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Wattenbarger

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[54] **FLUX AMPLIFIER CIRCUITS FOR CONTROLLING INDUCTION MOTORS AND THE LIKE**

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[21] Appl. No.: **225,458**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 106,415, Jan. 14, 1971, abandoned, and a continuation-in-part of Ser. No. 106,416, Jan. 14, 1971, abandoned, and a continuation-in-part of Ser. No. 131,959, April 7, 1971, abandoned.

[52] **U.S. Cl.** **318/220,** 318/228, 318/230, 323/86

[51] **Int. Cl.** **H02p 7/14,** G05f 3/04

[58] **Field of Search** ..... 323/56, 89 R, 89 M, 323/66; 318/220, 228, 229, 230; 330/8

[56] **References Cited**

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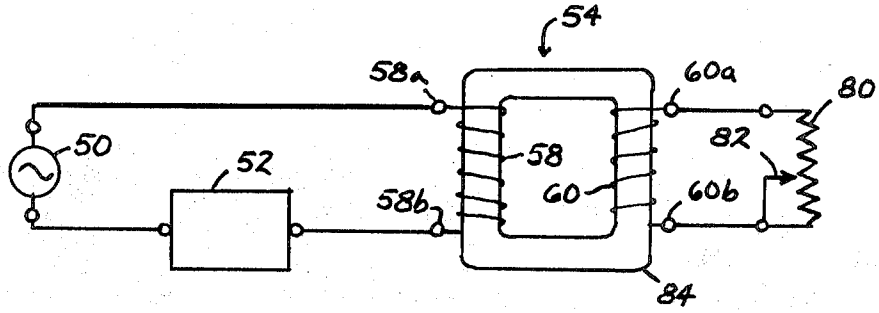
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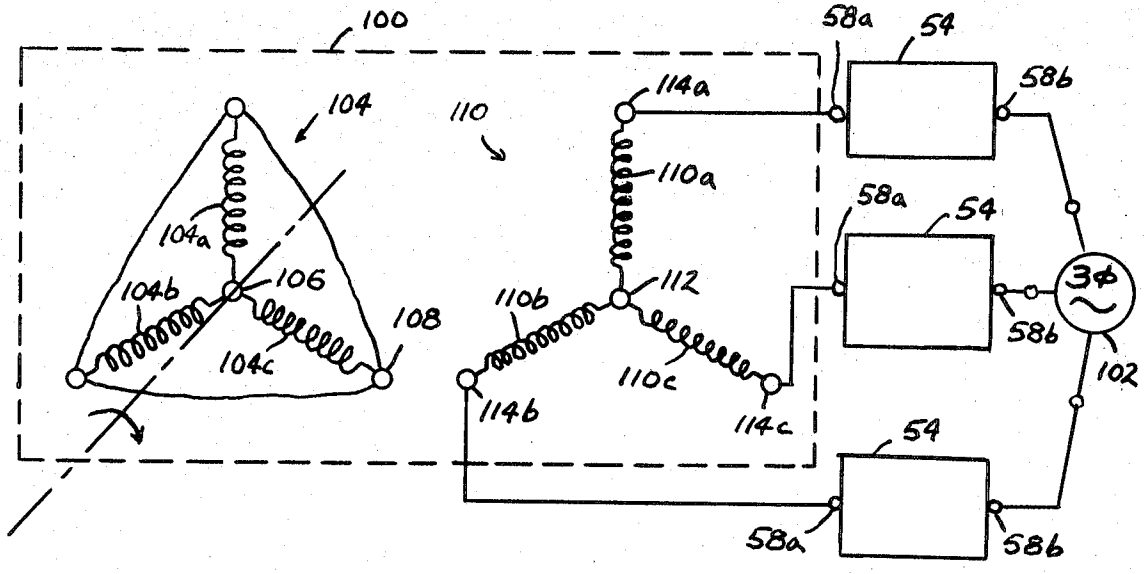
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[57] **ABSTRACT**

An induction motor supplied from a source of sinusoidal alternating current is provided with stator windings and rotor windings. The primary coil of a flux amplifier is connected in circuit with one of the windings. The secondary coil of the amplifier is energized, either from the primary directly or from a separate source, with sinusoidal current at the same fundamental frequency of the current in the primary coil. Means are provided to vary the amplitude and/or phase of the secondary current in the secondary coil to effect corresponding reactance changes at the primary which in turn vary the voltage and current supplied to the motor. The primary and secondary coils are coupled by a magnetic circuit having characteristics that cause fluxes from the primary and secondary coils to be linearly combined with each other so that voltage and current at the motor is controlled without developing harmonics of the fundamental frequency.

