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3,517,323

FOUR-QUADRANT PHASE SHIFTER

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FIG. 1

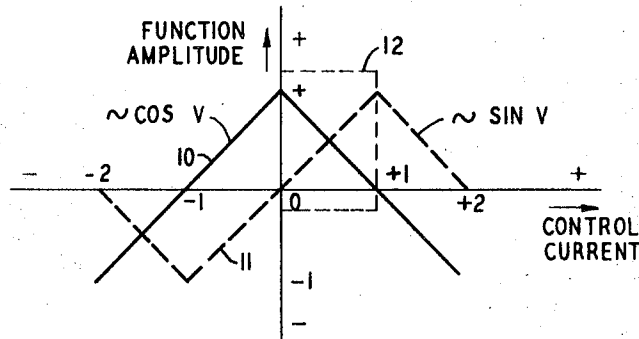


FIG. 2

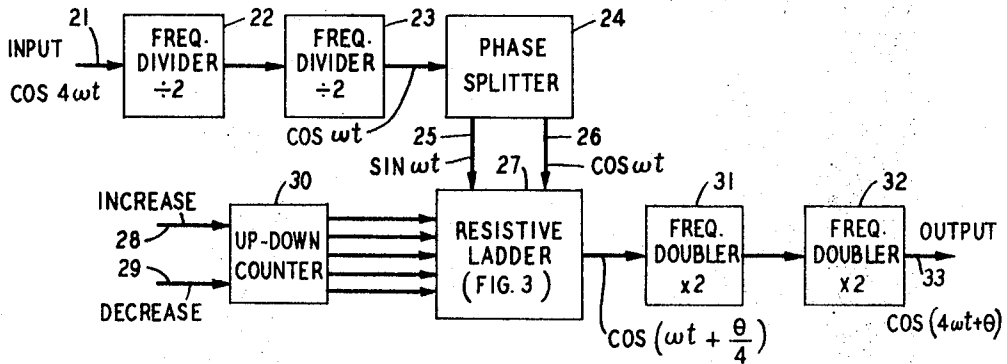
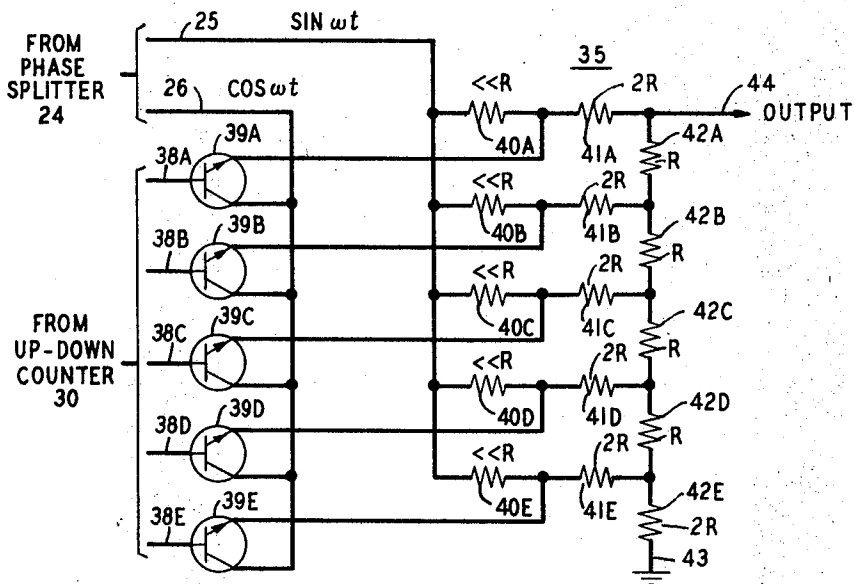


FIG. 3



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FOUR-QUADRANT PHASE SHIFTER

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7 Claims

ABSTRACT OF THE DISCLOSURE

An all-electronic phase-shifter provides digital control of phase over a 360-degree range with a single resistive ladder network. The stable oscillation to be phase shifted is divided in frequency by four and split into quadrature phases. The quadrature phases are differentially attenuated by a control signal and recombined to yield one-fourth the desired phase shift. Frequency multiplication by four completes the phase-shifting operation with a considerable saving in critical apparatus components.

