PRECISION DIRECT-CURRENT TRANSFORMERS WITH ACTIVE ELEMENTS - A PROGRESS REPORT

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I. Abstract

The principal features are recalled of the Brentford DC Transformers which measure the excitation currents of the main ring and beam transfer magnets of the CERN ISR, with reproducibility errors of a few parts per million. For reasons discussed the power supplies for the DESY ISR now under construction at Hamburg, West Germany, require similar precision stability with greatly enhanced linearity and signal-to-noise ratio. The paper analyses the main sources of instrument errors and demonstrates how these may be reduced or eliminated by the addition of simple active elements to the basic passive element circuit. Some details are quoted of the performance improvements obtained on development models in the laboratory with the use of these active-element circuits and the paper concludes with some general remarks on the costs of the new circuits under discussion.

II. Historical Note

One major and continuing problem for the power supply engineer associated with particle accelerator projects is the extremely high order of accuracy required in the measurement of direct currents in the order of several hundreds to several thousands of amperes. For example, in normal industrial measurements a reproducibility error in a dc current transformer of 0.1% (1000 ppm) would place the transducer in the "precision" class. For beam transfer magnet and storage ring magnet work however, reproducibility errors of between 100 and 1000 times smaller are required. To maintain the overall system errors in the same order, the transducer is always associated with a high-gain amplifier. This in turn (depending upon the system dynamics) sets a severe limitation on the permissible level of ac noise superimposed upon the dc signal from the burden of the current transformer.

It was for this reason that at the beginning of the last decade, Brentford Electric Limited decided to abandon the use of the Kraemer type series-connected transductor current transformer which had hitherto been used for this purpose and which has been extensively developed all over the world.[1] Instead, a considerable development programme was set on foot to bring the performance of the parallel-connected transductor circuit of Dr. Hingorani[2,3] up to the performance levels required. The first major accelerator project on which this type of dc current transformer was used was the power supplies for the beam transfer magnets of the Northern Universities Electron Synchrotron (NINA) at Daresbury in England. Since that time considerable further experience has been gained at the various University laboratories throughout the world and at the Rutherford Laboratory in the U.K. However the most testing project to date for this type of current transformer was the power supplies for the main ring magnets and the beam transfer magnets of the CERN intersecting storage ring installation at Geneva in 1969. For this project a range of DCCTs was required with nominal full load currents from a few hundred amperes up to 2000 amperes and with reproducibility errors in the order of 4 or 5 parts per million of full current. Linearity errors of one or two hundred parts per million were however acceptable, since each power supply and transducer was calibrated with its associated magnet, the linearity errors of which were considerably larger. Like all previous systems on which this C.T. had been used, constant current power supplies were required and the problem of a relatively high temperature coefficient (2 p.p.m. per ^{o}C.) was overcome by fitting each transducer with a heater and temperature detecting winding which, with its associated electronics, maintained the cores and windings of the transducer at a constant temperature within $\pm$ 0.5^{o}C.

Early in 1971 discussions were started on the power supplies to energise the Intersecting Storage Rings for the Deutsches Elektronen-Synchrotron (DESY) at Hamburg, which is currently under construction. For these ISRs two modes of operation are envisaged for all magnets. The constant current mode of operation presents no undue problems, but the alternative mode, in which all power supplies have their currents ramped-up or down linearly at a rate corresponding to full current in 200 seconds, presented very severe problems, since velocity lags greater than 16 parts per million were inadmissible.

If one considers the transfer function of the main current control loop to roll off from its dc gain value at -6dB per octave, a quick calculation will show that to achieve the above velocity-lag errors, a bandwidth of at least 50 Hz is required. Under these conditions a signal-to-noise ratio about a thousand times better than has previously been required is necessary. It is also doubtful whether compensation of the relatively high temperature coefficient by means of a thermal stabilisation loop would be acceptable, due to thermal time lags.

An additional complication was that linearity errors not exceeding 50 parts per million of the maximum value over a current range down to 1% were mandatory. Work was therefore put in hand to see how the already excellent performance of the current transformers used for the CERN ISR project could be still further improved to meet the requirements of DESY.

