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[56]

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[54] **AXIAL AMPERE-TURN BALANCING IN  
MULTIPLE, SEGREGATED SECONDARY  
WINDING TRANSFORMERS**  
13 Claims, 14 Drawing Figs.

[52] U.S. Cl. .... 321/5,  
323/48, 336/170  
[51] Int. Cl. .... H02m 7/12  
[50] Field of Search .... 321/5, 8;  
323/48; 336/170

**ABSTRACT:** A tertiary winding is provided for a multi-secondary transformer wherein the tertiary winding has axially separated parallel connected sections which are disposed adjacent respective axially displaced secondary windings and corresponding axially displaced series connected sections of the primary winding, to provide ampere turn neutralization for the primary and secondary windings at each instant.

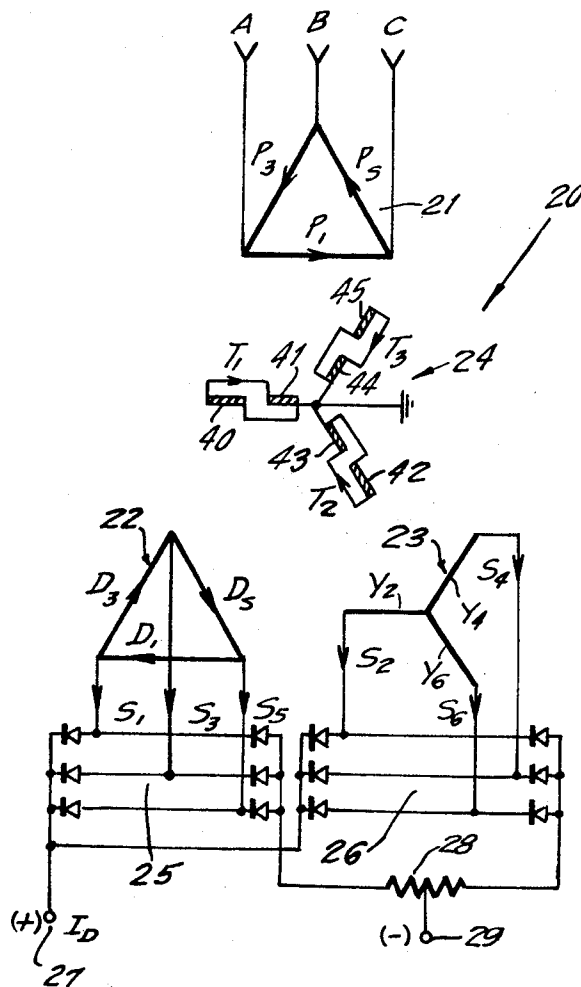


FIG. 1

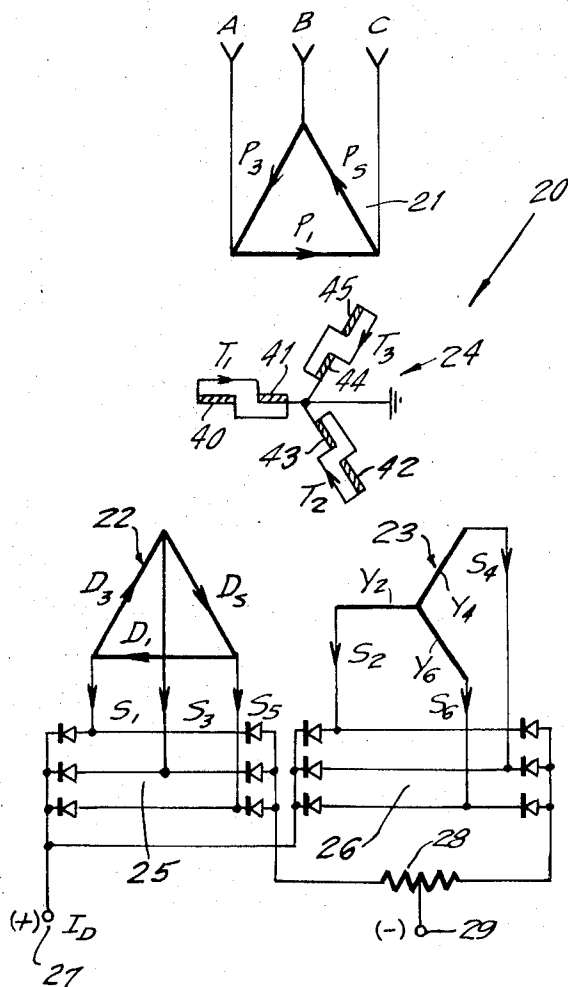


FIG. 2

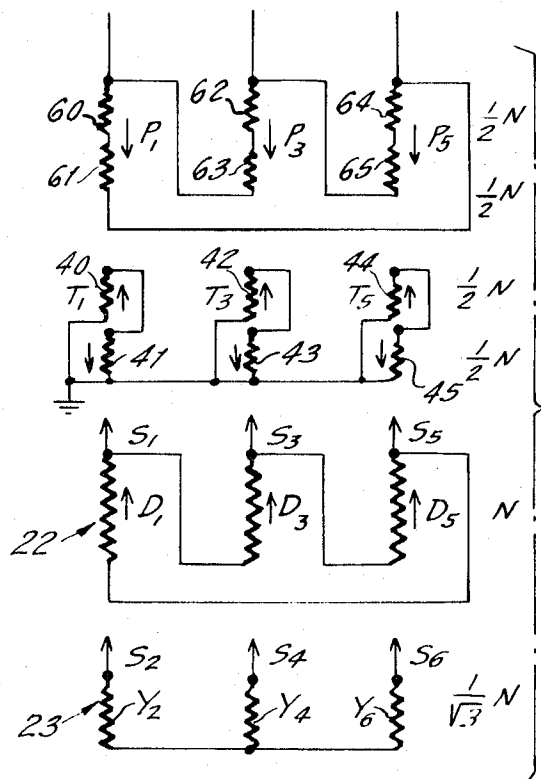


FIG. 3

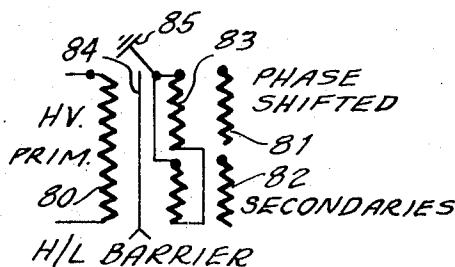


FIG. 4

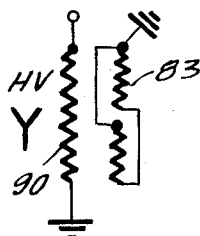
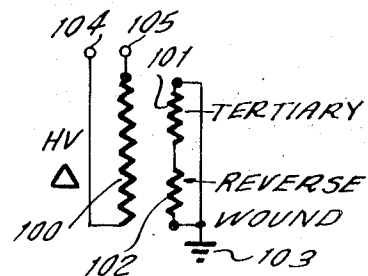


FIG. 5



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FIG. 6a.

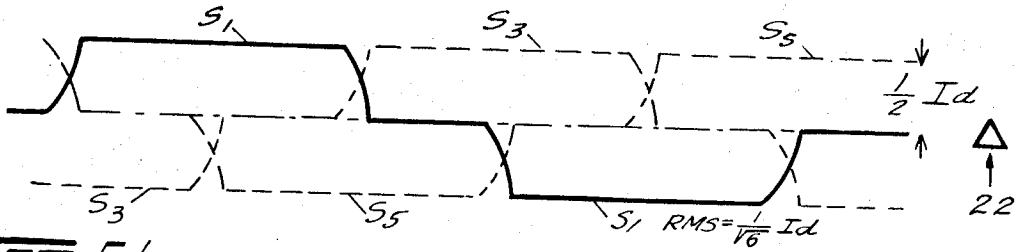


FIG. 6b.

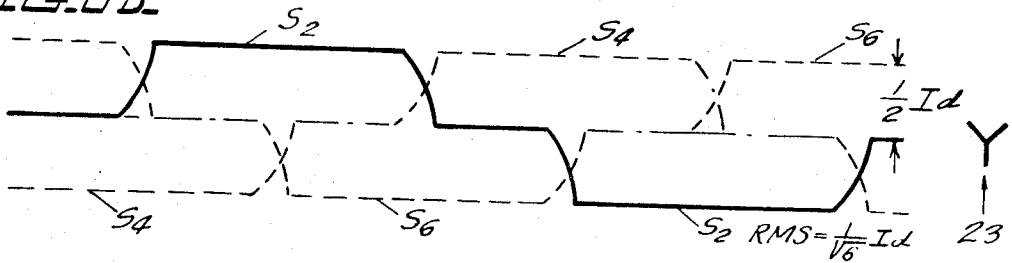


FIG. 7.

