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CURRENT LOSS COMPENSATING DEVICE

Filed June 26, 1956

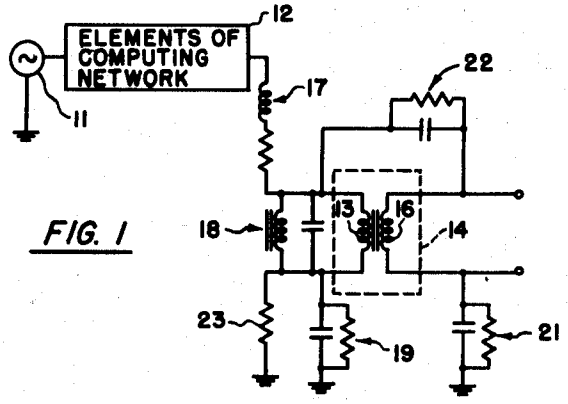


FIG. 1

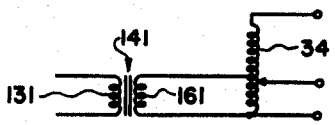


FIG. 3

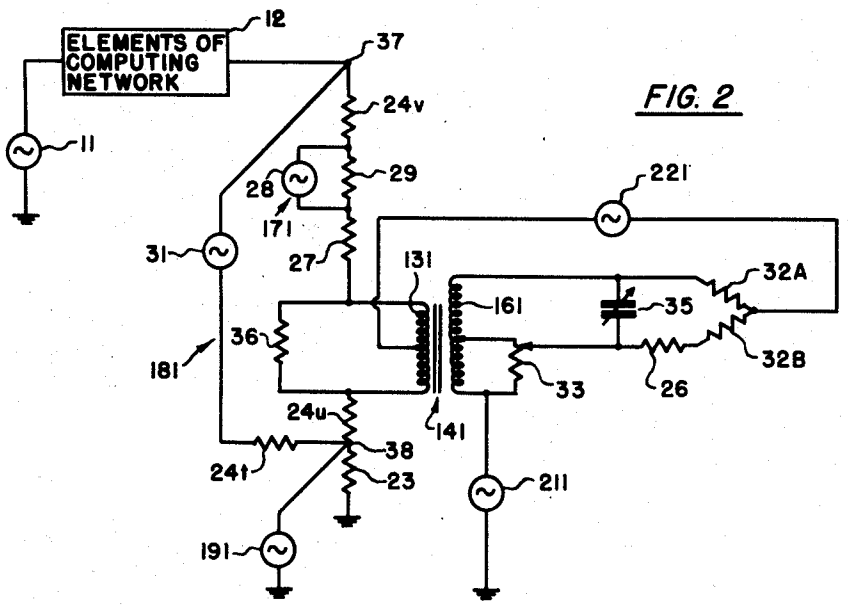


FIG. 2

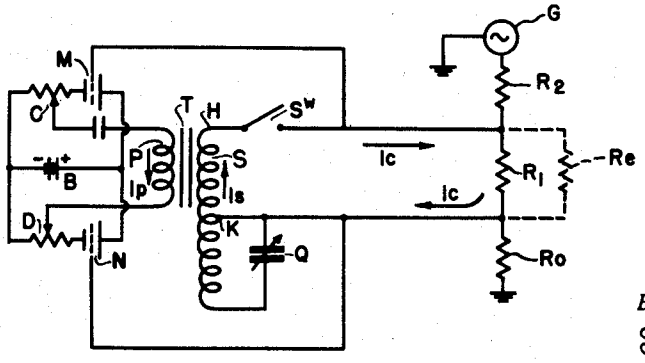


FIG. 4

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CURRENT LOSS COMPENSATING DEVICE

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4 Claims. (Cl. 323—44)

This invention relates to corrected transformers and more particularly to transformers wherein compensation for losses therein have been made to thereby make them more ideal and approach the performance of theoretically perfect transformers in operation.