29 Claims, 10 Drawing Figures





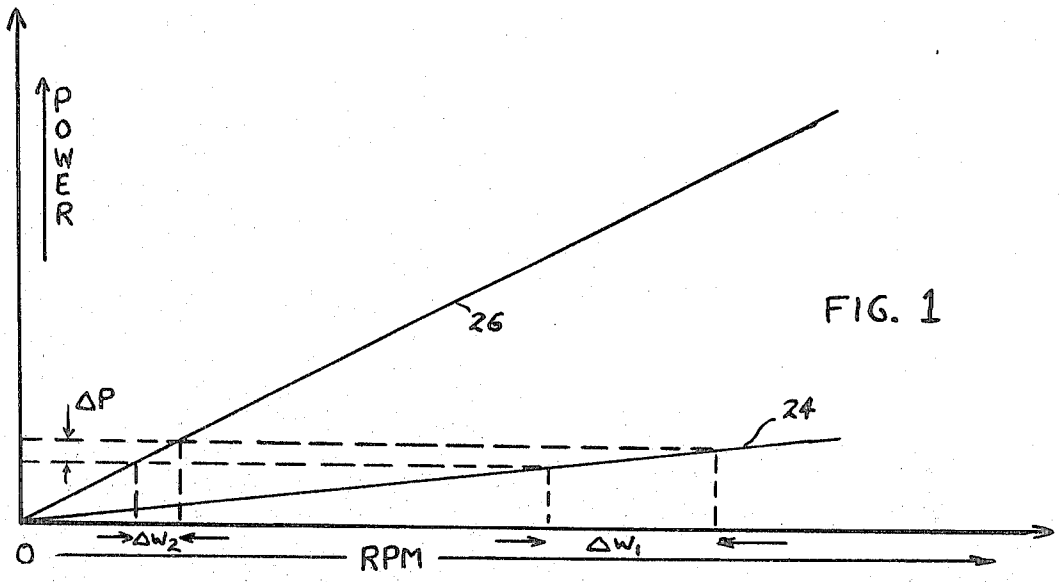


FIG. 1

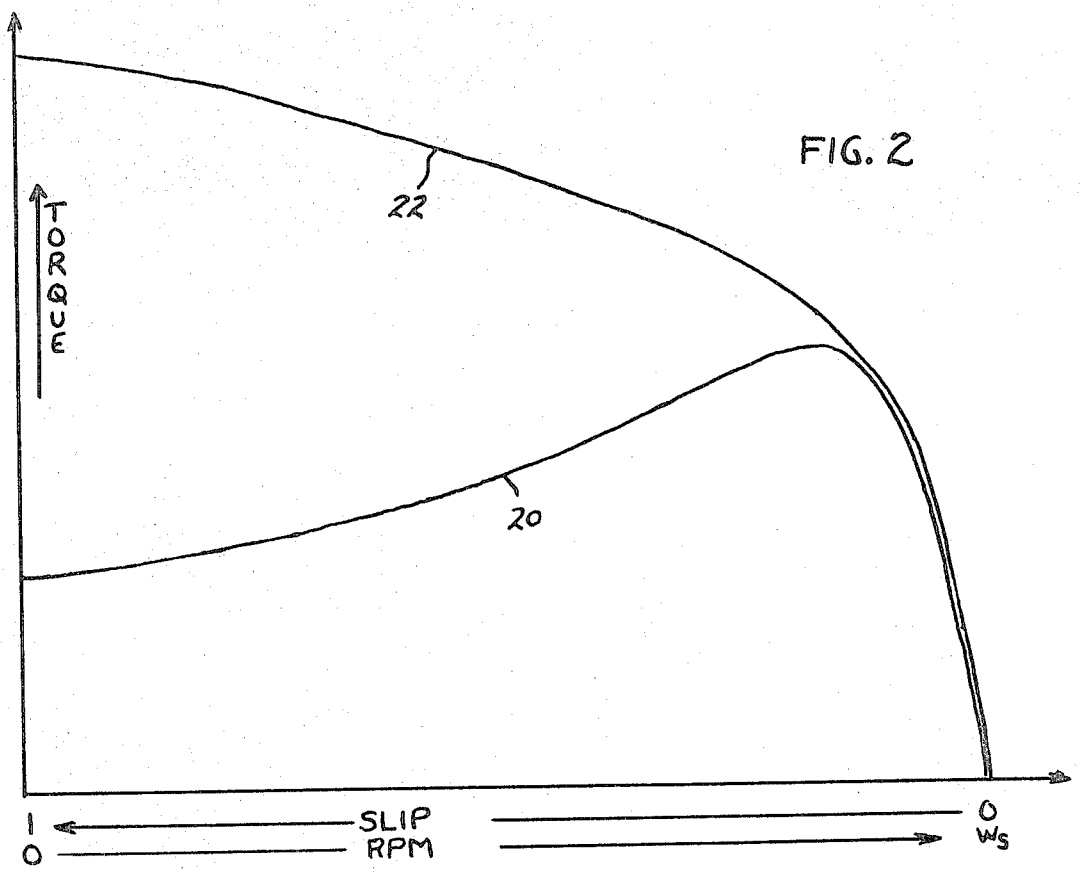


FIG. 2

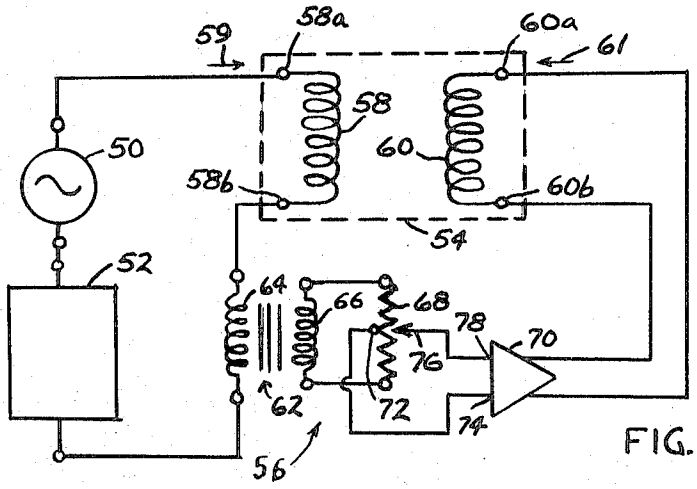


FIG. 3

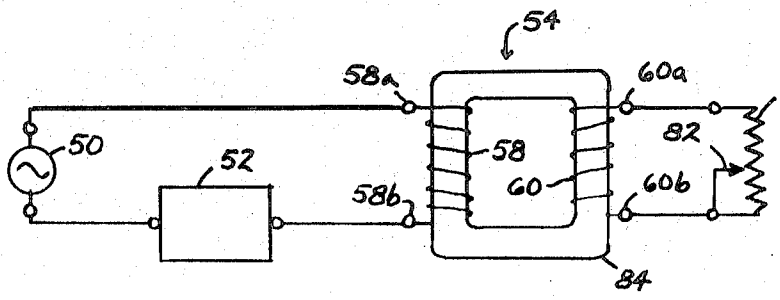


FIG. 4

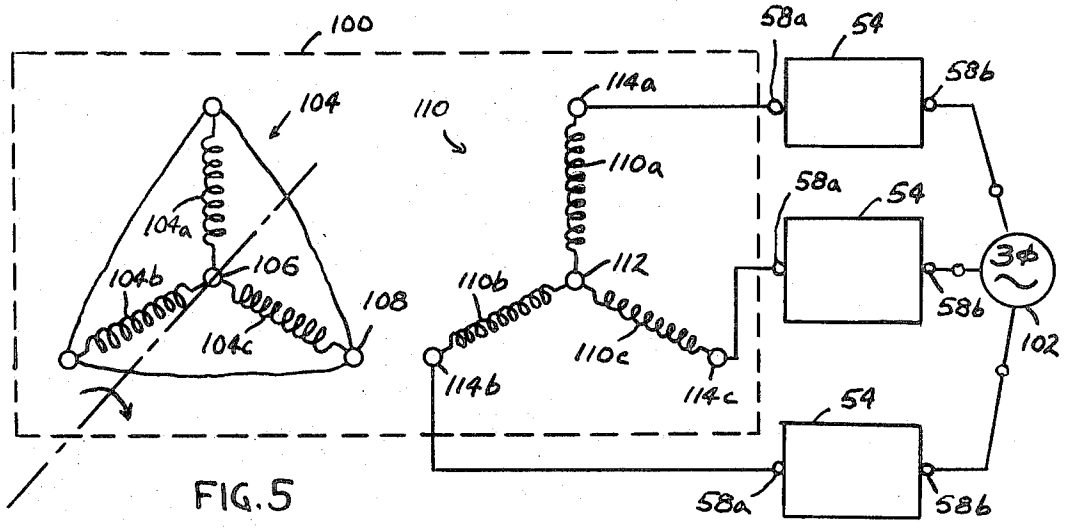


FIG. 5

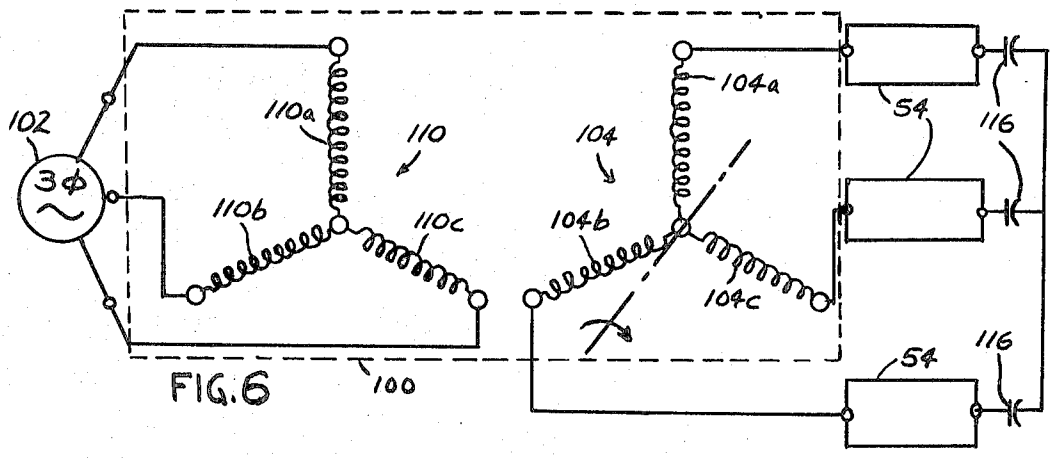


FIG. 6

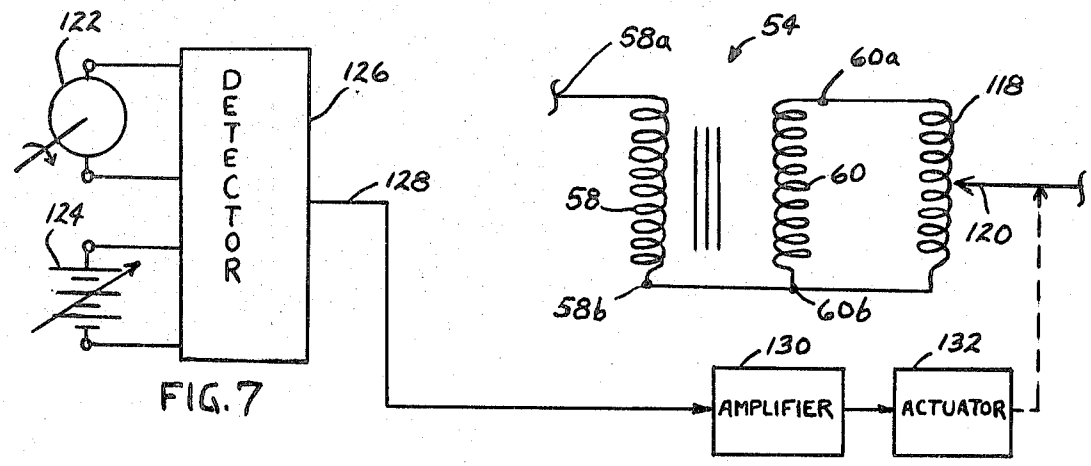


FIG. 7

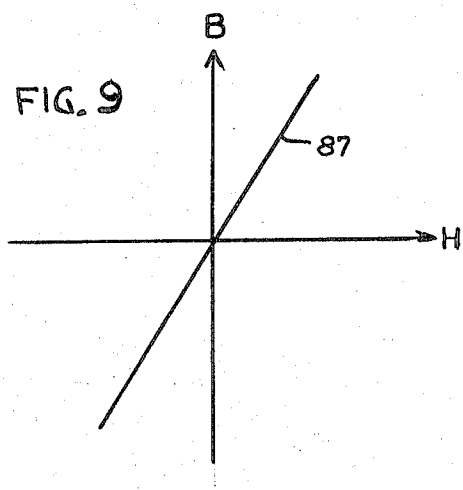


FIG. 9

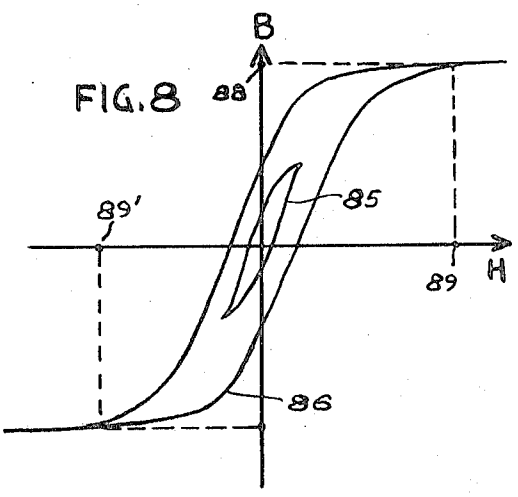


FIG. 8

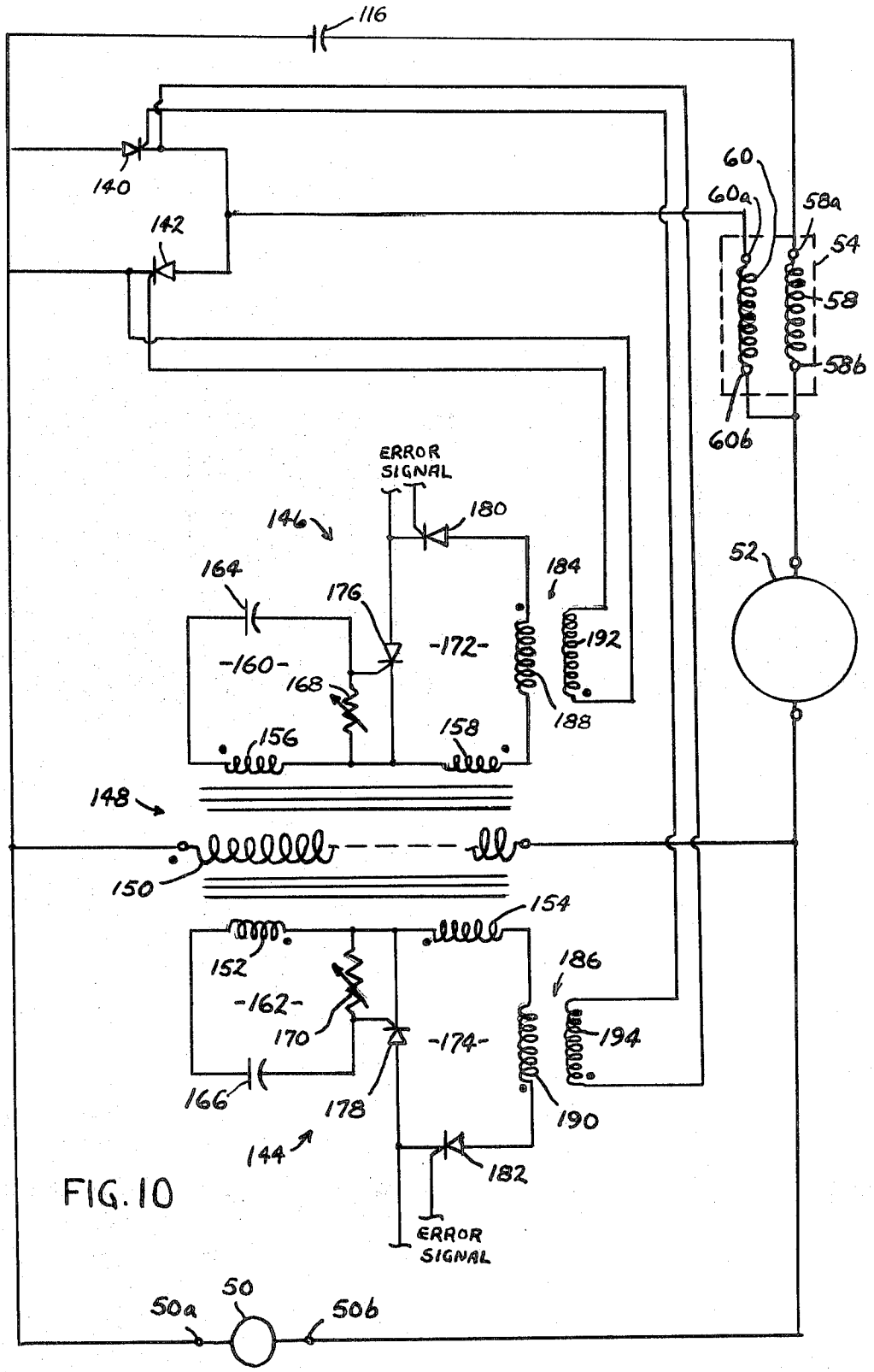

116
140
142
60
60a
58a
54
58
58b
60b
ERROR SIGNAL
146
180
164
176
184
-160-
168
-172-
192
188
156
158
52
148
150
154
152
186
-162-
170
-174-
194
166
178
190
144
182
ERROR SIGNAL
50a
50
50b

FIG. 10

FLUX AMPLIFIER CIRCUITS FOR CONTROLLING INDUCTION MOTORS AND THE LIKE

This application is a continuation-in-part of my copending applications: Ser. No. 106,415, now abandoned, filed Jan. 14, 1971; Ser. No. 106,416, filed Jan. 14, 1971; and Ser. No. 131,959, now abandoned, filed Apr. 7, 1971.

This invention relates to alternating current control circuits and in particular to control circuits for use with induction motors.

In general, I have found that a flux amplifier can be operated advantageously on a substantially linear B-H curve so that certain fluxes in the amplifier are added and subtracted in a manner that provides accurate voltage and reactance control in the primary winding of the amplifier. Such a linear flux amplifier can be electrically connected between an AC source and a load a variety of particular ways hereinafter disclosed to effectively control power flow from the source to the load. The circuit incorporating a linear flux amplifier operates ideally with maximum power efficiency and without harmonic transients. Even more significant, however, I have found that when the linear flux amplifier is used in a speed control circuit for AC induction motors, motors can be controlled at both very low speeds and light loads with efficiencies and accuracies heretofore not obtainable.