III. Principles of the Brentford/Hingorani DCCT with Passive Elements

In order to understand the operation of the Brentford/Hingorani DCCT it is as well to start from the more widely known Kraemer circuit which is shown in Figure 1. Here two magnetic cores made from a material with a rectangular B/H loop are wound with equal numbers of turns and placed over a primary busbar. The secondary windings are connected in opposition in series with a supply transformer and a rectifier bridge feeding the Burden resistor. Voltage, flux and current waveforms are shown in Figure 2. It is clear that in the simple prototype circuit as shown in Figure 1 the Burden current will show notches extending from the d.c. current level down to zero twice in every cycle of the supply waveform. Apart from producing a very poor signal-to-noise ratio, the primary and secondary windings of the transformer are effectively uncoupled at the moment that the notches occur. This also has a deleterious effect on the accuracy of the instrument. It is well known that it is possible to remove the notches by including reactance in series with the Burden resistor. This, while improving the accuracy and signal-to-noise ratio, produces a serious limitation of bandwidth of the current transformer. The circuit of the Brentford/Hingorani DCCT is shown in Figure 3 with its voltage, flux and current waveforms in Figure 4. Brief study will show that in this circuit the windings on cores C1 and C2 are effectively connected in parallel across the supply transformer through the four diodes. From Figure 4 it can be seen that each core is unsaturated (and therefore acting as a transformer with a true ampere-turns-ratio balance) for about three-quarters of a cycle and that the commutation of the Burden current from one winding to the other occurs twice per cycle at points where both cores are still unsaturated. Measuring accuracy is not therefore affected by commutation, and the depth of the notches which occur, instead of being equal to the full Burden current, is approximately twice the magnetising current of the cores, i.e. about one-thousandth of the Burden current.

IV. Causes of Error

As with any type of current transformer, the major component of the difference between the primary and secondary ampere-turns is the MMF required to magnetise the core. If the core magnetising current could be kept absolutely constant its presence would cause no difficulty and it could be easily compensated for. This is however not the case, and much of the recent work on the DCCT has been devoted to finding ways of improving the constancy of the magnetising current.

There are two main causes of variation of magnetising current which relate to load current and core temperature respectively. Firstly consider the case of the core with an ideal rectangular B/H loop having zero permeability when saturated and infinite permeability when unsaturated. Under these circumstances the value of the magnetising current in the unsaturated regime would be independent of the actual flux density swing in the core. Magnetic materials with approximations to this type of characteristic are available (for example in Britain under the trade name H.C.R.Metal). However, while these materials exhibit a very high and constant permeability in the unsaturated region, their coercivity and hence magnetising current, is some ten to twenty times higher than certain other nickel-iron alloys with a greater curvature of the hysteresis loop (e.g. Supermumetal). The permeability of both alloys is similar and varies with temperature at a similar rate. Thus although the use of the square loop alloy gives greater constancy of magnetising current under varying flux conditions it also gives ten to twenty times the temperature co-efficient obtained with Supermumetal, which is accordingly the material of choice.

The sensitivity of the transformation ratio to the extent of the swing in core flux density has been appreciated for a long time and until the present work was put in hand d.c. current transformers for the highest precision were fed from passive constant voltage supplies usually of the type comprising a transformer with a saturating third limb. By the use of such a device of which there are many available on the market, a very considerable improvement in stability may be achieved. The devices are however frequency-sensitive, and great care is needed to match the frequency coefficient of the voltage stabiliser with that of the d.c. current transformer. Furthermore, if one examines Figures 3 and 4 it will be clear that the total excursion of the core flux from the negative saturation limit depends on the positive voltage-time integral, which in turn depends upon the applied a.c. voltage V1 minus the zenner diode voltage V2 and minus the IR drop in Burden resistor, the auxiliary transformer and the windings of the coils. This latter term varies significantly with changing load current (and indeed with temperature if the transformer and the coil windings are made of copper) so that even if the supply voltage, V1, is maintained absolutely constant, the voltage-time integral and hence the flux excursion, and the magnetising current will vary in a significant manner with variations in both load current and temperature. This effect alone provides the main component of the non-linearity errors and the transducer temperature coefficient in the passive DCCT.

