Performance Enhancement of MAF based PLL with Phase Error Compensation in the Pre-Filtering Stage

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Abstract- The large scale integration of Renewable Energy Sources (RES) requires sophisticated control techniques for efficient power transfer under faults and/or off-nominal grid conditions. A RES is efficiently integrated to the grid via proper control of the Grid Side Converter (GSC) by accurately estimating the grid voltage phase angle. Moving Average Filter (MAF) based Phase Lock Loop (PLL) techniques provide reduced complexity, however, they present disadvantages under specific grid fault conditions. The most recent MAF based technique is the EPMAFPLL, which provides improved dynamic response and reduces the phase error under off-nominal grid frequencies. However, the EPMAFPLL presents high phase and frequency overshoot at the time of fault. Furthermore, inaccurate harmonic mitigation under off-nominal grid frequencies was not investigated in EPMAFPLL. A modified EPMAFPLL (EPMAFPLL Type 2) is proposed in this paper. The modified EPMAFPLL accurately compensates the offset errors under off-nominal grid frequencies, offers lower frequency overshoot and faster dynamics under faults. In addition, it provides accurate compensation of grid voltage harmonics under off-nominal grid frequencies.

Index Terms- Phase Lock Loop (PLL), Unbalanced Faults, harmonic distortion, Phase error, Frequency Overshoot, moving average filter (MAF).

I. INTRODUCTION

The increased penetration of Renewable Energy Sources (RES) necessitates the development of appropriate control techniques for the proper operation of Grid Side Converter (GSC). The control of GSC is mainly categorized in two domains, that is, the control of active/reactive power using stationary $\alpha\beta$-frame or using synchronous reference frame (SRF) [1]. The $\alpha\beta$-frame uses the Proportional Resonant (PR) controller in which the grid frequency is the major parameter affecting the controller's response because the PR controller provides an infinite gain only at a specific frequency. If the Alternating Current (AC) grid frequency is not stiff, a frequency lock loop (FLL) is needed to estimate the value of grid frequency. The SRF employs the control of active/reactive power as DC quantities, since it transforms the measured variables (voltages and currents) into equivalent DC values using the phase information of grid voltage. The voltage phase is typically extracted at the Point of Common Coupling (PCC) by a synchronization algorithm called Phase Lock Loop (PLL). The control in SRF uses a Proportional Integral (PI) controller and is mainly dependent on the fast and accurate performance of PLL. In this paper, SRF in combination with PLL is utilized in the GSC controller for enabling the accurate operation of grid connected RES. The structure of GSC controller in SRF is shown in Fig. 1.

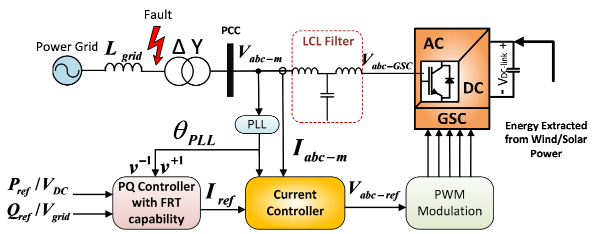

Figure 1. GSC controller in SRF domain.

The current and PQ controllers are directly influenced by the response of the synchronization method, and therefore, the behavior of PLL is very crucial for an appropriate operation of overall grid connected RES system. The performance accuracy of PLL is critical under off-nominal grid conditions such as grid voltage harmonics, voltage sags and swells, balanced and unbalanced grid faults, frequency variations, and phase jumps. For enabling the accurate extraction of phase information, many PLLs have been proposed in the literature. The dqPLL [2]-[3] uses the q-component of transformed grid voltage vector $\mathbf{v}_{dq}$ to extract the phase angle of voltage at PCC and performs accurately under balanced grid conditions. However, the existence of frequency components in voltage other than the fundamental result in oscillations when transformed with specific SRF speed. As a result, dqPLL cannot work under unbalanced gird voltage and/or harmonic distortion. The αβPLL [4]-[6] is similarly not responding accurately under abnormal grid conditions, however, it offers less frequency overshoot at the time of fault as opposed to dqPLL. The

