

DRAWINGS ATTACHED

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(54) PARAMETRIC DEVICE

(71) I, LESLIE KENT WANLASS, a citizen of the United States of America, of 1700, Candlestick Lane, Newport Beach, California, United States of America, do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to parametric devices and to circuits and methods for using the same.

Various types of parametric devices have been proposed in the past for numerous circuit applications, most commonly as amplifiers for signals in the microwave range or as binary computing elements for high speed computers. Such parametric devices produce amplification or oscillation by means of the variation of an energy storage parameter, and generally comprise an L-C resonant circuit in which the value of either the inductance or capacitance is varied at a critical time to add energy to the system. This addition of energy is called pumping and maximum energy is transferred if energy is added to the resonant circuit at the peaks of its output waveform, that is, if the pumping frequency is twice that of the output frequency and properly phased therewith. The L-C circuits of typical parametric devices utilize either a non-linear inductance element such as a saturable core having a pair of windings thereon, or one or more non-linear capacitors such as a silicon diode whose capacitance is dependent on the voltage impressed across it. In the case of a variable inductance device the pumping signal is applied to one of the windings and the other winding connected in the resonant circuit while in the case of a variable capacitance device the pumping signal is applied directly to the capacitor in the resonant circuit. Because of the inherent nature of these inductors and capacitors, previously proposed paramagnetic

devices have been restricted to very high frequency, very low power applications. Moreover, the requirement of a pumping source of twice the frequency of the output limits the use of such devices.

When properly constructed such parametric circuits are essentially self starting oscillators whose oscillations build up to a certain amplitude and then remain constant at that amplitude. Parametric oscillation is usually treated and explained in the literature in terms of Matheiu's equation. Such a treatment and explanation, together with additional explanatory material relating to parametric devices can be found in an article by E. Goto, entitled "The Parametron, a Digital Computing Element which Utilizes Parametric Oscillation" published in the August 1959 issue of The Proceeding of the IRE. As explained in that article, by making certain assumptions a curve can be plotted which has a saddle point at the origin and two spiral points which indicate the stable states of stationary oscillation and which are displaced from each other by 180°. Such a curve is shown herein in Figure 1.

In the referenced article, the author mentions that oscillation of a parametric device in the stationary state is extremely stable and states that this difficulty can be overcome, as it must in order for his binary element to operate properly, by providing means for quenching the oscillation so that the stable state condition is not reached.

According to the present invention a method of producing a regulated voltage from an unregulated AC voltage source comprises initiating oscillation of a parametric device by the unregulated voltage and transferring energy from said source to said device to build said oscillations up to and maintain them at the stable oscillation point of the device to produce a regulated voltage.

A parametric device suitable for use in apparatus for effecting voltage regulation com-

prises a variable inductor having a magnetic core, a control winding and a load winding wound on said core, a capacitor connected to the load winding to form a resonant circuit therewith resonant at a frequency f , the arrangement being such that an AC signal of frequency f applied to the control winding changes the inductance of the load winding at a frequency of $2f$, and input terminals for applying the AC signal to said control winding.

The inductance component of an L-C resonant circuit may be the load winding of a variable inductor device of the form disclosed in British Patent Specification No. 1,153,901. The theoretical considerations and operating principles of this variable inductor are described in detail in Specification No. 1,153,901. Briefly, the variable inductor disclosed in Specification No. 1,153,901 comprises a ferromagnetic core having a pair of windings thereon. The core is constructed so that it has four common regions or "legs" and two end or joining portions for magnetically coupling the common regions. The coils are wound on the end portions with their axes displaced at 90° so that normally there is no inductive coupling between them, and so that the flux components generated as a result of passing currents through the two windings are at all times in opposing relationship in two of the legs and in additive relationship in the other two legs. As a result of this construction the current in one of the windings, referred to as the control winding, generates a magnetic flux which controls the reluctance of the magnetic circuit encompassed by the second winding, referred to as the load winding, in such a manner that variations in this flux caused by variations in the current in the control winding cause the hysteresis loop of the magnetic circuit encompassed by the load winding to be effectively rotated thereby varying the inductance of the load winding. The relationship between control current and load winding inductance is shown in Figure 2.

