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Comparative Study Between the Improved Schemes of MAF-Based Robust PLLs

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***Abstract*—Phase-Looked loop (PLL) is nowadays the best suited technique to achieve grid synchronization. The Moving Average Filter (MAF) based PLLs have received in recent three years considerable attention owing to their attractive features. Indeed, they are able to completely eliminate the unwanted effect of harmonics, dc offset, and unbalanced voltages. Unfortunately, these advantages are paid in term of open-loop bandwidth reduction which worsens the system's dynamic response. To overcome this limitation, a variety of improved MAF-PLLs schemes were developed to improve the dynamic response. The main objective of this paper is therefore to perform an assessment and a comparative study between the performances these new improved PLL schemes. The proposed study is based on numerical simulation carried out for five cases of grid disturbances.**

Keywords_ Smart-grid, micro-grid, PLL, MAF-PLL, SRF-PLL, DSOGI-PLL, grid disturbance

I. INTRODUCTION

Due to environmental pollution, natural resources decrease, and the unstoppable increased electricity demand, Distributed Power Generation Systems (DPGS) are nowadays constantly growing. Approximately, 1% of worldwide energy is generated by DPGS, which are classified into non-renewable sources (micro gas turbines, fuel cells, etc…) as well as renewable sources of energy (solar, wind, etc…). The DPGS are mostly related to medium or small size power plants; it is expected in the medium term, that each home-user can become an autonomous entity, which is called a micro-generation system that is able to inject power into the grid [1].

The integration of DPGS into electrical grids requires a perfect synchronization of voltages of both systems (grid and DPGS) so as to ensure a safe coupling with the grid and the controllability of the active and reactive power transfer. Consequently, A PLL system is mandatory to estimate the frequency and instantaneous phase angle of positive sequence component of the voltages and the Point of Common Coupling (PCC). Unfortunately, the voltages waveforms at the PCC are currently affected by unwanted and severe disturbances such as voltages sags, high distortions, frequency jump, etc. According to the new grid codes, the DPGS must remain connected to the PCC and support the grid voltages by injecting an appropriate amount of reactive power. To fulfill thse requirements, the PLL system must be robust against grid disturbances and also it must provide a fast dynamic response so as to avoid the disconnection from the grid.

The PLL structure based on Moving Average Filter (MAF) proposed three years ago are able to provide a perfect synchronization with the grid voltage even in case of highly distorted waveforms [2]. The MAFs are linear-phase finite-impulse-response (FIR) filters that can act as low-pass filters or notch filters in order to eliminate the effect of the unbalanced voltages and low-order harmonics. Their real time implementation is simple; moreover, they are cost effective in terms of the computational burden. In [3], a comparative study made with conventional PLL methods such as the SRF, DSOGI, showed that the MAF method is the most robust in case of highly distorted grid voltages waveforms.

However, the MAF filters reduce the open-loop band-width of the synchronization system which consequently worsens its dynamic response. To overcome this serious limitation, a variety of improved schemes were developed to improve the dynamic response of the MAF PLL. In [4], the authors proposed the utilization of two proportional components namely DFID and DFIQ so as to eliminate the lowest harmonic components. This solution allows reducing the window length of the filter and therefore increasing the dynamic response. The obtained PLL is named DMAF. In [5], a phase-lead compensator (PLC) is used to improve the dynamic response. In [6], the authors replaced the PI controller by a simple proportional gain. The obtained scheme is named the QT1-PLL. In [7], the authors proposed a hybrid PLL (HPLL) scheme. As compared to the QT1PLL, two Delayed Signal Cancellation (DSC2) blocks are added which allows multiplying par two the window width of the MAF.

The main objective of this paper is therefore to perform an evaluation and a comparative study between the performances of the aforementioned improved PLL schemes based on MAF filters. The proposed study is based on numerical simulations carried out for five cases of grid disturbances.

This paper is therefore organized as follows. In section II, a brief overview of the improved MAF-PLL schemes is given. In section III, a comparative study is carried out between the performances of these methods. Finally, some concluding remarks are given in section IV.