Therefore, while in its broadest aspect, my invention has for its principal object the provision of a novel control circuit suited for a variety of applications; its more specific objects and advantages as disclosed herein relate to improved induction motor control circuits.

Hence, further objects of the present invention are to provide motor control circuits for electric motors and methods of controlling electric motors that are accurate and effective yet simple and economical; that achieve effective speed control over a range of motor speeds and particularly at low speeds; that also achieve effective speed control over a range of torque loads and particularly at light loads; that are useful in controlling a wide variety of electric motors of different horsepower; and/or that provide effective control of very large horsepower motors that heretofore required elaborate and expensive control circuits.

Other objects, features and advantages of my invention can be better appreciated with reference to the following description, the appended claims and the accompanying drawings in which:

FIG. 1 is a graph having two plots which are linear approximations from zero rpm to approximately maximum torque rpm of the power versus rpm characteristic of a typical induction motor for two different load conditions;

FIG. 2 is a graph having two plots of the torque versus rpm characteristic of a typical induction motor with and without a high torque modification in the control circuit of my invention;

FIG. 3 is an electrical schematic diagram of one embodiment of my invention in a series controller for a load;

FIG. 4 is an electrical schematic diagram of a second embodiment of my invention in a series controller;

FIG. 5 is an electrical schematic diagram of an induction motor control circuit embodying my invention;

FIG. 6 is an electrical schematic diagram of another induction motor control circuit embodying my invention;