Actual transformers differ from ideal transformers in a number of respects. All of these differences produce errors when the transformer is being used for computation purposes, as for example in static stress calculations. In the ideal transformer the product of the voltage across the primary times the current through the primary is exactly equal to the product of the voltage across the secondary times the current through the secondary. The primary current and voltage are in phase and the secondary current and voltage are in phase. In actual transformers, the windings have resistance, there are eddy currents and core losses, the primary inductance and mutual inductance are less than infinite, there is finite impedance between the primary and secondary windings, there is distributed capacitance among the turns of each winding, and there are impedances between each winding and ground. Further, the effective transformation ratio of the transformer varies with the lead applied to the secondary and with the voltage across the primary. All of these things upset the simple relationships of the ideal transformer.

Corrections heretofore have been made on current transformers, voltage transformers and instrument transformers. These comprise extra turns in the windings, artificially exciting the core to increase the effective permeability, and sensing and regulating devices for correcting errors. Since errors normally increase with increase in input, one such device adds a correction factor proportional to the input. Another device compares the output with load to the output of another transformer without load, the difference voltage controlling a correction feedback to the transformer output. Still another device uses the secondary current of the transformer to be corrected to oppose the primary current, the difference being added to the secondary as a correction current. However, none of these correcting devices approach the accuracy required in computer work. The transformation ratio varies with input voltage or load and there is no means for controlling the transformation ratio as desired. They do not provide for current measurements without affecting the characteristics of the transformer itself.

In the present invention a current-generator type of correction is used to correct for the above-mentioned transformer losses and errors and for losses involved in making the transformation ratio adjustable to any desired value and is independent of variations in input voltage or secondary load. Current generators of adjustable phase and magnitude are placed in error correcting circuits to provide current exactly equal to and out of phase with the current flowing through those elements causing the error. Stepless control of the transformation ratio

is achieved by the combination of error cancelling circuits and a potentiometer or variable resistance across part of one of the transformer windings. Additional elements are provided whereby current measurements may be made in which the error correction circuits nullify the additional errors introduced thereby, permitting elements of larger magnitude to be used for greater accuracy in current measurements.

An object of this invention is the provision of compensating means for making a transformer approach the performance of theoretically perfect transformers in operation.

Another object is the provision of a transformer circuit wherein all losses and phase shift due to transformer action are corrected.

Another object is the provision of a corrected transformer wherein the transformation ratio does not vary with change in voltage input or change in transformer load.

Still another object is the provision of transformer circuitry wherein current measurements may be made without affecting the ideal characteristics of the corrected transformer.

Still another object is the provision of stepless control of the transformation ratio of a transformer in combination with transformer error cancelling circuits.

A further object is the provision of a current-generator type of transformer error correction whereby an external current source provides an additional current to a transformer through a negative impedance in an amount equal to the transformer losses.

Other objects and features of the present invention will be readily apparent to those skilled in the art from the following specification and appended drawings wherein is illustrated a preferred form of the invention, and in which:

Figure 1 shows circuitry symbolic of transformer error in combination with a theoretically perfect transformer;

Figure 2 shows compensating circuitry for correcting the errors shown in Figure 1;

Figure 3 shows an alternate transformer showing stepless change in transformation ratio; and

Figure 4 shows one preferred embodiment of correction circuitry.

Referring now to Figure 1, the elements equivalent to those which produce error or loss in a transformer are shown externally of an ideal transformer for the purpose of emphasizing those errors for which corrections must be made, to thereby obtain a theoretically perfect transformer for use in analog computer work, for example. The excitation generator **11** energizes elements **12** of a computing network to provide an output signal across the primary windings **13** of an ideal step-up transformer **14**. In the ideal transformer **14** the product of the voltage across the primary **13** times the current through the primary is exactly equal to the product of the voltage across the secondary **16** times the current through the secondary and these currents and voltages have phase angles of 0° or 180°. However, this situation is ideal and not actually the case in conventional transformers because of the effects of error elements **17**, **18**, **19**, **21** and **22**.

Consider first error elements **17** in Figure 1. They consist of the effective leakage inductance and winding resistances of both the primary and secondary and are represented by their sum referred to the primary. Error elements **18** consist of the finite inductance of the primary **13**, here shown in parallel with the infinite inductance of the ideal transformer **14**, the distributed capacitance of the primary, and the power-absorbing (resistive) elements not included in **17**. Error elements **19**

represent the leakage resistance and capacitance between the primary winding **13** and ground. Error elements **21** consist of the same elements between the secondary winding **16** and ground. Error elements **22** represent the interwinding capacitance and leakage resistance. Impedance **23** between the low side of the primary winding and ground consists of circuit elements connected between these points. Impedance **23** does not represent an error term.