Authors Hadjidemetriou and Kyriakides acknowledge the financial support by the Cyprus Research Promotion Foundation, Project KOINA/SOLAR-ERA.NET/0114/02, through the SOLAR-ERA.NET instrument (EU FP7).

problem of unbalanced faults is overcome by ddsrfPLL [7] and dαβPLL [1], [8]-[9], in which a novel decoupling network is used to decouple the undesired double frequency oscillations imposed by the negative sequence fundamental component, thereby acquiring the phase information. The only difference between ddsrfPLL and dαβPLL is that in case of dαβPLL the αβPLL is used as phase detection algorithm resulting in less overshoot as compared to ddsrfPLL. The ddsrfPLL and dαβPLL cannot work accurately under harmonic distortion since the decoupling network employed is only used to separate the fundamental positive sequence components from the negative sequence oscillations. However, for mitigating the undesired effect of harmonic distortion, the decoupling network of dαβPLL is modified and extended in MSHDCPLL [10] and DNαβPLL [11] to include the decoupling of oscillations caused by other frequency components. The performance of MSHDCPLL and DNαβPLL is accurate under both unbalanced and harmonically distorted grid conditions. The computational complexity of these PLLs, however, is considerable due to the large number of Park's transformations and excessive computational resources are needed. With the increased computational burden in mind, the Moving Average Filter (MAF) based PLL algorithms provide a better alternative [12]-[14]. The MAF based technique mitigates the effect of unbalances and harmonic distortion at lower computational cost. The dqPLL and dsrfPLL are modified by adding a MAF as presented in [13]. The MAF based PLL performs satisfactorily under harmonics, however, considering the fact that MAF is highly dependent on nominal value of grid frequency, it suffers from the offset error when the grid frequency is not equal to the nominal value (50Hz for example) [13], [15]-[17]. The problem of phase drift under off-nominal grid frequencies can be mitigated by varying the sampling rate to be in agreement with the new frequency, as proposed in [13], [16]-[18]. This however, imposes practical limitations since the entire GSC controller should be developed using variable sampling rate. In addition, the aforementioned MAF based PLLs result in slow dynamic response due to presence of the filter in the control path. The stability analysis and tuning parameter calculation of these PLLs is also not straightforward because the additional MAF filter transfer function appears in the closed loop transfer function of small signal model [13].

The phase estimation error, stability analysis and slow dynamic response is overcome by a recent technique proposed in [15], referred to as EPMAFPLL. In EPMAFPLL, the MAF filter is shifted from the main closed loop control path to the pre-filtering stage, where the pre-filtering stage is rotated with a different speed as opposed to the one at which dqPLL is rotated. In addition, the phase error in case of off-nominal frequencies is mitigated by adding a compensation term to the rotational speed of phase extraction part. However, the EPMAFPLL offers high frequency and phase overshoot at the time of fault and cannot perform accurately for harmonics when operating under off-nominal grid frequencies. As suggested by [8], introducing αβPLL to phase detector (PD) part of PLL slightly reduces frequency overshoot, but this reduction is subjected to the condition of same settling time. The same settling time requires re-adjustment of tuning parameters every time in order to obtain lower frequency overshoot, which however is not considered practical.

As a result, in order to achieve low frequency overshoot under all fault conditions, irrespective of tuning parameters and settling time, a modified EPMAFPLL (EPMAFPLL Type 2) is proposed in this paper. The proposed PLL presents low frequency overshoot and fast dynamic response under faults for any selected value of tuning parameters (same tuning for both PLLs). In addition, the proposed PLL provides better harmonic and offset error compensation under off-nominal grid frequencies as opposed to EPMAFPLL. Altogether, the fast operation of GSC under grid faults by keeping the frequency within the assigned limits of grid regulations is achieved.

The existing MAFPLL, PMAFPLL and EPMAFPLL are discussed in section II. Section III introduces the proposed modified EPMAFPLL referred to as EPMAFPLL Type 2. Section IV describes the tuning procedure and stability analysis for proposed PLL. Finally, the improved performance of EPMAFPLL Type 2 is verified by comparing it to existing EPMAFPLL in section V and paper concludes in section VI.

