An Advanced Current Controller with Reduced Complexity and Improved Performance under Abnormal Grid Conditions

Zunaib Ali, Nicholas Christofides
Department of Electrical Engineering Department
Frederick University,
Nicosia, Cyprus
zunaib.ali@stud.frederick.ac.cy, n.christofides@frederick.ac.cy

Lenos Hadjidemetriou and Elias Kyriakides
Department of Electrical and Computer Engineering,
KIOS Research and Innovation Center Excellence,
University of Cyprus
Nicosia, Cyprus
{hadjidemetriou.lenos, elias}@ucy.ac.cy

Abstract- Electricity grid regulations are frequently revised in order to accommodate the ever-increasing penetration of distributed renewable energy systems (RES). Interconnected RES are required to operate conditionally under normal and abnormal grid conditions. Furthermore, RES are required to have fault ride through (FRT) capability so that they can provide voltage and frequency support to the grid. The FRT operation may necessitate the injection of positive, negative or both sequence components of current. Therefore, appropriate control techniques are needed that can perform under all grid conditions (faults and harmonics) without violating the grid codes. A benchmarking comparison between two existing current control techniques motivated the proposal of a new current controller with an improved performance and lower computational complexity. The proposed controller allows accurate injection of pure sinusoidal positive, negative or both sequences currents under normal and abnormal grid scenarios. The proposed control strategy can work with considerably lower computational complexity and with improved response as compared to the two existing controllers.

Index Terms- Current Controller, Harmonic Compensation, Fault Ride Through (FRT), Computational Complexity.

I. INTRODUCTION

For grids with high penetration of distributed generation systems many grid codes have already been published in order to regulate power generation form these interconnected sources [1]-[3]. Furthermore, this increasing integration is leading to the evolution of new grid regulations for the accurate operation of RES under disturbances and grid faults [4]-[5]. As per these regulations, RES are required to inject high quality current under normal and harmonically distorted grid conditions. In addition, RES must be equipped with Fault Ride Through (FRT) capability in order to remain interconnected and inject positive and/or negative sequence currents for improving the power system stability [6]-[9]. RES need grid side converters (GSC) for delivering available power to electrical grid in an efficient way [10]-[11]. Hence, the control system of grid side converter needs flexibility and continuous improvements for meeting the modern grid requirements. The appropriate operation of the GSC is ensured by the design of its controller for regulating the injection of the produced active power into the grid in a synchronized way [5]-[7],[12]. The control of GSC is often based on the outer active-reactive power (PQ) control loop and the inner (Current) control loop [11], [13]-[15]. The operation of both controllers is affected by the synchronization method, usually a Phase-Locked Loop (PLL) technique that ensures the grid synchronization of the GSC. The PQ and current control must be designed so as to operate accurately under both normal and abnormal grid scenarios. The main topology and the corresponding controller diagram for such a three-phase GSC is described in [11], [13]-[15] and is presented in Fig. 1.

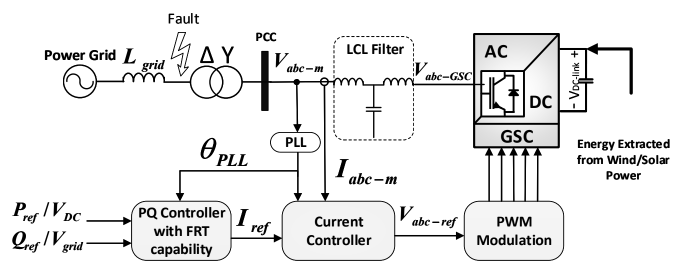

Figure 1. GSC controller in SRF domain.

In the literature, the conventional current controller [13]-[14] is designed in the Synchronous Reference Frame (SRF) of the fundamental component (dq^{+1}-frame) and uses two Proportional-Integral (PI) controllers in order to generate the reference voltage. However, the presence of negative sequence grid voltage causes unavoidable double frequency oscillations on the transformed dq^{+1}-frame voltage and current vectors. As a result, the controller does not respond optimally under unbalanced grid voltage. To alleviate the problem of double frequency oscillations, some current control strategies with dual SRF frames have been proposed in [16]-[17], where the effect of oscillations is mitigated by introducing filtering techniques. The use of filtering techniques in the controller

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path, however, causes undesirable deceleration of its dynamic response and performance.

To improve the performance of dual SRF current controller, an enhanced decoupled SRF controller is proposed in [18]. The enhanced dual SRF controller uses a novel decoupling network for accurately injecting both full positive and negative sequence currents with improved dynamic response. The controller however is more complex and the necessary dq voltage feedforward terms are not used in the control path, requiring undesired higher control effort.

