United States Patent

[11] 3,626,314

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[73] Assignee **International Standard Electric Corporation**
New York, N.Y.
[32] Priority **Mar. 25, 1966**
[33] **Netherlands**
[31] **6604008**
Continuation of application Ser. No. 625,519, Mar. 23, 1967, now abandoned. This application Feb. 26, 1970, Ser. No. 14,768

[54] **RESONANT TRANSFER EMPLOYING NEGATIVE RESISTANCE AMPLIFIERS**
5 Claims, 11 Drawing Figs.

[52] **U.S. Cl.** .... **330/61 A,** 333/80, 307/222, 330/207
[51] **Int. Cl.** **H03f 15/00**

[50] **Field of Search** .... 330/61 A; 307/222; 333/80; 328/341; 179/15 A, 15 AA

[56] **References Cited**

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3,117,185	1/1964	Adelaar	179/15
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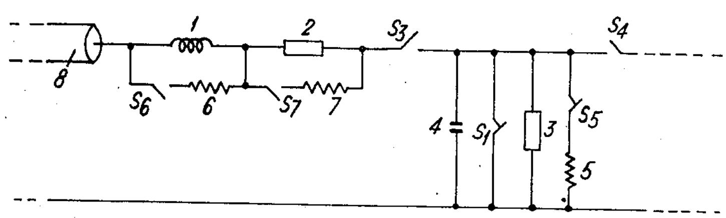
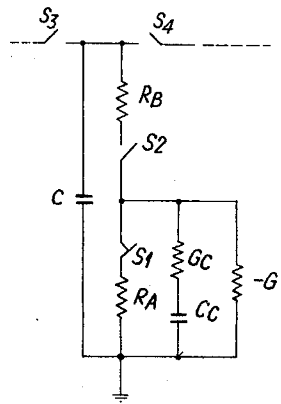
ABSTRACT: A sample of energy representing information is transferred, by use of the resonant transfer principle, to a storage capacitor. This sample of energy is amplified by being connected during a predetermined time to a negative resistance amplifier. The amplified energy is then retransferred by use of the resonant transfer principle to a load, i.e. to another capacitance.





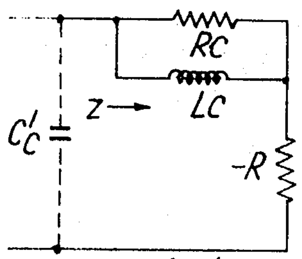


Fig. 1.

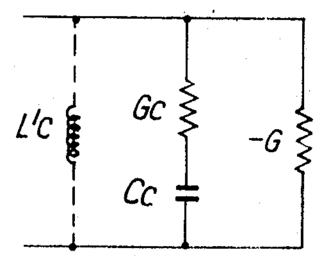


Fig. 2.

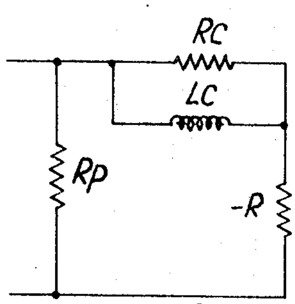


Fig. 3.

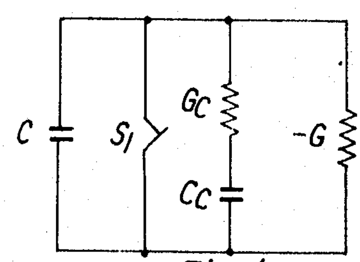


Fig. 4.

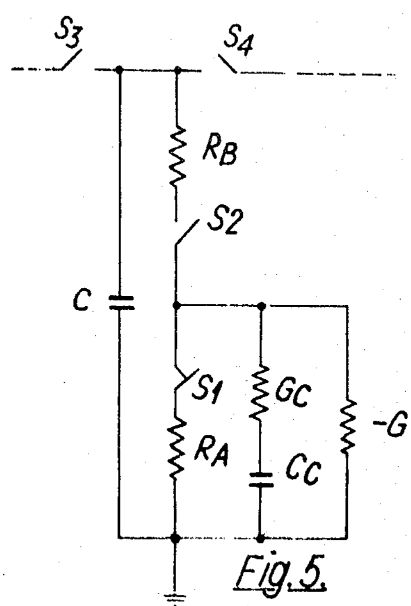


Fig. 5.

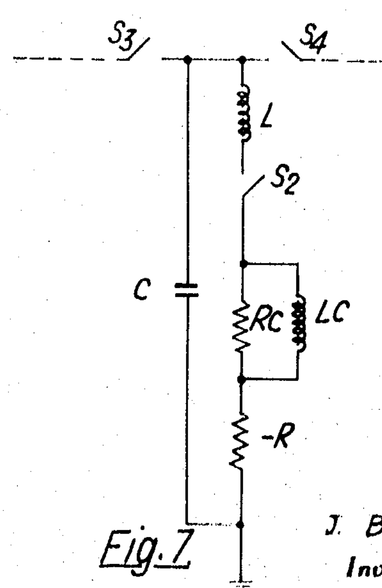


Fig. 7.

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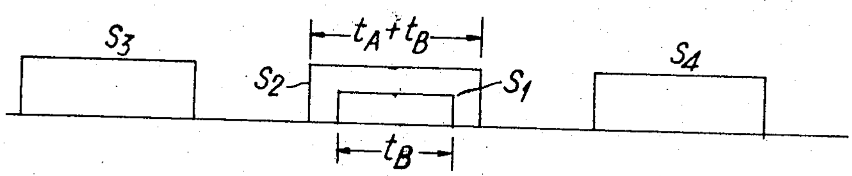


Fig. 6.

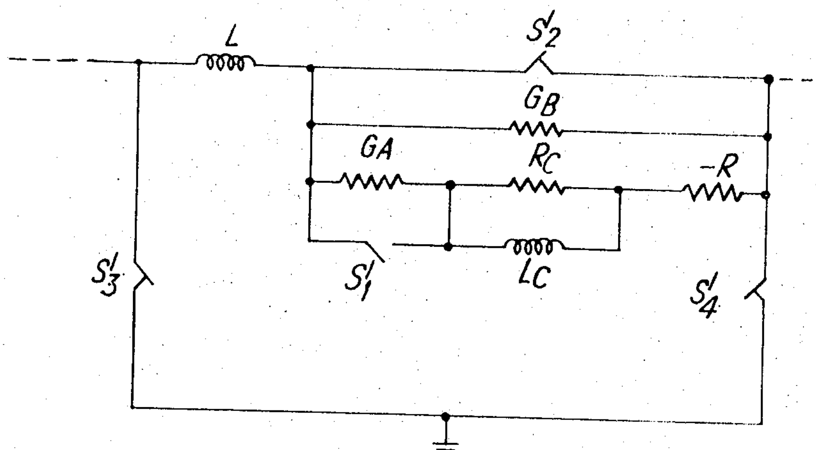


Fig. 8.