II. MOVING AVERAGE FILTER BASED PLL TECHNIQUES

A. MAFPLL

The small signal model of conventional dq based MAF PLL is shown in Fig. 2. The MAF is in the closed loop control path resulting in a 3rd order closed loop transfer function [13]. As a result, the tuning procedure is not straight forward and cannot be directly approximated in terms of settling time. The tuning of such a transfer function is based on symmetrical optimum method and the parameters are expressed in terms of phase margin [3], [19]-[22]. The reason for the slow dynamic response of MAFPLL is the limit on the lowest value of settling time while maintaining the stability margins. According to settling time, $T_s = 4.6/\xi\omega_n$ (where ξ and ω_n are the damping factor and natural frequency, respectively), increasing ω_n a lower settling can be achieved. However, according to [13], the value of ω_n cannot be increased beyond $2\pi 26\, rad/s$ for a MAF window length (T_ω) of 0.001 s. If $\omega_n = 2\pi 26\, rad/s$, a settling time of 0.028 s for $\xi = 1$ is obtained, implying that the lowest settling time (fastest response) that can be achieved using this MAF PLL cannot be reduced below 0.028 s (otherwise, phase margin starts reducing below 30°). The control parameters according to [12] are $K_p = 2/(T_\omega b)$ and $T_i = b^3 T_\omega^2/4$, where b relates to stability phase margin. In addition to slow dynamic response, the offset error in phase estimation under off-nominal grid frequencies is another major drawback of MAFPLL.

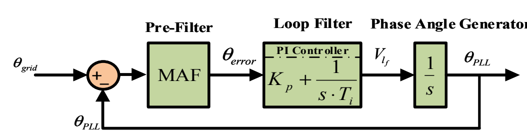

Figure 2. Structure of MAFPLL.

B. PMAFPLL

The slow dynamic response of MAFPLL is alleviated by moving the MAF out of the control path and incorporating it in the pre-filtering stage, a modification referred to as PMAFPLL [15]. After introducing the pre-filtering stage incorporated with MAF, the input/output signals of MAF are rotated with SRF speed (based on nominal grid frequency), which is different than the one used for operating the dqPLL in PD, as shown Fig. 3. In this way, the closed loop does not contain MAF, so the tuning parameter and stability analysis is straight forward [15]. However, the effect of offset errors under the scenario when the value of grid frequency changes from its nominal value is not mitigated in PMAFPLL.

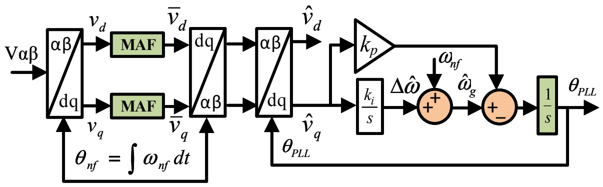

Figure 3. Schematic diagram of Pre-filtering MAF PLL (PMAFPLL).

C. EPMAFPLL

The phase error problem of PMAFPLL under off-nominal grid frequencies was addressed in the work carried out by Golestan et al in [15]. In order to compensate the phase error, the phase shift magnitude experienced by MAFPLL and PMAFPLL under off-nominal grid frequencies needed to be known. For analyzing the phase error, the z-domain transfer function, and corresponding phase and magnitude response of MAF is expressed in (1) and (2).

$$H_{MAF}(z) = \frac{1}{N}\frac{1-z^{-N}}{1-z^{-1}} \quad (1)$$

$$H_{MAF}\left(e^{j\omega T_{sp}}\right) = \left|\frac{\sin\left(\omega N T_{sp}/2\right)}{N\sin\left(\omega T_{sp}/2\right)}\right| \angle -\frac{\omega(N-1)T_{sp}}{2} \quad (2)$$

Where, T_{sp} is the sampling period and $T_\omega = NT_{sp}$ is the window length of MAF. The cause of offset error under off-nominal grid frequencies is because the fundamental component of voltage appears in the input of MAF as a component of frequency $\Delta\omega = \omega_g - \omega_{nf}$, where ω_{nf} and ω_g are the nominal and actual values of grid frequency, respectively. The aforesaid component undergoes a phase shift, given by (3) and derived using (2).

