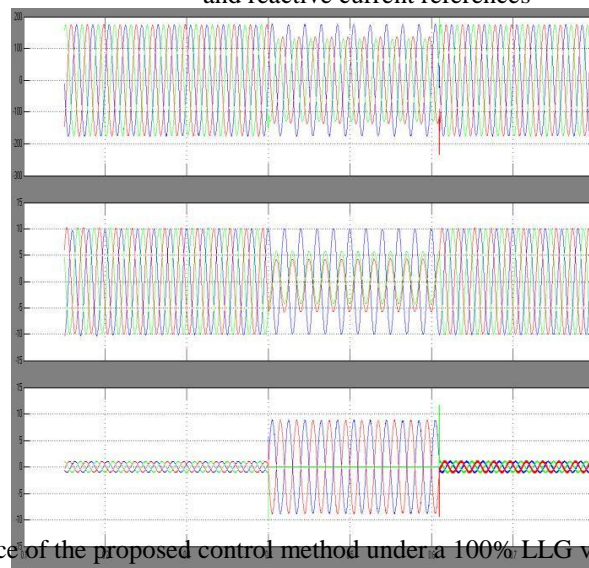
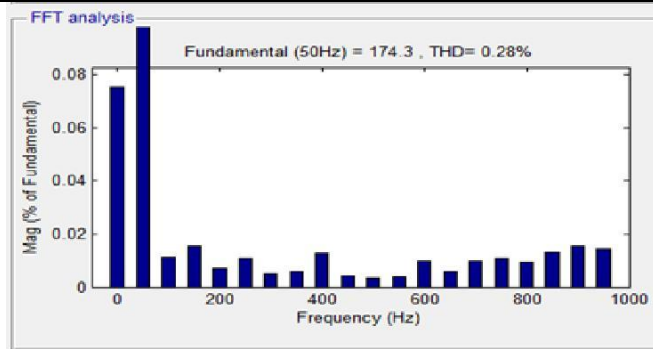
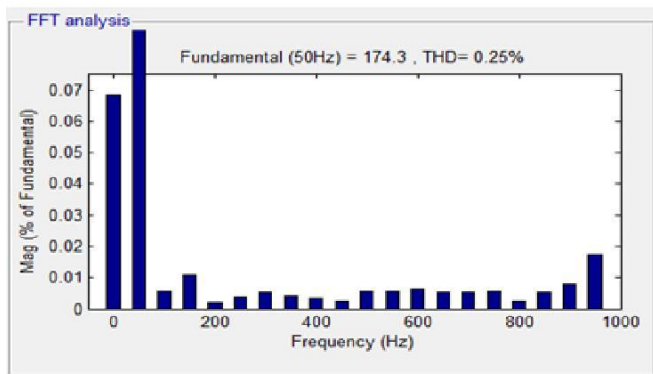


Fig: 11 Performance of the proposed control method under a 100% LLG voltage sag at the grid side of the transformer. From top to bottom: Grid voltages at the LV side of the transformer, output currents at the LV side, and reactive current references.

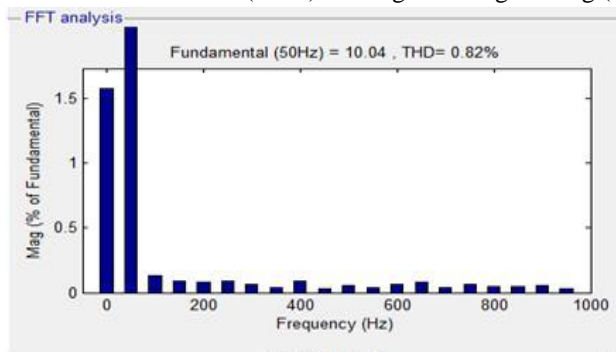


(a)