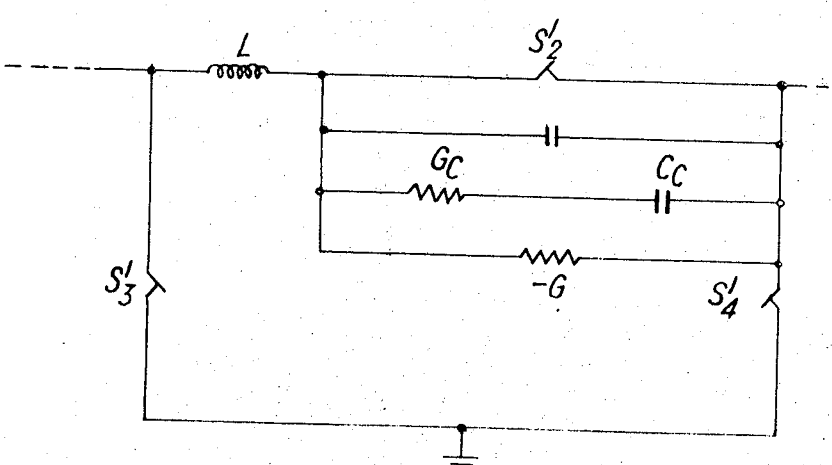
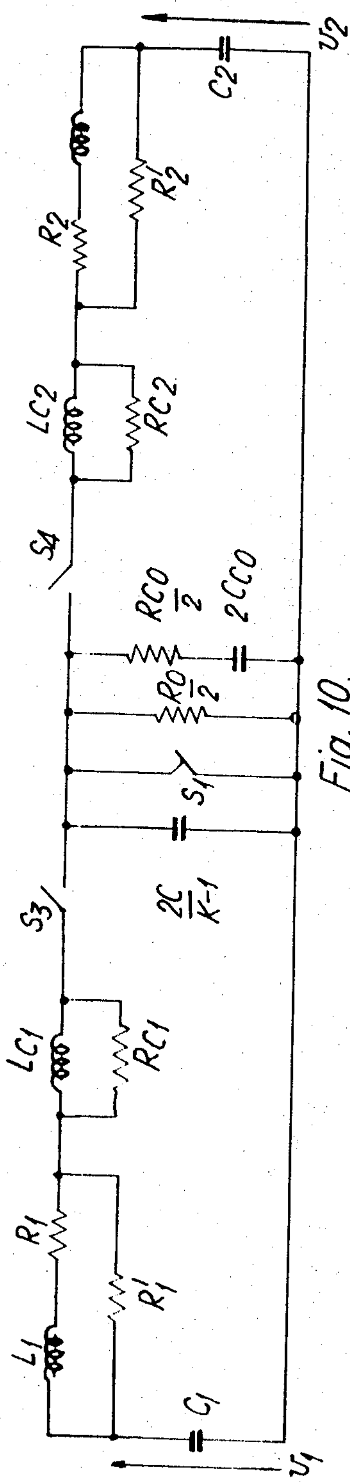


Fig. 9.


v2
C2
R'2
R2
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RC2
S4
RCO/2
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Fig. 10.

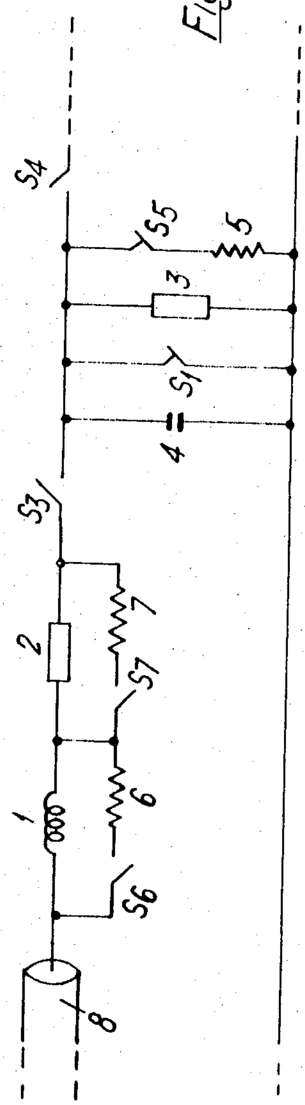
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Fig. 11.

RESONANT TRANSFER EMPLOYING NEGATIVE RESISTANCE AMPLIFIERS

This application is a streamlined continuation of application 625,519 filed Mar. 23, 1967, now abandoned.

The invention relates to negative resistance amplifiers including a reactive storage device, a negative resistance and switching means to couple said storage device and negative resistance during a predetermined time interval during which time the energy originally stored in the storage device is amplified by a predetermined amount.

Such a negative resistance amplifier has been disclosed in the U.S. Pat. No. 3,187,100. An arrangement of this kind may be advantageously used in time division multiplex systems using the resonant transfer principle and more particularly the principle of intermediate storage as disclosed in the British Pat. No. 822,297 (E.P.G. Wright-W. Bezdel 192–1). According to this principal, energy may be transferred, i.e., by a resonant transfer operation to an intermediate storage capacitor, and, before being retransferred therefrom, to a load, i.e., to another capacitance and again by resonant transfer operation, the sample on the intermediate storage capacitor may be amplified by connecting the latter during a predetermined time between the two resonant transfer operations, to a negative resistance. An amplification system of this kind may be of particular interest in relation to so called time division hybrid circuits disclosed in the French patent of addition No. 75,359 to H. Adelaar corresponding to U.S. Pat. No. 3,267,218 which enable the interconnection of four-wire and two-wire circuits on a time division multiplex basis by using the resonant transfer principle. In such a circuit, three intermediate storage capacitances may preferably be used and between transfers into and from such capacitances, they may be temporarily connected to negative resistances in order to amplify the samples stored before forwarding them to other circuits. Thus amplification in this manner may be carried out on a time division multiplex basis.

A first object of the invention is to provide conditions under which such negative resistance amplifiers may operate satisfactorily.

In accordance with a first characteristic of the invention, in a negative resistance amplifier of the type initially defined, said storage device and negative resistance when coupled by said switching means constitute a capacitance shunted by a short circuit stable negative resistance or a dual circuit thereof.

In accordance with another characteristic of the invention, said switching means include a switch which in the unoperated position couples said negative resistance to a positive resistance of such a value that the combined resistance is positive.