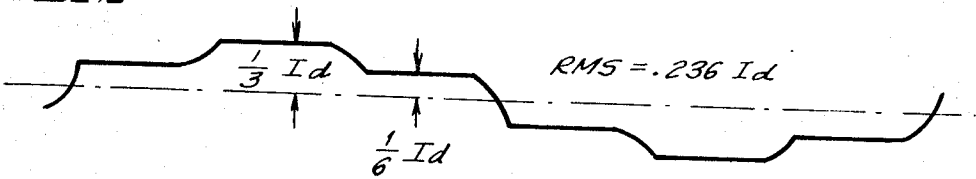


FIG. 8a.

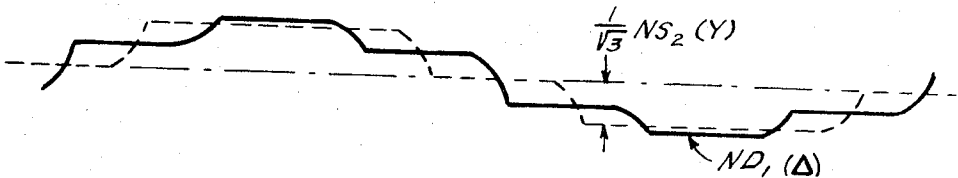


FIG. 8b.

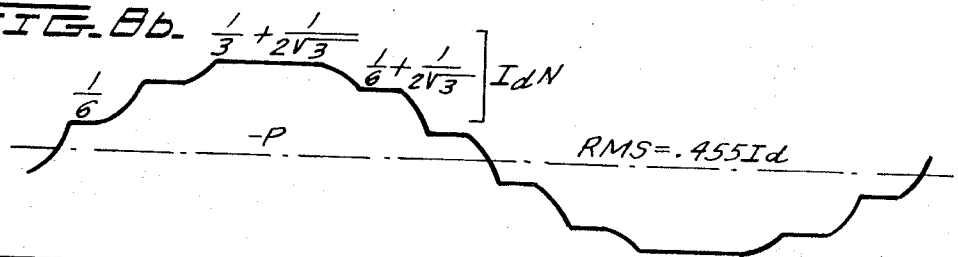
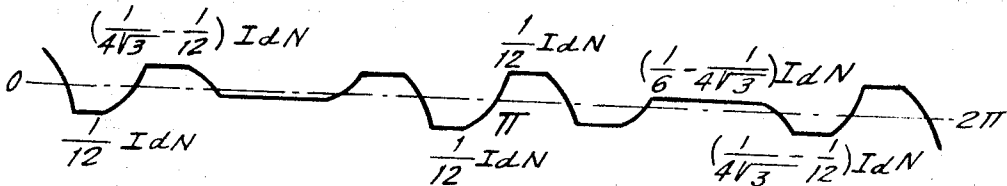


FIG. 9.



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FIG. 10.

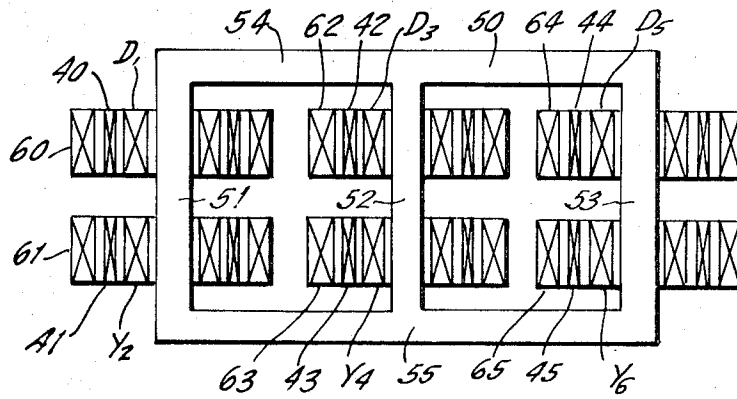


FIG. 11.