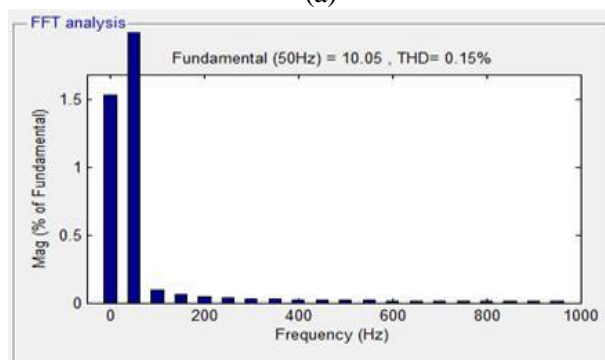


(b)

Fig:12 Total harmonic distortion (THD) of the grid voltages using (a) PR and(b) Fuzzy controllers



(a)



(b)

Fig: 13 Total harmonic distortion (THD) of the grid currents using (a) PR and(b) Fuzzy controllers

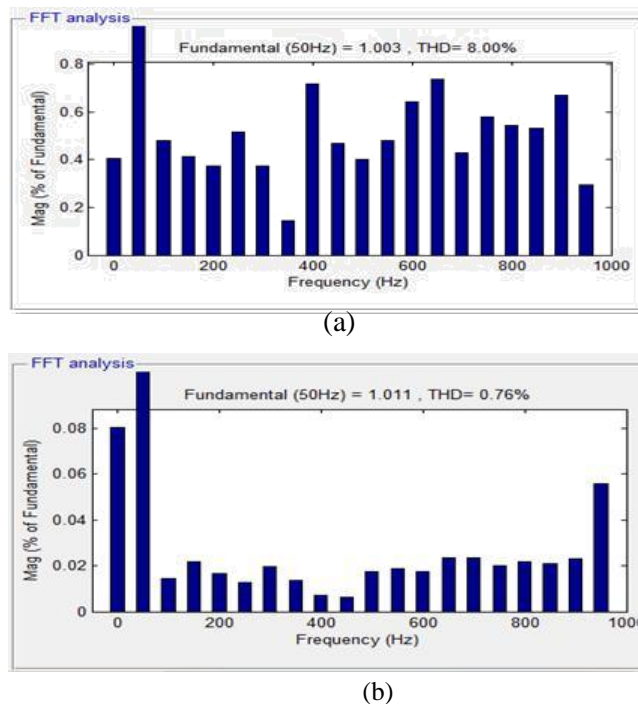


Fig: 14 Total harmonic distortion (THD) of the reactive currents using (a) PR and (b) Fuzzy controllers

This project can be verified using math lab/simulink. From mat lab software the FFT analysis of Vgrid and the corresponding THD for PR and Fuzzy-controllers are shown in Fig: 12 The analysis shows that both controllers display very good performance regarding THD; the PR-controller showed a THD of 0.28%, whereas the Fuzzy-controller outperformed this with a THD of only 0.23%. For Igrid the PR-controller showed a THD of 0.82%, whereas the Fuzzy-controller outperformed this with a THD of only 0.15% as shown in fig: 13.

For reactive current references the PR-controller showed a THD of 8%, whereas the Fuzzy-controller outperformed this with a THD of only 0.76% as shown in fig: 14.

IV. CONCLUSION

In this project, a new control method based on individual control of the three phases of a GCPMP has been proposed. The independent control of the reactive currents injected into the grid protects the non-faulty phases from over-voltage. The reactive currents are determined separately based on the amount of voltage drop in each phase. The active current references of each phase need to be limited based on the required amount of reactive currents. Furthermore, in a three-phase system, it is necessary to eliminate the zero-sequence from the current references generated. Finally, a method for rescaling the instantaneous current references to avoid producing over voltages in the non-faulty phases, while preventing the GCPMP from over-currents has also been proposed and THD of the grid voltages, currents and reactive currents was compared and found to be satisfactory for both controllers with the fuzzy-controller having superior performance achieving a THD of low compared by the PR-controller.