In addition to the errors that appear in the conventional transformer, it is generally necessary to add small series resistances such as **24** (*t*, *u* and *v*) and **26** in Figure 2 in order to be able to measure the currents in the primary and secondary windings. The correction circuits to be described will cancel the errors introduced by these metering resistors. Uses of resistors **24** and **26** will be described later. Resistor **27** in Figure 2 is the sum of the copper resistance in both primary and secondary windings plus the value of resistors **26**, **32A**, **32B** and the effective resistance of **33** as seen from the primary.

The correction of error **17** is done by correction circuit **171** in Figure 2. This consists of a negative impedance inserted in series with the primary **13** of the transformer **141**. The negative impedance is made up of a current generator **28** whose output is of controllable phase and amplitude, and resistor **29** through which the current from the generator flows. This negative impedance can be adjusted so that the current through the primary of the transformer is in phase with the voltage across the primary. The output of the current generator **28**, is, of course, at the same frequency as the excitation to the transformer from **11**. For reasons which will be developed hereafter, the correction impedance applied at this point usually will have a net resistive component. There is an alternative method for correcting error elements **17** that can be used, provided the resistance **29** is to be positive. In this method, **29** is chosen of the desired value and is shunted by an inductance or capacitance to obtain the desired phase angle to bring the primary voltage and current into phase with each other and with the exciting voltage. A further alternative is to put the inductance or capacitance in series with the resistance **29**. The current-generator type of correction as shown, however, is the most general, since it can produce impedance with either positive or negative resistive components.

The error elements **18** in Figure 1 can be corrected by a current generator **31** in correction circuit **181** in Figure 2, either alone or in combination with correction circuit **171**. By connecting current generator **31** as shown in Figure 2, its phase may be 0° with respect to the exciting voltage for the transformer. Other corrections for this current generator are possible, for example, its high side might be connected just below correction circuit **171** instead of above it. With this connection, however, the phase angle of current generator **31** would have to be adjustable since it would have to correct for the reactive part of error elements **18**. Current generator **31** operates on the resistive elements it sees looking into the transformer and causes current to flow through them. It is adjusted so that it feeds in just enough current to offset the losses caused by the resistive element in error elements **18** in Figure 1. If error correction circuit **171** has a positive resistive component, it will be necessary for correction circuit **181** to cancel this resistance as well as the resistive element of error elements **17**. Correction circuit **171** can be adjusted to take care of the phase angle errors caused by the finite inductance and distributed capacitance of error elements **18**.

Error elements **19** in Figure 1 may be cancelled by current generator **191** of adjustable phase and magnitude which is set to be the negative of leakage impedance **19**. Error elements **21** are corrected by current generator **211** in exactly the same way. In practice, it is probable that these error elements can be reduced to negligible significance by reasonable care in the design of a computer using transformers. In this case, of course, correction generators **191** and **211** would not be necessary. Note that correction generator **221** is connected to the secondary winding **161** through a pair of resistors **32A** and **32B**. These resistors should normally be chosen very large compared to any of the resistors driven by the secondary of the transformer when it is in use, to prevent leakage from the secondary **161** to primary **131** or vice versa. The errors caused by these resistors **32A** and **32B** can be cancelled by the correction circuits.

Error elements **22** are corrected by current generator **221** of adjustable phase and magnitude. It is set so that current produced by it is exactly equal to and exactly out of phase with the current flowing through error element **22**.

Since in a computing transformer, it is necessary to be able to adjust the transformation ratio to any desired value, a series of taps (or equivalent arrangement) is necessary on the secondary side **161**. In order to obtain nearly stepless variation in the effective transformation ratio, a low resistance potentiometer **33** may be placed across a small portion of the secondary winding as shown in Figure 2. The resistance which is added to the circuit by this and the power loss which is entailed in the current circulating through the potentiometer can be offset by the error correcting circuits previously described, principally by correction circuit **181**.

Another method for stepless adjustment of the transformation ratio of the corrected transformer is shown in Figure 3. In this case, the secondary **161** of the computing transformer **141** is connected to the tap and one side of an adjustable autotransformer **34**. While adjustable autotransformers have larger losses than some other types of transformers, the correction circuits are capable of effecting these losses so that an autotransformer can be made to appear like an ideal transformer of adjustable ratio.