FIG. 7 is an electrical schematic diagram showing a further embodiment of my invention;

FIG. 8 shows the hysteresis characteristics of a ferromagnetic material which may be used as a component of one form of my invention;

FIG. 9 illustrates a linear approximation of the hysteresis characteristic of FIG. 8; and

FIG. 10 is an electrical schematic diagram of a still further embodiment of my invention in an induction motor control circuit.

Before describing the circuit details of my invention illustrated in FIGS. 3 through 10, attention is first directed to FIGS. 1 and 2 for the purpose of understanding the concepts which distinguish my invention from the prior art. In FIG. 2, the graph plot designated 20 represents the torque-rpm characteristic of a conventional induction motor which is connected directly to an AC line. The abscissa axis is dimensioned in terms of both motor rpm and motor slip, it being understood that the motor has zero slip at synchronous speed w_s and unity slip at zero speed. The shape of plot 20 is characteristic of what is generally referred to as a "Class A" induction motor. A Class A induction motor is designed to develop maximum torque and maximum power at relatively low slips. A consequence of the Class A design is that the motor performs poorly at low speeds, having high rotor currents and low starting torque. Other classes of induction motors, for example, Class B, Class C and Class D motors, have torque-rpm characteristics which differ from that of the Class A induction motor. However, these designs have their own individual drawbacks. For example, while the Class D motor can develop a high starting torque at a low starting current, the torque at higher rpm is quite low; and at full load, the motor unfortunately runs at high slip and poor efficiency. Therefore, it is desirable to be able to have an induction motor operate at increased torque levels over a substantially greater speed range.