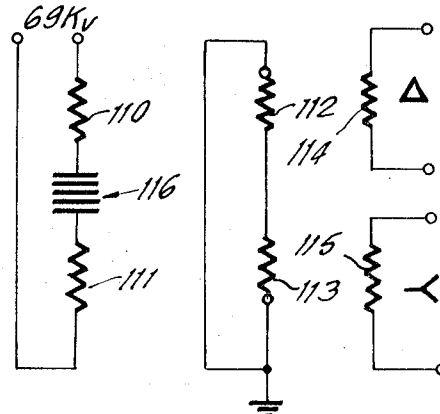
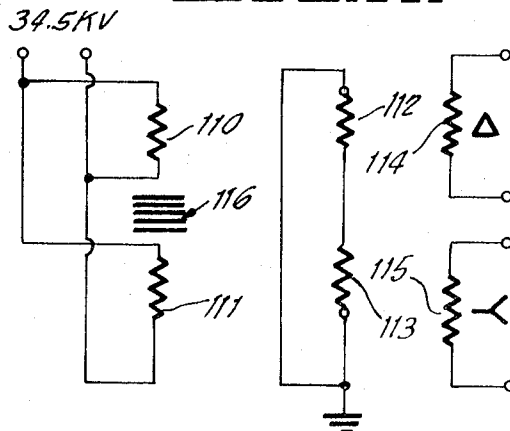


FIG. 12.



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# AXIAL AMPERE-TURN BALANCING IN MULTIPLE, SEGREGATED SECONDARY WINDING TRANSFORMERS

## FIELD OF THE INVENTION

This invention relates to multisecondary transformers, and more particularly relates to a novel tertiary winding for a multisecondary transformer in which the tertiary winding is separated, for each phase, into axially spaced portions which cooperate with separate respective winding portions of the primary and secondary windings of the transformer.

## THE PRIOR ART

High-voltage transformers with multiple output windings frequently experience disadvantages "crosstalk" between certain loads. For example, if a single transformer is used to supply a large lighting or other voltage-sensitive load from one secondary winding and a motor load with sizable cross-the-line starting induction motors from another winding, and if a large part of the transformer impedance were common to both windings, the light flicker in the lighting load could become intolerable. This interaction also manifests itself particularly in 12-phase rectifier transformers, which is the embodiment chosen herein for illustrating the invention; wherein a tertiary winding is applied to the transformer in a novel manner.

Twelve-phase rectifiers can be considered to consist of two six-phase systems displaced 30° from each other. In highpower semiconductor 12-phase rectifiers, there is generally found two 30° displaced secondary windings, each feeding a three-phase rectifier bridge. These bridges are generally connected in parallel on the DC side through an interphase transformer.

If the two secondaries are closely coupled, most of the leakage flux between them and the primary winding is common to both secondaries, and only a relatively small amount of leakage flux links only one secondary winding, so that the ratio of common-to-total leakage flux is large.

It is well known that when the ratio of common-to-total leakage flux is large, severe unbalance between the two halves of the rectifier will be experienced, unless remedial measures are taken, such as series linear or self-saturating controlled reactors in the leads to the bridge which would otherwise carry the heaviest load.

To overcome this problem in the past, the primary windings have been split axially into two relatively remote portions connected in parallel, each half juxtaposed to a secondary winding, respectively. In this manner, the common leakage flux is held to a minimum and unbalance is virtually eliminated.

While this method is economically feasible when the primary voltage is 15 kv. or lower, it becomes exceedingly difficult and expensive to use at higher primary voltages, such as for instance 69 kv. A great deal of additional insulation is required, and it is much more difficult to obtain inherent surge voltage protection.

A single series primary winding with two axially displaced secondaries would be the most satisfactory arrangement from the standpoint of insulation; but the commutating reactance of each secondary would be four to 12 times greater than if both halves of the rectifier commutated simultaneously as in six-phase operation. Therefore, the DC voltage drop from no-load to full load would be greatly increased; whereas with both secondaries short circuited, the total reactance would be decreased to the normal value of the total winding geometry, and the short-circuit current would be greatly increased.

The high impedance of each secondary to the total primary creates a high balancing voltage tending to force equal currents at each instant in the two secondaries. This is contrary to the requirements of two independent loads of any types, and particularly the phase-shifted six-phase rectifier systems of a twelve-phase rectifier.