II. Overview of Improved MAF-PLL Schemes

A The block diagram of a conventional MAF-PLL system is depicted in Fig 1a. A Moving Average Filter (MAF) is added in the open-loop of the SRF-PLL so as to increase the distorsion rejection capability and the noise immunity. The transfer function of the MAF filter in the continuous time domain is:

$$\bar{x}(t)=\frac{1}{T_w}\int_{t-T_w}^{t}x(\tau)\,d\tau \qquad (1)$$

Where T_w is referred to as the window width. Translating (1) into the s domain yields:

$$G_{MAF}(s)=\frac{1-e^{-sT_w}}{sT_w} \qquad (2)$$

Substituting in (2) s by jw yields:

$$G_{MAF}(jw)=\frac{2\left|\sin(wT_w/2)\right|}{wT_w}\angle-\frac{wT_w}{2} \qquad (3)$$

Fig. 3billustrates the Bode plot of the transfer function $G_{MAF}(jw)$. One can observe that the MAF provides zero gain at frequencies $f=n/T_w$, $n\in N$, and a unity gain at the zero frequency. This means that the MAF passes the dc component (which refers to the fundamental component before the dq transformation), and completely blocks all frequency components of integer multiples of n/T_w . Accordingly, a large value of T_w allows the MAF to block all the characteristic harmonics i.e. this filter is able to act as an ideal LPF if some conditions hold [8],[3]. However, this attractive feature is paid in terms of the open-loop band-width which decreases when increasing T_w leading to a slow dynamic response in closed-loop. In general the window width of the MAF is determined by the absolute value of the lowest order harmonic which is equal to $-2w_n$ in case of unbalanced grid voltages where w_n is the nominal grid frequency. Such a window-width is in general insufficient to ensure a fast dynamic response of the PLL. To overcome this serious limitation, a variety of improved MAF-PLL schemes were developed in recent years. In the reminder of this subsection, a brief review of the most popular schemes will be given.

- DMAF-PLL (Fig.2): Stand for differential MAF-PLL. As compared to the conventional MAF-PLL, two additional proportional components (DFID and DFIQ) are utilised to eliminate the lowest harmonic component so as to increase the system's bandwidth [4].

- MAF-PLL with PLC (Fig.3): Stand for MAF-PLL with phase-lead compensator. As compared to the conventional MAF-PLL, a phase-lead compensator (PLC) is incorporated into the open-loop path. This PLC provides a near unity gain (0 dB) and a near zero phase-angle at frequencies lower than the first not frequency [5].

- QT1-PLL (Fig.4): Stand for quasi-type-1 PLL. A type-N PLL (N=1,2,..) has N poles at the origin in the open-loop transfer function of its linearized mode. As compared to the conventional MAF-PLL, the PI controller will be replaced by a simple gain K_p. However, the removal of the integral action makes the PLL incapable of tracking frequency drifts. To overcome this problem, the input signal of the proportional gain K_p is added to the estimated phase-angle [6]

-HPLL (Fig.5): Stand for hybrid synchronous/stationary reference frame filtering technique. As compared to the QT1-PLL, two Delayed Signal Cancellation (DSC2) blocks are added between the (abc,αβ) and (αβ,dq) coordinate transformation blocs. This allows multiplying by two the window width of the MAF.

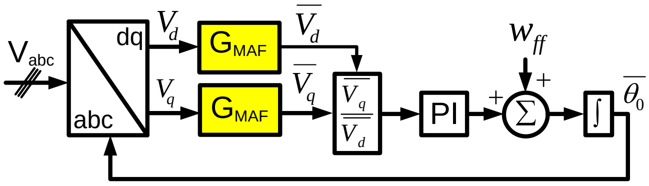

Figure 1a Block diagram of conventional three-phase MAF-PLL.

