Continued use of the phase/frequency comparator's charge pump system looks questionable in view of the increasing demands for spectral purity, argues Edward Forster.

Phase comparator purity

The phase/frequency comparator is one of the most widely used components in phase-locked loop technology It is applied in countless applications, increasing by the day as more radio-oriented products appear.

Although the basic logic within the phase/frequency comparator is simple and well understood, the output interface to the analogue world has several variations

The charge pump

The most popular output circuit is the charge pump system comprising transistors Tr_1 and Tr_2, **Fig. 1** Disregarding the logic for the moment, it is only necessary to know that when the phases are synchronised, the output on the up/down lines consists purely of short duration pulses, normally coincident, which occur as the comparator resets in every cycle

The duration of the reset pulses only depends on propagation delays in the logic. These can be very short compared to the reference clock period Resulting output for these short pulses is highly dependent on the matching of the transistors.

A perfectly complementary combination would probably avoid some of the variations in comparator gain which occur near zero error This type of output circuitry is tri-state with the third state being a high impedance state. Presumably, this fits in with the fact that the logic also has three stable states. The fourth state, in which both up and down lines are high, is inhibited by reset.

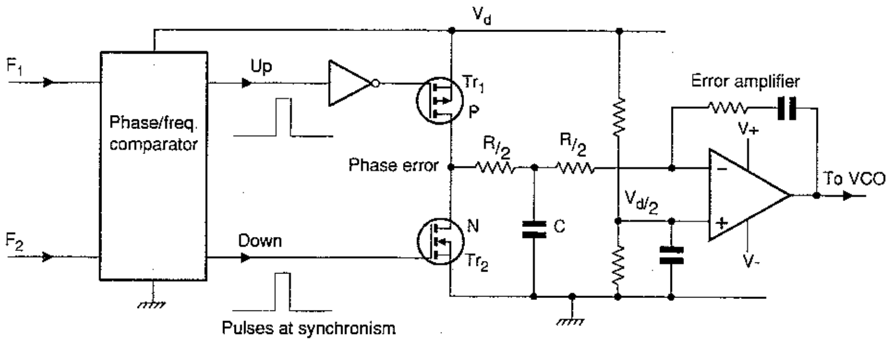
The output logic circuitry sounds more like a digital engineer's idea of analogue design. However, the main outcome is that at phase synchronism the output is essentially in the high impedance state almost continuously except for a momentary clamping of the output ideally to $V_d/2$.

Figure 1 shows a typical error amplifier and active filter for this approach which has to be protected against the fast pulses, usually by splitting the input resistance and adding a capacitance to ground. But the extra delay due to the filter $R/2$, C must not made so large as to affect loop stability.

The capacitor associated with the charge pump is the integrating capacitor in the active filter and not this C. The dc reference for the amplifier is $V_d/2$ so that the loop will settle at zero phase error. Reference frequency suppression is then at a maximum and the gain of the comparator is $V_d/4\pi$ volts/radian.

The source impedance seen by the op-amp is sometimes a critical factor in determining the intrinsic noise of the error amplifier and through the loop. noise on the voltage-controlled oscillator, or vco. That is, the vco may have higher close-in noise sidebands than expected or desired.

The differential output, **Fig. 2**, shows anoth-



g. 1. *Conventional phase/frequency comparator with charge-pump output.*

er arrangement in which a differential error amplifier is driven by the up/down logic outputs directly so as to subtract them. The fast coincident pulses then become a common mode problem for the amplifier which only additional *RC* pre-filtering will satisfactorily resolve. Note that the nominal output/common mode voltage at phase synchronism is either very close to V_d or ground, depending on the logic polarity. This is often inconvenient in single supply systems.

Overall noise performance tends to be improved by the higher gain, $V_d/2\pi$ V/rad, and because there is no high-impedance state.

The resistive combiner

A better approach, which does not rely on the op-amp as a subtractor, is shown in **Fig. 3**. It is simply to take the up line in Fig. 1 and add it to the inverted down line in a 1:1 resistive network.

At phase synchronism the pulses disappear in the output which is a dc voltage of nominally $V_d/2$; the exact value depends on the high/low saturation voltages of the logic. As before, this is only true when a zero error control loop is used and adjusted correctly. The comparator gain is $V_d/4\pi$ volts/radian. Figure 3 shows that – in principle at least – infinite reference suppression is possible without filtering and that the interface is inherently suitable for wide band applications. In practice however, additional *RC* filtering is still necessary in front of the error amplifier.