$$\angle H_{MAF}\left(z = e^{j\Delta\omega T_{sp}}\right) = -\Delta\omega \underbrace{\left(T_\omega - T_{sp}\right)/2}_{k_\varphi} \quad (3)$$

The problem of phase shift is mitigated by adding the compensation term represented by (3) to the output of dqPLL, as shown in Figure 4, and resulting angle is subsequently used to rotate the SRF of the phase detector. The drawback of EMAFPLL is that it results in high phase and frequency overshoot under unbalanced faults. Furthermore, it cannot accurately compensate for harmonics under off-nominal grid frequencies.

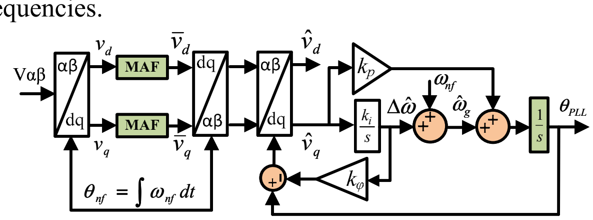

Figure 4. Schematic diagram of Enhanced PMAFPLL (EPMAFPLL).

III. PROPOSED EPMAFPLL TYPE 2

The original MAFPLL presented slow dynamic response and phase error under off-nominal grid frequencies. The PMAFPLL compensated for slow dynamic response and offered straightforward tuning procedure. The EPMAFPLL combined the fast dynamic response of PMAFPLL with improved offset errors. As mentioned however, EPMAFPLL presents relatively high frequency overshoot at the time of fault and inaccurate harmonic compensation under off-nominal grid frequency.

In [10] the response of EPMAFPLL is not investigated under grid faults. While investigating grid fault conditions, it was observed that the compensation factor $-\Delta\omega\left(T_\omega - T_{sp}\right)/2$ influences the overall PLL response because of the presence and significant magnitude of $\Delta\omega$ during the fault (in a similar way that PLL is affected under off-nominal grid frequency conditions). As a result, the added compensation in the phase detector [15] (containing the $\Delta\omega$ term) is the main reason for the relatively high overshoot in EPMAFPLL because when the phase detector is subsequently rotated with an angle having compensation added, it undergoes high overshoot and requires more time to settle.

The proposed EPMAFPLL Type 2 modifies the pre-filtering stage of EPMAFPLL, as shown in Fig. 5. The proposed modification results in lower frequency overshoot and faster dynamic response under faults, better harmonic compensation under off-nominal grid frequencies compared to EPMAFPLL and reduces the offset error in the phase similar to EPMAFPLL.

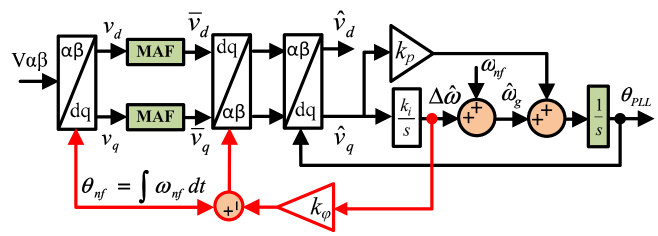

Figure 5. Modified EPMAFPLL Type 2.

In the proposed EPMAFPLL Type 2, the speed at which the MAF output is transformed back to the αβ is modified by adding the value of offset error just after the MAF (in pre-filtering stage), before the phase detector part, as shown in Fig. 5. As a result, the subsequent frame rotation is done using the angle obtained directly from the phase detector stage without $\Delta\omega$ affecting the calculations. The proposed modification decouples the effect of low voltage grid fault (and/or off-nominal grid frequencies) on the phase detector part thereby reducing the value of $\Delta\omega$ and improving the overall response of proposed EPMAFPLL Type 2. The value of $\Delta\omega$ in case of EPMAFPLL is greater than the value of $\Delta\omega$ in the proposed modification at the time of fault. Due to this increased value of $\Delta\omega$, EPMAFPLL undergoes high overshoot.