One more correction element is necessary before the characteristics of an ideal transformer is achieved. This is a controllable reactance **35** across the secondary. In all probability it will always be a capacitive reactance and may most simply be a variable capacitor as shown in Figure 2. However, a current generator with the proper phase angle could be used. It would also be possible, if desired, to correct the power losses in the secondary **161** by adding an in-phase current generator across the secondary winding. In practice, however, it is simpler and better to make all power loss corrections by correction circuits in the primary **131** instead of using the additional correction circuits **171**, **191**, **221** and **211**.

Before turning to the correction circuits themselves, the current metering system should first be considered. In Figure 2, there are three resistors marked **24**. These are further identified by *t*, *u*, and *v*, and all have the same resistance value. Assume that correction circuit **171** is adjusted so that the primary voltage and current are in phase. Correction circuit **181** is then making up for the power lost in the resistance **36** which is equal to the "equivalent shunt losses," and the current flowing through resistor **24***t* is in phase with the current in the primary winding **131**. The volt drop across **24***t* is, then, in phase with the volt drop across **24***u*. In the ideal transformer, the current flowing into one terminal of the primary winding equals the current flowing out of the other. With the correction circuits properly adjusted, the current flowing in at **37** equals the current flowing out at **38**. This is the corrected primary current I*p*.

The primary current may be measured without disturbing the ideal characteristics of the corrected transformer. Since **24***t* and **24***u* have the same resistance, the currents through them are proportional to the voltages across them. From Kirchoff's Law we know that the current flowing through **24***u*, I*u* is the sum of the current flowing out

through point **38**, I*p*, and the correction current, I*c*, flowing through **24***t* in correction circuit **181**. Thus

$$Iu=Ip+Ic.\ Ip+\frac{Et}{Rt}=\frac{Eu}{Ru};\ Ip=\frac{Eu}{Ru}-\frac{Et}{Rt}$$

also $Rt=Ru$. Thus the primary current Ip is proportional to the voltage drop across resistor **24***u* minus the voltage drop across resistor **24***t*.

$$Ip=\frac{Eu-Et}{Ru}$$

The secondary current is equal to the voltage drop across resistor **26** divided by the value of the resistance **26**. Thus, by measuring the voltage drops across resistors **24***u*, **24***t* and **26**, and knowing their resistance values, the current in both primary and secondary can be computed.

Resistor **24***v* in the primary circuits is used to help in adjusting correction circuits **191**, **221** and **211**. When the circuits are properly set, the voltage across **24***v* equals the voltage across **24***u*. With the resistances of **24***v* and **24***u* equal, the current into the transformer from the computing network equals the current out, indicating a correct compensation for transformer losses. Because the correction circuits completely nullify errors introduced by metering resistors **24** and **26**, these resistors need not be chosen very small (around 1 ohm is customary) to keep the errors small. Using resistances of 10 to 100 ohms greatly facilitates making current measurements.

Figure 4 shows one form of error correction circuit in which the error resistance is connected in parallel with the load resistor. By increasing the voltage drop across the load, the voltage across the error resistance also increases. Using a constant current source, this operates to increase the effective error resistance which, in parallel, becomes so great that all the current goes through the load resistor. Through the use of positive feedback the circuit acts as a negative impedance device which supplies power to the load in an amount controlled by the voltage drop across the load. Because the circuit in Figure 4 may be used in any of the correction circuits in Figure 2, letters instead of numerals are used to identify the parts to avoid confusion. As shown, the circuit consists of two cathode followers, M and N. In each cathode is a potentiometer. The potentiometer arms are connected to the ends of the primary coil of step-up transformer T. To keep direct current from flowing through the primary of the transformer, a blocking capacitor is placed in series with the primary. Each side of the secondary of the transformer is connected to one of the grids of the cathode followers. The terminals of the secondary winding (H and K) are the output terminals of the correction circuit. For correction circuits which require phase correction (and most of them probably will), the secondary winding can be connected to a variable reactance. Load resistance R_1, shunted by an "error" resistance R*e*, is connected between the two terminals of the correction device and is in series with other resistances, R_0 and R_2. Resistor R_0 is grounded and R_2 is driven by a sinusoidal current generator G. R*e* diverts some of the current that should flow through R_1 and causes the voltage across R_1 to be too small. Since R*e* is in parallel with R_1, if the voltage drop across R*e* is sufficiently large all of the current from generator G can be made to flow through R_1. In this manner the current generator G (through a positive feedback circuit) provides an additional current to the load, R_1, to compensate for transformer losses indicated by the "error" resistance, R*e*.