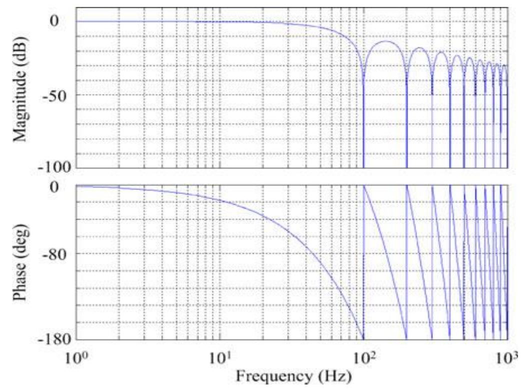

Figure 1b Bode plot of MAF for $T_w=0.01s$

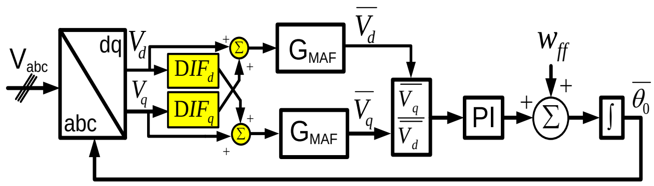

Figure 2 Block diagram of DMAF-PLL

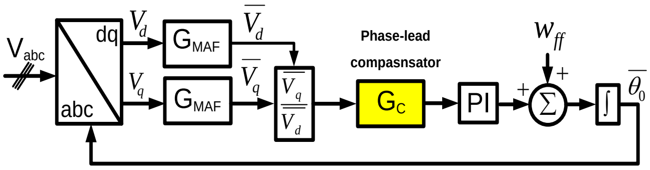

Figure 3 Block diagram of the MAF-PLL with the phase-lead compensator (PLC)

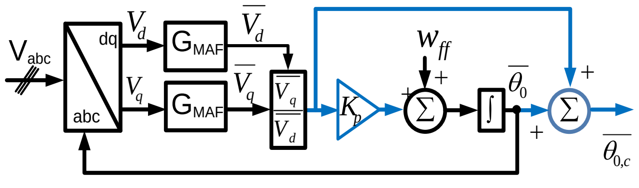

Figure 4 Block diagram of the QT1-PLL

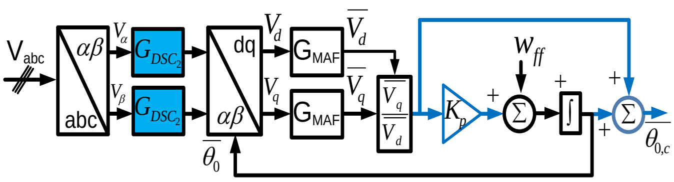

Figure 5 Block diagram of the HPLL

III. COMPARATIVE STUDY BETWEEN THE IMPROVED PLL SCHEMES

In this section, a comparative study based on numerical simulation is carried out between the four aforementioned improved PLL schemes. The performances criteria are the dynamics responses of phase and frequency errors as well as their ripples in steady-state operation. The following five cases of grid disturbances are considered:

Condition 1: Grid frequency jump of 3 Hz
Condition 2: Grid phase jump of -20° .
Condition 3: An abrupt decrease of 50% of phase A amplitude with a -20° phase jumps (voltage sags).
Condition 4: An abrupt increase of 50% of phase A amplitude with a -20° phase jumps (voltage swells).
Condition 5: Harmonics presented in Table I.

Note that all disturbances occurred at time t = 10 ms.

Remark1: The test of the HPLL scheme carried out in condition condition 5 , even odrer harmonics are added to those specified in table I. Moreover, the the window width of the MAF is divided by two to remove the effecet of even order harmonics.

Remark2: For each test, the MAF will be compared to one of the aforementionned improved schemes. The window width of the MAF is set to 0.01s when the latter is compared to DMAF, MAF_PLC and QT1 shemes. As for the comprasion with the HPLL, the window width of the MAF is set to 0.02s to eliminate even harmonics.

A. *Condition 1: Grid frequency jump of 3 Hz*

The obtained results are depicted in Figures 6-7. The following remarks are recorded:

- Frequency error: All improved schemes are faster than the conventional MAF-PLL. The best settling times are obtained with QT1 and DMAF.
- Phase error: the DMAF scheme provides the most accurate and faster response. The worst case occurs with the HPLL a scheme which is unable to detect the correct phase angle in steady state after a frequency jump.