An induction motor control circuit constructed in accordance with the high torque modification of my invention has been theoretically computed to improve the torque-rpm characteristic of conventional induction motor as illustrated by the plot designated 22 in FIG. 2. While the shape of this plot may appear to be the same general shape as that of a Class D induction motor, it has been calculated that the maximum torque which can be developed by a conventional induction motor using my invention is up to several times greater than that which can be developed with conventional motor control techniques. Moreover, it has been calculated that with my invention, a conventional induction motor can deliver a greater torque over a greater range of speeds than presently can be done with known techniques.

According to conventional induction motor theory, the greater the slip at which the motor operates, the more inefficient it becomes. Therefore, it is highly desirable for an induction motor speed control circuit to be as efficient as possible so that total system losses are minimized. Thus, heretofore, various methods have been devised to provide various elaborate arrangements for improving the efficiency of the motor when operating at various slips; for example, various schemes have been developed for recovering the energy in the

rotor currents which is otherwise dissipated as heat within the motor. My invention, when applied to an induction motor, is highly efficient and can be used without modification to conventional motor structures, although it is contemplated that existing motor designs may be modified to further improve their performance when utilizing my invention.

My invention also eliminates, or at least minimizes, a problem inherent in present motor speed control circuits which utilize nonlinear devices such as magnetic amplifiers, solid state switches, etc. These nonlinear devices introduce harmonics of the fundamental electrical frequency to both the control circuit and the motor circuit. These harmonics in the motor currents generate corresponding pulsating harmonic torques in the motor output. The pulsating torques produce an average torque of zero thereby contributing only instability in speed control. This instability can be explained with the aid of FIG. **1** which shows plots **24** and **26** respectively representing linear approximations of motor power versus motor speed between zero rpm and maximum power rpm for a lighter load and a heavier load respectively. Assume that these pulsating torques cause the power to fluctuate by an amount ΔP. For a lightly loaded motor as indicated by plot **24**, the motor speed correspondingly changes by an amount Δw_1. For a heavier loaded motor, the same power change ΔP causes a speed change Δw_2. It is readily apparent that the effect of these pulsating torques causes motor speed instability and becomes more serious as the motor load decreases. In contrast, my invention provides a more stable motor control because it does not generate the undesired harmonics which are present in conventional speed control circuits. I have operated a one horsepower three-phase, wound rotor induction motor with a speed control incorporating the flux amplifier shown in FIG. **7**, operated manually without automatic feedback control. The motor has been observed to operate efficiently at controlled speeds over the range from zero rpm up to almost synchronous speed.

Referring now to the circuit of FIG. **3**, a sinusoidal AC source **50** is connected in series with a load **52** and a linear flux amplifier **54**. A power supply **56** is connected in the series circuit for developing a control signal for flux amplifier **54**. Supply **50** may be, for example, a conventional voltage source (e.g., 115V, 60Hz) and load **52**, any type to which power from source **50** is being supplied. Flux amplifier **54** comprises a primary coil **58** for controlling the flow of power from source **50** to load **52**. Coil **58** is in turn controlled by means of a secondary coil **60** energized from supply **56**. The two coils **58** and **60** are magnetically coupled, preferably as closely as possible. Flux amplifier **54** is operated as a substantially linear device, and therefore it is essential that the magnetic coupling between the two coils be of substantially constant permeability over this operating range to achieve optimum results. For an air coupling as illustrated, the coupling is linear. However, when coils **58, 60** are coupled through a ferromagnetic core, it is important to prevent the core material from becoming magnetically saturated as this would impair linearity as will later be explained in greater detail. As will be apparent, the ferromagnetic core coupling as hereinafter described is preferred for higher coupling efficiencies, although it will be understood that an air core might be preferred for special applications; for example, high frequency applications. The air core coupling, being linear, exemplifies the present invention as contrasted to prior art magnetic amplifiers and saturable reactor controls.

Describing now the operation of flux amplifier **54**, let it be assumed that a sinusoidal current is flowing in secondary coil **60**; i.e., assume coil **60** open circuited. Also assume that the magnetic coupling between the two coils is 100 percent. The sinusoidal current flow in coil **58** causes a sinusoidal magnetic flux to be developed within both coils. Consequently, a voltage is induced between the terminals **60***a* and **60***b* of coil **60** and is equal to the number of turns of that coil times the time rate of change of the flux. Simultaneously, the voltage across primary coil **58** is equal to the number of turns in that coil times the time rate of change of the flux. Because secondary coil **60** is open circuited, no current can flow in the coil; and hence, the flux linking the two coils is a function only of the current flow in primary coil **58.**

However, if a sinusoidal current is allowed to flow in secondary coil **60** simultaneously with a sinusoidal current flow in primary coil **58,** the magnetic flux waveform described in the preceding paragraph will be modified. Assuming first sinusoidal current flow in coil **60** and no current flow in coil **58** (i.e., assume coil **58** open circuited), a sinusoidal flux linking the two coils will be developed by the current flow in coil **60.** Therefore, now assuming both coils **58** and **60** are energized by respective sinusoidal current flows, the linear characteristic of flux amplifier **54** causes the net, or resultant, flux linking the two coils to equal the algebraic sum of the individual flux waveforms developed by the respective current flows in the two coils.

Of course, it will be appreciated that the peak amplitude of the resultant or net flux common to both coils **58, 60** when current flows in both coils will be either greater or less than the peak amplitude of the flux linking both coils due to current only in coil **58** (when coil **60** is open) depending on the relative phase of the currents in coils **58, 60** and the polarity of coils **58, 60.** For example, assuming a positive current flow into the top of both of the coils as illustrated by the arrows **59, 61** (FIG. **3**) and assuming that the polarity of coils **58, 60** is such that the positive currents in coils **58, 60** both develop a corresponding positive flux in a clockwise direction, for example, then the peak amplitude of the resultant flux due to current flow in both coils **58, 60** will be greater than the peak amplitude of the flux linking both coils when current flows only in coil **58** with coil **60** open. This mode of operation where the peak amplitude of the resultant flux when current flows in both coils **58, 60** is greater than the peak flux amplitude due to current flow in coil **58** alone is hereinafter referred to as an additive flux amplifier. On the other hand, assuming the same positive current directions **59, 61,** if the polarity of one of the coils **58, 60** is reversed, then the peak amplitude of the resultant flux in coil **58** when both coils **58, 60** are energized will be less than the peak amplitude of the flux linking both coils when current flows only in coil **58** with coil **60** open. This mode of operation where the peak amplitude of the resultant flux when current flows in both coils **58, 60** is less than the peak flux amplitude due to current flow in coil **58** alone is hereinafter referred to as a subtractive flux amplifier. Of course, for coils **58, 60** connected to generate flux of a given polarity, the amplifier