Since current divides inversely as the resistances R_1 and R*e*, i.e., $I_1R_1=IeRe$, and it is desired that all the current from the generator pass through R_1, i.e., $I=I_1$, the correction current required from the correction circuit to compensate for the loss due to R*e* is therefore equal to I*e*. Thus

$$Ic=I\frac{R_1}{Re}$$

When the voltage drop across resistors R_1 and R_2 (to be measured) are proportional to their known resistive values, the compensating current I*c* equals the current I*e* through the error resistance. When the current I*c* has been adjusted so that

$$\frac{R_1}{E_1}=\frac{R_2}{E_2}$$

then $I_1=I$ and no current from G is going through R*e*. Since R*e* and R_1 are in parallel and the voltage drops across each are the same, $IR_1=IeRe$, I*e* being the current I*c*, the correction current. When the value of the current I is known, the use of known resistor R_2 is no longer necessary. In this case when correction current I*c* has been adjusted so that

$$\frac{E_1}{R_1}=I$$

compensation for the current loss through R*e* has been made. In this case only the voltage drop reading across R_1 need be made in adjusting I*c*. This correction current is derived by the proper positioning of the potentiometers C and D.

The arms of the two potentiometers C, D in the cathodes of the cathode followers are placed at the B— end of the potentiometers. Even though a voltage appears on the grids of tubes M and N, there is no signal across the primary of transformer T. With switch S^w open, the voltage across R_2, R_1 in parallel with R*e*, and R_0 will divide in proportion to their resistances. If we will now run the potentiometers up until such time as the voltage across secondary winding terminals H and K of transformer T is the same as the voltage across resistor R_1, we can close switch S^w without affecting the circuit. With switch S^w closed, we move the potentiometer arms farther up. The transformer will now deliver power to resistor R_1. This will increase the voltage drop across R_1, which amounts to exactly the same thing as increasing the resistance of R*e*.

Suppose that the potentiometer arms are not at the bottoms of the potentiometers. Since an A.C. voltage appears across resistor R_1, unequal A.C. signals with respect to ground will appear on the grids of the cathode followers M and N. The voltage on the grid of cathode follower M will be greater than that on the grid of cathode follower N. The potentiometers, if they are set for the same gain from each of the cathode followers, will deliver a signal across the primary of transformer T, which is normally a step-up transformer. It will try to increase the voltage across R_1 and so try to drive the grids more strongly, thus increasing the signal across the primary. Its ability to do this is limited by the fact that it must deliver power to resistor R_1 in order to increase the voltage across it. If the potentiometer arms are set too low, the transformer will absorb power from the external circuit and decrease the voltage across R_1. If the potentiometers are set so that the voltage across points H, K of the transformer secondary is greater than the voltage across R_1 when switch S^w is open, then when switch S^w is closed, there will be an increase in voltage across R_1 and an increase in drive on the cathode followers, further increasing the voltage across R_1. This is positive feedback and accounts for the behavior of the correction circuit as a negative impedance device. The correction device delivers power to the load R_1 in an amount controlled by voltage drop across R_1. It should be noted that since the feedback ratio is less than unity, it has a stable operation.

By setting potentiometer arm C enough nearer to B— than D, the flow of current through the transformer primary is reversed. This reverses the secondary voltage. Current I*s* flowing through R_1 and R*e* acts to reduce the volt drop across them. This reduces the excitation on M and increases the excitation on N, producing a further increase in secondary voltage and consequently in I*s* which

now flows in the opposite direction. Thus, while action on Is is regenerative, it diminishes the total current through R_1. By adjusting C and D, the magnitude of Is can be controlled and hence, Re can be made to appear infinitely large or even negative, as desired.