The proposed EPMAFPLL Type 2 enables the accurate estimation of phase angle in the event of grid faults and off-nominal grid frequency with improved performance in terms of lower frequency and phase overshoot, faster dynamic response and accurate mitigation of grid voltage harmonics without violating the frequency limits set by grid regulations. Hence, the proposed EPMAFPLL Type 2 enables fast and accurate operation of GSC under grid faults and off-nominal grid frequency conditions.

IV. TUNING AND STABILITY ANALYSIS OF PROPOSED EPMAFPLL TYPE 2

The small signal model of the proposed EPMAFPLL Type 2 under nominal frequency condition is equivalent with the one shown in Fig. 6. The closed loop transfer function is derived as:

$$G(s) = \frac{k_p s + k_i}{s^2 + \underbrace{\left(k_p - k_i k_\varphi\right)}_{2\xi\omega_n} s + \underbrace{k_i}_{\omega_n^2}} \quad (4)$$

The transfer function of proposed EPMAFPLL Type 2 is equivalent to that of existing EPMAFPLL [15], hence the stability analysis and tuning procedure is similar for both PLLs. The stability of $G(s)$ is ensured by Routh Hurwitz (RH) criterion applied to the denominator of $G(s)$, resulting in a stable system under the condition $0 < k_i k_\varphi < k_p$. The transfer function is a second order system and can be tuned according to desired dynamic performance. The damping coefficient of system is $\xi = \left(k_p - k_i k_\varphi\right)/2\omega_n$ and the natural frequency is $\omega_n = \sqrt{k_i}$. The desired dynamic response of the system corresponds to the appropriate selection of settling time T_s. The corresponding value of PI parameters are shown in (5).

$$k_p = 2\xi\sqrt{k_i} + k_i k_\varphi \quad \text{and} \quad k_i = (4.6/\xi T_s)^2 \quad (5)$$

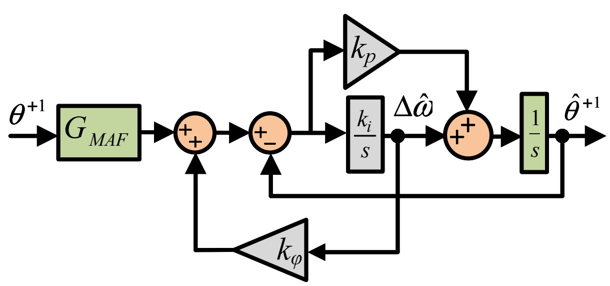

Figure 6. Small signal model of EPMAFPLL Type 2.

V. RESULTS AND DISCUSSION

The performance of the proposed EPMAFPLL Type 2 is analyzed by comparing it with the existing EPMAFPLL under symmetrical and asymmetrical faults, voltage swells, phase jumps and also under off-nominal grid frequencies requiring harmonic compensation.

The performance of proposed EPMAFPLL Type 2 is compared by measuring the voltage at PCC between GSC and $Y\Delta$ distribution transformer. Consequently, for $Y\Delta$ transformer, the propagation of fault is considered according to [23]. For example, the Type B (single phase to ground fault) propagates as Type C (phase to phase fault).

The performance of both PLLs is investigated under -5^{th} and $+7^{th}$ order voltage harmonic distortion with a magnitude of 0.04 pu and 0.03 pu, respectively. The time at which the fault is applied is common to all the results and is set to 1s. The faults are categorized as balanced three phase faults and unbalanced Type B, Type C, and Type E (two phase to ground fault) faults. The tuning parameters k_p and k_i are calculated according to (5) and are equal to 5132.1 and 423.34×10^3, respectively. The sampling period for the PLL developed is 0.1 ms.

Under balanced grid fault, as shown in Fig. 7, the proposed PLL presents less frequency overshoot. The proposed EPMAFPLL Type 2 is also investigated by applying one phase to ground fault propagated as Type C (Fig. 8), two phase with no ground fault propagated as Type D (Fig. 9) and two phase to ground fault propagated as Type F (Fig. 10). In all the cases, it is seen that the frequency overshoot is significantly reduced and faster dynamic response is achieved.