In accordance with a further characteristic of the invention, said switching means include a second switch which in the operated position couples said negative resistance to said storage device and to a second positive resistance of such a value that the combined resistance is negative.

In accordance with yet a further characteristic of the invention the time during which said second switch is operated encompasses the time during which said first switch is operated.

Indeed, it has now been proved that, as will be explained later in the description, a short circuit stable negative impedance converter may be coupled across a capacitance without creating an unstable condition. However, if this capacitance must be able to receive an initial charge and then be able to deliver an amplified charge to a load, at such moments it must not be short-circuited whereas in rest condition, a short circuit is essential for the short circuit stable negative impedance converter. In the manner indicated, by the use of two switches it becomes however possible to avoid any undesired transient condition during which the short circuit stable negative impedance converter would be left open-circuited.

Nevertheless, when placing a negative resistance in shunt across a capacitance, or when using a dual circuit involving an inductance, the currents at the time the circuit is switched in or switched out may be large and this may impose severe requirements on the electronic gates or other switches used to perform such operations.

Accordingly, the invention also relates to negative resistance amplifiers including a resonant transfer network with a reactive storage device, a negative resistance and switching means to couple said resonant transfer network and negative resistance during a predetermined time interval whereafter the energy originally stored in said storage device is amplified by a predetermined amount.

Such negative resistance amplifiers are also disclosed in the U.S. Pat. No. 3,187,100 to H. Adelaar and due to the resonant transfer operation they offer the advantage that the currents when switching the negative resistance in or out of the circuit across the storage capacitance are zero.

A second object of the invention is to provide conditions under which such amplification by resonant transfer operation may adequately be secured.

In accordance with a characteristic of the invention, said resonant transfer network and negative resistance when coupled by said switching means constitute a capacitance, an inductance and an open-circuit stable negative resistance all in series or a dual circuit thereof.

Thus, contrary to the case of amplification without resonant transfer operation, the type of the negative impedance converter is now reversed.

In accordance with a third aspect of the invention, it also relates to negative resistance amplifiers including a resonant transfer network between two reactive storage devices, negative resistances and switching means to couple said storage devices via said resonant transfer network during a predetermined time interval, said network being so designed that with a given energy in any one of said storage devices and none in the other at the beginning of an effective interconnecting time, after said time, amplified energy is now stored in said other device while there is substantially none in said one device.

Such negative resistance amplifiers enabling to secure amplification during a resonant transfer operation from one storage device to the other and vice versa, are already known from the U.S. Pat. No. 3,117,185 to H. Adelaar as well as from the Belgian patent No. 654,515 to A. Fettweis corresponding to U.S. Pat. No. 3,324,247. In the latter patent, circuits are disclosed which make it possible to take into account the highway capacitance which is inevitably present in resonant transfer networks used in telecommunication exchanges and which highway capacitance may be dealt with by using the so called harmonic resonant transfer principle disclosed in the French Pat. of addition No. 72,050 **of K. W. CATTERMOLE—R. B. HERMAN—W. BEZDEL—K. S. DARTON, corresponding to U.S. Pat. No.** 3,073,903.

Yet a third object of the invention is to provide a condition under which suitable bidirectional amplification may be secured in a resonant transfer circuit using the so called second harmonic principle.

In accordance with another characteristic of the invention, said storage devices and said network constitute a pair of capacitances interconnected via at least one series branch including an open-circuit stable negative resistance and shunt branch including a short circuit stable negative resistor or a dual circuit thereof.

Under such conditions, it can be shown that no unstability will arise, which is not the case if other combinations of negative resistances are employed.

The above and other objects and features of the invention as well as the best manner of attaining them and the invention itself will be better understood from the following description of embodiments thereof to be read in conjunction with the accompanying drawings which represent:

FIG. 1, the equivalent circuit of a practical open-circuit stable, negative resistance;

FIG. 2, the equivalent of a practical short circuit stable negative conductance;

FIG. 3, the open-circuit stable negative resistance of FIG. 1 shunted by a positive resistance;

FIG. 4, the short circuit stable negative conductance of FIG. 2 in association with a capacitance;

FIG. 5, the circuit of FIG. 4 arranged to secure amplification in a system using the intermediate storage principle;

FIG. 6, a timing diagram for the four switches used in FIG. 5;

FIG. 7, a circuit enabling amplification by using the intermediate storage principle in conjunction with a resonant transfer circuit including the open-circuit stable negative resistance of FIG. 1;

FIG. 8, the dual circuit of that shown in FIG. 5;

FIG. 9, the dual circuit of that shown in FIG. 7;

FIG. 10, a bidirectional resonant transfer amplifier using two open-circuit stable negative resistances and one short circuit stable negative resistance;

FIG. 11, part of a circuit corresponding to FIG. 10 modified in order to realize an adjustable gain.

While the negative resistance concept is a very useful one in the study of transmission networks and while it has also led to useful practical realization, like an ideal transformer, an ideal negative resistance cannot be realized in practice. Amplifiers being involved in the realization of negative resistances, since the bandwidth of amplifiers are finite, it is clear that the negative resistance will only be such over a predetermined frequency band and will no longer afford a negative resistance outside predetermined frequency limits. It is already known from such prior patents as Belgian Pat. No. 654.515 to A Fettweis corresponding to U.S. Pat. No. 3,324,247, that negative resistances can be advantageously used in resonant transfer networks so that multiplex amplification can be secured in time division multiplex telecommunication system. The latter usually employ a sampling frequency of the order of 10 kc./s. and with 25 channels using the same multiplex highways, the channel time slot is then equal to 4 microseconds out of which half is reversed as a guard time in order to reduce crosstalk between adjacent channels to an acceptable value. Thus, amplitude modulated pulses of 2 microseconds duration appear at the rate of 250 kc./s. and as it can be shown that the contribution to the total waveform power by frequencies higher than the fifth harmonic of the frequency is less than 0.15 percent, for resonant transfer time division multiplex systems, there is no reason to require a larger frequency bandwidth than 1.25 Mc./s. for the negative resistances used in such systems to secure amplification. Indeed, it will be shown that the larger the required bandwidth the more the negative resistance becomes critical.