FIELD OF THE INVENTION

This invention relates to variable phase shifting circuits which permit the output wave of a stable oscillator to be shifted controllably in phase over a range of 360 degrees.

BACKGROUND OF THE INVENTION

In the copending patent application of L. N. Holzman and B. R. Saltzberg, Ser. No. 584,833, filed Oct. 6, 1966, now U.S. Pat. No. 3,475,626 issued Oct. 28, 1969, there is disclosed means for providing a continuously variable phase shift for a sine wave at a frequency $\omega/2\pi$ Hz. Their disclosure is based on the implementation of the trigonometric identity

$$\cos(\omega t - V) = \cos V \cos \omega t + \sin V \sin \omega t \quad (1)$$

In that application implementation of Equation 1 is accomplished by using straight-line approximations of the functions $\cos V$ and $\sin V$. Each of these control functions is generated in an individual digital-counter controlled ladder network. The ladder networks simulate these control functions over a range of 2π radians.

It is an object of this invention to simplify and further improve digital phase-shift circuits of the general type disclosed by Holzman and Saltzberg.

It is another object of this invention to provide a four-quadrant phase shifter for a sinusoidal wave which uses a control signal extending over a range of only $\pi/2$ radians.

It is still another object of this invention to generate the control signal for a four-quadrant phase shifter from a single constant-impedance ladder network.

SUMMARY OF THE INVENTION

The above objects and others are accomplished according to this invention by making linear approximations to the control functions $\sin V$ and $\cos V$ in Equation 1 over the range of zero to $\pi/2$ radians only, multiplying quadrature components of one-fourth the frequency of the sinusoidal wave to be phase shifted by these approximations, and quadrupling the frequency of the resultant wave to obtain the desired phase shift over a range of 2π radians. Since the linear approximation of the function $\sin V$ over the range of $\pi/2$ radians can be represented by a constant K , the function $\cos V$ becomes simply $1-K$. Consequently, according to this invention, both functions are capable of being approximated in the same resistive ladder network. Moreover, in place of ap-

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plying the quadrature components of the wave to be shifted to separate ladder networks and combining the outputs of the separate ladders to obtain the desired phase shift, both components are applied to the input of the same ladder network and the combining is performed internally of the single ladder network.

The two-fold function of the ladder network in generating both control functions and in recombining the quadrature wave components is accomplished by removing the conventional ground returns from the steps of the ladder network and substituting one of the quadrature signal sources therefor. The other quadrature signal source is then applied to the ladder steps selectively under the control of a digital up-down counter.

DESCRIPTION OF THE DRAWING

For a better appreciation of this invention reference is made to the following detailed description and the drawing in which:

FIG. 1 is a wave diagram of the control function used in the practice of this invention;

FIG. 2 is a block schematic diagram of a four-quadrant digital phase shifter according to this invention; and

FIG. 3 is a schematic diagram of a counter-controlled constant impedance ladder network modified according to this invention to generate the required phase shifting control function.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 is a piecewise linear representation of the functions $\sin V$ and $\cos V$ over a complete cycle. Solid curve 10 follows the peaks and zero crossings of the cosine wave. Broken-line curve 11, on the other hand, follows the peaks and zero crossings of the sine wave. In the phase-shifter of the cited Holzman et al. application these complete curves extending over a range of 2π radians are utilized as a control function. According to the present invention, however, only the portion of the curves in the quadrant enclosed in dashed-line box 12 is required. Over this portion $\sin V$ reduces to KV , and $\cos V$ reduces to $(1-K)V$, where K is a dimensionless number in the range of zero to unity. Therefore, Equation 1 can be rewritten as:

$$\cos(\omega t - V) \cong KV \sin \omega t + (1-K)V \cos \omega t \quad (2)$$

It can be shown from Equation 2 that the phase angle varies as $\arctan [K/(1-K)]$ in the range of zero to $\pi/2$ radians (0° to 90°). In order to extend the range of phase angle adjustment to 2π radians (360 degrees) it is only necessary to divide the frequency to be phase-shifted by four and multiply the converted frequency after phase shifting by four to restore the desired frequency.