can be operated as either an additive flux amplifier or a subtractive flux amplifier by properly selecting the relative phase or polarity of the currents in the two coils. As will later be described in detail, particularly when using a ferromagnetic core as contrasted to an air coupling, the flux amplifier **54** is preferably operated as a subtractive flux amplifier for most applications to achieve a linear combination of the respective fluxes in the core. As will later be described, when using a ferromagnetic core and operating in the additive flux mode, the relative amplitudes and phases of the currents in coils **58, 60** must be properly selected so that the core is not driven into saturation. Further, it can be proven mathematically that the algebraic sum (i.e., addition or subtraction) of two sine waves is also a sine wave, regardless of the amplitudes of the two sine waves or their relative phases so long as the two sine waves are of the same frequency. Therefore, by causing a current to flow in secondary coil **60** so that the flux waveform developed by that current is a sinusoid of the same frequency as the sinusoidal flux waveform developed by current flow through primary coil **58,** then the amplitude and phase of the net flux developed in flux amplifier 54 become functions of the amplitude and phase of the current waveform in secondary coil **60,** but the net flux developed does not lose its sinusoidal character. The effect on coil **58** changes both the coil voltage and the coil reactance simultaneously. Thus, it can be seen that the coil voltage and reactance are controlled by controlling the current flow in coil **60.** This combined voltage and reactance control of coil **58** while maintaining linear operation thereof contributes to the improvement in the control circuits described herein.

In the circuit of FIG. 3, power supply **56** supplies the sinusoidal current for coil **60** and is adjustable to vary both the amplitude and the phase of this current to thereby vary the amplitude and phase of the resultant net magnetic flux in flux amplifier **54.** Therefore, looking at the details of power supply **56,** a transformer **62** has its primary winding **64** connected to conduct AC current. The AC current in winding **64** induces an AC voltage in the secondary winding **66** which is applied across a potentiometer **68.** Potentiometer **68** is connected to the input of a conventional amplifier **70** by connecting the center-tap terminal **72** of the potentiometer to one input terminal **74** of amplifier **70** and by connecting the wiper terminal **76** of potentiometer **68** to the other input terminal **78** of amplifier **70.** When wiper **76** is moved increasingly away from center-tap **72** in one direction, a voltage of increasing amplitude is applied to amplifier **70;** and when wiper **76** is moved away from center-tap **72** in the opposite direction, a voltage of increasing amplitude and of opposite phase is applied to amplifier **70.** Amplifier **70** is a linear amplifier constructed in accordance with well-known amplifier designs to linearly amplify the input voltage into an output current. Coil **60** is connected as a load to the output of amplifier **70** and therefore, power supply **56** operates to deliver sinusoidal current to coil **60,** the amplitude and phase of which are determined by the setting of potentiometer wiper **76.** As a result, a sinusoidal current of variable amplitude and phase may be conducted through secondary coil **60.** The amplitude is incrementally variable from zero up to a maximum value. However, the phase of the current is either 0° or 180° depending upon the direction in which wiper **76** is moved away from center-tap **72.** The illustrated arrangement is merely exemplary and it is to be appreciated that other arrangements may be constructed in accordance with well-known techniques to provide continuously variable phase and/or continuously variable amplitude.

The operation of the circuit of FIG. 3 as a whole may now be considered. Source **50,** primary coil **58** of flux amplifier **54,** primary winding **64** of power supply **56** and load **52** are electrically connected in a series loop referred to for convenience as the primary loop. Primary winding **64** has a negligible impedance at the frequency of source **52** in comparison to the sum of the impedance of load **52** and the impedance of coil **58.** Hence, primary winding **64** has substantially no effect on the current and voltages in the primary loop circuit. (It should be appreciated, of course, that other types of power supplies may be utilized for energizing secondary coil **60** and that they can be independent of the primary loop.) Considering first only current flow in the primary loop, source **50** applies its sinusoidal voltage across the series circuit consisting of coil **58,** winding **64** and load **52.** In response, a sinusoidal current at the same frequency as that of the voltage passes through coil **58,** winding **64** and load **52.** In passing through coil **58,** this sinusoidal current causes a sinusoidal flux waveform to be developed in flux amplifier **54.** With wiper **76** positioned away from center-tap **72,** a sinusoidal current is also caused to flow in secondary coil **60** of flux amplifier **54.** The phase and amplitude of this current flow depend upon the setting of wiper **76** as previously noted. The flux waveform developed by the current flow in coil **60** is algebraically added to the flux waveform developed by the current flow in coil **58** with the resulting net flux waveform having an amplitude either greater than or less than the amplitude or the flux waveform caused by current flow in coil **58** alone. Thus, the flux amplifier is either additive or subtractive. For example, the phase of the current flow in coil **60** relative to the phase of the current flow in coil **58** may be such that the two individual flux waveforms reinforce each other to develop a resulting sinusoidal flux waveform whose peak amplitude is equal to the sum of the peak amplitudes of the two individual flux waveforms. In this instance, the power flow from source **50** to load **52** is reduced to a minimum value. On the other hand, the phase and amplitude of the current flow in coil **60** may be such that the net flux developed in flux amplifier **54** equals zero. In this case, the impedance of coil **58** becomes only the resistance drop of the coil itself and hence maximum power can flow from source **50** to load **52.** Power flow to load **52** may be controlled anywhere in the range between these two extremes. Thus, the flux amplifier provides a high degree of versatility in possible control functions.

However, it is to be observed that the resulting net flux always retains a sinusoidal shape so that the amplifier and the system as a whole always operate in the linear mode. Because the flux amplifier is a linear device, harmonics are not generated in the system; and this is particularly important in motor control circuits as will be later seen in connection with further embodiments of the invention.