## BRIEF SUMMARY OF THE INVENTION

The problems discussed above have been solved, in accordance with the present invention, by the provision of a tertiary winding having axially spaced portions which cooperate with respective primary and secondary winding sections on the transformer. Thus, the problems of insulation of high-voltage parallel connected primary winding portions is eliminated; the individual reactance of each secondary winding to primary winding is held small; total reactance of the transformer in percent is maintained substantially the same as that of the individual secondaries; and the ratio of common-to-total leakage flux is small to prevent unbalance between the two halves of a 12-phase rectifier.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a vectorial circuit diagram of a twelve-phase rectifier system using the tertiary winding construction of the present invention.

FIG. 2 schematically illustrates the winding arrangement for the transformer of FIG. 1, this arrangement being further illustrated in FIG. 10.

FIG. 3 schematically illustrates the manner in which a tertiary winding of one phase or multiphase system can be used as an electrostatic shield between the high-voltage primary and the secondaries.

FIG. 4 illustrates the manner in which the ground connection is made to the tertiary winding for a wye-connected high-voltage winding.

FIG. 5 illustrates the tertiary winding as having a reverse-wound portion where the high-voltage or primary winding is a delta-connected winding.

FIG. 6a shows the output currents of the delta-connected secondary winding of FIGS. 1 and 2.

FIG. 6b shows the output and coil currents of the wye-connected secondary winding of FIGS. 1 and 2.

FIG. 7 shows the secondary coil current in the delta-connected secondary winding of FIGS. 1 and 2.

FIG. 8a shows the ampere turns of the wye and delta secondary windings of FIGS. 1 and 2 superimposed on one another.

FIG. 8b shows the total secondary ampere turns and primary coil current for the windings of FIGS. 1 and 2.

FIG. 9 shows the ampere turns of the tertiary winding which are necessary in order to balance the ampere turns of the transformer in each section.

FIG. 10 illustrates the physical placement of the windings on a magnetic core for an arrangement of the type shown in FIGS. 1 and 2.

FIG. 11 illustrates one phase of an arrangement, in accordance with the invention, in which the primary winding can be switched between a series and parallel arrangement where the primary winding sections are shown in series with one another.

FIG. 12 is the same transformer as in FIG. 11, with the primary winding sections connected in parallel with one another.

Referring first to FIG. 1, there is illustrated a 12-phase rectifier which comprises a rectifier transformer 20 which has a primary winding 21, a delta-connected secondary winding 22, a wye-connected secondary winding 23 and, in accordance with the invention, a tertiary winding 24. Secondary windings 22 and 23 are connected to six-phase full-wave rectifier bridges 25 and 26, respectively, in the usual manner. The positive output terminals of bridges 25 and 26 are connected to one another and to a common terminal or a bus 27, while their negative terminals are connected to one another through the interphase transformer 28. A negative terminal 29 is connected to a centertap of the interphase transformer 28.

The primary winding 21 of transformer 20 in FIG. 1 is a delta-connected primary winding having individual phase windings labeled as windings P<sub>1</sub>, P<sub>3</sub> and P<sub>5</sub>. The delta-connected secondary winding 22 has labeled windings D<sub>1</sub>, D<sub>3</sub> and D<sub>5</sub> and wye-connected secondary winding 23 has three windings labeled as windings Y<sub>2</sub>, Y<sub>4</sub> and Y<sub>6</sub>. The output cur-

rents of transformer winding 22 are labeled  $S_1$ ,  $S_3$  and  $S_5$ , while the output currents of winding 23 are labeled  $S_2$ ,  $S_4$  and  $S_6$ . In selecting the various labels for FIG. 1, the arrows are shown in assumed positive directions.

The tertiary winding 24 is a wye-connected winding which carries circulating currents  $T_1$ ,  $T_2$  and  $T_3$  where it will be noted that the tertiary windings are illustrated as each being made of two axially separated segments. Thus, windings  $T_1$ ,  $T_2$  and  $T_3$  consist of axially separated windings 40-41, 42-43 and 44-45, respectively.

The transformer configuration of FIG. 1 is schematically repeated in FIG. 2 with the windings disposed one above the other for illustration only, where each of the windings disposed above one another are wound on a common core leg of three conventional core legs in the transformer construction. Note that, physically, windings 60, 40 and  $D_1$  are concentric and 61, 41 and  $Y_1$  are concentric. Thus, windings  $P_1$ ,  $T_1$ ,  $D_1$  and  $S_2$  are all wound on a common leg. Note that in FIG. 2, the heavy black dot is a polarity mark, indicating the start of the winding in conventional fashion.

