Disturbance Rejection Ability Enhancement Using Repetitive Observer in Phase-locked Loop for More Electric Aircraft

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Abstract—Under the concept of transportation electrification, more electric aircraft (MEA) involves more electrical energy to reduce emissions. Phase-locked loops (PLLs) have been well developed for synchronizing different power sources in a grid. Since MEA operates at variable frequency from 360 Hz to 800 Hz, a third-order model based steady-state linear Kalman filter PLL (SSLKF-PLL) has been proposed in literature to achieve fast tracking performance during such grid frequency variations. To suppress the potential disturbances due to harmonics in the grid, sensor scaling errors/unbalances and d.c offsets while maintaining low computational burden, this paper aims to enhance the disturbance rejection ability of SSLKF-PLL by adding a repetitive observer (RO). Simulation tests show that RO allows stable and effective suppression of disturbances from all above-mentioned sources during variable frequency operation.

Keywords— *repetitive control, phase-locked loops, more electric aircraft, power system harmonics, fault tolerant control*

I. INTRODUCTION

The move towards more electric aircraft (MEA) under the concept of transportation electrification requires the use of more electrical power to partly or completely replace the mechanical, hydraulic and pneumatic power. Taking the military standards MIL-STD-704 for example, one of the main power buses should be a 115 Vac three-phase bus with its frequency varying from 360 Hz to 800 Hz. Accurate and fast tracking of phase and frequency of the three-phase voltages generated from multiple power sources is important for grid synchronization.

A distinctive three-phase PLL is desired to achieve quick response to phase jumps with strong rejection ability against disturbance due to harmonics in grid, sensor scaling errors/unbalances, d.c. offsets in the grid. Besides, for MEA, the PLL also need to be adaptive to variable frequency.

Vast majority of the existing PLLs in literature are proposed for constant-frequency grid with slight grid frequency variations allowed. If the operation frequency is too far from the design point, the performance of those constant-frequency PLLs will degrade. For MEA, according to the recent research in [1], the key shortcomings for the few

available variable frequency PLLs techniques can be summarized as the follows:

- Adaptive observer [2] and sliding mode observer [3] based method cannot handle the d.c. offsets.
- Discrete Fourier transform (DFT) [4] based method has heavy computational burden.
- Complex least mean square [5] based method cannot maintain its performance with grid unbalances.

Therefore, authors in [1] has proposed an estimator to solve the d.c offsets issue. However, the harmonics in grid has not been considered in [1].

A third-order model based PLL, namely the steady state linear Kalman filter PLL (SSLKF-PLL), has been proposed in [6-9]. Fast tracking performance during grid frequency variation is achieved for MEA in [9] by the SSLKF-PLL because the Kalman filter not only observes the grid frequency, but also observes and compensates the acceleration of the grid frequency. It is also confirmed in [9] that SSLKF-PLL has faster dynamic than the DFT based method in [4]. Regarding the disturbance rejection ability, although SSLKF-PLL can reject the disturbance by reducing its control bandwidth, it cannot remove the disturbance completely. Therefore, this motivates the use of a repetitive observer (RO).

RO is first proposed in [10] for motor drive applications. Benefiting from its disturbance-observer-like structure, it can be designed independently from the feedback controller of the system. Another big convenience of using RO is that no pre-knowledge of the target disturbance is required. It will self-learn and tackle disturbances at all harmonics within the Nyquist frequency. What is more, with the development of high-performance control platform [11], the extra execution time required for RO would be about 5 to 10 μ s. Thus, RO is can be a promising add-on tool for the intended PLL.

Hence, this paper proposes a novel dual-observer PLL (DO-PLL). In section II, the SSLKF-PLL will be reviewed. In section III, the proposed DO-PLL will be discussed. The case study section in IV will discuss how the parameters can be selected. Simulation tests in V will show that the proposed DO-PLL can achieve superior grid frequency and phase

Fig. 1: Diagrams of the SSLKF-PLL.

tracking performance in presence of harmonics in the three-phase voltages, sensor scaling errors/unbalances, sensor offset errors, while maintaining the fast response of the Kalman filter during phase jumps and grid frequency variations. The paper will be concluded in section VI.