In addition, all the control techniques mentioned above do not consider the effect of harmonic distortion. The Proportional-Resonant (PR) controller designed in $\alpha\beta$ frame proposed in [19], is equivalent to conventional dq controller and cannot work for abnormal conditions. Another controller proposed in [20] uses a Resonant (R) controller in combination with PI. The PI controller is used in SRF for injection of positive sequence current and the R controller is employed to compensate the voltage harmonics. However, the effect of unbalanced voltage conditions is not considered. To overcome the problem of both unbalanced fault and harmonic distortion, a multiple SRF based controller is proposed in [21]. The computational complexity of the aforementioned controller is an issue due to significant number of Park's transformations and additionally, the decoupling of cross-coupled dq axis currents plus the feedforward terms make the implementation more complex [22]. Furthermore, it cannot inject positive and negative sequence currents simultaneously.

In this paper, two existing controllers [18] and [21] are compared in terms of their operating performance and computational complexity. Based on this benchmarking analysis, this paper proposes an advanced current controller that can work with improved performance and requires less computational effort. The new current control technique enables the injection of high quality positive and/or negative sequence symmetrical currents under grid faults and voltage harmonic distortion. Furthermore, a modified PQ controller is developed in which the proposed technique is used for enabling the proper FRT operation of grid connected RES.

The study of existing current controllers is presented in Section II. The proposed current controller and modified PQ controller is discussed in Section III. Section IV describes the computational complexity analysis. Finally, to verify the accurate performance of the proposed current controller simulation results are analyzed in Section V and paper concludes in section VI.

II. ANALYSIS OF EXISTING CURRENT CONTROLLERS

Two existing current controllers are discussed and analyzed that justify the proposal of new advanced controller.

A. Modified dq based Controller

The controller proposed in [21] reformed the conventional dq controller by combing it with harmonic compensation module (HCM) and unbalance compensation module (UCM). The HCM and UCM are implemented using Integral controllers implemented in multiple reference frames (SRFs). The main contribution of the paper was the introduction of unbalance compensation module that can compensate for unbalance grid faults. The controller can inject full positive or negative sequence current under grid faults and harmonic distortion. The structure of the controller is shown in Fig. 2.

The complexity of the controller is an issue due to the large number of Park's transformation, and the presence of feedforward and cross-coupling terms. Moreover, it cannot inject both positive and negative current sequences simultaneously.

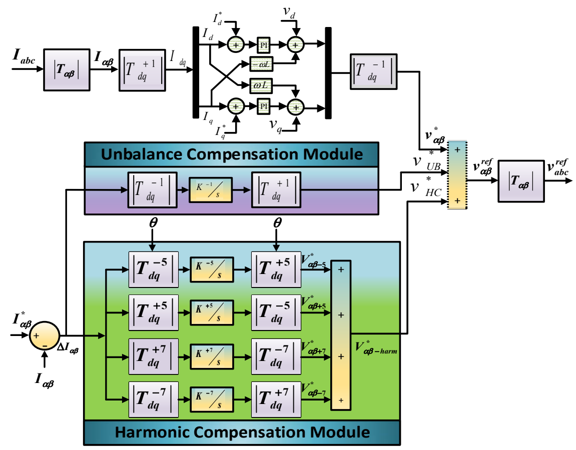

Figure 2. Modified current controller of [21].

B. Decoupled Double Synchronous Reference (DDSRF)

When both positive and negative sequence currents are being injected simultaneously, the performance of conventional dq based PI controller is degraded due to the presence of undesired double frequency oscillations. The effect of oscillations must be removed for allowing an accurate performance by the PI controllers. Many filter based control techniques have been proposed for reducing these oscillations. The current controller proposed in [18] uses two SRF frames with a novel decoupling network for eliminating the effect of these oscillations. The controller can inject both positive and negative sequences of current simultaneously. The structure of the current controller is presented in Fig. 3.

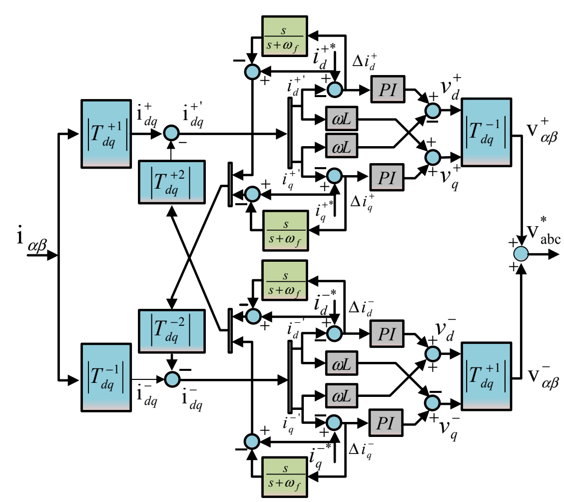

Figure 3. Schematic of EDDSRF current controller of [18].

The controller is more complex in terms of implementation and also the effect of grid voltage harmonic distortion is not considered. Since the injection of negative sequence needs an extra SRF frame, two dq based PI controllers are implemented in each corresponding SRF frames for simultaneous injection of positive and negative sequence. Consequently, the computational cost of controller is significantly increased due to extra number of Park's transformation and cross-coupling terms. Moreover, the use of feedforward is necessary in case of dq, which is not included in the design, resulting in higher control effort. Moreover, the use decoupling networks for cancelling the effect of oscillations further increases the complexity.