V. Stabilisation of the Core Flux Density with Active Elements

The most successful line of attack on the above-mentioned problems lay through the well explored territory of negative feed-back. As shown in Figure 5, each of the two cores of the DCCT was provided with a feedback winding W1, W2, connected in series opposition and providing a voltage Vo depending on the rate of change of flux in both cores. This voltage fed to the input terminals of an integrator I produced at its output terminals a voltage Vo' directly proportional to the instantaneous flux excursion in the two cores. From Figure 4 it may be seen that the maximum flux excursion in either core occurs at the moment that the back e.m.f. in the corresponding winding reverses sign. The crossing detector circuit D connected to the feedback windings, detects the two instants per cycle when the voltage Vo passes through zero and produces two strobe pulses per cycle which are fed to the sample-and-hold circuit S/H which samples the voltage Vo' at these same two instants, i.e. at the moment of maximum flux swing in the cores. The output voltage Vo'' is compared in amplifier A with a fixed bias potential and the amplified error voltage is fed to the a.c. bridge circuit B, one arm of which comprises an F.E.T. transistor. The bridge B is supplied at mains supply frequency (i.e. 50 Hz in Europe) and is arranged to produce zero output for zero error signal from the amplifier A. In the presence of an error signal of a given size and polarity, a 50 Hz a.c. signal of corresponding amplitude and polarity is fed to Transformer 2, and injected in series with the main energising voltage from Transformer T1, thus raising or lowering the a.c. voltage applied to the two measuring cores. It will be quickly appreciated that the whole circuit forms a closed feedback loop controlling the voltage supplied to the current transformer windings, such that their peak flux swing is maintained constant at a value determined by the bias potentiometer P.

The effect of this new feedback circuit on all the main performance parameters of the transducer is dramatic. Thus it has been our practice in the past with the passive DCCT to quote the linearity errors measured between 100% and 10% of nominal full-load current; these errors being normally in the order of ± 100 to 200 parts per million. In the region between 10% full-load current and zero, linearity errors became so large that special measures were required to overcome them in the case of wide current range equipments, and they were regarded as falling outside the specified performance range of the transducer.

Now with prototype feedback DCCTs, linearity errors measured over the range from 100% - 1% of nominal current are within the limits ± 20 p.p.m. and within the range from 70% - 1% of full load current linearity errors are no greater than ± 5 p.p.m. Similar improvements are noted in the temperature coefficient of the DCCT without thermal stabilisation. Thus, over the temperature range from 20°C to 60°C ambient, the passive DCCT shows a temperature coefficient somewhat in excess of 2 parts per million. The use of the flux stabilising feedback circuit reduces the temperature coefficient by 10 times to less than 0.2 p.p.m. per degree C.

The voltage coefficient (i.e. the variation in transformation ratio error for a given variation in the supply voltage) is reduced from 8 - 10 p.p.m. per % for the passive CT to less than 1 p.p.m. per % for the feedback type. The frequency coefficient, which defines the change in transformation ratio error with variation of supply frequency, remains of the same order at about 5 p.p.m. per %. However, the rather arduous task of matching the frequency coefficient of a constant voltage transformer with that of the d.c. current transformer is now eliminated.

VI. Supply Voltage Harmonics, their Effects and Elimination

While the variation in core magnetising current is the main cause of transformation ratio error, it is not by any means the only one. A secondary contributor to the error is the interwinding capacitance C, C' as shown in Figure 5. With careful design this capacitance may be made comparatively small, but particularly with heavy current d.c. current transformers where a large turns ratio is required, the capacitance current even at 50 Hz (60 Hz in the U.S.A.) is not insignificant when compared with the magnetising current. If the mains supply voltage contains harmonics, particularly the higher harmonics produced by rectifying equipments, there is a considerable probability that harmonic currents flowing in the interwinding capacitance will produce an offset error, which while comparatively independent of load current and ambient temperature, will obviously vary with the variation of harmonic voltages in the supply and is thus inadmissible. This problem may obviously be overcome by adequate filtering of the incoming supply mains with passive LC components. With the feedback CT however, a more elegant solution is at hand. As shown in Figure 6 the total supply voltage across the secondary windings of transformers T1 and T2 is fed through notch filter F, having a notch of adequate Q and frequency centred on the supply frequency to the input of the power amplifier PA. This arrangement produces negligible negative feedback at the frequency of the filter notch, but considerably attenuates all voltages present in the main supply at frequencies removed from the fundamental. Typically, without the notch filter, transferring the auxiliary supply of a 500 amp DCCT from normal industrial mains supply to an approximately square wave supply of the same frequency produced an error offset of just over 100 p.p.m. By including the notch filter with a Q of about 20 in the circuit of Figure 6 this offset was reduced to less than 2 p.p.m.

