Nonlinear PFD free of glitches and blind zone for a fast locking PLL with reduced reference spur

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Abstract: A simple nonlinear PFD circuit designed to achieve reduced reference spur and faster acquisition process for a PLL is proposed in this paper. The proposed nonlinear PFD is found to offer higher gain, eliminate glitches at the output and reduce both dead zone and reset delay when compared with the operation of conventional linear PFD (CL-PFD) and conventional NL-PFD (CNL-PFD). The PLL acquisition time got reduced by 50% and 11.69% while the reference spur 45% and 38.6% with respect to the CL-PFD and CNL-PFD respectively. Reference spur of -72.2 dBc, lock time of 1.548 μ s, area of 0.2 mm² and power dissipation of 6.2 mW are obtained for the prototype PLL using Proposed NL-PFD designed with 180 nm CMOS process.

Keywords: nonlinear PFD, PLL, reference spur, lock time, blind zone

Classification: Integrated circuits

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1 Introduction

Phase locked loop (PLL) with quicker locking process and minimum reference spur is an essential component in variety of applications in modern electronics such as frequency synthesizer, synchronization of chips in GPS receiver, jitter attenuator etc. PFD is one of the important constituent blocks in the PLL system which plays a significant role in defining its lock time and reference spur. As the CL-PFD given in Fig. 1(a) cause dead zone, blind zone, lower gain, glitches at the output and associated large lock time and high reference spur [1, 2], NL-PFDs have been proposed as a popular alternative [3, 4, 5]. Even though NL-PFDs offers higher gain, complicated design, complex circuits, presence of dead zone, blind zone and glitches at the output, all of these raise serious design constraints [4, 5]. The CNL-PFD given in Fig. 1(b) reported by Jinbao et al. [3] is very effective for achieving higher gain and suppressing blind zone, however dead zone and cycle slip caused by higher reset delay result in glitches at the output. Glitches would be carrying spurious tones at the output spectrum. In view of this a NL-PFD which eliminates glitches, suppresses blind zone and dead zone; and reduces reset delay is proposed in this paper.

2 Transistor level implementation of proposed NL-PFD

The proposed NL-PFD offers higher gain whenever phase difference ($\Delta\phi$) between two inputs is greater than π and lower gain when $\Delta\phi < \pi$. Major design constraint of eliminating glitches from the output has been addressed in the proposed circuit by using pass transistor logic and series of inverting buffers. Reset process has been accelerated by using both reset and reset bar signals simultaneously, due to which dead zone has been significantly reduced. The requirement of reset process has been eliminated, whenever phase difference is greater than π , as either UP or DN only will be at logic high so long as $\Delta\phi$ is between π and 2π , in the proposed NL-PFD. Hence it was possible to eliminate blind zone also completely.

Transistor level implementation of proposed NL-PFD is given in Fig. 1(c). Initially, when CLK_{ref} and CLK_{vco} are at logic zero, both P_1 and P_2 would be

Fig. 1. (a) Block diagram of CL-PFD (b) and CNL-PFD (c) Transistor level implementation of Proposed NL-PFD.

turned ON, pulling the nodes P and Q up to logic high. Considering the case when $|\Delta\phi| < \pi$ and CLK_{ref} (CLK_{vco}) is leading CLK_{vco} (CLK_{ref}), at the rising edge of CLK_{ref} (CLK_{vco}), N_1 and N_3 (N_2 and N_4) turn ON, pulling the node R (S) down to logic zero, which makes N_7 (N_8) turn OFF and the combination of inverters INV_2 to INV_4 (INV_6 to INV_8) causes UP (DN) signal go to logic high. UP (DN) would remain at high until the rising edge of CLK_{vco} (CLK_{ref}) wherein N_2 and N_4 (N_1 and N_3) turn ON, pulling the node S (R) down to logic zero, and making N_8 (N_7) turn OFF. When N_7 and N_8 turn OFF, reset signal would be pulled up to logic high and reset-bar signal down to logic zero. Simultaneously the nodes R and S would be pulled up to logic high making both UP and DN to become logic zero. This prevents the condition of both UP and DN simultaneously reaching logic high. And the reset signal ensures that both the nodes P and Q would be pulled down to logic zero through N_3 – N_5 and N_4 – N_6 respectively.