III. PROPOSED CONTROLLER TECHNIQUE

A. *Proposed Current Controller*

The main contribution of the paper is the design of a new current controller and its comparative study with existing ones. The proposed current controller is hybridization of PR and I controllers implemented in $\alpha\beta$ and dq frame for minimizing the requirement of excessive computational resources. The PR controller allows the perfect injection of full positive and/or negative sequence currents and additionally compensates for unbalanced grid faults. The unbalance compensation by PR controller restricts the generation of zero sequence as well. The PR controller is based on Internal Model Principle (IMP). According to IMP, a good tracking and rejection capability of periodical signals are possible without the need of frame transformation if the internal models of signal (unstable poles of Laplace transform of commanded or disturbance signals) are included in the control loop [Appendix C, 13].

The I controllers are used to compensate the effect of voltage harmonics to enable the injection of high quality current. The proposed current controller ensures advanced performance both in terms of enhanced operational responses and low computational resources.

The proposed current controller is modular in structure and can be divided into three parts as shown in Fig. 4. The first module is responsible for choosing the mode of operation i.e. positive and/or negative current injection. The second module consists of conventional PR controller implemented in stationary frame. The last module called harmonic compensation module (HCM) is responsible for modifying the reference voltage of GSC for effective mitigation of harmonic distortion present in the grid voltage. The HCM is implemented in multiple SRFs where the disturbance $\Delta i_{\alpha\beta}$ is transformed every time into the corresponding harmonic reference frame in order to compensate the effect of harmonic distortion in grid voltage [Chapter. 12, 13], [21].

Since the dynamics of PR controller do not change by adding extra HCM, therefore it is convenient to tune the conventional part of controller as mentioned in [Chapter 9, 13]. The values of K_p and K_r used in this paper are 71 and 6000, respectively. The stability of HCM is ensured by the use of I controller and can be tuned easily. The dynamics of grid voltage harmonics are slow, therefore the I controllers are tuned at relatively low gains (1000) [21].

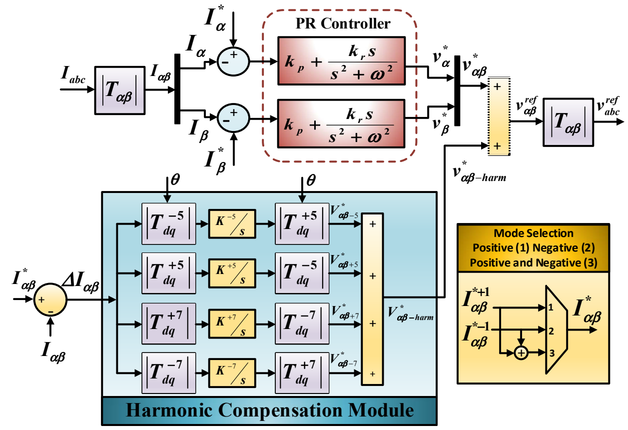

Figure 4. Proposed current controller structure

B. *Proposed Modified PQ Controller for FRT*

The current references that enable FRT operation in this proposed modified PQ controller are calculated using a decoupling network as an added feature in the conventional PQ controller. The decoupling network [23]-[24] is implemented in stationary reference frame for generating pure sinusoidal current reference signals by dynamically canceling out the effect of harmonic distortion and unbalance negative sequence components from positive sequence grid voltage and vice versa. The decoupling network accurately determines every voltage component $v_{\alpha\beta}^{*n}$ (including positive/negative sequence and all the harmonics). Thereafter by using the voltage components $v_{\alpha\beta}^{*+1}$ and $v_{\alpha\beta}^{*-1}$, the reference for positive and/or negative sequence currents (free of undesired oscillations) are being calculated according to (1) and/or (2). Consequently, the reference generation will be free of harmonics and/or unbalance terms, and thereby accurate performance of current controller can be achieved. Furthermore, by injecting a harmonic free positive and/or negative sequence current, the oscillations in active and reactive power will also be minimized. The active/reactive power references P^* and Q^* are provided based on FRT technique mentioned in [6] in order to avoid violation of converter current limits under grid faults.

$$\begin{bmatrix} i_\alpha^{*+1} \\ i_\beta^{*+1} \end{bmatrix} = \frac{2}{3}\frac{1}{(v_\alpha^{*+1})^2 + (v_\beta^{*+1})^2}\begin{bmatrix} v_\alpha^{*+1} & v_\beta^{*+1} \\ v_\beta^{*+1} & -v_\alpha^{*+1} \end{bmatrix}\begin{bmatrix} P^* \\ Q^* \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha^{*-1} \\ i_\beta^{*-1} \end{bmatrix} = \frac{2}{3}\frac{1}{(v_\alpha^{*-1})^2 + (v_\beta^{*-1})^2}\begin{bmatrix} v_\alpha^{*-1} & v_\beta^{*-1} \\ v_\beta^{*-1} & -v_\alpha^{*-1} \end{bmatrix}\begin{bmatrix} P^* \\ Q^* \end{bmatrix} \quad (2)$$