VII. Improvement of the Signal-to-Noise Ratio

The feedback circuit referred to above, while significantly improving the d.c. characteristics of the current transformer, has of course, no effect on the signal-to-noise ratio. The major noise component present in the output of the Brentford/Hingorani DCCT appears at twice the supply frequency and has an rms value of about 10 millivolts related to the 10-volt d.c. output for nominal load current. For the present application at least another 60 dB of attenuation is required with a bandwidth of not less than

250 Hz, although a bandwidth of several kHz is to be preferred. Herein lies the essence of the problem, namely that the major disturbing frequency lies well embedded in the passband of the transducer itself.

A well-known passive filter circuit designed to cope with this type of problem is shown in Figure 7. Here the a.c. transformer T has the same turns ratio as the DCCT and has its secondary winding connected in series with the Burden resistor R. Due to the mutual cancellation of d.c. ampere turns in the primary and secondary windings the secondary of the transformer may be designed to have a comparatively high inductance L and any ripple voltages generated in the DCCT itself are attenuated by this inductance in series with the Burden resistor R. The inductor and Burden resistor of course, form a low pass filter circuit with a time constant L/R and a correspondingly limited bandwidth. This is however compensated for by direct a.c. coupling of the primary circuit through the transformer and capacitor C directly into the Burden resistor R. By careful choice of components it is possible to obtain reasonable attenuation of the ripple with a fairly high bandwidth. However, there are a considerable number of constraints on the circuit designer and in this particular case we were unable to obtain an acceptable bandwidth, and attenuation of the ripple, without at the same time an unacceptable undamped high-Q ringing effect at a frequency of the order of 1 to 2 Hz. The passive filter approach was therefore abandoned in favour of an active filter concept, which appeared to show greater promise.

Figure 8 shows the arrangement. An a.c. transformer with windings W1, W2, W3, W4 is coupled to the load busbar through W1 while a current directly proportional to the current in the DCCT Burden resistor R1 is driven through winding W2 by wideband amplifier A1. The d.c. and a.c. ampere turns in W1 and W2 are opposed to each other as in the case of the two windings of transformer T in Figure 7. If the DCCT and amplifier A1 both have infinite bandwidth and perfect linearity the core of the a.c. transformer will remain unenergised. The appearance of a ripple voltage in R1 which has no corresponding component of current flowing in the load busbar, will then produce an uncompensated flux variation in the core of the a.c. transformer. This will generate in the winding W3 and its load resistor, a circulating current by ordinary transformer action. The voltage across the load resistor amplified in amplifier A2 causes a current to circulate in winding W4, which opposes the ampere turns of the winding W2. If amplifier A2 had infinite gain and bandwidth, the ampere turns in winding W2 would equal the sum of the ampere turns in W1 and W4 and the a.c. flux in the core of Transformer T would be zero, that is to say the current flowing in W4 would represent both the ripple component generated by the DCCT and any a.c. dynamic errors of measurement of the DCCT. By suitable choice of resistor R3 a voltage may be generated which is equal to the ripple component present in the resistor R1. If now, instead of taking the output of the instrument from the top end of R1 and ground, we take the output through a differential amplifier D from the top end of R1 and the top end of R3, the ripple component may be virtually completely cancelled. The only bandwidth limitation of the complete system is that due to the a.c. transformer and to the amplifiers A1 and A2 which may without difficulty be made above 100 kHz.