FIG. 4 illustrates a passive type flux amplifier as contrasted to the active type flux amplifier illustrated in FIG. 3. In FIG. 4, parts corresponding to similar parts in FIG. 3 are identified by like numerals. This type of flux amplifier **54** is referred to as passive because there

is no separate active power supply (such as power supply **56** in FIG. **3**) which energizes secondary coil **60**. In FIG. **4**, an adjustable resistor **80** is connected between terminals **60***a* and **60***b* of coil **60** to form a current path, referred to for convenience as the secondary loop. Current flow in coil **58** induces voltage in coil **60** as was previously described for FIG. **3**. However, because resistor **80** is connected as a load on secondary coil **60** in FIG. **4**, this induced voltage causes a sinusoidal current to flow in the secondary loop. This sinusoidal current flow is a function of the amount of resistance connected as a load on coil **60** as determined by the setting of the adjustable wiper **82** of adjustable resistor **80**. The effect of this sinusoidal current flow is to develop a magnetic flux in flux amplifier **54** which tends to oppose the flux developed by the sinusoidal current flow in primary coil **58**. Therefore, with the full value of resistor **80** connected to coil **60**, the secondary loop current flow is of minimum amplitude thereby developing a corresponding opposing sinusoidal flux of minimum amplitude. The magnitude of the net resultant flux waveform developed in flux amplifier **54** is therefore a maximum with the secondary loop resistance being a maximum. Power flow to load **52** is therefore a minimum. On the other extreme, with coil **60** short circuited, secondary loop current flow is of maximum amplitude thereby having maximum effect on the flux waveform developed in flux amplifier **54**. Under this condition, maximum power flows from source **50** to load **52**. The flux amplifier **54** of FIG. **4** will operate only as a substractive flux amplifier because the current in coil **60** is solely an induced current due to current in coil **58**. When the flux amplifier **54** of FIG. **4** was used in the motor control for a one horsepower induction motor previously referred to, the turns ratio of coils **58**, **60** was one to one.

It is to be observed in the flux amplifier **54** of FIG. **4** that the two coils **58** and **60** are linked by a core of ferromagnetic material **84**. As previously mentioned, flux amplifier **54** is a linear device; therefore, the magnetic characteristics of the core **84** must be considered. A typical ferromagnetic material may have magnetic characteristics similar to those shown in the B-H curves **85**, **86** in FIG. **8**. FIG. **9** illustrates the B-H plot **87** of a theoretically linear magnetic material with no core losses and no residual magnetization. If the magnetic intensities H in core **84** are such that the core is operating on the B-H curve **86**, it will be apparent that when the flux density B reaches or exceeds the value **88**, the core is driven into saturation and substantial nonlinearities are introduced. Moreover, some nonlinearity is present prior to saturation as compared to the idealized characteristic **87**. Of course, the nonlinearities would be even greater when using the so-called "square loop" ferrites. Hence, when the flux amplifier **54** includes a ferromagnetic core, the maximum flux density in the core cannot exceed the value **88**; i.e., the flux density due to maximum current flow in coils **58**, **60** could not exceed the value **88** in the case of an additive flux amplifier and, in the case of a subtractive flux amplifier, the flux density due to current flow in coil **58** could not exceed the value **88**. Moreover, operation on the curve **86**, even with the maximum flux density never exceeding the value **88**, is still somewhat nonlinear by comparison to the theoretical characteristic **87**. Hence, in the preferred embodiment of the present invention, the maximum flux density B is restricted so that the core **84** operates on a substantially more linear characteristic **85** that more closely approximates the ideal characteristic **87** of FIG. **9**. It will be appreciated that the B-H curves **85**, **86**, **87** are for purposes of illustrating the operation of a linear flux amplifier according to the present invention. It should also be appreciated that if the core is driven into saturation, the harmonic content in the resultant flux would increase substantially, in turn producing a corresponding increase in harmonics in the current through coil **58**. Hence, the present invention viewed in a different light contemplates restricting the peak magnetic intensity H so that the core operates on a hysteresis curve without highly saturating the core, for example, by not exceeding the limits **89**, **89'** during the entire sine wave cycle of the magnetizing currents and over the full control range of the amplifier. While it is theoretically desirable to have zero harmonic content in the flux amplifier, it is to be appreciated that as a practical matter a small amount of harmonic content actually is present. This may be tolerated so long as the instability generated thereby in the load being controlled is not intolerable.

Turning now to FIG. **5** which illustrates an induction motor control circuit constructed in accordance with my invention, motor **100** is a conventional three-phase induction motor which is powered from a three-phase sinusoidal AC source **102**. The motor rotor **104** has individual rotor phase windings **104***a*, **104***b* and **104***c*. The windings **104***a*, **104***b* and **104***c* have common terminals **106** and **108**. The stator **110** has corresponding stator phase windings **110***a*, **110***b* and **110***c*. Stator phases each have one common terminal **112** while the other terminal **114***a*, **114***b* and **114***c* of each individual phase is connected through an associated linear flux amplifier **54** to a corresponding terminal of the three-phase source **102**. Linear flux amplifiers **54** are identical and may be, for example, either of the flux amplifiers **54** shown in FIGS. **3** and **4**. Of course, if the flux amplifier of FIG. **3** is used, the coils **64** of the power supplies **56** could be connected in series with the associated rotor winding **104***a*, **104***b* and **104***c* to supply secondary coil **60** via terminals **60***a*, **60***b*. Each flux amplifier **54** is connected in circuit with its associated stator phase **110** so that its primary coil **58** is in series with its associated stator phase winding **110**. Terminals **114***a*, **114***b* and **114***c* are respectively connected to the terminal **58***a* of the primary winding **58** of the associated flux amplifier **54** while each of the three terminals of the three-phase source **102** is connected to the other terminal **58***b* of the primary winding. Terminals **60***a* and **60***b* of the secondary coil **60** of each flux amplifier are not illustrated in FIG. **5**.

FIG. **6** is similar to FIG. **5** and like numerals are used to designate similar parts. The differences between the two figures are twofold. First, the flux amplifiers **54** in FIG. **6** are connected in series with each rotor phase (through suitable slip rings, not shown) rather than in series with each stator phase. Secondly, each rotor phase also includes a capacitor **116**, whose purpose will be later described, connected in series with the primary loop of its flux amplifier.

Referring now to both FIGS. **5** and **6**, because of the linear operating characteristic of the flux amplifiers **54**, control of voltage and current flow from source **102** to motor **100** is controlled in a linear fashion. This eliminates the undesired pulsating torques previously mentioned. A further advantage of the linear flux amplifier

applied to an induction motor is that the motor speed can be controlled over a wide range with maximum efficiency. Each flux amplifier 54 is essentially a reactance at the frequency of the AC source and dissipates very little power. This helps to keep the overall system inefficiency to a minimum. While the construction details of the flux amplifier will depend upon the particular application in which it is to be used (for example, motor size, motor current, controlled speed range, etc.), the operating characteristics of the flux amplifier over the control range may be described as tending to compensate for the changes in the operating characteristics of the motor over the motor speed range. Thus, it is the cooperative effect between the changing coil voltage and reactance on the one hand and the changing motor characteristics on the other hand which achieve the aforementioned results, i.e., improved efficiency and speed control over a wide range.

The circuit of FIG. 6 shows one arrangement for improving the torque-rpm characteristic of a conventional induction motor, as exemplified by plot 22 in FIG. 2. In general, the high torque capability is achieved by connecting a capacitor 116 in each of the three phases.