According to [11], [21], the relation for active/reactive power delivered by GSC under unbalanced harmonically distorted grid voltage is given by (3). It is obvious from (3) that the active and reactive powers suffer from oscillations due to the presences of voltage or current negative sequence unbalanced and harmonic components. The proposed PQ controller however, minimizes these oscillations. Considering the references in (1), the active and reactive powers for positive sequence current injection is given by (4). Similar relation can be written for negative sequence by replacing +1 by -1. It can be inferred from (4) that the oscillations within active and reactive powers are minimized compared to oscillations in (3). Henceforth, it is the responsibility of current controller to ensure the proper injection of currents according to (1) and (2).

$$p=\frac{3}{2}\left\{\underbrace{\begin{bmatrix}\mathrm{v}_{\alpha\beta}^{+1}\cdot\mathrm{i}_{\alpha\beta}^{+1}+\mathrm{v}_{\alpha\beta}^{-1}\cdot\mathrm{i}_{\alpha\beta}^{-1}\\+\mathrm{v}_{\alpha\beta}^{h}\cdot\mathrm{i}_{\alpha\beta}^{h}\end{bmatrix}}_{P\rightarrow Non-Oscillating}+\underbrace{\begin{bmatrix}\left(\mathrm{v}_{\alpha\beta}^{-1}+\mathrm{v}_{\alpha\beta}^{h}\right)\cdot\mathrm{i}_{\alpha\beta}^{+1}+\\\left(\mathrm{v}_{\alpha\beta}^{+1}+\mathrm{v}_{\alpha\beta}^{h}\right)\cdot\mathrm{i}_{\alpha\beta}^{-1}+\left(\mathrm{v}_{\alpha\beta}^{+1}+\mathrm{v}_{\alpha\beta}^{-1}\right)\cdot\mathrm{i}_{\alpha\beta}^{h}\end{bmatrix}}_{\tilde{p}\rightarrow Oscillating}\right\}$$

$$q=\frac{3}{2}\left\{\underbrace{\begin{bmatrix}\mathrm{v}_{\alpha\beta\perp}^{+1}\cdot\mathrm{i}_{\alpha\beta}^{+1}+\mathrm{v}_{\alpha\beta\perp}^{-1}\cdot\mathrm{i}_{\alpha\beta}^{-1}\\+\mathrm{v}_{\alpha\beta\perp}^{h}\cdot\mathrm{i}_{\alpha\beta}^{h}\end{bmatrix}}_{q\rightarrow Non-Oscillating}+\underbrace{\begin{bmatrix}\left(\mathrm{v}_{\alpha\beta\perp}^{-1}+\mathrm{v}_{\alpha\beta\perp}^{h}\right)\cdot\mathrm{i}_{\alpha\beta}^{+1}+\left(\mathrm{v}_{\alpha\beta\perp}^{+1}+\mathrm{v}_{\alpha\beta\perp}^{h}\right)\\\cdot\mathrm{i}_{\alpha\beta}^{-1}+\left(\mathrm{v}_{\alpha\beta}^{+1}+\mathrm{v}_{\alpha\beta\perp}^{-1}\right)\cdot\mathrm{i}_{\alpha\beta}^{h}\end{bmatrix}}_{\tilde{q}\rightarrow Oscillating}\right\}\quad(3)$$

$$p=\frac{3}{2}\left\{\underbrace{\left[\mathrm{v}_{\alpha\beta}^{+1}\cdot\mathrm{i}_{\alpha\beta}^{+1}\right]}_{P\rightarrow Non-Oscillating}+\underbrace{\left[\left(\mathrm{v}_{\alpha\beta}^{-1}+\mathrm{v}_{\alpha\beta}^{h}\right)\cdot\mathrm{i}_{\alpha\beta}^{+1}\right]}_{\tilde{p}\rightarrow Oscillating}\right\}$$

$$q=\frac{3}{2}\left\{\underbrace{\left[\mathrm{v}_{\alpha\beta\perp}^{+1}\cdot\mathrm{i}_{\alpha\beta}^{+1}\right]}_{Q\rightarrow Non-Oscillating}+\underbrace{\left[\left(\mathrm{v}_{\alpha\beta\perp}^{-1}+\mathrm{v}_{\alpha\beta\perp}^{h}\right)\cdot\mathrm{i}_{\alpha\beta}^{+1}\right]}_{\tilde{q}\rightarrow Oscillating}\right\}\quad(4)$$

Altogether, the modified PQ controller with the proposed current controller enables the accurate injection of full pure positive and/or negative sequence of currents by compensating the effect of unbalance and harmonic distortion.