Since, as discussed in Specification No. 1,153,901, inductance is an absolute quantity, it does not follow zero crossings of the phenomena causing it, but rather in effect provides full wave rectification of the casual phenomena. Therefore, if an alternating current is applied to the control winding of an inductor of the type described, the inductance of the load winding will be controlled in accordance with the alternating current in the control winding, but because the inductance ignores the polarity of the alternating current, the inductance change will be at twice the frequency of the alternating current applied to the control winding as shown in Figure 3. This is precisely what is required for the operation of a parametric device. Therefore, by coupling the load winding of

such inductor to a suitable capacitor to form a resonant circuit, energy can be transferred to the resonant circuit by pumping the control winding with an alternating current of the same frequency as that to which the resonant circuit is tuned, that is, the output frequency.

The fact that the pumping frequency of the device is the same as the output frequency open up many new applications for the device as does the fact that it can be provided with a high power rating. It has, for example, been found that the parametric device of the present invention operates as an extremely accurate regulator at conventional power frequencies when the power line is connected to the control winding. Since, as pointed out previously, it is extremely difficult to change the amplitude of oscillation of a parametric device oscillating at a stable point, the normal variations of the line voltage use as the pumping source have no effect on the amplitude of the output from the resonant circuit. This regulator has the further advantage that because there is no direct transformer coupling between the windings, transients such as SCR spikes in the line are filtered out and the output is an almost perfect sine wave. This isolation, of course, is also present in the opposite direction, i.e., from load to line. Moreover, overloading, caused, for example, by a short in the load, will not result in current limiting as in currently available constant voltage transformers, but rather will have the effect of driving the parametric device out of its stable point and preventing it from building up again with the result that the output will be completely removed. Once the disabling condition is rectified, the circuit will immediately build up to the stable oscillation point and the regulated output voltage will be restored.

The objects and advantages previously described will become more apparent upon reference to the accompanying description and drawings in which:

Figure 1 is a curve illustrating the modes of oscillation of a parametric device in the phase plane;

Figure 2 is a curve illustrating the inductance-control current characteristic of a variable inductance device used in the present invention;

Figure 3 illustrates the variation of the inductance of such a variable inductor in response to an AC control current;

Figure 4 is a schematic diagram of a first embodiment of the present invention;

Figure 5 is a schematic diagram of a first modification of the embodiment of Figure 4;

Figure 6 is a schematic diagram of a second modification of the embodiment of Figure 4;

Figure 7 is a schematic diagram of a third

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modification of the embodiment of Figure 4;

Figure 8 is a schematic diagram of a second embodiment of the present invention;

Figure 9 is a schematic diagram of a third embodiment of the present invention;

Figure 10 is a schematic diagram of a fourth embodiment of the present invention; and

Figure 11 is a schematic diagram of a fifth embodiment of the present invention.

In the drawings, the convention adopted in Specification No. 1,153,901 for indicating a core is followed, that is, such a core is indicated by the use of a T-shaped iron symbol. While any of the various core structures illustrated and described in Specification No. 1,153,901 could be used in this invention, in the circuits according to this invention which have actually been built, cores similar to that shown in Figure 6 of the Specification No. 1,153,901 have been used.