FIG. 2 shows the required system in block diagram form. The phase shifter comprises an input circuit 21, frequency dividers 22 and 23, phase splitter 24, resistive ladder network 27, up-down counter 30 controlled by increase-decrease inputs 28 and 29, frequency doublers 31 and 32 and output circuit 33. In operation an input frequency to be phase shifted is applied at input circuit 21, for example, $\sin 4\omega t$. This input frequency is divided down in conventional dividers 22 and 23 which may advantageously be bistable flip-flop circuits. The resultant frequency, for example, $\sin \omega t$, is split in circuit 24 into quadrature components $\sin \omega t$ on lead 25 and $\cos \omega t$ on lead 26. The two components on leads 25 and 26 are applied to resistive ladder 27, where they are attenuated by selected factors K and $1-K$ established by settings of up-down binary counter 30 and recombined into the phase-shifted form defined by Equation 2. The phase-shifted output of ladder 27 is translated back to the input frequency level in conventional frequency doublers 31

and 32. Output circuit 33 contains the desired phase-shifted input frequency, for example, $\sin(4\omega t + \theta)$, where θ is 4 v.

FIG. 3 shows in detail the constant-impedance resistive ladder network as modified to practice this invention. The ladder network generally designated 35, comprises a series chain of resistors 42A through 42E connected between an output circuit 44 and a ground reference 43. All the series resistors are of the same value R except that one returned to ground. (In an exemplary embodiment R is of the order of 100,000 ohms.) The grounded resistor is 2R. At each junction point between the series resistors 42 there is connected a resistor 41 of value 2R. Normally the outer ends of resistors 41 would be connected either to ground or to a constant voltage source.

It can be shown that a resistive ladder like that designated 35 in FIG. 3 has an output resistance of R ohms regardless of the number of steps on the ladder between output terminal 44 and ground 43. Resistor 42E in parallel with resistor 41E yields R ohms. When this resultant is added to resistor 42D and paralleled with resistor 41D, the impedance at the junction of resistors 41D and 42D is again R ohms. This relation continues to the top of the ladder.

If now the left terminal of resistor 41E, for example, is connected to a voltage E, while the terminals of all other resistors 41 remain grounded, the voltage $E/2^n$ appears at output 44, where n is the number of ladder steps (resistor 41-42 junctions) between the point of voltage application and output terminal 44. In this case there are five rungs shown and $E/32$ volts appears at output 44. Similarly, by the superposition principle of linear circuits, the input voltage E is attenuated by the appropriate factor related to 2^n . If all the terminals of resistors 41 are connected to voltage E, then the output at terminal 44 is E volts attenuated by the sum of $1/2^n$, $1/2^{n-1}$, $1/2^{n-2}$, $1/2^{n-3}$ and $1/2^{n-4}$. Selective connection of a source voltage to different ones of the left terminals in binary counting order thus can yield output voltages in incremental steps of $E/2^n$ from zero volts to $E \times (2^n - 1)/2^n$ volts.

In FIG. 3 the source voltage E for application to the steps of ladder 35 is chosen to be $\cos \omega t$ as it appears on lead 26. Lead 26 is selectively connectable through emitter follower transistor switches 39A through 39E to the respective left terminals of resistors 41A through 41E. The base circuits of transistors 39 are turned on in accordance with the binary count standing in an associated up-down counter 30 (FIG. 2) whose several outputs are connected to base leads 38A through 38E in order of most to least significant digits. Therefore, there will appear at output terminal 44 the wave $\cos \omega t$ multiplied by a factor in the range of zero to $(2^n - 1)/2^n$ (31/32 for a five-step ladder).

Instead of returning to ground the left terminals of resistors 41 not connected through a transistor 39 to lead 26 as would be conventional, additional resistors 40 are connected between these left terminals of the resistors 41 and a lead 25 to which the quadrature component $\sin \omega t$ of the wave to be phase shifted is applied. If the resistors 40 are small with respect to the ladder resistors (of the order of one-hundredth R), the sine component will be effectively grounded through the low-impedance cosine supply any time the associated transistor switch is closed. Thus, the sine component will appear at output terminal 44 attenuated by a factor which is complementary to that by which the cosine component is attenuated. The sine and cosine components are mixed at output terminal 44 substantially in accordance with Equation 2. The maximum value of the factor K can be made to approach unity as closely as necessary by increasing the number of steps on the ladder network.