IV. COMPUTATIONAL COMPLEXITY ANALYSIS

In this section, the computational complexity of proposed current controller is compared with those of [18] and [21]. It is worth mentioning that the proposed control strategy doesn't need extra unbalance compensation module (UCM) as compared to the controller proposed in [21] for compensating the effect of unbalanced grid faults. This is because the PR controller can compensate for inverse sequence generated by unbalance grid faults on its own. Furthermore, since the PR controller provides infinite gain at a specific frequency, no feedforward compensation and decoupling of currents are needed in the case of PR controller as opposed to control in SRF frame. The elimination of cross-coupling and feedforward terms significantly reduces the calculations complexity [22]. For a three-phase system, the control strategy with PI controller increases the complexity of implementation due to large number of transformations between the reference frames. However, the proposed control technique requires considerably less number of Park's transformations for the implementation of control algorithm.

Furthermore, as the PR controller mainly depends upon the grid angular frequency that is fixed for both the positive and negative sequence, the simultaneous injection of both sequences does not require an additional decoupling network as in [18]. Consequently, one PR control loop is required to control both sequences, unlike controller proposed in dq (base quantity is grid voltage phase angle and is different for both sequences) where two separate SRFs and decoupling network is employed for each sequence. This further reduces the overall complexity.

The proposed controller strategy is therefore more efficient and computationally less complex than the controllers in [18] and [21]. The proposed current controller requires the least number of calculations and is computationally faster, as analyzed in Table I. The computational time analysis was done using the MATLAB Profiler tool.

V. RESULTS AND DISCUSSION

The dynamic response of the proposed current controller is verified under unbalanced grid faults and harmonically distorted grid voltage through simulations. The LCL filter parameters are calculated according to [25]. The results in Fig. 5 show the positive or negative sequence injection of proposed controller under FRT. The -5^{th} and $+7^{th}$ order of voltage harmonic distortion is set to 0.03 pu and 0.02 pu, respectively, (same for all cases). Until 0.8 s, 2 kW of power is delivered in positive sequence injection mode, thereafter a step change from 2 kW to 3 kW is applied. An unbalance Type C fault occurs at 0.9 s and grid support is ensured by injecting positive sequence according to FRT *Q/P=3:1* (2395 VAr/800 W), without violating the converter's limit. Under fault, the injection of reactive power provides support to grid voltage. Hence the amount of Q power injected must be greater than the P power. The *Q/P=3:1* is selected to validate the FRT operation of proposed control strategy (a more accurate value of *Q/P* depending on fault can be obtained from grid operator or reactive power profile or according to [6]). At 1s the mode of operation is changed to negative sequence and 842 VAr/285 W of power is delivered. Under all variations, proposed controller is responding accurately with improved performance (low overshoot/oscillations and faster dynamic response).

Table I: Complexity Analysis for Three Controllers in terms of required Multiplications $(\times)$, Additions $(+)$and Subtractions $(-)$ in each control loop.

Current Controller		Proposed	[21]	[18]
Complexity Analysis	Main Controller	PR Controller in $\alpha\beta$ $(3(\times)+4(+)+1(-))\times 2$	PI Controller in dq $(3(\times)+5(+))\times 2+1(+)$	PI Controller in dq $(3(\times)+4(+))\times 4$
	$[T_{dq}]$ in each block	$PR\ in\ \alpha\beta$: 0; HCM: 8 UBM: 0; DN: 0	$PI\ in\ dq$: 2; HCM: 8 UBM: 3; DN: NA	$PI\ in\ dq$: 4; HCM: 10 UBM: NA; DN: 2
	HCM and UBM Calculations	Integral: $(1(\times)+1(+))\times 8$	Integral: $(1(\times)+1(+))\times 10$	Integral: $(1(\times)+1(+))\times 8$
	Feed-forward	Not Needed	Needed	Not Needed
	Cross-Coupling	Not Needed	Needed	Not Needed
	Decoupling for Simultaneous Injection	Not Needed	Not Applicable	Needed $(5(\times)+8(+)+6(-))$
	Total mathematical operations in each loop	$(\times)$: 62; $(+)$: 20; $(-)$: 10; Total: 92 (100%)	$(\times)$: 94; $(+)$: 34; $(-)$: 13; Total: 141 (153.26%)	$(\times)$: 121; $(+)$: 48; $(-)$: 22; Total: 191 (207.60%)
	Processing time for each loop (MATLAB profiler report)	1.54 ms (100%)	1.90ms (123%)	2.23ms (144%)
Current Injection Performance Capabilities		Positive **and/or** Negative	Positive **or** Negative	Positive **and/or** Negative

Note:- Harmonic Compensation Module (HCM), Unbalance Compensation Module (UBM), Decouple Network (DN); **Each $[\mathbf{T}_{dq}^{n}]$ requires:** 6 Multiplications $(\times)$ + 1 Addition $(+)$ +1 Subtraction $(-)$; **Each PI requires:** 2 $(\times)$ + 2$(+)$; **Cross Coupling:** 2$(\times)$ + 1$(+)$; **Feedforward:** 1$(+)$; **Each PR requires:** 3 $(\times)$ + 4$(+)$ + 1$(-)$; **Each I require** 1 $(\times)$ + 1$(+)$