Turning now to Figure 1, there is shown a typical curve illustrating the amplitude-to-phase locus of an oscillating parametric device. The abscissa represents the sine component I_s , and the ordinate, the cosine component I_c . If polar coordinants R (amplitude) and ϕ (phase) are introduced in the I_s , I_c plane it can be seen that R and ϕ , respectively, indicate the instantaneous amplitude and phase of the oscillation. The saddle point at the origin indicates the exponential build-up of oscillation which is in a definite phase relation to the pumping signal. The spiral points in the Figure indicate the stable states of stationary oscillation. The choice between these two modes of stationary oscillation is effected entirely by the sign of the sine component of the small initial oscillations that exist in the circuit. An anitial oscillation of quite small amplitude is sufficient to control the mode or the phase of stationary oscillation of large amplitude which is to be used as the output signal and hence an amplifying action is obtained. A more complete treatment of the mathematical and physical phenomena involved in parametric oscillation can be found in the literature, for example the previously cited Goto article. While all of the assumptions made in the literature in order to obtain the curve shown in Figure 1 may not precisely apply to the present invention, it is believed that reference to this Figure and an understanding of it are helpful in understanding the operation of the present invention and it is therefore included for that purpose.

Figures 2 and 3 illustrate the relationship of the inductance of the load winding of a variable inductor constructed in accordance with the teachings of Specification No. 1,153,901 with the current applied to the control winding thereof. Figure 2 shows that the inductance presented by the load winding

is at a maximum when the current in the control winding is zero and decreases in the same manner irrespective of the polarity of the current applied to the control winding. Figure 3 shows the manner in which the inductance of the load winding varies when an alternating current is applied to the control winding. Curve A plots current in the control winding versus time while curve B plots inductance of the load winding versus time. As can be seen, the inductance of the load winding reaches a maximum at 0° and 180° , that is, when the control current is zero, and a minimum at 90° and 270° , that is, where the control current is at a maximum. Thus, the inductance change of the load winding is at a frequency twice that of the current applied to the control winding.

Turning now to Figure 4, there is shown a voltage regulator constructed in accordance with the present invention. A variable inductor 10 of the type described has its control winding 11 connected to a source 12 of voltage to be regulated, for example, a conventional 60 cycle/second, 120 volt power line. A capacitor 13 may be connected across the winding 11 to reduce the input surge current and correct the power factor of the unit; however, this capacitor is not required for proper circuit operation. The load winding 14 of the inductor 10 is connected in parallel with a capacitor having a value such that the LC circuit made up of the winding 14 and capacitor 15 is tuned to a frequency of 60 cycles/second. A load, represented by resistor 16 is connected across the resonant circuit 14, 15.

The circuit of Figure 4 operates in the manner set forth above. When a signal is produced by the source 12, the alternating current passing through the winding 11 causes the inductance of the winding 14 to vary at twice the frequency of the source 12, as shown in Figure 3. Because of inevitable noise, at least a component of which will be at the frequency to which the LC circuit 14, 15 is tuned, a small signal will be present in the tuned circuit. The energy transferred to the tuned circuit by the pumping action of the source 12 operating through the inductor 10 will cause this noise component to increase in amplitude until a stable point is reached, the particular stable point reached being dependent upon the sign of the sine component of the noise signal. In other words, the pumping action of the source 12, by changing the inductance of the winding 14 at twice the frequency to which the resonant circuit, 14, 15 is tuned, results in the onset of parametric oscillation. It will be observed that once the stable oscillation point is reached, variations in the amplitude of the output of the source 12 will not appreciably affect the output of the LC circuit 14, 15 because of the very large signal required to

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drive the circuit away from its stable oscillating point. Moreover, because of the nature of the inductor 10, there is complete isolation of the load from the line and vice versa and the output wave form is essentially a pure sine wave independent of the input wave form.

Figure 5 is a schematic diagram of a circuit very similar to that of Figure 4 with certain practical considerations taken into account. In this Figure, a variable inductor 20 of the form described in Specification No. 1,153,901 has its control winding 21 connected to a source of voltage 22, for example, the conventional 120 volt AC power line. A second winding 23 is wound on the core with its axis parallel to that of the winding 21 and a capacitor 24 is connected across the winding 23. The capacitor 24 serves the same purpose as the capacitor 13 in Figure 4 but the use of a separate winding 23 permits the establishment of a voltage across the capacitor 24 at which it can operate more efficiently. Similarly, the load winding 25 of the inductor 20 has a capacitor 26 connected across its entire length and the load 27 connected across only a portion of it. This arrangement permits the capacitor 26 to be operated at a higher voltage where it is more efficient, for example, 600 volts, while maintaining the voltage across the load at a lower value, for example, 110 volts. The operation of the circuit is similar in all respects similar to Figure 4.