Noise performance of the op-amp can be adjusted by setting the resistors *R* and the total input resistance to optimum values for the device. At phase synchronism, the output effectively shunts the supply line with a constant resistance of 2*R*. Since this resistance may at times be quite low, the extra current drain must be considered. It may be seen as a price worth paying.

See it work

Typical discrete logic would use standard D-type bistable devices, namely positive edge-triggered 7474s with 'clear on low' inputs.

While it is possible to illustrate the waveforms, there is no better way to appreciate the circuit than to make one and test it. The simplest method is to take a signal generator, feed one input directly, and the other via a 100m of RG58, giving a delay of 500ns. By varying the frequency, all possible phase errors can be generated and the response seen.

While the comparator has a nearly –360 to +360° linear range you will find that it also has a 360° phase ambiguity, which depends on the initial conditions. As a result, it is not useful as an absolute phase comparator but it does excel in phase-locked loop applications.

Differential resistive combiner

Figure 4 shows a differential comparator which allows the op-amp to reject common-mode noise arising from the supply line, V_d. This comparator also has twice the gain ($V_d/2\pi$ volts/radian) of Fig. 3, which means that the effective op-amp noise is halved when considering its relative effect on the noise sidebands of the voltage-controlled oscillator.

Lock detection is also shown and a complete comparator can be made with just two standard ics. Extended frequency range comparators for special applications are thus very simple indeed. ■

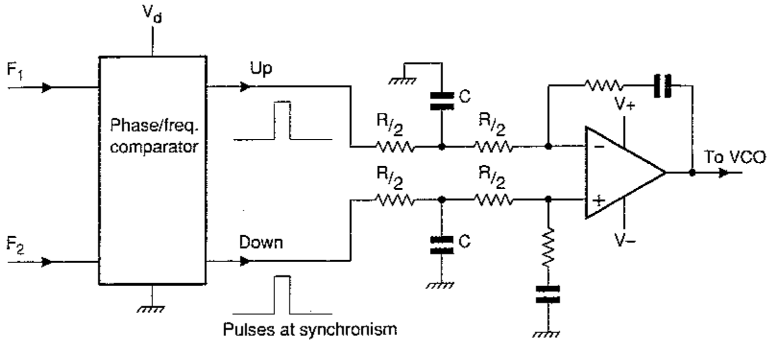


Fig. 2. Using a differential output with the conventional phase/frequency comparator improves noise performance.

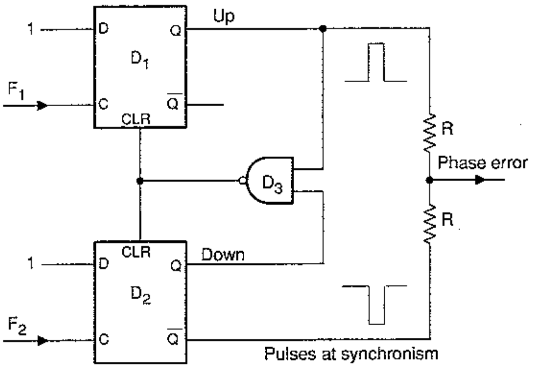


Fig. 3. Phase/frequency comparator with resistive combiner is an improvement over Fig. 2's differential output. In theory, infinite reference suppression is possible.

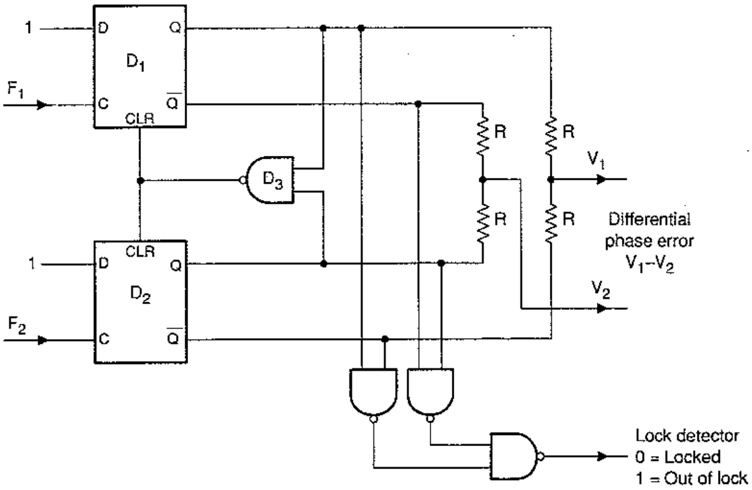


Fig. 4. Differential phase/frequency comparator allows common-mode supply noise rejection and reduces noise due to its higher gain.