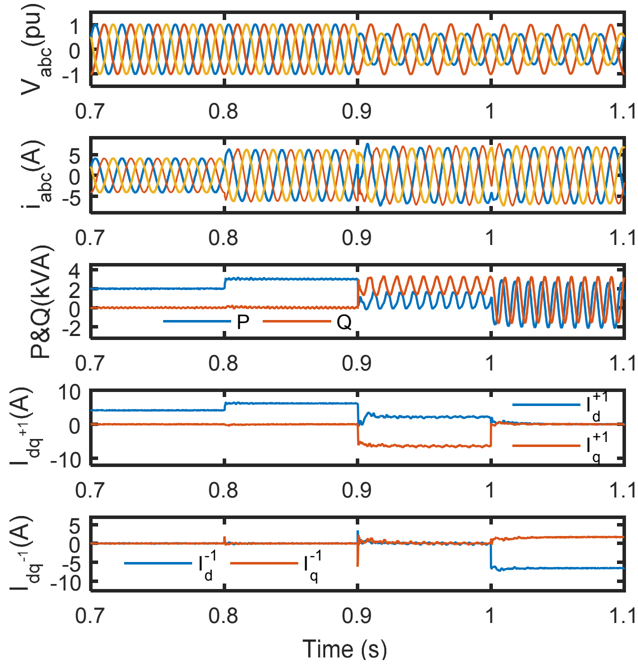

Figure 5. Fault ride through response of proposed controller in positive or negative injection mode.

The proposed current controller is also validated for mitigation of grid voltage harmonic pollution (shown in Fig. 6). The controller is operated in positive injection mode. The I_d^{+1} and I_q^{+1} are respectively subjected to a step change of 4.5 A and 2.25 A at 0.4 s and 0.65 s. The voltage harmonics (-5^{th} and $+7^{th}$) are injected into the grid voltage at 0.4 s with HCM deactivated until 0.55 s. The oscillations in injected I_{dq}^{+1} current can be observed in Fig. 6. After 0.55 s however, when the HCM is activated, the undesired oscillations are compensated and thereafter harmonic free currents are injected. The subplot 2 clearly reflects the presence of harmonics in three phase currents (distorted waveforms) before 0.55 s, which however becomes pure sinusoidal as the HCM is activated.

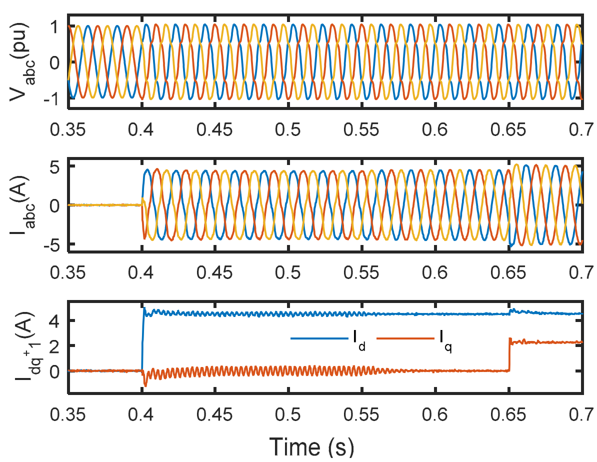

Figure 6. Mitigation of harmonic pollution using proposed current controller.

The performance of the proposed current controller is also compared with those of [18] and [21]. The tuning procedure used is similar for all the controllers. The first comparison is for injection of positive sequence current, Fig. 7. At 0.4 s and 0.6s I_d^{+1} and I_q^{+1} are respectively subjected to a step change of 4.5 A and 2.25 A. At 0.8 s when fault occurs, the controllers in [18] and [21] take more time to overcome the oscillations and get back to the reference value.

The comparison for injecting negative sequence is shown in Fig 8. Until 0.6*s* all the controllers are injecting positive sequence current. At 0.6*s* the mode of operation is changed to negative injection and also a type B grid fault occurs. It can be seen from Fig. 8 that from the three controllers, the proposed current controller gives less overshoot, lower oscillations and takes less time to get back to the reference (generated by PQ controller). The improved performance of controller is achieved at lower calculation complexity, verifying the effectiveness of proposed strategy.

Since, the controller in [21] cannot inject both sequences simultaneously, a comparison with the controller of [18] only is shown in Fig. 9. The unbalance Type B (propagated as Type C) fault occurs at 0.6 s. With zero initial value, a step change of 4.5 A and 2.25 A is applied to I_d^{+1} and I_q^{+1} at 0.4 s and 0.5 s, respectively. Similarly, at 0.7 s and 0.8 s I_d^{-1} and I_q^{-1} is changed to 4.5 A and 2.25 A. The proposed current controller experiences low overshoot and less oscillations (at 0.6 s) both in I_{dq}^{+1} and I_{dq}^{-1}. Similar kind of behavior can also be observed at 0.7 s, where the proposed controller behaves better than the controller of [18].