The secondary loop containing the amplifier A2 is not required to have any d.c. gain but considerable problems arise in providing an a.c. coupling for the amplifier with a sufficiently low break frequency. The amplifier is therefore d.c. coupled to the transformer, which is designed with a core capable of sustaining the small d.c. ampere turn unbalance due to drift of the amplifier A2 without saturating, and the auxiliary Burden resistor R3 is a.c. coupled to a resistor R4, the other end of which is grounded. Resistor R4 therefore sees only the ripple component without any d.c. offset, while resistor R1 carries the precision d.c. signal plus the ripple component. The coupling capacitor C is a polycarbonate film type, with a leakage resistance exceeding 10^{11} ohms.

VIII. Choice of Components

The substantial improvement in performance of the DCCT reported above, is of course obtained at the cost of increased complexity of the circuit and it may well be asked whether the cost of the additional electronic components is justified by the improvement in performance for which they are responsible. The answer to this question must, of course, always depend upon the particular application envisaged. None of the additional electronic components however, is a very expensive item. None of the operational amplifiers, for example, is required to have a closed-loop gain greater than about 60 dB or a gain-bandwidth product greater than about 20 to 30 MHz. Professional components of this type are available commercially for about 1 dollar. Excluding the main Burden resistor R1, only three resistors are required to have tolerances or stabilities higher than normal industrial grade and these latter do not require stabilities higher than 0.1%. A small number of high-leakage-resistance capacitors is required and the components for the notch filter of Figure 6 must be trimmed or selected on test with an accuracy of about 0.1%.

With the extremely low noise levels associated with the active filter, very great care must be taken with the screening of the DCCT, and the active filter transformer, against a.c. magnetic fields, particularly at higher frequencies. For this purpose, screening cans of aluminium have been found to be considerably more effective than any form of magnetic material.

While the choice of the main Burden resistor R1 is not strictly speaking dependent on the use of active elements in the DCCT it is perhaps worth noting that our practice in the past has been to use commercially available precision resistors with temperature coefficients in the region of 2 - 3 p.p.m. per °C. mounted in a temperature stabilising oven. For the present project these resistors are being replaced by specially developed resistors, each comprising two series-connected bifilar windings of copper and Zeranin respectively, mounted on brass tubes to equalise temperature gradients throughout the winding, and with the length of the two windings chosen such that the positive temperature coefficient of the copper nearly compensates for the negative temperature coefficient of the Zeranin. Prototype resistors have shown a maximum resistance deviation of 2 - 3 p.p.m. over a temperature range of from 20°C.-60°C. and a maximum slope of 0.2 p.p.m. per °C. These results encourage us to hope that with careful positioning of the Burden resistors the temperature stabilising ovens can be dispensed with.

IX. Conclusion

The present paper is an interim progress report on development work currently in hand. Results quoted so far are based on laboratory tests on development models and it is not appropriate therefore to list tables of definitive performance figures. The first production models will be available, however, in the course of the next few weeks, and it is hoped to publish these results elsewhere as soon as these models have been thoroughly evaluated.

We have devoted some attention in the past to the feasibility of improving the performance of the passive DCCT by the use of differential techniques. For example if two transducers have relatively large errors of the same sign and approximately the same magnitude, it is possible to devise differential circuits which will produce overall errors no larger than the difference of the errors of the individual transducers. However, our efforts in this direction in the past were vitiated by the fact that the spread of errors from one unit to the next was of the same order of magnitude as the errors themselves. There is some indication that with the use of the flux-stabilising feedback techniques referred to above, the spread in errors between units may be reduced even further than the magnitude of the errors themselves. Should this be proved to be the case, when the results from a production series of transducers are available, it could well prove possible to produce relatively cheaply a laboratory d.c. ratio standard of even higher precision than is required for the project at present in hand.