II. REVIEW OF SSLKF-PLL

The block diagram and small-signal model of SSLKF-PLL are drawn in Fig. 1a and Fig. 1b, respectively. Where, U_a, U_b, U_c are the measured three-phase voltages. U_α, U_β are the alpha-beta-axis voltages. U_d and U_q are the dq-axis voltages. U_s is the peak value of the phase-to-neutral voltage. Define the phase θ , grid frequency ω and grid frequency acceleration a as the three state variables in vector $\mathbf{x}$, $\mathbf{x} = [\theta \ \omega \ a]^T$, the Kalman filter observes the three variables as $\hat{\mathbf{x}} = [\hat{\theta} \ \hat{\omega} \ \hat{a}]^T$. Matrix $\mathbf{A}$ is derived based on the third-order model as in (1). Vector $\mathbf{g} = [g_1 \ g_2 \ g_3]^T$ is the observer gain vector which can be tuned according to the procedure in [12] by specifying the desired poles.

$$\mathbf{A} = \begin{bmatrix} 1 & T_s & T_s^2/2 \\ 0 & 1 & T_s \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The closed loop transfer functions of the $\hat{\theta}, \hat{\omega}, \hat{a}$ can be derived from Fig. 1b as in (2-4).

$$\frac{\hat{\theta}}{\theta} = \frac{\left(g_3 \frac{T_s^2}{2} + g_2 T_s + g_1 \right) z^2 + \left(g_3 \frac{T_s^2}{2} - 2g_2 T_s - 2g_1 \right) z + g_1}{z^3 + \left(g_3 \frac{T_s^2}{2} + g_2 T_s + g_1 - 3 \right) z^2 + \left(g_3 \frac{T_s^2}{2} - 2g_2 T_s - 2g_1 + 3 \right) z + g_1 - 1} \quad (2)$$

$$\frac{\hat{\omega}}{\omega} = \frac{(g_3 T_s + g_2) z^2 + (-2g_3 T_s - 2g_2) z + g_2}{z^3 + \left(g_3 \frac{T_s^2}{2} + g_2 T_s + g_1 - 3 \right) z^2 + \left(g_3 \frac{T_s^2}{2} - 2g_2 T_s - 2g_1 + 3 \right) z + g_1 - 1} \quad (3)$$

$$\frac{\hat{a}}{\theta} = \frac{g_3 z^2 - 2g_3 z + g_3}{z^3 + \left(g_3 \frac{T_s^2}{2} + g_2 T_s + g_1 - 3 \right) z^2 + \left(g_3 \frac{T_s^2}{2} - 2g_2 T_s - 2g_1 + 3 \right) z + g_1 - 1} \quad (4)$$

According to [12], for a given natural frequency ω_n , the three poles in (2-4) can be placed in s domain as one real pole and two complex poles at $s_0 = -\omega_n$, $s_{1,2} = (-\omega_n \zeta \pm j\omega_d)$, respectively, where, $\omega_d = \sqrt{1 - \zeta^2}$. $\zeta = 0.9659$ is chosen in this paper.

The poles can be mapped at ρ_0 and $\rho_1 e^{\pm j\phi}$ in z domain, where, $\rho_0 = e^{-\omega_n T_s}$, $\rho_1 = e^{-\omega_n \zeta T_s}$, $\phi = \omega_d T_s$. Gains g_1, g_2, g_3 can be calculated as in (5).

$$\begin{cases} g_3 = \frac{c_1 + c_0 + c_2 + 1}{T_s^2} \\ g_2 = \frac{c_1 - c_0 + 3c_2 + 5}{2T_s} - g_3 T_s \\ g_1 = c_2 + 3 - g_2 T_s - \frac{g_3 T_s^2}{2} \end{cases}, \begin{cases} c_0 = -\rho_0 \rho_1^2 \\ c_1 = 2\rho_0 \rho_1 \zeta + \rho_1^2 \\ c_2 = -\rho_0 - 2\rho_1 \zeta \end{cases} \quad (5)$$

It is worth pointing out that the dash parts in Fig. 1b is based on the approximation in Fig. 1a that with perfectly sinusoidal three-phase voltages and when phase error θ^{err} is small, $U_q/U_s \approx \theta - \tilde{\theta}$. However, when there is disturbance, U_q will contain extra harmonics. Therefore, this approximation may not be true. The equivalent diagram considering disturbance will be discussed in the following section.

III. THE PROPOSED DUAL-OBSERVER PLL

As analyzed in [13], U_q will contain a variety of harmonics if the three-phase voltages are non-ideal. In summary:

- Odd harmonics in the three-phase grid leads to even harmonics in U_q .
- Scaling error of current sensors or unbalances in the grid produces 2nd harmonic in U_q .
- Offsets in the three-phase voltages cause 1st harmonic in U_q .

It is also concluded in [13] that the phase can still be tracked if the PLL can ignore the harmonics and force just the d.c. part of U_q to zero.

Therefore, in Fig.2, the state U_q is modeled by two parts: the ideal part and the disturbance part. The ideal part can be approximated as the d.c. part, while the disturbance part U_q^{ac} includes multiple orders of harmonics, of which the fundamental period is defined as DT_s . DT_s equals the grid frequency f , where, $T_s=1/f_s$, is the sampling period. f_s is the sampling frequency. D can be a fractional number.