It is also well known that negative resistance converters can be of the open-circuit or of the short circuit stable type. If one assumes an open-circuit stable negative resistance converter, one may consider the conditions which the impedance $Z(p)$ seen through that negative resistance converter should fulfill. This will permit to define the structure of the equivalent circuit of a negative resistance which will be useful to determine suitable negative resistance amplifier circuits. A first condition is that the impedance $Z(p)$ should be a rational function of p, i.e., the imaginary angular frequency. In other words $Z(p)$ may be written as

$$Z(p)=(K)\,\frac{p^{a}+A_{a-1}p^{a-1}+\ .\ .\ .\ +A_1p+A_0}{p^{b}+B_{b-1}p^{b-1}+\ .\ .\ .\ +B_1p+B_0}=\frac{N(p)}{D(p)} \qquad (1)$$

In the above expression, A_0, A_1, ...,B_0, B_1, ..., K are constant together with the exponents a and b of the power series in the numerator and in the denominator of the expression which are identified by $N(p)$ and $D(0$respectively.

A second condition should be that when p tends to zero, $Z(p)$ should reduce to a purely negative resistance $-R$, i.e. $KA_0/B_{oah}=-R$ (2)

A third condition is that since the circuit has been assumed to be open-circuit stable, $Z(p)$ should have no poles in the right half of the p-plane or in other words the denominator $D(p)$ should be a Hurwitz polynomial.

Finally since an open-circuit stable negative resistance converter is short circuit unstable, $Z(p)$ should at least have one zero in the right-half p-plane which means that the numerator $N(p)$ should not be a Hurwitz polynomial.

Clearly, the simplest way to satisfy the above conditions for an open-circuit stable negative impedance is to represent the latter, as is already well known, by a negative resistance, in series with a positive inductance.

Obviously, in the dual case of a short circuit stable negative impedance, the latter may be represented by a negative conductance in parallel with a positive capacitance.

Such a simple equivalent circuit for a negative impedance while it corresponds to the fact that a purely resistive negative impedance can never be secured, does not clearly exhibit the other limitation of negative impedance converters, mainly their limited frequency bandwidth, since though the inductive term becomes more and more significant as the frequency increases, a constant negative term remains. This can be remedied by considering a slightly more complex circuit for Z which will still satisfy the four conditions given for $Z(p)$ expressed by (1), but whose resistive component will cease to be negative when a certain frequency is reached.

FIG. 1 represents this network for Z and it is seen to include a negative resistance $-R$ in series with a parallel circuit constituted by the inductance L_c and the resistance (positive) R_c. The shunt capacitance C'_c shown in dotted lines across the impedance Z can for the moment be disregarded. The impedance Z can be written as

$$Z=-R+\frac{pL_cR_c}{pL_c+R_c} \qquad (3)$$

It can be seen that in order to satisfy the above conditions for Z, the resistance R_c shunting the inductance l_c should have a magnitude larger than that of the negative resistance $-R$. Thus clearly, from a certain frequency, the resistive component of Z will become positive. This resistive component is given by

$$-R+\frac{w_c^2L_c^2R_c}{w_c^2L_c^2+R_c^2}=-(1-k_c)R \qquad (4)$$

in which w_c represents an angular cut off frequency at which this resistive component of Z has become a certain predetermined fraction of the resistive component $-R$ at zero frequency. This fraction is defined by the coefficient k_c. From equation (4) an explicit relation for the angular cut off frequency w_c can be obtained, i.e.,

$$w_c=\frac{R_c}{L_c\sqrt{\frac{R_c}{k_cR}-1}} \qquad (5)$$

which clearly shows that the latter is inversely proportional to the spurious inductance L_c inevitably associated with a negative impedance of the open-circuit stable type. A factor of merit may be associated to a negative impedance by expressing the ratio of the real part to the imaginary part of the impedance, which ratio will of course decrease as the frequency increases.

The shunt capacitance C'_c will now be considered. It may represent a stray capacitance inevitably associated with the input of a negative impedance converter. If this spurious capacitance reaches a certain value, the arrangement will become unstable. This can be shown by considering the admittance dipole of FIG. 1 and by equating this admittance expression to zero. This gives the following quadratic in p implicitly defining the resonant frequency;

$$p^2+\frac{p}{R_c-R}\left(\frac{1}{C'_c}-\frac{RR_c}{L_c}\right)+\frac{R_c}{(R_c-R)L_cO'_c}=0 \qquad (6)$$

It will be clear from the above that as long as C_c is small enough to keep the term in p positive, the circuit remains stable but an oscillatory instability condition will occur as soon as C_c reaches the value L_c/RR_c which makes that term in p equal to 0. For higher values of C_c still instability will occur by exponential increase.

Calling C_{c0} that critical value at which instability occurs, the ratio R_c/L_c appearing in (5) can be eliminated so that one may write

$$w_o C'_{c0} = \frac{1}{\sqrt{\left(\frac{R_c}{k_c} - R\right) R}} \quad (7)$$

showing quite clearly that the larger the required bandwidth (w_c), the smaller will be the critical capacitance C'_{c0} leading to instability. An analogous condition will occur in the case of a short circuit stable negative impedance converter which is shown in FIG. 2. Therein, the negative pure conductance $-G$ is shunted by the series combination of the positive conductance G_c with the capacitance C_c. In this case, it is the shunt stray inductance L'_c shown in dotted lines in FIG. 2, which will be the critical element leading to a formula corresponding to (7).

The effect of spurious reactive terminations on the negative impedances of FIGS. 1 and 2 having been investigated, the possibility of varying the negative resistance $-R$ will now be examined with the help of FIG. 3. The latter represents the open-circuit stable negative resistance of FIG. 1 but with a resistance R_p connected in parallel thereto. This kind of connection may be desireable if one wishes to adjust the gain provided by a negative resistance. A gain variation may for instance be desired in the case of time division multiplex interconnection on a resonant transfer basis as envisaged for instance in the above mentioned Belgian Pat. No. 654,515 A. FETTWEIS, corresponding to U.S. Pat. No. 2,324,247. Indeed, while the latter shows that negative resistances may be employed to secure amplification in multiplex fashion, i.e. economically, in such connections it may not always be desirable to have such negative resistances used in multiplex fashion provide their maximum gain in all circumstances. For instance, when a connection is being established, as long as the called subscriber has not replied, there is an open termination on the called side which is known to be a very unfavorable condition. Yet, if voice frequency signalling is used, transmission must however be assured for that purpose before the speech connection is set up. Thus, in such conditions it would be best to have a higher gain of the multiplex amplifier realized by way of negative resistances when the speech connection is finally set up. Indeed, as shown in the Belgian Pat. No. 655,952 to A. FETTWEIS, corresponding to U.S. Pat. No. 3,431,360, losses in the actual resonant transfer circuit may be compensated by negative resistances used in multiplex fashion, but in order to have a stable overall amplification compensating losses outside the resonant transfer circuit, it was shown therein that so-called pulse impedance reflection coefficients should be sufficiently small and proper line terminations will usually be necessary to achieve this. Adding or withdrawing positive resistance in series usually imply inadequate tolerances on the values and shunt additions may be deemed preferably. In FIG. 3, by putting a positive resistance R_p in parallel with the negative impedance circuit, this leads to an increase magnitude of the negative resistance. This will be true provided the magnitude of R_p is larger than R since the increase factor will be R_p/R_p-R. The network of FIG. 3 involving three resistances and one inductance may of course by simplified to a two-resistance/one-inductance structure, i.e., the basic one for the open-circuit stable negative impedance. It may also be shown that the value of the critical capacitance will be increased so that there is no worsening of the stability condition. Only the figure of merit will be reduced by this increase of the negative resistance. Similar results can be secured for the short circuit stable type of negative impedance

represented in FIG. 2. Again, paralleling such a negative impedance with a positive resistance of larger magnitude than the original one will result in a combined negative resistance of larger magnitude without a deterioration of the stability condition, but merely with a decreased figure of merit.