X. Acknowledgments

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XI. References

1. W. Kraemer, I.E.E.E. Trans. 83, 73 pp. 382-390, 1964, N.Y., U.S.A.

2. Adamson and Hingorani, Proc. I.E.E., 110, 4 pp. 739-750 (1963), London, U.K.

3. M.G.J. Fry, I.E.E.E. Trans. on Nuclear Science, Vol. NS18, 3, pp. 865-868 (1971), N.Y., U.S.A.

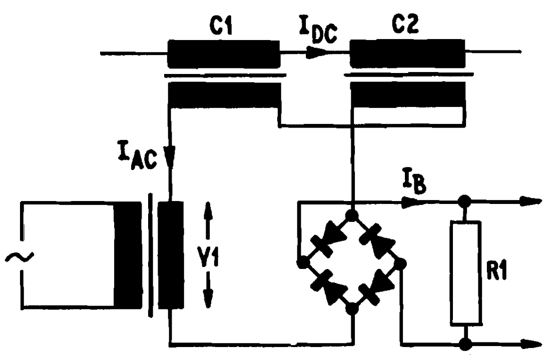

FIG.1 KRAEMER CIRCUIT.

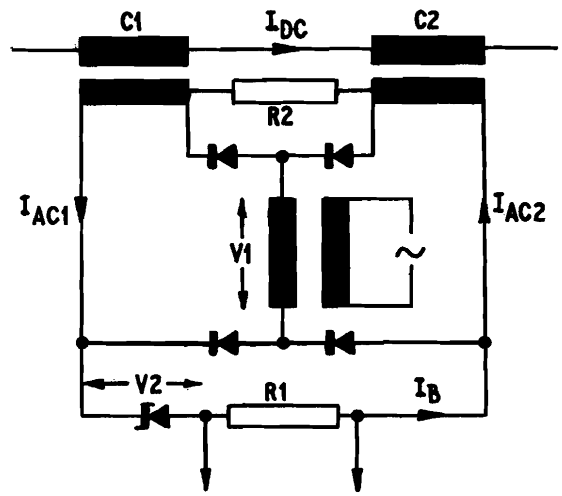

FIG. 3 BRENTFORD CIRCUIT.

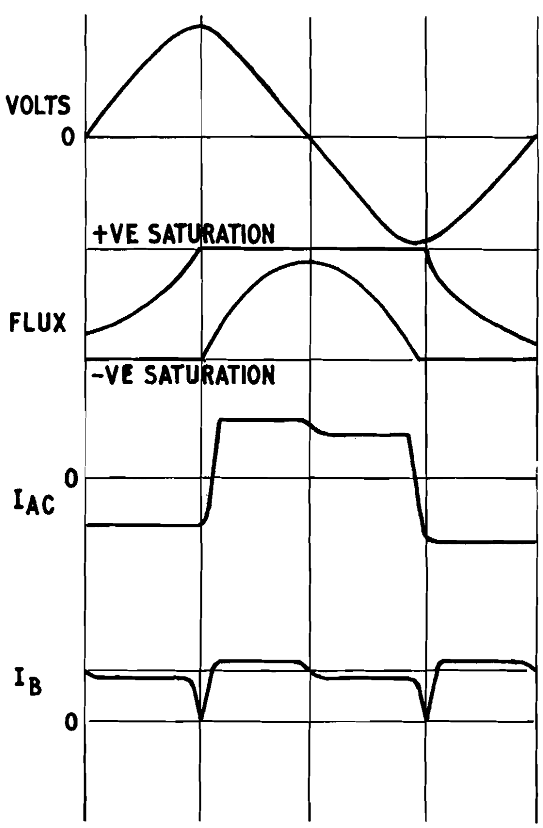

FIG. 2 WAVEFORMS (KRAEMER)