In Figure 6 there is shown another modification of this circuit. In this Figure, the variable inductor 30 of the type described has its control winding 31 connected to a source of AC voltage 32. Two windings 33 and 34 are wrapped on the core in place of the single windings 14 and 25 shown in Figures 4 and 5. These windings 33 and 34 are wound on the core so that their axes are parallel and a capacitor 35 is connected across the winding 33 and a load 36 is connected across the output winding 34. The winding 33 and capacitor 35 serve as the resonant circuit to which energy is transferred by the pumping action of the source 32 and the control winding 31. The oscillating output of the tuned circuit 33 and 35 is transformer coupled to the output winding 34 so that a regulated output is produced across the load 36 in the same manner as previously described. The separation of the windings 33 and 34 permits a high voltage to be developed across the capacitor 35 so that this capacitor is operated more efficiently.

A circuit constructed in accordance with Figure 6 was found to regulate very accurately with the following parameters:

Winding 31 equals 250 turns
Winding 33 equals 1100 turns
Winding 34 equals 170 turns

Capacitor 35 equals 6 microfarads 65
Load Resistance 36 equals 50 ohms
Core weight equals 6 pounds
Input voltage equals 120 volt, AC. 60 cycle
Output voltage equals 110 volts rms 70
Output power equals 250 VA.

The core used for this circuit was similar to that shown in Figure 6 of Specification No. 1,153,901, that is, two C-cores rotated 90° and joined together. 75

If more than one regulated output voltage value is desired, or if isolation is required for practical reasons, the circuit of Figure 7 can be used. In this circuit, an inductor 40 of the type described has its control winding 41 connected to a source 42 of AC voltage. As was the case in Figure 6, a load winding 43 is provided across which is connected a capacitor 44 to form the resonant circuit. A plurality of output windings 45, 46 and 47 are also provided, each having its axis oriented in parallel with the axis of the winding 43 so that they are transformer coupled thereto. By choosing the number of turns of the output windings 45, 46 and 47, any desired output voltage can be developed across the loads 48, 49 and 50. The manner in which the circuit operates is identical to that of Figure 6. 80 85 90

Figure 8 illustrates a circuit constructed according to the present invention which produces a regulated DC output voltage. In this circuit, an inductor 52 of the type described has its control winding 53 connected to a source of AC voltage 54. The load winding 55 has a capacitor 56 connected there across to form the resonant circuit. An output winding 57 which is transformer coupled to the load winding 55 has its output rectified by the full wave rectifier 58 and applied to the load 59. If desired, of course, a filtering network can be interposed between the rectifier 58 and load 59. The operation of the circuit of Figure 8 is identical to that of Figure 6, that is, the LC resonant circuit 55, 56 produces an AC output voltage of constant amplitude. This output voltage is coupled to output winding 57 by transformer coupling and is rectified by the rectifier 58 and applied to the load 59 in a conventional manner. If desired, the rectifier 58 could be directly connected to the resonant circuit and the separate output winding eliminated. If desired, a plurality of output windings may be provided to supply different voltages. 95 100 105 110 115 120

Figure 9 shows a DC-AC converter using the present invention. In this Figure, an inductor 60 of the type described has its control winding 61 connected to the output of an SCR switch 62 which is supplied by a source of DC voltage 63. The load winding 64 of the inductor 60 is connected in parallel with a capacitor 65 to form a resonant circuit 125

tuned to the desired output frequency. The output of this resonant circuit is applied across a load 66. In operation, the SCR switch 62 chops the output of the DC source 63 at a frequency equal to the frequency at which the resonant circuit 64, 65 is tuned so that a square wave of this frequency is applied to the control winding 61. The operation of the switch 62 must be such that the square wave is AC, that is, that it has both positive and negative excursions. This is the manner in which most conventional SCR switches operate. As previously pointed out, the output wave form of the resonant circuit 64, 65 is independent of the wave form of the signal applied to the control winding 61. This is true even if the signal applied to the control winding is a square wave such as that produced by the SCR switch 62. Consequently, an essentially pure sine wave output at the desired frequency is obtained.