FIG. 10 also illustrates the physical disposition of the windings of FIG. 2, and particularly the manner in which certain windings are disposed radially adjacent one another. In FIG. 10, there is illustrated a typical magnetic core 50 of a core-form transformer having three legs 51, 52 and 53 joined by upper and lower yokes 54 and 55, respectively. The various windings are then located on core legs 51, 52 and 53 as shown.

In accordance with the invention and as shown in FIGS. 1, 2 and 3, the primary windings are made of two series-arranged sections, such as series sections 60-61, 62-63 and 64-65 which are wound adjacent respective halves of the tertiary winding 24. Thus, winding sections 60 to 65 are disposed adjacent tertiary winding sections 40 to 45, respectively. Similarly, a respective portion of each primary winding and each tertiary winding cooperates with one of the windings of either the delta secondary winding 22 or wye-connected secondary winding 23. Thus, in FIGS. 2 and 10, the delta-connected windings  $D_1$ ,  $D_3$  and  $D_5$  cooperate with primary windings 60, 62 and 64, respectively, and tertiary windings 40, 42 and 44, respectively. In a similar manner, secondary windings  $Y_2$ ,  $Y_4$  and  $Y_6$  cooperate with primary windings 61, 63 and 65, respectively, and tertiary windings 41, 43 and 45, respectively. It is to be noted that the sequence of placing the various windings concentrically with respect to one another can be varied without departing from the scope of the present invention. Thus, the primary winding could be wound adjacent the core leg and the other windings could have been disposed concentrically outwardly thereof.

While the cooperating groups of primary, secondary and tertiary section windings are shown arranged concentrically, they could also be disposed adjacent to each other axially as is commonly done on shell-form transformers.

The various turns ratios for the windings will, of course, be adjusted depending upon the voltage ratios desired and the particular circuit selected. In the case of FIG. 2, the primary winding sections have the same number of turns  $\frac{1}{2}N$  each; the tertiary winding sections have an equal number of turns  $\frac{1}{2}N$  each; the delta-connected secondary winding 22 has a number of turns  $N$ ; and the secondary wye-connected winding 23 has a number of turns equal to

$$\frac{1}{\sqrt{3}}N$$

It should be noted that delta and wye secondary windings are illustrated herein since it was desired to obtain a 30° displacement for the rectifier arrangement. Obviously, the same results could have been obtained with symmetric secondary windings of zigzag, polygon or pinwheel configuration, while the primary winding similarly can be delta, wye or any other configuration. Moreover, it can be shown that the present novel arrangement for the tertiary winding and secondary windings can be applied to single-way as well as double-way (bridge) connected rectifiers, provided the diametrically opposite winding on each leg are closely interleaved.

FIGS. 6a to 9 demonstrate the manner in which the tertiary winding and arrangement of FIGS. 1, 2 and 10 operate, FIG. 6a shows the output currents  $S_1$ ,  $S_3$  and  $S_5$  of delta-connected winding 22, while FIG. 6b shows the output currents  $S_2$ ,  $S_4$  and  $S_6$  of wye-connected winding 23. Clearly, the wye-connected winding will carry the same current as that delivered to bridge 26. FIG. 7 shows the current within the delta of secondary winding 22.

All of the current wave shapes are shown as modified by commutation currents. The RMS values, however, which are shown, are computed on the basis of rectangular currents with no commutating effects in accordance with United States and International standards.

FIG. 8a shows how the ampere turns of the current in the delta-connected winding 22 (FIG. 7) and the current in the wye windings (FIG. 6b) combine to produce the primary winding current which is shown in FIG. 8b. It is important to note that the primary winding current is not a replica of either of the two secondary currents. Therefore, there cannot be a balance of ampere turns between either windings 22 and 23 and their associated halves of the primary winding when the two secondary windings are not closely coupled. Since the two bridges 25 and 26 do not commute at the same time, the commutating impedance of each rectifier section, without the presence of the tertiary winding 24, would be the impedance of each secondary winding 22 or 23 against the entire primary winding. Because of the axial unbalance ampere-turns, this impedance is very high.