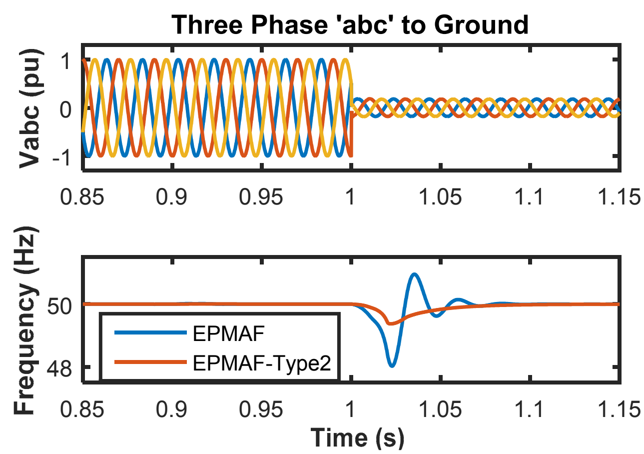

Figure 7. Response to symmetrical three phase to ground fault: a comparison.

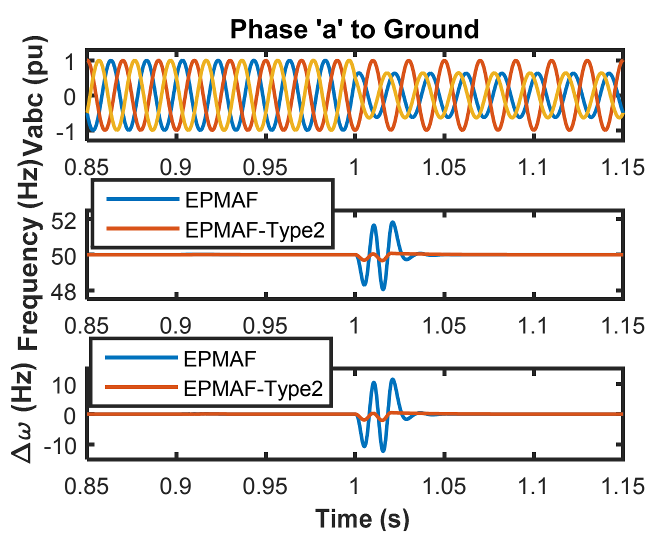

Figure 8. Response to single phase 'a' to ground fault: a comparison.

Furthermore, the proposed PLL is also verified under a voltage sag event with phase jump, and voltage swell event as shown in Fig. 11 and Fig. 12, respectively. From Fig. 11, the frequency/phase overshoot of EPMAFPLL is around 7.46Hz/

$0.04117 rad$ and for the proposed controller it is $2Hz/0.00704 rad$. The harmonic compensation capability of proposed PLL under off-nominal frequency is validated from results shown in Fig. 13, where frequency is varied from 50 Hz to 46 Hz in a ramp form. It can be observed that the proposed PLL gives lower magnitude oscillations (both in frequency and phase estimation) in comparison to EPMAFPLL. The slightly longer time needed to track the desired grid frequency in this case, however, does not affect the overall response of controller. Also, the grid frequency faults are usually with slow dynamics due to the large inertia of the system.

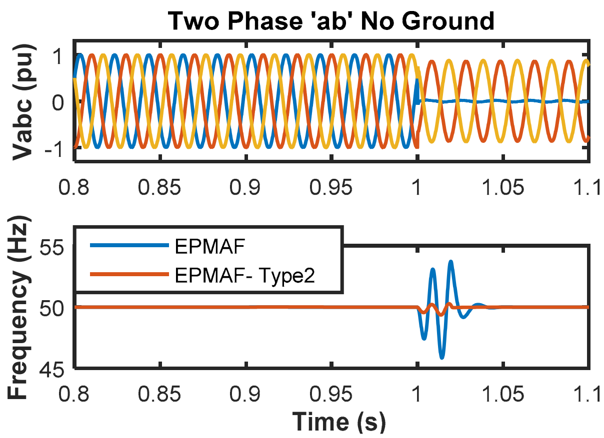

Figure 9: Response to two phase 'ab' with no ground fault: a comparison.