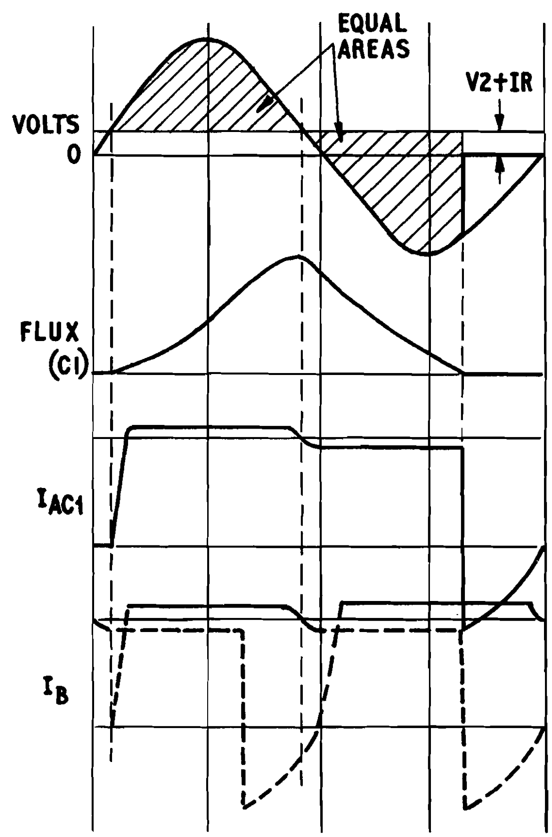

FIG. 4 WAVEFORMS (BRENTFORD)

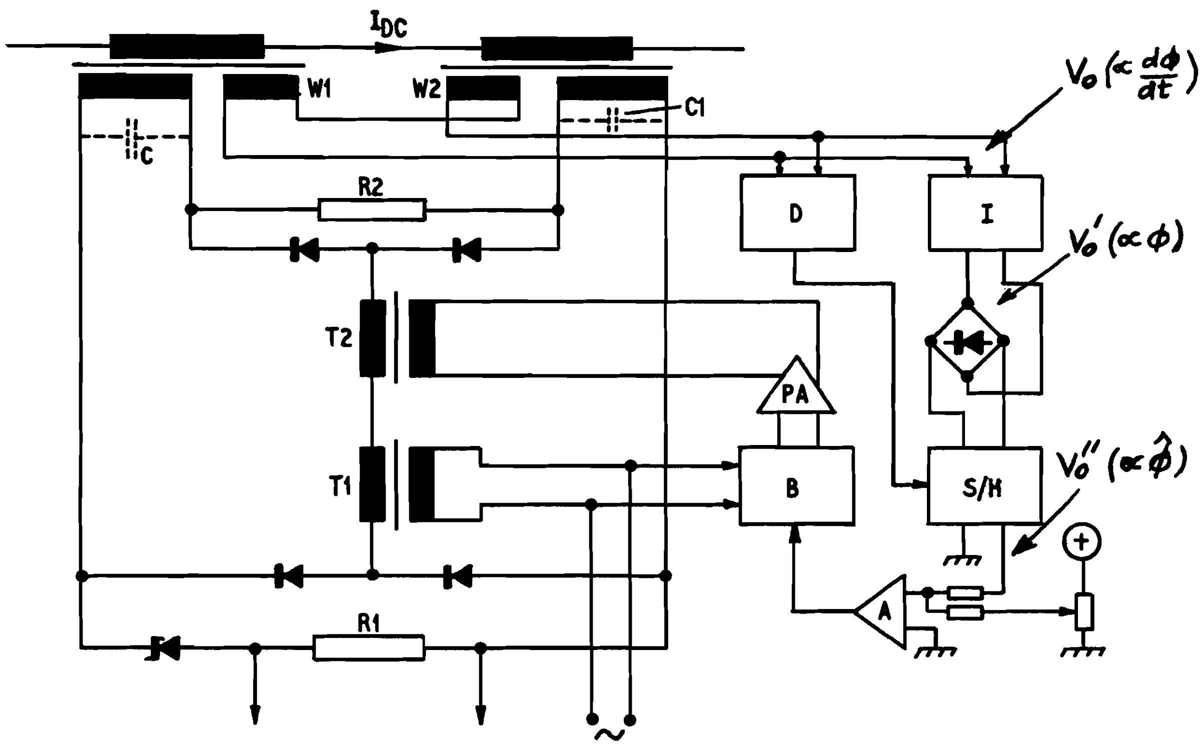

FIG. 5 BRENTFORD D.C.C.T WITH FEEDBACK FLUX STABILISATION.