Therefore it can be concluded that the DMAF provides the best performance in response to a frequency jump of the grid voltages.

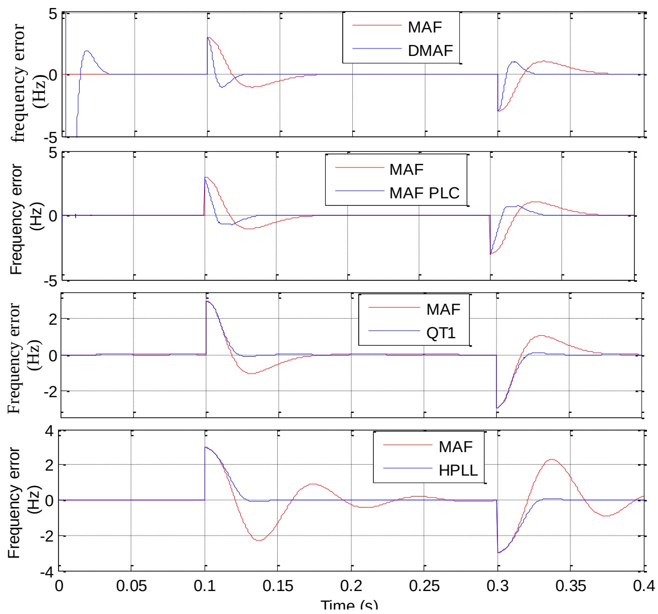

Figure 6 Frequency error responses under a grid frequency jump equal to 3 Hz.

B. *Condition 2: Grid phase jump of – 20°*

The obtained results are illustrated Figures 8-9. One can observe that:

- Frequency error: All improved schemes are faster than the conventional MAF-PLL. The best dynamic responses are obtained with QT1 and DMAF which provide also less ripple in steady state. The DMAF provides a larger peak of the estimated frequency that reaches ±15 Hz.
- Phase error: All improved schemes are faster than the conventional MAF-PLL. As The PLC and HPLL provides less ripple in steady state operation.

Accordingly, the MAF with PLC is the best one for phase estimation while the QT1 provides the best performances for frequency estimation.

Table I Content ratio harmonics for the test of condition 5

Order	*Content (%)*	*Sequence*
1	10	-
5	10	-
11	10	+

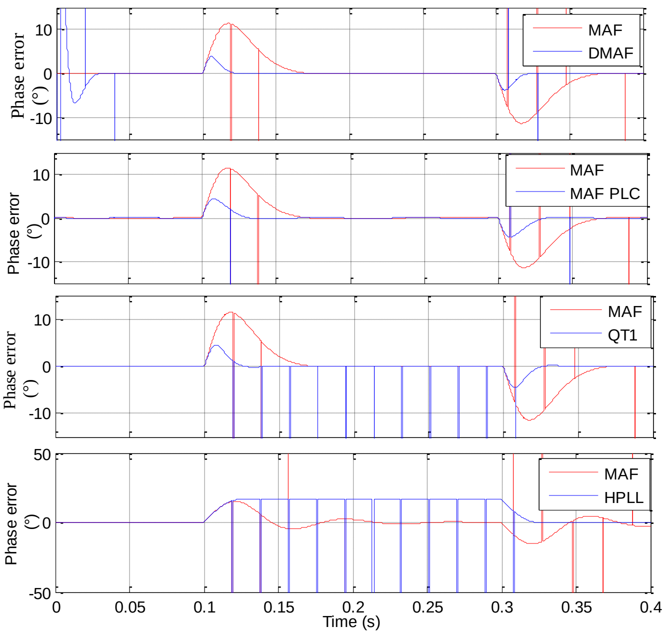

Figure 7 phase-angle error responses under a grid frequency jump equal to 3 Hz.