Considering the case when $|\Delta\phi| > \pi$ and CLK_{ref} (CLK_{vco}) is leading CLK_{vco} (CLK_{ref}), at the rising edge of CLK_{ref} (CLK_{vco}), node R (S) would be at logic low, N_7 (N_8) would be OFF and UP (DN) would be at logic high. Even when CLK_{ref} (CLK_{vco}) makes a high to low transition which happens before CLK_{vco} (CLK_{ref}) makes the low to high transition, UP (DN) would remain at logic high as N_1 (N_2) turns OFF. At the rising edge of CLK_{vco} (CLK_{ref}), node S (R) would be at logic zero and N_8 (N_7) would be OFF. Under the condition when both N_7 and N_8 are simultaneously OFF, even though reset signal would be at logic high and reset-bar signal at logic zero, only DN (UP) signal would get reset to logic zero while UP (DN) would remain at logic high as N_1 (N_2) is OFF, and this status viz UP = 1 and DN = 0 (UP = 0 and DN = 1) would continue until the phase difference between CLK_{ref} (CLK_{vco}) and CLK_{vco} (CLK_{ref}) becomes less than π . Switching characteristics of the circuit is discussed in the following section.

3 Simulation results of proposed NL-PFD, CL-PFD and CNL-PFD

The transient analysis of CL-PFD, CNL-PFD and proposed NL-PFD are presented in Fig. 2(a). It has been found that the magnitude of signals at nodes T and U marked in circuit in Fig. 1(c) have had a peak of 1.2 V and not 1.8 V (V_{dd}), due to the V_{TN} drop across the NMOS pass transistor (N_1, N_2), while the amplitude of glitches at same nodes T and U is has been found to be about 0.6 V. Output voltage

Fig. 2. Proposed NL-PFD, CL-PFD and CNL-PFD (a) Transient response (b) Transfer characteristics.

Fig. 3. Transistor level implementation of (a) CP (b) VCO (d) Delay cell (c) Transfer Characteristics of VCO.

is restored to V_{dd} by adding a buffer with four inverters INV_1 through INV_4 for UP and INV_5 through INV_8 for DN respectively. The buffers are also found to be effective in eliminating glitches at the output of UP and DN as well. Another factor which is effective in eliminating glitches is the reduction in reset delay obtained due to removal of delay element as well as operation of reset and reset-bar signals simultaneously. This ensures fast reset process as neither UP nor DN get enough time to reach logic high simultaneously.

It can be observed that for an initial duration of 36 ns, when the phase difference between CLK_{ref} and CLK_{vco} is less than π , the pulse width of UP signal is increasing as the phase difference $\Delta\phi$ is increasing. After 36 ns, when the phase difference is greater than π with CLK_{ref} leading CLK_{vco} , the UP signal is held at high until the phase difference become less than π which happens after about five cycles of CLK_{ref} and CLK_{vco} . Similar characteristics have been obtained for DN signal when CLK_{vco} is leading CLK_{ref} . The major achievement in the proposed design is that, glitches are completely eliminated at the output, whereas it does exist for both CL-PFD and CNL-PFD.

The output voltage as a function of input phase difference for proposed NL-PFD is presented in Fig. 2(b) and can be expressed as:

$$f(\varphi) = \begin{cases} \frac{V_{dd}}{2\pi} \varphi & -\pi < \varphi < \pi \\ V_{dd} & |\pi| < \varphi < |2\pi| \end{cases} \quad (1)$$

The function $f(\varphi)$ representing both linear and nonlinear operating regions is determined using Fourier series as:

$$f(\varphi) = \sum_0^{\infty} \frac{V_{dd}}{2\pi} \left[\cos\left(\frac{n\pi}{2}\right) - 2\cos(n\pi) + \frac{2}{n\pi} \sin\left(\frac{n\pi}{2}\right) \right] \sin\left(\frac{n\varphi}{2}\right) \quad -2\pi < \varphi < 2\pi \quad (2)$$

Equation (2) has been plotted in MATLAB as φ is varied from -2π to 2π , with n varying from 1 to 200 and is plotted in Fig. 2(b). φ -V characteristics of proposed NL-PFD, CL-PFD and CNL-PFDs have also been determined from circuit simulation by introducing delay between CLK_{vco} and CLK_{ref} and is also appended in Fig. 2(b) with time delay varying from -10 ns to 10 ns corresponding to phase difference varying from -2π to 2π . It can be observed that the results from both

Fig. 4. (a) PLL Diagram (b) Leakage current simulation setup

Cadence and MATLAB simulations are exactly matching with each other. It can also be observed that dead zone and blind zone are present in CL-PFD while only dead zone is present in CNL-PFD. More importantly both dead zone and blind zone get completely eliminated from the ϕ -V characteristics of the proposed NL-PFD and this result in increased gain.