FIG. 4 shows the short circuit stable negative impedance of FIG. 2, normally short-circuited by the closed break contacts S_1 applied across a capacitance C. It can be shown that with a certain amount of energy stored in the capacitance C, by the parallel connection of such a short circuit stable negative impedance, amplification of the stored energy can be secured. Considering the admittance of the dipole shown in FIG. 4, when the break contact S_1 is open, this can be equated to zero in order to find the roots of the network. This produces the equation

$$p^2 + p\left(\frac{G_c}{C_c} + \frac{G_c - G}{C}\right) - \frac{GG_c}{CC_c} = 0 \quad (8)$$

which is a quadratic in p having always two real roots, as can readily be verified. In order to determine if amplification is possible with such a circuit, one will consider what happens when the capacitance C_c inevitably associated with a negative resistance of the short circuit stable type tends towards zero. Then, by looking at (8) it is seen that only the first part of the term in p together with the term independent of p play a role in the determination of one of the roots which tends towards G/C. But the last term of equation (8) which is negative, gives the product of the two roots of the quadratic and accordingly, as C_c tends towards zero, the other route tends toward minus infinity thus providing that a short circuit stable converter can operate correctly if it is connected in shunt across a capacitance. By a similar reasoning, it can however by proven that if an open-circuit stable converter of the type shown in FIG. 1 is connected across a capacitance, no amplification will be possible because as L_c tends towards zero, while one of the roots will tend towards 1/CR, the other will tend towards plus infinity. This means that a parasitic mode will exist which increases very rapidly in amplitude and prevents normal operation of an open-circuit stable negative impedance converter when connected across a capacitance.

In using the circuit of FIG. 4 to secure an amplification of an energy sample stored in the capacitance C, one however encounters the problem that the energy must initially by stored into C while the amplified sample must thereafter be extracted from C. At that moment, the short-circuiting break contact S1 must be open and this brings the problem of avoiding at any time that the short circuit stable negative impedance should be open-circuited since an unstable condition would immediately develop.

FIG. 5 shows how such an amplification may be achieved. The capacitance C has one of its plates grounded, while the other may be connected either to a source of energy (not shown) through the normally open make contact S_3, or alternatively, to a load (not shown) through the normally open break contact S4. One side of the negative resistance circuit of the type shown in FIGS. 2 and 4 is grounded, while its other terminal may be connected to the upper plate of C through a normally open make contact S2 in series with resistance R_B. Finally, the open-circuit stable negative impedance is normally short-circuited through closed break contact S1 in series with resistance R_A.

FIG. 6 identifies the sequence of operation when transferring a sample of energy into C in order to withdraw thereafter an amplified sample. The pulse S3 indicates the closure of the corresponding contact so that an energy sample is stored, e.g., by resonant transfer operation (not shown), into C. Thereafter, S3 being again open, S2 is closed so that the energy stored in C is allowed to be partially discharged through resistance R_B in series with resistance R_A shunted by the negative resistance. Thereafter S2 being still closed, S1 is now opened whereby capacitance C is now coupled to a resultant negative resistance equal to the difference between the magnitude of the negative resistance device minus R_B. Thus, the sample is now amplified in a measure which depends on the time t_B during which switch S1 is open. This switch will close again while S2 is still closed so that there will be then a second period during which the voltage across C will be allowed to decrease. Thereafter, S2 will again be opened as shown and finally, make contact S4 will be temporarily closed in order to allow the withdrawal of the amplified energy sample on C, e.g., by a resonant transfer operation, towards the load (not shown). Thus, during t_B there will be amplification while during t_A corresponding to the difference in operation times of the switches S2 and S1, the first of which must always encompass the second, there will be attenuation of the voltage across C. The total gain in Nepers may be expressed by

$$\frac{1}{G}\left(\frac{t_B}{\frac{1}{G}-R_B}-\frac{t_A}{R_B+\frac{R_A}{1-GR_A}}\right) \quad (9)$$

A possible drawback of the circuit of FIG. 5 is that the switches S1 and S2 must be able to pass sufficiently high currents as the operating times of closure. FIG. 7 shows that this may be remedied by resonant transfer operation for the amplification, but provided an open-circuit stable type of negative impedance is used in conjunction with capacitance C. Switch S1 is no longer necessary and the negative resistance of FIGS. 1 and 3 has one of its terminals connected to the grounded plate of C while its other terminal may be coupled to the other plate of C through make contact S2 in series with the resonant transfer inductance L. In such a case, it is known that by suitably adjusting the resonant frequency in function of the time of closure of make contact S2, the current through this switch may be zero both at the closure and at the opening time. The roots of the dipole established when S2 is closed can be found by equating the impedance of this dipole to zero and this gives

$$p^3+p^2\left(\frac{R_c-R}{L}+\frac{R_c}{L_c}\right)+p\left(\frac{1}{LC}-\frac{RR_c}{LL_c}\right)+\frac{R_c}{L_cLC}=0 \quad (10)$$

which is a cubic in p having the complex conjugate roots $n_o \pm jw_o$ as well as a third real root n_1. The real and imaginary parts of the roots, i.e. n_o, n_1 and w_o may be found from the coefficients of equation (10) and from the term independent of p one will in particular obtain

$$-n_1(n_0^2+w_0^2)=\frac{R_c}{L_cLC} \quad (11)$$

giving the product of the spurious real root n_1 by the sum of the squares of the real and imaginary parts of the complex conjugate roots. Again, the possibilty of there being a parasitic oscillatory mode which prevents adequate operation of the arrangement of FIG. 7 will be investigated by considering what happens when the spurious inductance L_c tends towards zero. Considering (10) it is clear that when L_c tends towards zero the second parts of the terms in p^2 and p together with the constant term will give

$$p^2-p\,\frac{R}{L}+\frac{1}{LC}=0 \quad (12)$$

which is the quadratic equation giving the complex conjugate roots in the absence of spurious elements. Form this last equation, it is clear that

$$n_0^2+w_0^2=\frac{1}{LC} \quad (13)$$

which means that by comparing (11) and (13) n_1 is seen to tend towards minus infinity when L_c tends towards zero. Accordingly the circuit of FIG. 7 enables amplification on a resonant transfer basis by using an open-circuit stable negative impedance, amplification with or without phase shift being permissible depending on the time during which the switch S2 is closed in relation to the natural resonance of the circuit.