The currents induced in the tertiary winding 24 supply the necessary ampere turns which produce radial and axial balance in accordance with the invention, this current being illustrated in FIG. 9. It should be noted that the instantaneous values and directions of the tertiary current of FIG. 9 for the phase illustrated (the phase including tertiary winding sections 40 and 41) is such that the net flux in the space between each section of the primary winding and its adjacent section of the tertiary winding is proportional at each instant to the primary current, while the net flux between each section of the tertiary winding and its adjacent secondary winding is proportional each instant to the current in that secondary winding.

An important feature of the invention is that the tertiary winding may be further used as a static shield between the primary and secondary windings where this static shield becomes necessary at higher voltages to control the capacitive coupling between the primary and secondary windings which could produce extremely high-voltage spikes on the secondary winding at the instant that the high-voltage breaker or switch is closed. Thus, as shown in FIG. 3, for example, a multiphase transformer can be provided, in accordance with the invention which has, for each phase, high-voltage primary winding 80 and phase-shifted secondary windings 81 and 82. A tertiary winding 83 is then provided on the illustrated phase where, again, the polarity markings are shown as darkened circles and wherein the arrangement of FIG. 3 is similar to that of FIG. 2. A high-to-low voltage insulation barrier is schematically illustrated as barrier 84. In accordance with the invention, tertiary winding 83 is grounded at ground 85 and then serves the purpose of the desired static shield.

The grounded end of the tertiary winding should be adjacent to the line end of the high-voltage winding which is exposed to the highest surge voltage. Thus, in FIG. 4 where the primary winding 90 is a wye-connected winding which is grounded at its bottom, as illustrated, the tertiary ground connection should be made at the top of the tertiary winding 83, adjacent to the line terminal of the primary winding.

In the case of a delta-connected primary as in FIGS. 2 and 5, both ends of the primary windings are equally exposed to surge voltage. Accordingly, and in order to reduce surge voltage difficulties, the high-voltage primary winding 100 of FIG. 5 may cooperate with a tertiary winding which includes reverse-wound sections. Thus, the tertiary winding of FIG. 5 consists of a winding portion 101 and a second winding portion 102 where the direction of winding is reversed between windings 101 and 102. A ground connection is then made at

ground 103 which is opposite from the terminals 104 and 105 of highvoltage primary winding 100.

It can be shown that the tertiary winding used in accordance with the invention will have a total kva. rating which is about 52 percent of the rating of one secondary winding. The equivalent two-winding kva. of the transformer is, therefore, increased by about 13 percent. This, however, compares favorably in cost with a parallel section primary winding with a static shield for operation at or above 69 kv.

The invention may also be used advantageously in connection with transformer arrangements in which the primary winding consists of several sections which can be arranged in series-parallel arrangements. For example, in the case of a twelve-phase rectifier to be used for traction purposes, a unit was required to be operated from either a 69 kv. primary system or a 34.5 Kv. primary system. Such an arrangement, if executed without the tertiary winding of the present invention, would require four sections for the primary with very serious insulation and tapping problems.

In accordance with the present invention, the transformer would be made as illustrated in FIGS. 11 and 12 for one phase of the transformer. FIG. 11 illustrates the transformer as having two primary winding sections 110 and 111 connected in series with one another with 69 kv. input to the primary winding. The tertiary winding then consists of reversely wound axially spaced sections 112 and 113 which cooperate, respectively, with delta-connected secondary winding 114 and wye-connected secondary winding 115. The transformer is then provided with sufficient insulation between the two primary winding sections 110 and 111 for 34.5 kv. service. This insulation is schematically illustrated in FIG. 11 as insulation 116.

In order to operate the transformer from 34.5 windings 110 and 111 are connected in parallel as illustrated in FIG. 12, with normal service voltage of 34 kv. impressed across insulation 116.

As a further advantage of the present invention, it is possible to use the tertiary winding, including windings 40 to 45 in FIG. 2 as a source of power for auxiliary equipment associated with the transformer and rectifier arrangement. This is done, for example, by providing suitable terminals at the tops of windings 40, 42 and 44 of FIG. 2.

As a further feature of the invention, it should be understood that the three pairs of parallel-connected tertiary sections 40-41, 42-43 and 44-45 of FIG. 2 could be connected in delta instead of in wye, if the tertiary winding is not to be used as a static shield. Connecting the tertiary windings in delta could be useful, for example, in a twelve-phase single-way rectifier transformer having a wye-connected primary and two displaced sets of secondary zigzag-connected windings. The delta-connected tertiary would then serve both to equalize ampere-turns and would also stabilize the neutral.