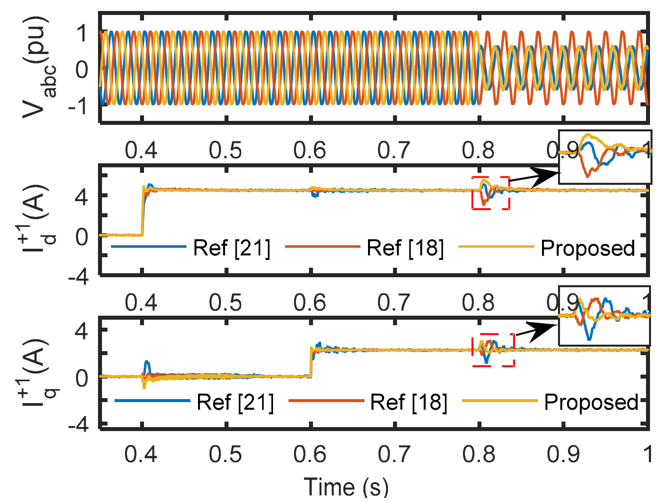

Figure 7. Comparing the response of controllers under positive sequence current injection mode.

The proposed current controller presents faster response and better performance with less oscillations/overshoots, as can be verified from results in Fig. 7-9. The improved performance is achieved with considerable reduced computational complexity compared to the other controllers. This is a very important characteristic when implementing a control algorithm in real time since current digital signal processors (DSP) [22] employed in GSCs have limited processing resources resulting from attempts to minimize the cost. As a result, a decrease in processing resources has a positive impact and provides greater flexibility to GSC manufacturers.

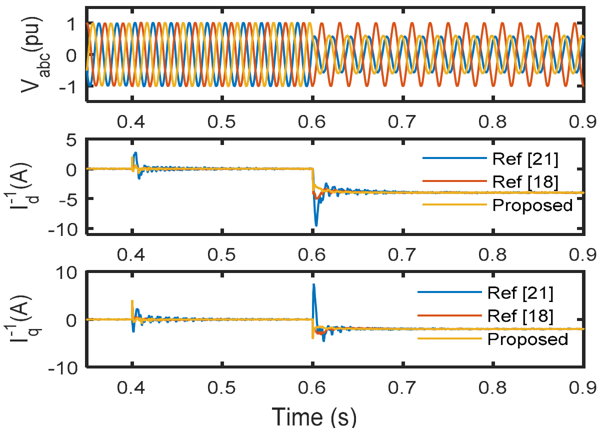

Figure 8. Comparing the response of controllers under negative sequence current injection mode.

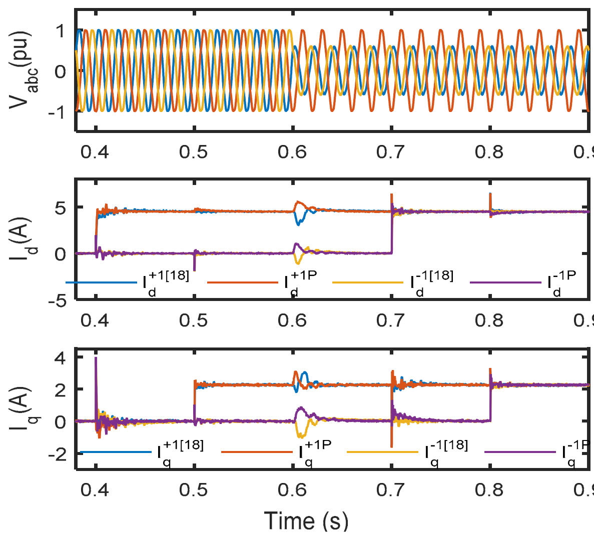

Figure 9. Comparison of simultaneous injection of positive and negative sequence currents (legend superscript P refers to proposed current controller and number 18 refers to the controller in reference 18).

VI. CONCLUSION

This paper proposes an advanced current control technique enhanced with harmonic compensation and FRT capabilities for harmonically distorted unbalanced voltage conditions. The proposed controller can inject high quality positive and/or negative sequence of currents accurately with considerably lower computational complexity as demonstrated in Table I. Furthermore, the response of proposed controller presents lower overshoot and less oscillations. The proposed controller is designed to adapt to any modern grid regulations ensuring reliable, safe and stable feed-in operation of grid side converters and distributed renewable energy systems.

REFERENCES

[1] F. Iov, A. D. Hansen, P. E. Soerensen, and N. A. Cutululis, "Mapping of grid faults and grid codes," Risø Nat. Lab., Tech. Univ. Denmark, 2007.

[2] E.ON Netz GmbH. (2006). "Grid code—High and extra high voltage," Tech. Rep. [Online]. Available: http://www.eon-netz.com/

[3] F. Blaabjerg, M. Liserre, and K. Ma, "Power electronics converters for wind turbine," *IEEE Trans. Ind. Appl.*, vol. 48, no. 2, pp. 708–719, 2012.