While the circuits of FIGS. 5 and 7 use capacitances as the energy storage element, this could also be achieved by way of an inductive element.

FIG. 8 shows the dual circuit of FIG. 5. This time, L is the energy storage element and instead of being isolated from the other circuits as in FIG. 5 with the help of the normally open switches S2, S3, S4, it is now normally short-circuited with the help of the normally closed break contacts S'2, S'3 and S'4. Normally open make contact S'1 corresponds to the normally closed break contact S1, conductances G_A and G_B correspond to the resistances R_A and R_B, while an open-circuit stable negative impedance involving the element −R, R_c and L_c now corresponds to the short circuit stable negative impedance of FIG. 5. Obviously the circuit of FIG. 8 will operate in a dual manner to that of FIG. 5.

FIG. 9 represents another variant, again obtained by the normal duality rules. Circuit of FIG. 9 is dual of that of FIG. 7 and as in FIG. 8, the energy stored in L can be kept therein due to the break contact S'2, S'3 and S'4 being normally closed. Capacitance C normally short-circuited by S'2 corresponds to inductance L while the short circuit stable negative impedance also short-circuited by S'_r and involving the elements −G, G_c and C_o corresponds to the open-circuit stable negative impedance of FIG. 7. The circuit of FIG. 9 of course operates in a dual manner to that of FIG. 7.

So far, negative resistance amplification has been discussed in relation to stored samples, that is to say where the amplified energy sample is to be found on the original reactive storage element as disclosed for instance by the circuit of FIG. 5 or by that of FIG. 7 using the resonant transfer principle with the advantage that no timing problem arises whereby a switch can be saved, this apart from securing zero currents at the start and the end of the amplification operation. As always disclosed in the U.S. Pat. No. 3,117,185 to H. Adelaar and in the Belgian Pat. No. 654,515 to A. FETTWEIS, corresponding to U.S. Pat. No. 2,324,247, offering the advantage that the parasitic highway capacitance can be considered, amplification of the energy sample may also be secured when transferring energy from one storage device to the other, such an amplifier arrangement being bidirectional.

FIG. 10 shows the arrangement represented in FIG. 3 of the above mentioned Belgian patent. The storage capacitance C1 may be coupled to the other storage capacitance C2 when the normally open make contacts S3 and S4 are closed and when simultaneously, the normally closed break contact S1 is opened. The resonant transfer network is essentially a T-circuit which as disclosed in the above mentioned Belgian patent has symmetrical series branches including the inductance L1 and L2 associated with their respective resistance R1, R'_1 and R_2, R'_2. The shunt branch includes the capacitance $2c/k-1$ in parallel with resistance $R_0/2$. With a symmetrical circuit and with C representing the common capacitance of C_1 and C_2, L the common inductance of L_1 and L_2, R the common resistance value of R_1 and R_2, R' the common resistance value of R'_1 and R'_2, all the element values of the circuit of FIG. 10 which have been mentioned so far can be expressed in function of the capacitance C determining the impedance level of the network:

$$LC=\frac{1}{w_0^2}\left(\frac{w_0^2-n^2}{w_0^2+n^2}\right)^2 \quad (14)$$

$$k-1=\frac{(w_0^2-n^2)\,(w_1^2-w_0^2)}{(w_0^2+n^2)^2} \quad (15)$$

$$nCR=\frac{n^2(w_0^2-n^2)\,(3w_0^2-n^2)}{w_0^2\,(w_0^2+n^2)^2} \quad (16)$$

$$nCR'=\frac{n^2-w_0^2}{n^2-w_0^2} \quad (17)$$

$$nCR_0=\frac{(w_0^2-n^2)\,(w_1^2-w_0^2)}{(w_0^2+n^2)\,(w_1^2+n^2} \quad (18)$$

which corresponds identically to the equations (51) to (55) of the above mentioned Belgian patent. In this manner, with k having a value determined from (15) with w_0 and w_1 being suitably chosen, for instance with

$$w_0 t_1 = \pi \qquad (19)$$

$$w_1 t_1 = 2\pi \qquad (20)$$

wherein t_1 is interconnecting time, reflectionless resonant transfer may be secured between C_1 and C_2 and at the end of time t_1 amplified or attenuated energy samples will be found on the opposite capacitances C_2 and C_1. In particular, it will be possible to provide an amplification of up to 27 decibels provided the resistance R_1, R_2 and $R_0/2$ are negative while R'_1 and R'_2 are positive. Such dipoles as L_1, R_1, R'_1, may be considered as equivalent dipoles corresponding to the original transfer inductance with its associated series and shunt resistances corresponding to the losses inevitably associated with physical inductances, in series with the resistance of the electronic transistorized gates symbolized by the switch such as S3 and also in series with a negative resistance which will be responsible for the negative value of R_1 in the resultant dipole shown in FIG. 10. Thus, while the latter does not show the original dipoles corresponding to the inductances, to the gate resistances and to the negative resistances, nevertheless it will be seen that dipole L_1, R_1, R'_1 is in series with an additional dipole comprising the inductance L_{c1} in shunt with the resistance R_{c1}, a like dipole being also shown in the other series branch going towards the capacitance C_2. Such dipoles as L_{c1}, R_{c1}, obviously correspond to the dipole L_c, R_c represented in FIG. 1 as inevitably associated with practical negative impedances which can never by purely resistive. Likewise, FIG. 10 also shows a branch in shunt with $R_0/2$ and comprising resistance $R_{c0}/2$ in series with capacitance $2C_{c0}$ which corresponds to the spurious elements shown in FIG. 2 as inevitably associated with a short circuit stable negative impedance, i.e., the conductance G_c and the capacitance C_c.

Thus, the resonant transfer amplification circuit of FIG. 10 is seen to include in its series branches, negative impedances of the open-circuit stable type while it has a short circuit stable negative impedance in its shunt branch. In the rest condition, since the switches S3 and S4 are open while S1 is closed, a stable condition is attained. When the positions of the switches shown in FIG. 10 are reversed, amplified resonant transfer operation may take place and after a time t_1 amplified samples will be found on capacitance C_2 and C_1 corresponding to the original samples on capacitances C_1 and C_2 respectively. As for the circuits of FIGS. 5 and 7, it will now be proved that such a particular combination of negative impedance may indeed result in a stable amplifier.