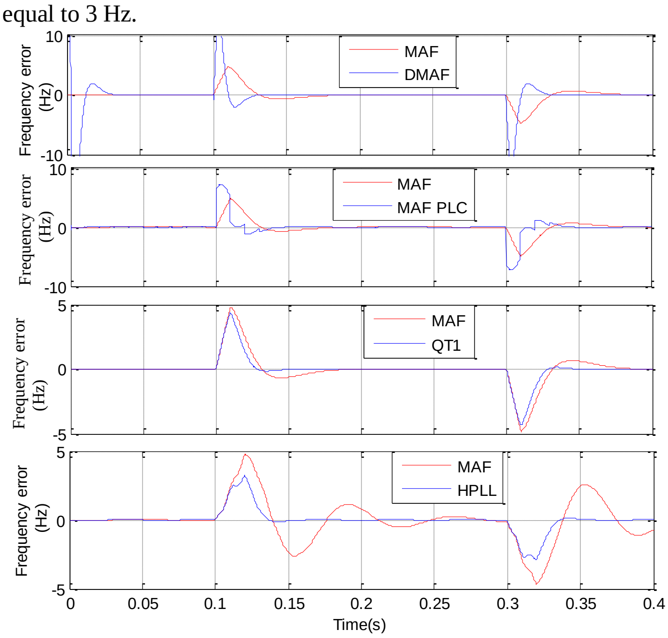

Figure 8 Frequency error responses under a grid frequency jump equal to -20°.

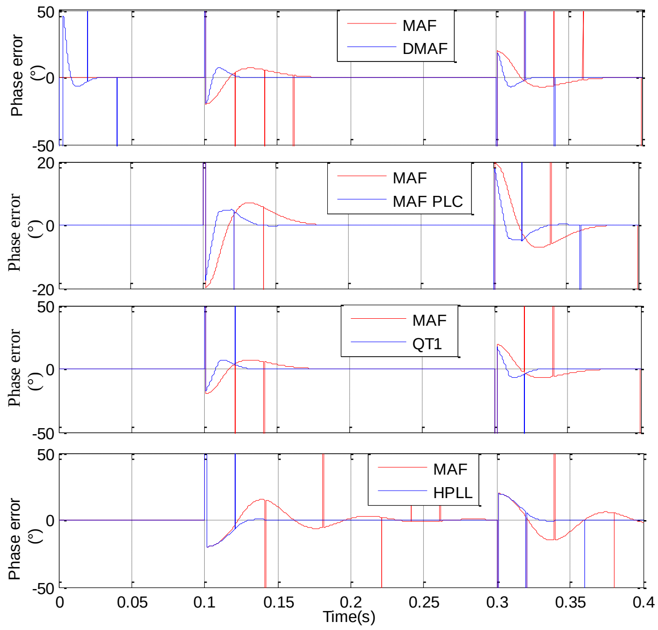

Figure 9 phase-angle error responses under a grid frequency jump equal to -20°.

C. *Conditions 3 and 4: An abrupt decrease/increase of 50% of phase A amplitude with a -20° phase jumps (voltage sags/swells).*

The obtained results are depicted in figures 10-11 (voltage sags) and 12-13 (voltage swells). The following remarks are recorded:

- Frequency error: QT1 and DMAF schemes give the fastest transient response. The DMAF provides a peak more than ±16.5 Hz while the one provided by the PLC is near ±10.5 Hz. In steady state operation, QT1 and HPLL provide less ripple. The worst scheme is obviously the DMAF which provides a ripple of ±0.3 Hz.
- Phase error: The QT1and HPLL provide less ripple in steady state operation. The worst result is obtained with the DMAF scheme which provides a ripple of ±0.2° .

Accordingly, the QT1 and HPLL are the best schemes in case of abrupt decrease/increase of one phase amplitude (sags/swells).