The count standing in up-down counter 30 of FIG. 2 can be set either manually or automatically as part of an automatic phase control circuit wherein the frequency being controlled is the output of a local oscillator pro-

viding a demodulating carrier wave or sampling wave, such as, for example, in the timing recovery circuit disclosed in the copending application of B. R. Saltzberg, Ser. No. 584,893, filed Oct. 6, 1966, now U.S. Pat. No. 3,440,548 issued Apr. 22, 1969.

While this invention has been set forth in terms of a specific illustrative embodiment, many modifications within the scope of the appended claims will be apparent to those skilled in the art.

What is claimed is:

1. A phase-shift circuit comprising in combination a sinusoidal wave source the phase of whose output is to be adjusted, means splitting the output of said source into quadrature components, and means selectively multiplying one of the components from said splitting means by a first factor in the range of zero to one and the other of said components by a second factor which is equal to one reduced by such first factor and linearly combining such products into a sinusoidal wave of the same frequency as said source wave and phase shifted therefrom by an angle whose tangent is the ratio of such first and second factors.
2. The phase-shift circuit according to claim 1 in which said multiplying and combining means comprises a resistive ladder network having a plurality of inputs connected to binarily weighted junctions therealong and a single output.
3. The phase-shift circuit according to claim 2 in combination with first means connecting one of the components from said splitting means to all inputs of said ladder network in parallel and second means connecting the other of the components from said splitting means selectively to the plurality of inputs of said ladder network such that the one of said components is shorted out at any ladder input to which the other of the components is connected.
4. The phase-shift network according to claim 3 in which said second connecting means includes a binary counter having as many outputs as there are inputs to said ladder and a plurality of switching means controlled by the outputs of said counter interconnecting said other component from said switching means to individual inputs of said ladder network.
5. The phase-shift circuit according to claim 1 in which the fundamental frequency of said sinusoidal wave source is four times that of its output in further combination with means for quadrupling the frequency of the output of said multiplying and combining means such that the range of phase shift of said fundamental frequency extends over 360 electrical degrees.
6. A phase-shift circuit comprising in combination a sinusoidal wave source whose output phase is to be adjusted, means splitting the output of said source into quadrature components, a resistive ladder network having a plurality of inputs and binarily weighted junctions therealong and a single output, means connecting one of the quadrature phases from said splitting means to all inputs of said ladder network in parallel, a binary counter, and switching means selectively connecting the other of the quadrature phases from said splitting means to the inputs of said ladder network in accordance with the output of said counter, the phase of the wave at the output of said ladder network relative to that at said source being a direct function of the binary number standing in said counter.
7. A phase-shift circuit comprising in combination a sinusoidal wave source having an output whose phase is to be adjusted over a range of 360 electrical degrees,

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means dividing the frequency of the output of said source by a factor of four,
means splitting the output of said dividing means into quadrature components,

a resistive ladder network having a series chain of resistors between an output point and a ground reference point, each of said resistors but the one connected to said ground reference being equal and the resistor connected to ground reference being of double such equal value, and a plurality of input points connected by further resistors of double such equal value to said output point and to each junction of said series chain such that a voltage applied to a given input point is attenuated by a factor equal to the digit two raised to the power equivalent to the number of junctions between such input and said output point,

means connecting one of the quadrature phases from said splitting means to all input points of said ladder network through isolating resistors,

a binary counter having a plurality of outputs equal in number to the input points on said ladder network, means selectively connecting the other of said quadrature

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ture phases from said splitting means to the input points of said ladder network in accordance with the binary outputs of said counter, each other quadrature phase so connected to an input point on said ladder network blocking the one quadrature phase connected thereto, and complementarily attenuated one and other quadrature components being combined at the output point of said ladder network to form a phase-shifted sinusoidal wave, and means multiplying the wave at the output point of said ladder network by a factor of four.

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U.S. Cl. X.R.

235—186; 307—254, 295