Since the circuit is symmetrical, as previously done for example in the case of the above mentioned Belgian patent, it may be analyzed by separately considering the difference $v_1 - v_2$ and the sum $v_1 + v_2$ of the instantaneous voltages across the storage capacitances C_1 and C_2. The voltage $v_1 - v_2$ is determined by the series branches including the capacitances C_1 and C_2 or in order words by the dipole obtained for instance by closing S3 while keeping S1 closed. On the other hand, the voltage $v_1 + v_2$ will be determined by folding the network over its central branch normally shunted by S1, or in other words by interconnecting the plates of capacitors C_1 and C_2 which are not connected together. Thus, in this second case it is the dipole obtained for instance by closing S3 while leaving S4 open and while S1, provided the impedances of the shunt dipole are doubled (it is for this reason that the factor 2 appears in the definitions of the elements of the shunt branch since such factor will therefore disappear in the analysis) which must be studied.

The stability of the circuit will first be examined by studying $v_1 - v_2$ and the natural frequencies are obtained by equating the corresponding dipole impedance to zero, i.e.

$$\frac{1}{pC} + \frac{R'(pL+R)}{pL+R+R'} + \frac{pL_cR_c}{pL_c+R_c} = 0 \qquad (21)$$

Due to the presence of the third term corresponding to the spurious element of the open-circuit stable negative resistance, the equation in p will be a cubic instead of a quadratic and three relations between the impedance elements appearing in (21) and the roots of the dipole, i.e., $-n \pm jw_0$ the complex conjugate roots and n_c the additional real root caused by the spurious elements of the negative impedance converter, can be secured. Only that corresponding to the term independent of p need by considered here, i.e.

$$-n_c(n^2+w_0^2) = \frac{(R+R')R_c}{LCL_c(R'+R_c)} \qquad (22)$$

which thus corresponds to equation (11) previously considered in relation to FIG. 7. But, when the elements such as L_c and R_c are not present, n^2+w^2 is known to be given by

$$n^2+w_0^2 = \frac{R+R'}{LCR'} \qquad (23)$$

which corresponds to equation (47) of the above mentioned Belgian patent. Therefore, remembering that in the case of amplification, the resistance R'_1 and R'_2 of FIG. 10 are positive, and considering equations (22) and (23), n_c has a negative value inversely proportional to L so that when the latter tends toward zero n_c tends towards minus infinity proving as before that the circuit is stable. By making a similar analysis with short circuit stable negative impedances in the series branches instead of open-circuit stable negative impedances as used in FIG. 10, it can be shown that the opposite situation arises and such a circuit would be associated with a parasitic mode preventing normal operation.

Considering now the dipole associated with $v_1 + v_2$, i.e., obtained by folding the network about its axis of symmetry, the dipole equation will include the terms of (21) plus the impedance of twice the central branch shown in FIG. 10, i.e.

$$\frac{1}{pC} + \frac{R'(pL+R)}{pL+R+R'} + \frac{pL_cR_c}{pL_c+R_c} + \frac{1}{\dfrac{pCR_0+k-1}{(k-1)R_0} + \dfrac{pC_{c0}}{pC_{c0}R_{c0}+1}} = 0 \qquad (24)$$

It will be recognized that this equation in p is now of the fifth degree involving the complex conjugate roots $-n \pm jw_1$ and the real root $-n$, plus two additional real roots n_{c1} and n_{c2} which are due to the spurious negative impedance elements R_{c0} and C_{c0} of the central branch which raise the degree of the equation in p from the third to the fifth. Again, suitable equations can be established to link the parameters n, n_{c1}, n_{c2}, and w_1 with the values of the elements appearing in (24) but these relations obviously become cumbersome and since only n_{c1} and n_{c2} are of interest to study the stability of the network, it is not necessary to write them all out in full. First of all, it is again the identity between the constant term of the equation of the fifth degree in p and the product of the real roots with the sum of the squares of the real and imaginary parts of the complex conjugate roots which will be of interest, i.e.

$$nn_{c1}n_{c2}(n^2+w_1^2) = \frac{(k-1)(R+R')R_c}{LC^2(R'+R_c)R_0R_{c0}C_{c0}L_c} \qquad (25)$$

Since the corresponding equation when the spurious elements are not present is

$$n(n^2+w_1^2) = \frac{(k-1)(R+R')}{LC^2R'R_0} \qquad (26)$$

which corresponds to equation (50) of the above mentioned Belgian patent, it is clear when considering (25) and (26), while remembering that for amplification R' is positive, that the product of the spurious real roots n_{c1} and n_{c2} will be positive, thus indicating that n_{c1} and n_{c2} have the same sign.

The factor of the term in p^4 of equation (24) gives the sum of the real parts of the five roots but it will not be necessary to write out this complex expression in full since only the real roots n_{c1} and n_{c2} are of interest when the spurious reactive elements L_c and C_{c0} both tend towards zero. Thus, the sum of n_{c1} and n_{c2} will be given by those terms which include either L_c or C_{c0} in the denominator, i.e.

$$-n_{c1}-n_{c2}=\frac{R'}{L_c}+\frac{R'+R_c}{C_{c0}R_cR_{c0}} \qquad (27)$$

from which it is clear that R' being positive in order to secure amplification with the circuit of FIG. 10 and since n_{c1} and n_{c2} have the same sign, that both must be negative whereby upon L_c and C_{c0} both tending towards zero, both n_{c1} and n_{c2} tends towards minus infinity showing that the conditions are stable. It can be shown that even if open-circuit stable negative impedances are used in the series branches, but an open-circuit stable negative impedance is also used in the shunt branch, one of the spurious real roots would in such conditions as mentioned above tends towards plus infinity whereby at least one of the series and parallel negative impedance converters would not operate normally.