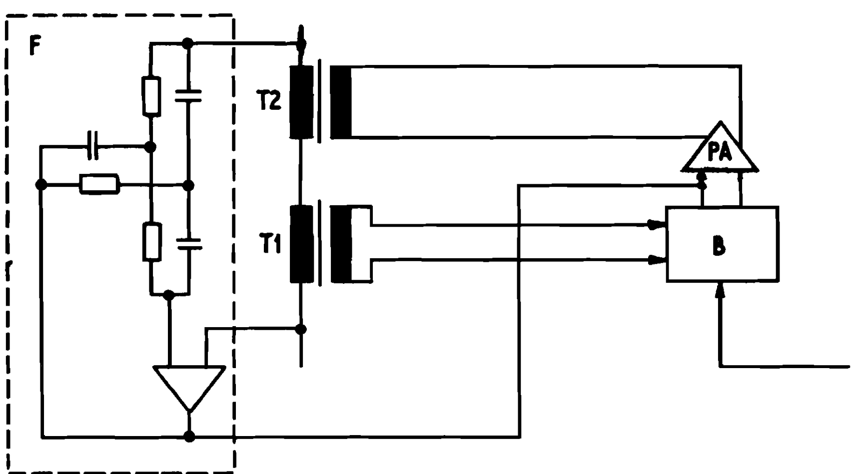

FIG. 6 ADDITION OF NOTCH FILTER FOR SUPPLY HARMONIC SUPPRESSION.

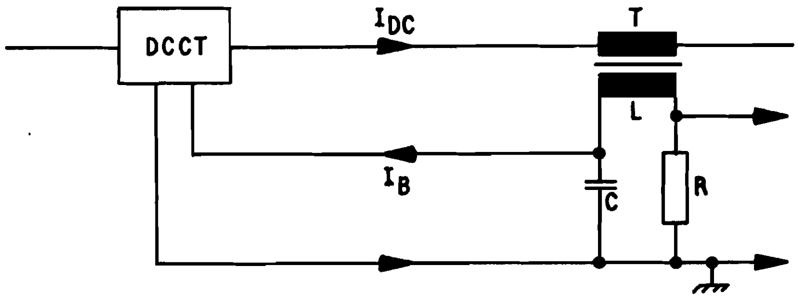

FIG. 7 D.C.C.T. WITH COUPLED PASSIVE A.C.C.T.

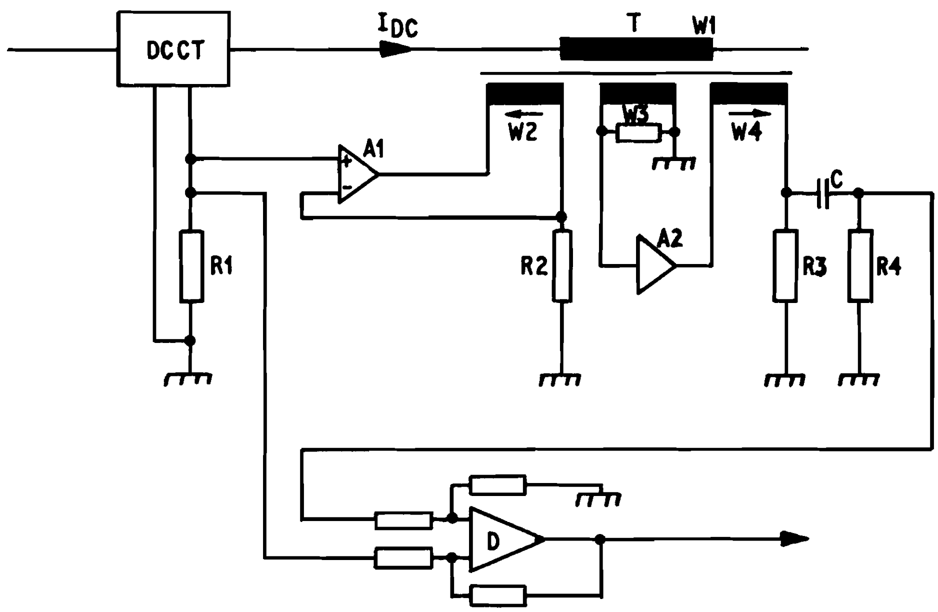

FIG. 8 D.C.C.T WITH ACTIVE FILTER AND EXTERNAL DIFFERENTIAL AMPLIFIER.