Figure 10 shows a frequency converter constructed in accordance with the present invention. In this Figure an inductor 70 of the type described has its control winding 71 connected to the output of an SCR switch 72 in the same manner as was the case with Figure 9. A conventional transformer T has its primary winding 73 connected to the output of a source 74 of AC voltage of any given frequency. The voltage induced in the secondary 75 of the transformer T is rectified by diodes 76 and 77, filtered by capacitor 78 and applied to the input of the SCR switch 72. In some cases, it may not be necessary to rectify the input voltage before chopping it, particularly if the input or carrier frequency is much greater than the chopping frequency.

As was the case in the case in Figure 6, a first load winding 79 is connected in parallel with a capacitor 80 to form a resonant circuit tuned to the desired output frequency. A second load winding 81 wound so as to be transformer coupled to the winding 79 has a load 82 connected there across.

The operation of this circuit is similar to that of Figure 9. The SCR switch 72 is adjusted to chop the rectified signal passed by the transformer T at a frequency equal to the desired output frequency. The AC square wave thus formed is passed through the control winding 71 with the result that the resonant circuit 79, 80 is pumped in the manner previously described and a regulated output is obtained across the load 82.

Turning now to Figure 11, there is shown a parametric amplifier embodying the present invention. In this Figure, an inductor 84 of the type described has its control winding 85 connected across the source of AC voltage 86. The load winding 87 of inductor 84 is connected to a capacitor 88 to form a resonant circuit tuned at the desired output frequency. The output is taken across a resistor 89 con-

nected to an output winding 90. The input of the circuit is applied to input terminals 91 which are connected across the load winding 87. In this case the output of the tuned circuit 87, 88 is not dependent upon a noise signal but rather is dependent on the input to the terminals 91. This input, although of small amplitude, will cause the tuned circuit 87, 88 to begin to oscillate and these oscillations will be built up or amplified by the pumping action of the AC current passing through the control winding 85 in the manner previously described.

It should be understood that in these embodiments previously illustrated and described as having a separate output winding, the output may, if desired, be taken directly across the resonant circuit. Similarly, in those embodiments where output is taken directly across the resonant circuit, one or more additional output windings could be provided if desired.

In Specification No. 1,153,902, it is pointed out that frequency doubling can be prevented by impressing a suitable bias on the core of a magnitude sufficient to prevent zero crossing of the flux causing the inductance change. Such a bias can be used in connection with the present invention although if it is used, the pumping frequency will have to be double the output frequency as in the conventional parametric device. The device of the present invention will still retain its other advantages, such as a high power handling capacity.

As used herein and in the Claims the term "AC" as applied to a voltage current or signal is not meant to be limited to a sine wave signal but rather is meant in its broadest sense as applying to a waveform that has cyclic positive and negative excursions.

From the foregoing description it can be seen that a method has been provided for producing a regulated voltage by utilizing the stable oscillating characteristic of a parametric device. An improved parametric device has also been provided that is capable of operating at low frequencies and high power levels. The improved parametric device also has the great advantage of operating with a pumping frequency equal to the tuned frequency of the resonant circuit. The parametric device has the further advantage of being extremely rugged and inexpensive to manufacture.

WHAT I CLAIM IS: —

1. A method of producing a regulated voltage from an unregulated A.C. voltage source comprising initiating oscillation of a parametric device by the unregulated voltage and transferring energy from said source to said device to build said oscillations up to and maintain them at the stable oscillation point of the device to produce a regulated voltage.

2. A method as claimed in claim 1 in which the parametric device includes a resonant circuit and in which energy is transferred to said resonant circuit by varying an inductive component thereof.