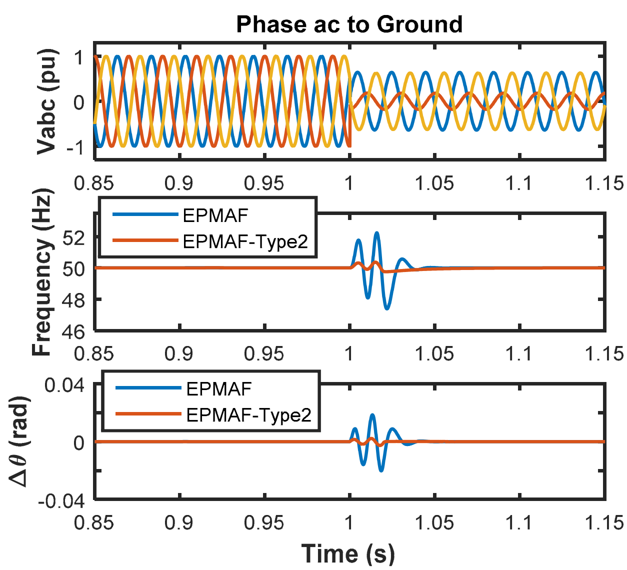

Figure 10. Response to two phase 'ac' to ground fault: a comparison.

Further, the proposed PLL is also tested for the control of grid connected RES under unbalanced fault and FRT mode, as shown in Fig. 14. Before 0.9 s, RES is injecting 2 kW of active power, however, at 0.9 s a step change of 0.5 kW is applied. At t=1 s, an unbalanced fault occurs and FRT scheme with *Q/P*= 3/1 is enabled to support the grid voltage [24].

A comparison of the proposed PLL in terms of frequency overshoot and settling time (time required for error to reach and stay within 1 % of 'zero', after the disturbance is applied) under various types of faults is summarized in Table I. The proposed EPMAFPLL Type 2 has less overshoot and faster dynamics under all the kind of faults, verifying the improved performance.

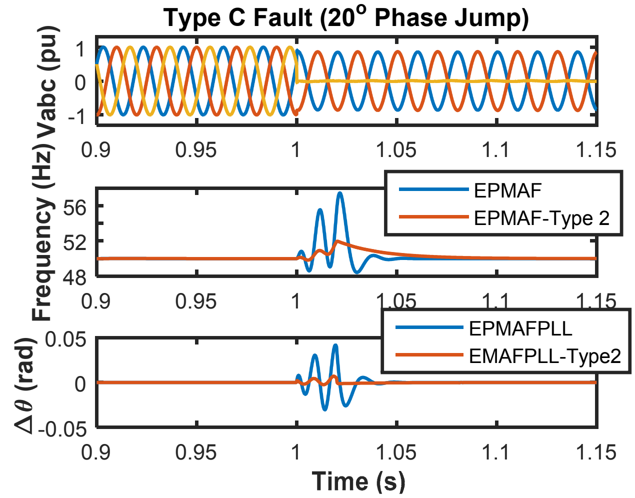

Figure 11. Type C fault with 20^0 phase jump: a comparison.

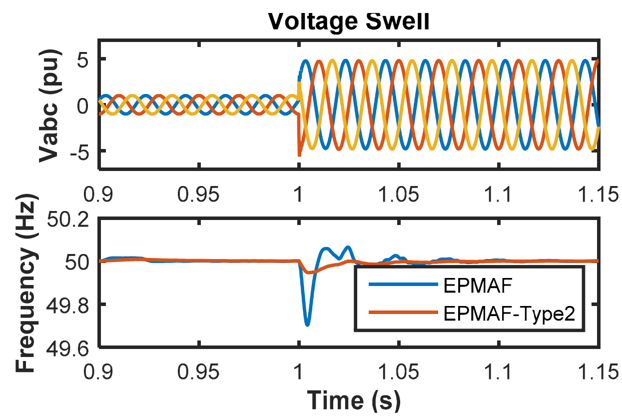

Figure 12. Response to grid voltage swell.