The embodiments of the invention in which an exclusive privilege or property I claim are defined as follows:

1. An electrical transformer comprising, in combination:
  - a. a magnetic core having a core leg;
  - b. a primary winding wound on said core leg;
  - c. a first and second secondary winding wound on said core leg contiguous with said primary winding; said first and second secondary windings being axially separated from one another and wound on axially separated portions of said core leg;
  - d. a tertiary winding wound on said core leg; said tertiary winding having first and second axially separated winding portions respectively contiguous with said first and second secondary windings; said first and second tertiary winding portions connected to one another in parallel.
2. The transformer of claim 1 wherein said second winding portion of said tertiary winding is wound in a reverse direction from the winding direction of said first winding portion of said tertiary winding.
3. The transformer of claim 2 wherein one end of said first winding portion of said tertiary winding is connected to ground; said tertiary winding being disposed between said primary and secondary windings.

4. The transformer of claim 1 wherein one end of said primary winding is at line potential, and wherein one end of said first tertiary winding is connected to ground; said one end of said primary winding and said one end of said tertiary winding are adjacent one another.

5. The transformer of claim 1 wherein said primary winding consists of first and second axially separated portions which are respectively coextensive with said first and second secondary windings in the direction of their principal leakage flux.

6. A multiphase electrical transformer comprising, in combination:

- a. a magnetic core having a plurality of core legs;
- b. a plurality of primary windings, each wound on a respective one of said core legs and connected together in a predetermined circuit relation;
- c. a first and second plurality of secondary windings, at least one winding of each of said first and second pluralities of secondary windings wound on a respective one of said core legs with a respective one of said primary windings; each of said first and second plurality of secondary windings on each of said core legs respectively connected to one another in a predetermined circuit relation; said first plurality of secondary windings being each axially separated from said second plurality of secondary windings and being wound on axially separated portions of said core leg;
- d. a first and second plurality of tertiary windings, at least one winding of each of said first and second pluralities of tertiary windings wound on a respective one of said core legs and being concentric with a respective winding of said first and second plurality of secondary windings, respectively; each of said tertiary windings of said first and second plurality of tertiary windings being axially separated on their respective core leg; each of said tertiary windings on each of said core legs being connected to one another in parallel.

7. The transformer of claim 6 wherein said second plurality of tertiary windings are wound in a reverse direction with respect to said first plurality of tertiary windings.

8. The transformer of claim 6 wherein said primary windings are connected in delta and wherein said first and second plurality of secondary windings are connected in wye and delta, respectively.

9. The transformer of claim 6 wherein one end of said primary winding is at line potential, and wherein one end of said first tertiary winding is connected to ground; said one end of said primary winding and said one end of said tertiary winding are adjacent one another.

10. A multiphase rectifier system comprising, in combination: a first and second bridge-connected rectifier and a multiphase rectifier transformer;

said multiphase electrical transformer comprising, in combination:

- a. a magnetic core having a plurality of core legs;
- b. a plurality of primary windings, each wound on a respective one of said core legs and connected together in a predetermined circuit relation;
- c. a first and second plurality of secondary windings, one winding of each of said first and second pluralities of secondary windings wound on a respective one of said core legs with a respective one of said primary windings; each of said first and second plurality of secondary windings respectively connected to one another in a predetermined circuit relation; said first plurality of secondary windings being each axially separated from said second plurality of secondary windings and being wound on axially separated portions of said core leg;
- d. a first and second plurality of tertiary windings, at least one winding of each of said first and second pluralities of tertiary windings wound on a respective one of said core legs and each being concentric with a respective winding of said first and second plurality of secondary windings, respectively; each of said tertiary windings of

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said first and second plurality of tertiary windings being axially separated on their respective core leg; each of said tertiary windings on each of said core legs being connected to one another in parallel.

11. The rectifier system of claim 10 wherein said first plurality of secondary windings are connected in wye, and wherein said second plurality of secondary windings are connected in delta.

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12. The rectifier system of claim 10 wherein at least one of said first plurality of tertiary windings is provided with accessible terminal means adapted for connection to a load.

13. The electrical transformer of claim 1 wherein said tertiary winding has terminal means extending therefrom for connection to external loads which are energizable independently of said first and second secondary windings.

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