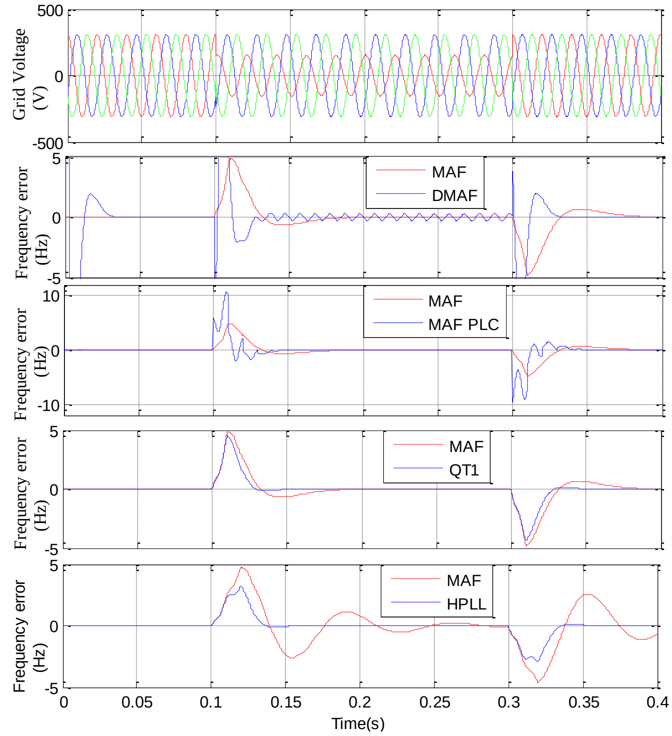

Figure 10 Frequency error responses under a voltage sags

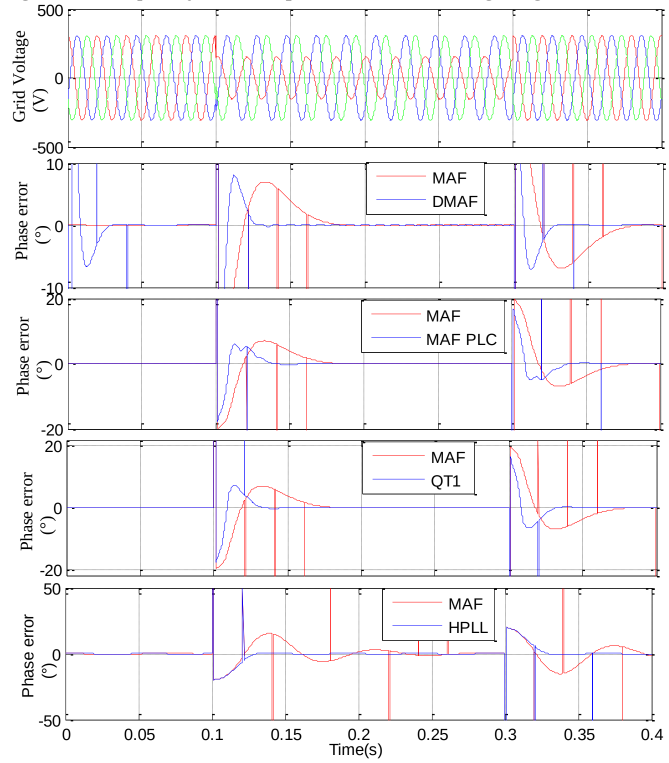

Figure 11 Phase-angle error responses under a voltage sags

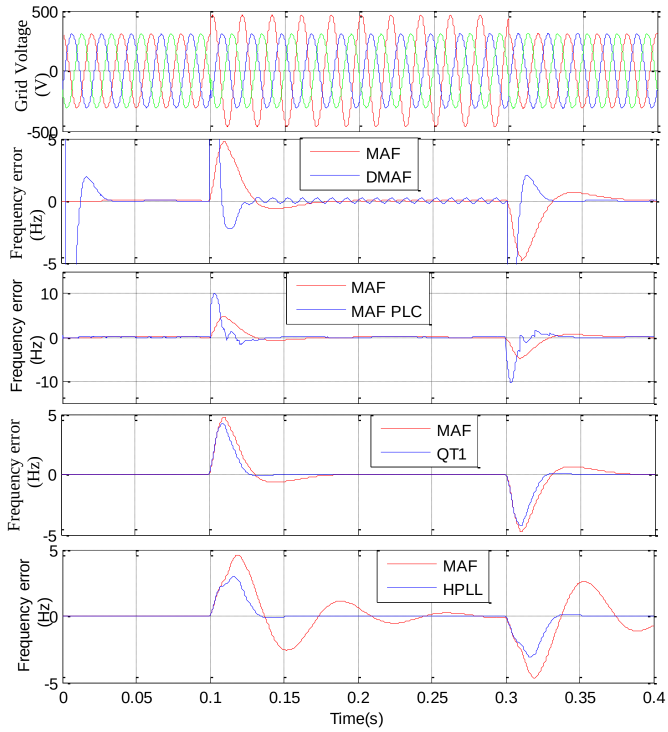

Figure 12 Frequency error responses under a voltage swells

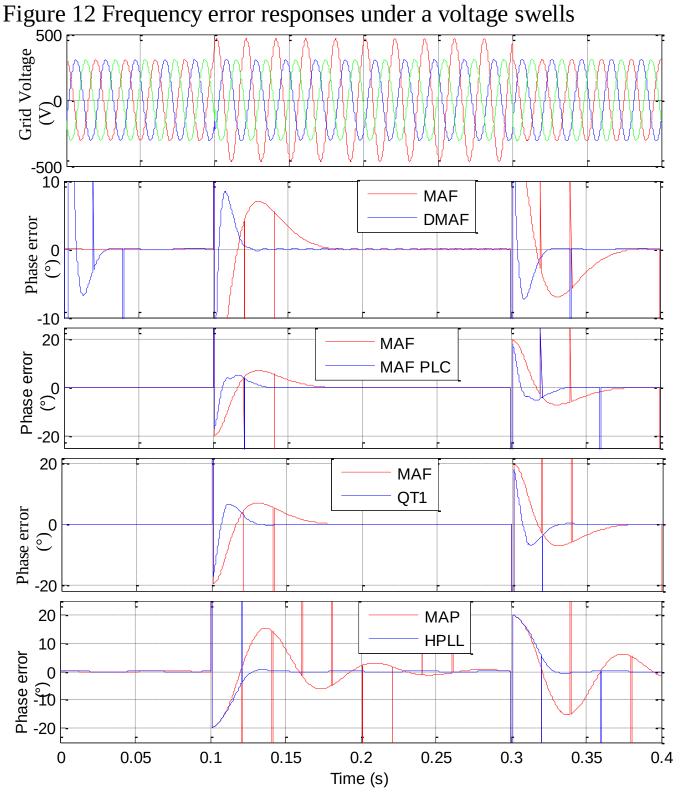

Figure 13 Phase-angle error responses under a voltage swells

D. Condition 5: Harmonics presented in table I.

The obtained results are depicted in figures 14-15. One can observe that:

- Frequency error: QT1 and DMAF schemes give the fastest transient response. But in steady state operation, the lowest ripple is obtained with QT1 (1 Hz) and HPLL (0.5 Hz) schemes. The worst results are obtained with the DMAF scheme which provides a ripple of ±4.3 Hz.
- Phase-angle error: All schemes provide a dynamic response faster than the one of the conventional MAF-PLL. The worst result in steady state operation is obtained with the DMAF scheme which provides a ripple of ±0.5°.

Therefore one can conclude that QT1 and HPLL schemes provide the best performances in case of distorted grid voltages.

The obtained performances of the five tests corresponding to a variety of grid voltages disturbances are summarized in table II.