3. A voltage regulator comprising a parametric device having a resonant circuit oscillatable at a stable point, the regulator having input terminals for connection to a source of unregulated AC voltage, output terminals for delivering a regulated output voltage, and means for coupling the input terminals and output terminals to the resonant circuit for, respectively, transferring energy from the source to the circuit to maintain the oscillations at the stable point and transferring energy from the circuit to produce the regulated voltage.

4. A voltage regulator as claimed in claim 3 in which the resonant circuit comprises a variable inductor comprising a magnetic core having four common regions and two end regions magnetically joining said common regions, a load winding wound on said core and linking a magnetic circuit therein, the effective reluctance of said magnetic circuit controlling the inductance of the load winding, a control winding wound on said core, said control winding being responsive to current therein for generating magnetic flux in said core, said flux controlling the effective reluctance of said magnetic circuit whereby variations in said flux vary the inductance of said load winding, and a capacitor connected to said load winding to form a resonant circuit therewith, the input terminals being connected to the control winding, and the output terminals being connected to the resonant circuit.

5. A voltage regulator as claimed in claim 4 in which the resonant circuit is tuned to the frequency of the unregulated AC source.

6. A parametric device comprising a variable inductor having a magnetic core, a control winding and a load winding wound on said core a capacitor connected to the load winding to form a resonant circuit therewith resonant at a frequency f , the arrangement being such that an AC signal of frequency f applied to the control winding changes the inductance of the load winding at a frequency of $2f$, and input terminals for applying the AC signal to said control winding.

7. A device as claimed in claim 6 in which the core has four common regions and two end regions magnetically joining the common regions.

8. A device as claimed in claim 7 in which the load winding is wound on the core substantially transversely of the control winding.

9. A device as claimed in claim 7 in which the arrangement is such that energisation of the control winding generates a magnetic flux in the core which controls the effective re-

luctance of a magnetic circuit encompassed by the load winding in such manner that variations in the flux cause the hysteresis loop of the magnetic circuit to rotate and the inductance of the load winding to change.

10. A device as claimed in claims 6, 7, 8 or 9 in which input terminals are connected to said control winding by which the control winding is energisable by an AC signal, and in which the resonant circuit resonates at the frequency of the AC signal.

11. A device as claimed in claim 7 or 8 in which the arrangement is such that, in use, the load winding generates a first magnetic flux in the core following a first flux path, through a first one of the end portions, a first region of the common regions, the other end portion and a fourth region of the common regions and a second path in the core through the first end portion, a second region of the common regions, the other end portion and a third region of the common regions, the control winding generating a second magnetic flux in the core following a third path therein through the first end portion, the first region, the other end portion and the second region, the second flux also following a fourth flux path through the first end portion, the third region, the other end portion and the fourth region, the first and second fluxes being in opposing relationship in two of the common regions and in additive relationship in the other two of the common regions, each of the first and second paths including one opposing flux common region and one additive flux common region.

12. A device as claimed in any one of claims 6—11 in which there is a capacitor connected across the control winding.

13. A device as claimed in any one of claims 6—12 in which there is a load connected across a portion of the load winding.

14. A device as claimed in any one of claims 6—13 in which there is at least one other winding wound on the core in such manner that the or each other winding is inductively coupled to the load winding.

15. A device as claimed in claim 14 in which there is one other winding and rectifier means connected across it.

16. A device as claimed in any one of claims 6—15 when connected to AC source of square waveform.

17. A device as claimed in claim 16 in which the AC source comprises a DC source and means for chopping the output of the DC source.

18. A device as claimed in claim 14 in which there is one other winding or as claimed in claim 14, in which there is a load resistor connected across the other winding, there being also input terminals connected to the load winding for applying an input signal across that winding.

19. A device as claimed in any one of

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claims 6—15 when connected to an AC source of frequency equal to the resonant frequency of the resonant circuit.

5 20. A parametric device substantially as described with reference to and as illustrated by Figs. 1, 2, 3 and 4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 of the accompanying drawings.

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