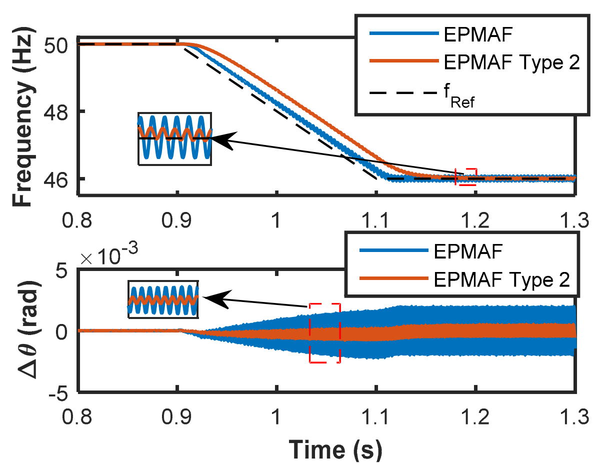

Figure 13: Frequency variation and harmonic compensation

VI. CONCLUSION

The proposed EPMAFPLL Type 2 presents the best response out of all MAF based PLLs investigated. It operates accurately with reduced frequency overshoot and fast dynamic response under balanced and unbalanced faults. In addition, it provides better immunity to grid harmonic distortion. The outstanding performance of the proposed PLL is verified through simulation results summarized in Table I. Under all cases, the proposed EPMAFPLL Type 2 offers lower frequency overshoot and less settling time when compared against EPMAFPLL. The precise and robust response of the new PLL improves the performance of RES by allowing the proper FRT operation and by enhancing the power quality of injected currents under grid instabilities/abnormalities.

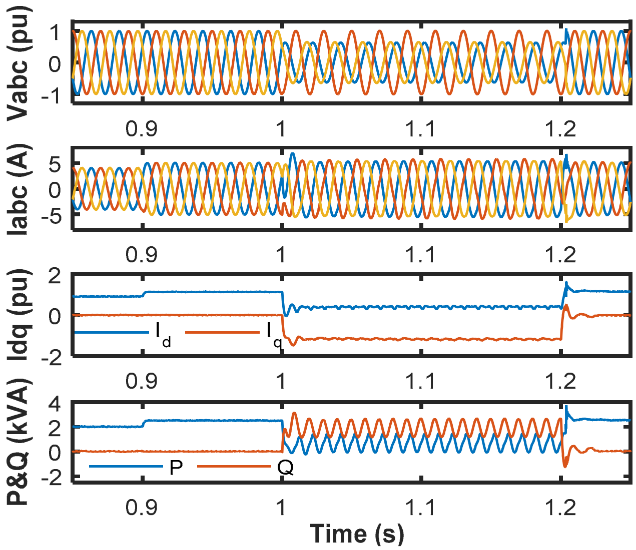

Figure 14. Proposed PLL in grid connected RES under FRT mode.

Table I: Performance Comparison of EPMAFPLL and EPMAFPLL Type 2

Fault Type		Overshoot (Hz)		Settling Time (s)	
		EPMAF	EPMAF Type 2	EPMAF	EPMAF Type 2
1	Phase a to Ground	2.06	0.38	0.019	0.033
2	Phase b to Ground	1.92	0.18	0.05	0.05
3	Phase c to Ground	2	0.23	0.047	0.035
4	Phases ab to Ground	2.5	0.43	0.057	0.047
5	Phases bc to Ground	2.72	0.31	0.031	0.031
6	Phases ca to Ground	2.68	0.49	0.047	0.04
7	Phase ab with No Ground	4.01	0.62	0.045	0.02
8	Phase bc with No Ground	4.23	0.36	0.05	0.06
9	Phase ca No Ground	4.12	0.67	0.045	0.021
10	3 Phases to Ground	2	0.63	0.089	0.089
11	Swell Fault	0.30	0.05	0.1	0.05
12 *	Two phase with Phase Jump of 20^0	7.46/ 0.0412	2/ 0.007	0.05/0.0 41	0.069/ 0.02

Note: * #/# represents frequency/phase settling time and (Hz)/(rad) overshoot

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