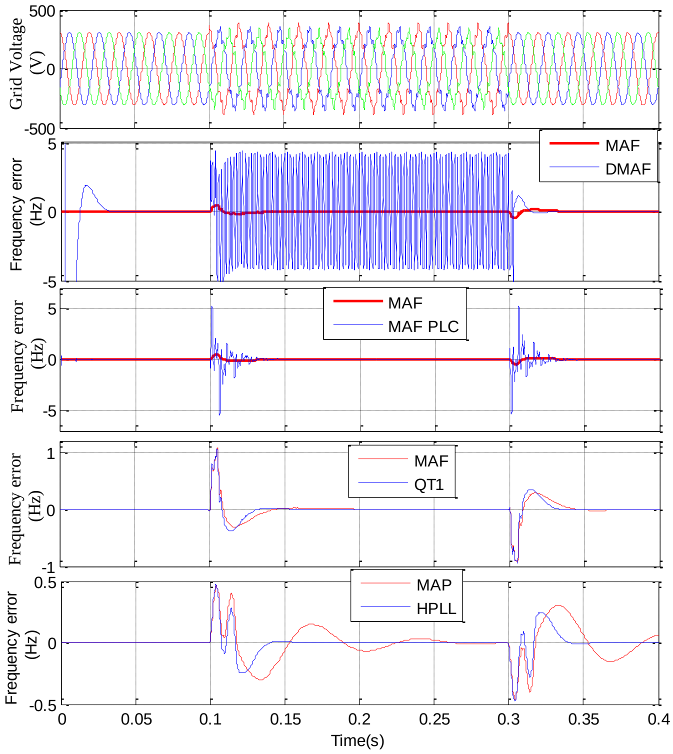

Figure 14 Frequency error responses under highly distorted grid voltages.

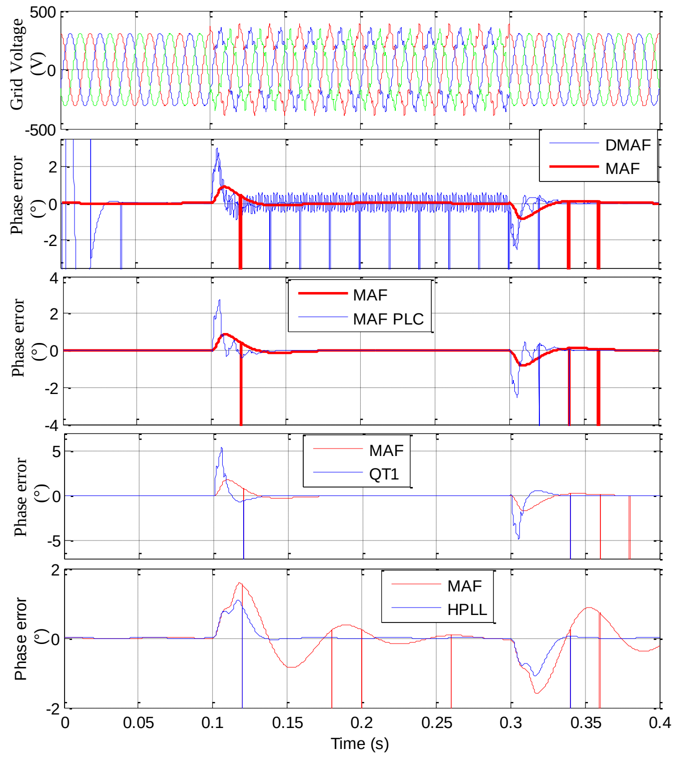

Figure 15 Phase-angle error responses under highly distorted grid voltages.

Table II Summary of the obtained results

	Cond.1		*Cond.2*		*Cond.3/4*		*Cond.5*	
	f	ph	f	ph	f	ph	f	ph
MAF	slow				slow			
DMAF	+	+	peak	+	draft			
PLC	+	+	+	+	Peak			
QT1	+	-	+	+	+	+	+	+
HPLL	+	-	+	+	+	+	+	+

IV. CONCLUSION

In this paper a comparative study is carried out between four improved MAF-PLL schemes that were proposed in the recent literature to improve the dynamic response of the conventional MAF-PLL. Five tests are performed under various conditions of the grid faults. The obtained results have led to the following remarks:

- All improved schemes provide a faster transient response as compared to the conventional MAF-PLL.
- The DMAF provides the best transient response as compared to the remaining three other schemes. However, it suffers from many drawbacks. Indeed, it provides the largest peak of the estimated frequency in case of phase jump. It provides also more ripples in case of voltage sags/swells as well as distorted grid voltages.
- The HPLL is unable to detect the correct phase angle in steady state after a frequency jump.

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