4 PLL circuit simulation using proposed NL-PFD:

In order to compare the performance of PLL built with proposed NL-PFD, CL-PFD and CNL-PFD, three PLLs of similar structure as given in Fig. 4(a) has been implemented using 180 nm CMOS technology in Cadence. Each of proposed NL-PFD, CL-PFD and CNL-PFD is used as the PFD in each while a modified cascode configuration given in Fig. 3(a) is used as the charge pump. Second order loop filter has been implemented with $R_1 = 1\text{ K}\Omega$, $C_1 = 277\text{ pF}$ and $C_2 = 25\text{ pF}$. Current starved Voltage Controlled ring Oscillator given in Fig. 3(b), has been implemented using 3 stage CMOS differential delay cell given in Fig. 3(d). Transfer characteristics of VCO is plotted in Fig. 3(c), from which the gain of VCO has been computed to be $K_{vco} = 20\text{ Grad/V}^{-1}$. PLL output has been scaled down to reference frequency of 20 MHz using divide by 128 counter. Post layout simulation have been performed and the lock time has been calculated to be 1.548 μs , 3.1 μs and 1.753 μs for the PLLs using proposed NL-PFD, CL-PFD and CNL-PFD respectively and the graphs are plotted in Fig. 6(b). Final placement of the PLL using proposed NL-PFD is found to require a chip area of 0.2 mm^2 with 485 μm in width and 414 μm in length as given in Fig. 6(a) while its total power dissipation from the chip is found to be 6.2 mW.

Output spectrum of PLLs have been plotted to determine the reference spur in each case and is found to be -72.2 , -39.52 and $-44.3\text{ dBc}@20\text{ MHz}$ offset from the PLL output frequency of 2.56 GHz for the PLL using proposed NL-PFD, CL-PFD and CNL-PFD respectively. The spectra for CL-PFD and CNL-PFD are given

Fig. 5. Output spectrum of PLL using (a) CL-PFD and CNL-PFD (b) proposed NL-PFD

Fig. 6. (a) PLL Layout (b) Acquisition process of PLL using proposed NL-PFD, CL-PFD and CNL-PFD.

in Fig. 5(a) with that of proposed one in Fig. 5(b). Reference spur also has been determined analytically from leakage current. Schematic of the setup for simulation of leakage current of the PFD under test is given in Fig. 4(b) [6] and it is calculated as 5.4 nA for proposed NL-PFD. Hence the phase offset could be determined as [7]:

$$\phi_e = 2\pi \times \frac{I_{leak}}{I_{CP}} \quad (3)$$

And the reference spur could be expressed as [7];

$$P_r = 20 \log \left[\frac{N\phi_e f_{LBW}}{f_{ref} \sqrt{2}} \right] - 20 \log \left[\frac{f_{ref}}{f_{pl}} \right] \quad (4)$$

The reference spur for the PLL using proposed NL-PFD is calculated to be -72.08 dBc and is found to be exactly matching with the data from circuit simulation as presented in Fig. 5(b). Results obtained from proposed circuit, CL-PFD and CNL-PFD and reported works are compared in Table I and the proposed circuit is found to achieve better performance parameters when compared with the conventional and reported data.

Table I. Performance comparison of PLL

Parameter	Con. L-PFD	Con. NL-PFD	[10]	[8]	[9]	This work
Lock Time (μ s)	3.1	1.753	4	20	21K	1.548
Reference Spur (dBc)	-39.52	-44.3	-41	-54	-55	-72.2

5 Conclusion

A simple NL-PFD circuit suitable for fast locking and reduced reference spur PLL has been proposed in this paper. The proposed NL-PFD is found to offer higher gain, eliminate glitches at the output and reduce both dead zone and reset delay when compared with the operation of CL-PFD and CNL-PFD. The PLL acquisition time for proposed circuit got reduced by 50% with respect to CL-PFD, and 11.69% to CNL-PFD while the reference spur by 45% and 38.6% respectively. Reference spur of -72.2 dBc, lock time of 1.548μ s, area of 0.2 mm^2 and power dissipation of 6.2 mW are obtained for the prototype PLL using Proposed NL-PFD designed with 180 nm CMOS process.