REFERENCES

- [1]. MitraMirhosseini, JosepPou, and Vassilios G.Agelidis "Individual Phase Current Control With the Capability to Avoid Overvoltage in Grid-Connected Photovoltaic Power Plants Under Unbalanced Voltage Sags" *IEEE Transactions on Power Electronics*, Vol. 30, No. 10, October 2015.
- [2]. P. Rodriguez, A. Timbus, R. Teodorescu, M.Liserre, and F. Blaabjerg, "Flexible active power control of distributed power generation systems during grid faults," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2583–2592, Oct. 2007.
- [3]. F. Wang, J. Duarte, and M. Hendrix, "Design and analysis of active power control strategies for distributed generation inverters under unbalanced grid faults," *IET Generation, Transmission and Distribution*, vol. 4, no. 8, pp. 905–916, Aug. 2010.
- [4]. M. Reyes, P. Rodriguez, S. Vazquez, A. Luna, R. Teodorescu, and J. Carrasco, "Enhanced decoupled double synchronous reference frame current controller for unbalanced grid-voltage conditions," *IEEE Trans. Power Electron.*, vol. 27, no. 9, pp. 3934–3943, Sep. 2012.

- [5]. A. Camacho, M. Castilla, J. Miret, J. Vasquez, and E. Alarcon-Gallo, "Flexible voltage support control for three-phase distributed generation inverters under grid fault," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1429–1441, Apr. 2013.
- [6]. M. Castilla, J. Miret, A. Camacho, J. Matas, E. Alarcon-Gallo, and L. de Vicuna, "Coordinated reactive power control for static synchronous compensators under unbalanced voltage sags," in *Proc. IEEE International Symposium on Industrial Electronics (ISIE)*, May, 2012, pp. 987–992.
- [7]. J. Miret, A. Camacho, M. Castilla, L. de Vicuna, and J. Matas, "Control scheme with voltage support capability for distributed generation inverters under voltage sags," *IEEE Trans. Power Electron.*, vol. 28, no. 11, pp. 5252–5262, Nov. 2013.
- [8]. A. Camacho, M. Castilla, J. Miret, R. Guzman, and A. Borrell, "Reactive power control for distributed generation power plants to comply with voltage limits during grid faults," *IEEE Trans. Power Electron.*, vol. 29, no. 11, pp. 6224–6234, Nov. 2014.
- [9]. M. Reyes, P. Rodriguez, S. Vazquez, A. Luna, R. Teodorescu, and J. Carrasco, "Enhanced decoupled double synchronous reference frame current controller for unbalanced grid-voltage conditions," *IEEE Trans. Power Electron.*, vol. 27, no. 9, pp. 3934–3943, Sep. 2012.
- [10]. European Network of Transmission System Operator (ENTSO), "Entsoe draft network code for requirements for grid connection applicable to all generators," [requirements-for-generators/Pages/default.aspx](#), Jan. 2012.
- [11]. A. Uphues, K. Notzold, R. Wegener, S. Soter, and R. Griessel, "Support of grid voltages with asymmetrical reactive currents in case of grid errors," in *Proc. IEEE International Conference on Industrial Technology (ICIT)*, Feb. 2013, pp. 1781–1786.
- [12]. M. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions*. Wiley-IEEE Press, 2000.
- [13]. M. Mirhosseini, J. Pou, V. G. Agelidis, E. Robles, and S. Ceballos, "A three-phase frequency-adaptive phase-locked loop for independent single-phase operation," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6255–6259, Dec. 2014.
- [14]. E. Robles, S. Ceballos, J. Pou, J. Martin, J. Zaragoza, and P. Ibanez, "Variable-frequency grid-sequence detector based on a quasi-ideal low pass filter stage and a phase-locked loop," *IEEE Trans. Power Electron.*, vol. 25, no. 10, pp. 2552–2563, Oct. 2010.
- [15]. M. Mirhosseini, J. Pou, and V. G. Agelidis, "Single- and two-stage inverter-based grid connected photovoltaic power plants with ride through capability under grid faults," *IEEE Trans. Sustain. Energy*, vol. PP, no. 99, pp. 1–10, Sep. 2014.
- [16]. /IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 30, NO. 10, OCTOBER 2015