[4] S. Yang, Q. Lei, F. Z. Peng, and Z. Qian, "A robust control scheme for grid connected voltage-source inverters," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 202–212, Jan. 2011.

[5] IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems, IEEE Std 1547-2003, 2003, pp. 1–27.

[6] L. Hadjidemetriou, P. Demetriou and E. Kyriakides, "Investigation of different Fault Ride Through strategies for renewable energy sources," *IEEE PowerTech*, Eindhoven, pp. 1-6, Eindhoven, 2015.

[7] P. Rodriguez, A. Timbus, R. Teodorescu, 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, 2007.

[8] P. Rodriguez, A. V. Timbus, R. Teodorescu, M. Liserre, and F. Blaabjerg, "Reactive power control for improving wind turbine system behavior under grid faults," *IEEE Trans. Power Electronics*, vol. 24, no. 7, pp. 1798–1801, Jul. 2009.

[9] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renewable Power Generation*, vol. 3, pp. 308-332, 2009.

[10] F. Blaabjerg , Z. Chen and S. B. Kjaer "Power electronics as efficient interface in dispersed power generation systems", *IEEE Trans. Power Electronics.*, vol. 19, no. 5, pp.1184 -1194 Sep. 2004

[11] Z. Chen, J. M. Guerrero and F. Blaabjerg, "A review of the state of the art of power electronics for wind turbines", *IEEE Trans. Power Electronics*, vol. 24, no. 8, pp. 1859-1875, Aug. 2009.

[12] B.I. Craciun, T. Kerekes, D. Sera, and R. Teodorescu, "Overview of recent grid codes for PV power integration," in *Proc. OPTIM*, pp. 959–965, Brasov, Romania, 2012.

[13] R. Teodorescu, M. Liserre and P. Rodriguez, *Grid converters for photovoltaic and wind power systems*, John Wiley & Sons, 2011.

[14] F. Blaabjerg, R. Teodorescu, M. Liserre and A. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398-1409, 2006.

[15] F. Blaabjerg and K. Ma, "Future on power electronics for wind turbine systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 139-152, Sep. 2013.

[16] H.S. Song and K. Nam, "Dual current control scheme for PWM converter under unbalanced input voltage conditions," IEEE Trans. Industrial Electronics, vol. 46, no. 5, pp. 953-959, Oct. 1999.

[17] Y. Suh and T.A. Lipo, "Control scheme in hybrid synchronous stationary frame for PWM AC/DC converter under generalized unbalanced operating conditions," *IEEE Trans. Industry Applications*, vol. 42, no. 3, pp. 825-835, May 2006.

[18] P. Rodriguez, S. Vazquez, A. Luna, R. Teodorescu, and J. M. Carrasco, "Enhanced decoupled double synchronous reference frame current controller for unbalanced grid-voltage conditions," *IEEE Trans. Power Electronics*, vol. 27, no. 9, pp. 3934–3743, Sep. 2012.

[19] D. N. Zmood and D. G. Holmes, "Stationary frame current regulation of PWM inverters with zero steady-state error," *IEEE Trans. on Power Electronics*, Vol. 18, pp. 814 -822, May 2003

[20] M. Liserre, R. Teodorescu, and F. Blaabjerg, 'Multiple Harmonics Control for Three-Phase Grid Converter Systems with the Use of PI-RES Current Controller in a Rotating Frame'. *IEEE Tran. on Power Electronics*, 21(3), pp. 836–841, May 2006.

[21] L. Hadjidemetriou, E. Kyriakides, and F. Blaabjerg, "A grid side converter current controller for accurate current injection under normal and fault ride through operation," in *Proc. IEEE IECON*, pp. 1454–1459, Vienna, Austria, 2013.

[22] R. Teodorescu, F. Blaabjerg, "Proportional-Resonant Controllers. A New Breed of Controllers Suitable for Grid-Connected Voltage-Source Converters", International Conference on Optimization of Electrical and Electronic Equipments, Vol. 3, p. 9-14. 2014.

[23] L. Hadjidemetriou, E. Kyriakides and F. Blaabjerg, "A robust synchronization to enhance power quality of renewable energy systems," *IEEE Trans. Ind. Electron.*, vol. 62, no. 8, pp. 4858-4868, 2015.

[24] L. Hadjidemetriou, E. Kyriakides, Y. Yang and F. Blaabjerg, "A synchronization method for single-phase grid-tied inverters," *IEEE Trans. Power Electronics*, vol. 31, no. 3, pp. 2139-2149, Mar. 2016.

[25] A. Reznik, M. G. Simoes, A. Al-Durra and S. M. Muyeen, " LCL Filter Design and Performance Analysis for Grid-Interconnected Systems," *IEEE Trans. on Industry Applications*, vol. 50, no. 2, pp. 1225-1232, Apr. 2014.