Hence, in the proposed dual-observer PLL, the RO is designed to cancel only the a.c. part of the q-axis voltage U_q . The remaining part of U_q^{err} will be forced to zero by the same Kalman filter as in Fig.1b. The transfer function of RO is as in (6).

$$RO(z) = \frac{\tilde{U}_q^{ac}}{U_q} = \frac{G_{ro}[z^{\tilde{D}+1}LPF(z)]}{1-(1-G_{ro})z^{\tilde{D}}}, \quad \tilde{D}=f_s/\tilde{f} \quad (6)$$

Where, the length of the delay chain $z^{\tilde{D}}$ is updated in real-time by the observed grid frequency $\tilde{f}$. Since $\tilde{D}$ can be a fractional number. G_{ro} is the gain of RO. The $LPF(z)$ is a low-pass filter to calculate the d.c. part in U_q . A sixth order Lagrange fractional delay filter as in [13] has been adopted in this paper to implement the fractional delay chain as in (7).

$$\begin{aligned} \hat{U}_q(k-\tilde{D}) &= \sum_{i=0}^6 P_i \hat{U}_q(k-\tilde{D}_0-i) \\ P_i &= \prod_{\substack{h=0 \\ h \neq i}}^6 \frac{\tilde{D}_f - h}{i - h}, \text{ for } i=0,1,\dots,6 \end{aligned} \quad (7)$$

Where, $\tilde{D}_0$ and $\tilde{D}_f$ denote the integer part and fractional part of $\tilde{D}$, respectively. $\hat{U}_q(k-\tilde{D})$ is the estimated U_q at $t_{k-\tilde{D}}$.

It can be seen from Fig.2 that adding RO does not affect the Kalman filter part of the original SSLKF-PLL. Thus, the small-signal model in Fig.1b still applies in the proposed DO-PLL, and the transfer function of the Kalman filter part remains the same as in (2-4). The $(1-RO(z)z^{-1})$ part in Fig.2 can be understood as another filter to remove any harmonics with Nyquist frequency. The bode plot of this part will be provided in the next section.

Overall, there are four parameters to be designed in the proposed DO-PLL: the sampling frequency f_s , the RO observer gain G_{ro} , the lowpass filter $LPF(z)$, the bandwidth of the Kalman filter loop. The design procedure for these four parameters are discussed in the following section.

IV. CASE STUDAY

Considering the worst condition when the three-phase grid suffers from harmonic distortions, sensor scaling error/unbalances, and d.c. offsets at the same time, the following imperfections are contained in the three-phase voltages for testing:

- 1) 3% 3rd harmonic, 4% 5th harmonic, 3% 7th harmonic, 1.5% 9th harmonic, 3.5% 11th harmonic and 3% 13th harmonic in U_{abc} .
- 2) Phase b has an offset of 5%.
- 3) The amplitude of phase c is 5% smaller than the other two phases.

The resultant unified three-phase voltages at 360 Hz are shown in Fig.3.

A. The choice of f_s

Since the 13th harmonics of the maximum 800 Hz grid is 10.4 kHz, 20.8 kHz sampling frequency is the minimum requirement according to principles of sampling. Therefore, $f_s=80$ kHz is chosen, such that there are 7.7 samples per period for the 13th harmonics.

Fig.3: The unified three-phase voltages at 360 Hz.

Fig.4: Bode plots for the observed phase, angular frequency and acceleration without RO.

Fig.5: Amplitude response of $(1-RO(z)/z)$ with grid frequency is 400 Hz and $D=200$ with and without $LFP(z)$.

B. The choice of the Kalman filter bandwidth

The natural frequency of the Kalman filter is kept the same as in [9], i.e. 60 Hz. As a result, the bode plot of the intended PLL without RO (i.e. SSLKF-PLL) is shown in Fig.4. It can be seen that the Kalman filter already has some attenuation effect against harmonics considering all potential harmonics are at least 360 Hz.

C. The choice of G_{ro}

To ensure the stability of RO, poles in (5) must locate within the unity circle. Therefore, the stability criteria for G_{ro} is $0 < G_{ro} < 2$. G_{ro} is set to 0.5 in this paper.

D. The choice of $LPF(z)$

As mentioned in Section III, it is desired that the $(1-RO(z)/z)$ part can be designed to attenuate only the harmonics. When without $LPF(z)$ (i.e. $LPF(z)=0$), the amplitude response of $(1-RO(z)/z)$ is drawn in Fig.5. As shown, not only the harmonics are attenuated, but also the low frequency region is filtered. Hence, this motivates the use of $LPF(z)$ to maintain the zero dB gain in the low frequency region.