Since it is not possible to have an ideal synchronization for the simultaneous operation of switches S1, S3 and S4 from the position shown in FIG. 10 to that in which both S3 and S4 are closed while simultaneously S1 is open, one may wonder if transient unstable conditions might not arise. Since there are three switches which may either be open or closed, there are thus eight possible conditions all together. There are four conditions corresponding to S1 being closed as shown and apart from that which corresponds to both S3 and S4 being simultaneously open, there are three further conditions with either S3 or S4 closed or both. It is clear however that these three conditions correspond to the analysis made above for v_1-v_2 which has thus shown then to be a stable condition. In fact, such temporarily established circuit would correspond also to that of FIG. 7. The remaining four possible conditions for the states of the switches correspond to S1 being open and apart from S3 and S4 being simultaneously closed which is the desired operative condition, there are the two conditions when either S3 or S4 is closed. Such conditions however correspond to the analysis made above for v_1+v_2 which has been shown to be a stable situation. FInally the last of the eight possible conditions correspond to both S3 and S4 being open together with S1, but then, this is the situation corresponding to FIG. 5 which has also been shown to be a stable one. Additionally, for such a spurious transient condition it can be shown that the basic time constant is large enough to avoid disturbing the overall operation of the circuit even when a substantial gain is desired. Indeed, with all three switches of FIG. 10 open, from (15) and (18) the time constant formed by the resistance $R_0/2$and the capacitance $2c/k-1$ is given by

$$\frac{CR_0}{k-1}=\frac{1}{n}\frac{n^2+w_0^2}{n^2+w_1^2} \qquad (28)$$

and even with the maximum gain of π Nepers, using (19) and (20) it is found that the time constant defined by (28) is equal to $2t_1/5\pi$ which is still a reasonable portion of the interconnecting time to avoid that a short incorrect transient condition would impair the operation of the resonant transfer amplifier.

Considerations have been given by means of FIG. 3 regarding the use of a shunt resistance across an open-circuit or a short circuit stable negative impedance in order to vary the magnitude of the negative resistance, e.g. to increase the negative resistance of an open-circuit stable converter by shunting. This may be advantageously carried out in the circuit of FIG. 10 when the latter represents the multiplex amplifier inserted between two highways leading to telephone subscribers. As long as the connection has not been completely established, an open subscriber line on the called side could as explained in the Belgian Pat. No, 655,952 could, (A. Fettweis 12), lead to unstability if the amplification arrangement of FIG. 10 is adjusted to secure an overall gain. However, it has shown in this Belgian patent that conditions external to the resonant transfer circuits do not affect stability if the multiplex resonant transfer amplification means using negative resistances merely compensate the resonant transfer losses. The equation (16), (17) and (18) indicate that whereas R should increase for an increasing gain, i.e., an increasing value of n, the reverse is true for R' and R_0. Thus, remembering that both R and R_0 are negative resistances for an amplifying arrangement while R' is positive, if when the complete connection has been established, upon the called subscriber lifting his receiver, it is desired to then provide a gain which more than compensates the losses of the actual resonant transfer circuit, the magnitude of R should be increased while those of R' and R_0 should be decreased. As seen in relation to FIG. 3 this result can be achieved by putting a positive resistance in parallel with R, one in parallel with the positive resistance R' and finally by removing some positive resistance in parallel with the negative resistance R_0.

FIG. 11 illustrates this possible technique for adjusting the gain after the complete connection has been established, by representing the left hand side of FIG. 10 but this time with the original inductance coil 1 and the original open-circuit stable negative impedance converter such as 2 as well as the original short circuit stable negative impedance converter 3, the shunt capacitance of value $2C/k-1$ being indicated by 4. In addition to the switches S1, S3 and S4 of FIG. 10, FIG. 11 shows the additional switches S5, S6 and S7 serially associated with the resistances 5, 6 and 7 respectively. Of course, switches S'6 and S'7 (not shown) are used for the right-hand series branch of FIG. 10. As long as the complete connection between the two subscribers is not established, the switches S5, S6 and S7 will remain in the positions shown, that is to say closed for S5 and open for S6 and S7. At the required sampling rate, the switches S3 and S4 will be simultaneously closed while S1 will be open thus enabling resonant transfer amplification of the energy sample arising for instance from the left hand subscriber (not shown) through the coaxial cable 8 constituting the highway serving this group. When the connection is completely established however, switch S5 may then open in unison with S1 while switches S6 and S7 will close simultaneously with S3 and S4 whereby the disconnection of resistance 5 and the connection of resistances 6 and 7 may lead to a suitable increase in the gain which may become permissible due to both ends of the connection being terminated.

With the arrangement of FIG. 11, it will be noted that the resonant transfer inductance 1 is not inserted between the coaxial cable 8 and the storage capacitance C_1 (not shown in FIG. 11) of the subscriber's line circuit so that the capacitance of the coaxial cable, plus the parasitic capacitance accumulated at the entrance of this cable where all the various subscribers line circuits are multiplied, will be put directly in shunt with the storage capacitance C_1 whenever the switches of the connection are closed. This direct interconnection of the capacitances will of course create a loss but this can be kept reasonably small if this spurious capacitance is relatively small with regard to the storage capacitance. It will also means that the coaxial cable 8 serving at highway will be left with some residual energy after each sampling operation but this is not a serious drawback since in any event clamping means must always be provided to discharge the highway as conditions are never ideal in practice. These clamping discharge means may of course be operated during the guard time between successive channel time slots. As to the additional loss caused by the interconnection (direct) of the capacitance at the entrance of the coaxial cable such as 8, this can of course by compensated by the amplifying arrangement of FIG. 11.

While the principles of the invention have been described above in connection with specific apparatus, it is to be clearly understood that this description is made only by way of example and not as a limitation on the scope of the invention.

What is claimed is:

1. A negative resistance amplifier comprising a short circuit stable negative resistance device, a first open-circuit stable negative resistance device and a second open-circuit stable negative resistance device; said short circuit stable negative resistance device including a reactive storage device, a negative resistance and first switching means coupled to selectively interconnect said reactive storage device and said negative resistance; said first and second open-circuit stable negative resistance devices each including a positive inductance coupled in series with second switching means to a negative resistance; and third switching means coupling said first open-circuit stable negative resistance device in series to the short circuit stable negative resistance device and fourth switching means coupling said second open-circuit stable negative resistance device to the short circuit stable negative resistance to provide bidirectional amplification.

2. A negative resistance amplifier as claimed in claim 1, in which said first switching means includes a switch having an operated and an unoperated position, said switch in the unoperated position coupling said negative resistance to a positive resistance of such a value that the resultant resistance is positive.

3. A negative resistance amplifier as claimed in claim 2, including a second positive resistance and said switching means including a third switching means which in the operated position couples the negative resistance in said short circuit stable resistance to said storage device and to the second positive resistance, said second positive resistance having a value such that the resultant resistance is negative.

4. A negative resistance amplifier as claimed in claim 3, in which the time during which said third switching means is operated encompasses the time during which said first switching means is operated.

5. A negative resistance device as claimed in claim 4 in which the difference between said times divided by the magnitude of said resultant negative resistance is larger than the total time during which said first switch is operated while said third switch is not operated, divided by the sum of said resultant positive resistance with said second positive resistance.

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