Different connections within the correction device also can be used to substitute negative feedback for positive feedback, if desired. Terminals H and K may be reversed and arm D set nearer B— than arm C so that current will flow in the windings of P_1, as shown. A decrease in driving current from I now results in a decrease of Is, which is likely to fit "real-life" situations better than the positive feedback case.

Note that if R_1 of Figure 4 had been replaced by a general impedance, the phase angle of the current from the correction circuit of Figure 4 would have to have been adjusted by capacitor Q to the appropriate value to cancel the reactive portion of the impedance.

It should be noted that this correction circuit shown in Figure 4 would not operate unless R_1 is greater than 0. This is the reason that it is necessary to have an impedance greater than 0 across the terminals of the correction network.

If the effective resistance across the terminals of the correction device is trimmed to be the optimum value for a particular application, substantial changes in the value of the load resistance on the secondary of the transformer can be made without requiring readjustment of the potentiometers of the correction circuit. Further, changes in the voltage applied across the primary can be automatically compensated for.

If the correction circuit is to be applied to a transformer one side of which is grounded, it can be simplified by omitting one of the cathode followers (replacing it by a connection to ground) and grounding one side of the secondary and one side of the primary.

It should be understood that the particular form of the correction circuit in Figure 4 is not intended to limit the scope of the invention to this particular kind of amplifier. In general, any type of amplifier could be used in place of the cathode followers and isolation circuits other than transformers could be used in place of transformer T.

It is not necessary to use amplifiers and vacuum tube circuits at all for these corrections, though it is believed that they are the most convenient form of correction work. It would be entirely possible to pick up power from the main source of exciting voltage for the computer and feed it through resistors, transformers, and phase-shifters into the various points of the computing transformer networks where it is needed for correction purposes.

While certain preferred embodiments of the invention have been specifically disclosed, it is understood that the invention is not limited thereto as many variations will be readily apparent to those skilled in the art and the invention is to be given its broadest possible interpretation within the terms of the following claims:

What we claim is:

1. Means for correcting transformer error comprising in combination, a transformer having current losses between a first and second point having a current flow therebetween, said first point receiving current from an energy source, means connected between said first point and its energy source for measuring the amount of input current flowing into said first point from said source, means connected to said second point for measuring the amount of output current flowing out of said second point, and circuit means connected across said points for producing a correction current flowing into said first point to equalize said input and output currents, said circuit means comprising means comparing said input and output currents for controlling the amount of correction current flowing into said first point and including generating means producing a current corresponding to the resultant of said input and output currents, said circuit means also including a transformer having its primary winding connected to said generating means and its secondary winding connected across said first and second points.

2. Means for correcting transformer error comprising in combination, a transformer having current losses between two points, said means comprising cathode follower circuits having potentiometer resistors therein, said cathode follower circuits generating a current in said potentiometer resistors responsive to grid bias from a current source connected to said transformer, said points being connected to said potentiometer resistors to receive said current in predetermined amounts therefrom.

3. Means for correcting transformer error comprising in combination, a transformer having current losses between a first and second point having a current flow therebetween, means connected between said first point and its energy source for measuring the amount of input current flowing into said first point, means connected to said second point for measuring the amount of output current flowing out of said second point, and circuit means connected across said points for producing a correction current flowing into said first point to increase the output current to the value of the input current to said first point from its energy source, said circuit means comprising a power supply, a resistor and vacuum tube connected to said power supply, the grid of said tube being connected to said first point for biasing thereby to regulate current flow through said resistor, an isolation step-up transformer, means connecting said resistor to said step-up transformer to induce a current flow therein, the secondary of said step-up transformer being connected across said points to provide said correction current thereto.

4. Means for correcting transformer error comprising in combination, a transformer having current losses between two points, a first known resistance connecting one of said two points to a current source, a second known resistance connected across said two points, current means connected to said one of said points for supplying a correction current thereto, and means for adjusting said current means until the voltage drops across said resistances are proportional to their resistive values, said current means comprising cathode follower circuits having potentiometer resistors therein, said cathode follower circuits generating a current in said potentiometer resistors responsve to grid bias from said current source, an isolation transformer having the primary thereof connected to said potentiometers to receive said current in predetermined amounts therefrom, the secondary of said isolation transformer being connected to said one of said points for supplying said correction current thereto.

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