In this paper, $LPF(z)$ is chosen to be a fourth order low-pass filter with cut-off frequency equals 60Hz as in (6).

$$LPF(z) = \frac{2.381 \times 10^{-8}}{z^4 - 3.95z^3 + 5.852z^2 - 3.853z + 0.9512} \quad (6)$$

It can be seen from Fig.5 that with $LPF(z)$, only harmonics within the Nyquist frequency (i.e. 4kHz) are attenuated.

V. SIMULATION RESULTS

A simulation model has been built in Matlab/Simulink. The harmonics, unbalance and offset conditions of the intended testing grid are as drawn in Fig.3. According to MIL-STD-704 standard, the maximum allowed acceleration for grid frequency variation is 250 Hz/s (measured over a period longer than 25 ms) under normal operation, and 500 Hz/s under abnormal operation. Hence, the grid frequency of the intended three-phase grid is kept 360 Hz from 0 s to 1 s. Then, the frequency increases to 800 Hz following a 500 Hz/s slope from 1 s to 1.88 s and is kept 800 Hz for 0.12 s before decreases to 360 Hz following a -250 Hz/s slope. Moreover, a 50-degree phase jump is applied at 0.5 s.

To evaluate the dynamic performance, the proposed DO-PLL is compared with SSLKF-PLL at start-up and during a phase jump in subsection A and B, respectively. To confirm the steady-state performance, the two PLLs are compared at 360 Hz in subsection C. Finally, the results during grid frequency variation will be given in subsection D.

A. Performance at start-up

The original SSLKF-PLL have set the initial values of the observed phase, grid frequency and acceleration all to zero. Since it is already known that the grid frequency will be between 360 Hz to 800 Hz, the initial value of the observed frequency has been set to 400 Hz in DO-PLL. Consequently, the transient during start-up is shorter in the proposed DO-PLL in Fig.6. The frequency and phase error shown in Fig.6 are the observed frequency $\hat{f}$ and the error between the real phase θ and the observed phase $\hat{\theta}$.

Fig.6: Observed frequency and phase error at start-up.

Fig.7: Observed frequency and phase error at phase jump.

Fig.8: Observed frequency and phase error at 360 Hz.

Fig.9: Observed frequency, frequency error and phase error during grid frequency variation.

B. Performance at phase jump

The observed frequency $\tilde{f}$ and phase error ($\theta - \hat{\theta}$) during phase jump are shown in Fig.7. It can be seen that the DO-PLL and SSLKF-PLL have comparable recover time after the phase jump. This implies that the RO will not affect the transient response while improving the steady-state performance.

C. Performance at constant grid frequency

The observed frequency $\tilde{f}$ and phase error ($\theta - \hat{\theta}$) at 360 Hz are shown in Fig.8. It can be seen that under 360 Hz constant grid frequency, DO-PLL reduces the frequency tracking error from $-1.79 \text{ Hz} \sim +1.51 \text{ Hz}$ to $-0.03 \text{ Hz} \sim +0.03 \text{ Hz}$. The phase tracking error is significantly reduced from $-1.42^\circ \sim +1.74^\circ$ to $-0.03^\circ \sim +0.03^\circ$.

D. Performance during grid frequency variation

The observed frequency $\tilde{f}$, the frequency error ($f - \tilde{f}$) and phase error ($\theta - \hat{\theta}$) during grid frequency variation are shown in Fig.9. It can be seen clearly from Fig.9 that the DO-PLL has significantly less ripple in its observed frequency $\tilde{f}$ and phase $\hat{\theta}$.

Another distinctive feature of the RO is that the disturbance rejection ability of DO-PLL when at 360 Hz grid frequency is as strong as when at 800 Hz, while the SSLKF-

PPL naturally has increasing tracking error as the grid frequency decreasing.

VI. CONCLUSION

The repetitive observer (RO) has been added to improve the disturbance rejection ability of the existing steady state linear Kalman filter PLL (SSLKF-PLL) for more electric aircraft (MEA) applications. The SSLKF-PLL is particularly suitable for the variable frequency bus in MEA because it is based on third-order model and can actively compensate the lag/lead in observed frequency and phase due to acceleration/deceleration. By combining RO and SSLKF-PLL, a novel dual-observer PLL (DO-PLL) is proposed. Simulation tests considering the worst condition has been carried out. The following benefits of DO-PLL can be concluded:

- Significant reductions of ripple due to harmonics distortions, sensor scaling errors/three-phase unbalances, and d.c. offsets have been achieved.
- RO can suppress the disturbances without affecting the dynamic of the Kalman filter during phase jumps and grid frequency variation.
- Another big convenience of using DO-PLL is that no pre-knowledge of the target disturbance is required.

It will self-learn and tackle all afore-mentioned disturbances.

- The attenuation of disturbance is always strong regardless of the operating frequency of the grid.
- RO as an add-on tool can be applied to other PLLs operating at different grid frequencies to solve periodic errors.

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