In order to better understand the high torque embodiment of FIG. 6, it is necessary to refer to conventional induction motor theory. Accordingly, each phase of an induction motor may be represented by a T equivalent circuit which incorporates both rotor and stator parameters. The T equivalent circuit may be converted into an equivalent Thevenin series circuit wherein the rotor and stator parameters are combined to produce the Thevenin circuit. The Thevenin parameters may be determined by test according to well-known methods. The value of each capacitor 116 is selected to provide series resonance of the Thevenin equivalent circuit at the fundamental system frequency and operating speed; i.e., a function of slip. While capacitors 116 may be theoretically connected in either the rotor circuit or the stator circuit, their actual connection is a matter of practical consideration. For example, in a squirrel cage type induction motor, the capacitors must be placed in the stator circuit since the rotor circuit is not accessible for connection. An advantage of connecting the capacitors in the stator is the convenient accessibility of the external motor leads. As a result, a conventional motor structure need not be modified, and if desired, the capacitors may be located remotely from the motor itself. On the other hand, it may be more desirable and economical to connect the capacitors in the rotor phase of a wound rotor type motor especially where the turns ratio of the stator phase to the rotor phase is greater than unity as is usually the case. Since the value of each capacitor, and hence its physical size, is a function of the square of this turns ratio, the size of the capacitors may be made substantially smaller by connecting them in the rotor phase of a conventional motor where this ratio may be perhaps as high as two or three to one.

In calculating the maximum torque capability, the net flux in flux amplifier 54 is assumed to be zero. Hence, coil 58 presents solely the resistance of the coil itself. As the flux amplifier is adjusted from this position, the combined voltage and reactance control causes the motor operation to change accordingly. With the improved motor torque capability afforded by utilizing my invention, it is contemplated that an induction motor can become economically competitive with a DC motor for many adjustable speed applications. The present invention also contemplates simultaneous adjustment of amplifiers 54 and capacitors 116, for example, as applied to a motor control circuit using the flux amplifier 54 of FIG. 4, a variable capacitor could be used with the capacitance being varied along with resistor 80.

FIG. 7 also illustrates a passive linear flux amplifier 54 which has an automatic control circuit for automatically adjusting the setting of the flux amplifier. The arrangement is merely exemplary and it is intended that various automatic controls may be used with other types of linear flux amplifiers to also accomplish automatic control functions. An autotransformer 118 is connected across secondary coil 60 of flux amplifier 54. Terminal 58*b* of primary coil 58 is connected to terminal 60*b* of secondary coil 60. Autotransformer 118 has an adjustable wiper 120 which is connected to the load to which the flow of power is being controlled. If this flux amplifier 54 were utilized in a motor control arrangement, for example, as shown in FIGS. 5 and 6, wiper 120 rather than terminal 58*b* would be connected to the load; i.e., the stator windings 110 in FIG. 5 or the rotor windings 104 in FIG. 6. With wiper 120 operated to the lowermost position in FIG. 7 (i.e., in contact with terminal 60*b*), current flow from the source through primary coil 58 to the load is of minimum value and hence power flow to the load is also a minimum. As wiper 120 is moved increasingly upwardly toward terminal 60*a* of secondary coil 60, increasing current is caused to flow through secondary coil 60. Because flux amplifier 54 is of the subtractive flux type, the flux developed by increasing secondary current flow subtracts from the flux developed by current flow in primary coil 58 so that the net flux linking the two coils is increasingly reduced as wiper 120 is moved upwardly. With wiper 120 contacting terminal 60*a*, the net flux developed in the flux amplifier is of minimum amplitude; and hence, maximum current and power can flow from the source to the load. Power flow is adjustable between these two extremes in accordance with the setting of wiper 120. Of course, amplifier 54 of FIG. 7 could be operated as an additive flux amplifier by reversing the polarity of coil 60. However, as indicated earlier, operation as a subtractive flux amplifier is preferred for most applications. Autotransformer 118 could also be replaced by a resistive potentiometer although an autotransformer is preferred to minimize losses.

Also shown in FIG. 7 is an automatic control arrangement for adjusting wiper 120. The automatic control shown is essentially a servo arrangement, the details of which can be obtained from a conventional servo handbook. One way in which the arrangement of FIG. 7 might be incorporated in either arrangement of FIGS. 5 and 6, the automatic control would operate to secure correspondence between actual motor speed and a programmed motor speed. In applying the automatic control to one of the induction motor circuits of FIGS. 5 and 6 for this purpose, a feedback tachometer 122 is operatively coupled to the motor shaft and generates a signal correlated to motor speed. An adjustable voltage reference 124 supplies an adjustable signal correlated to programmed motor speed. Both signals are input to an error detector 126 which compares the two signals and develops an error signal at its output 128. The error signal, which represents the difference between

the two input signals, is in turn amplified by an amplifier 130. Amplifier 130 operates an actuator 132 mechanically coupled to the adjustable wipers 120 of each of the three flux amplifiers by any suitable coupling or linkage. Whenever the motor speed, as sensed by tachometer 122, differs from the desired value programmed by the setting of source 124, the amplified error signal operates actuator 132 to move wipers 120 in directions which tend to null out the error signal. Such an arrangement provides automatic speed control of the motor by insuring that the motor runs at a speed exactly equal to the programmed speed. The automatic control illustrated is merely exemplary and it is to be appreciated that other types of automatic control may be used in accordance with the particular requirements for the given installation. For example, command speed could be set by tape control, and other parameters such as temperature, pressure, etc. could be utilized to provide feedback information. For example, a motor may be used to perform an automatic control function of another device. Thus, the feedback information need not come from the motor shaft but rather may be derived from a parameter which varies with the operation of the device which is being controlled by the motor. For example, parameters such as temperature, pressure, etc. could be utilized with an appropriate transducer to provide feedback information to the automatic control.

FIG. 10 shows a further embodiment of my invention. The primary current loop consists of the sinusoidal AC source 50, the primary coil 58 of flux amplifier 54 and the load 52 which may be, for example, a single phase induction motor. The secondary current loop comprises the secondary coil 60 of flux amplifier 54, a capacitor 116 and a pair of reversely connected solid state switches 140 and 142 (for example, four-layer PNPN devices such as the silicon controlled rectifiers illustrated) which are reversely connected in parallel with each other and are operable to control the current flow in secondary coil 60 as will be hereinafter described. Although it is to be observed that the terminal 60*b* of secondary coil 60 is connected to terminal 58*b* of primary coil 58 and not directly to the other side 50*b* of the AC line, the secondary coil 60 could be connected to terminal 50*b*. Flux amplifier 54 is preferably of the subtractive flux type. Switches 140 and 142 conduct on alternate half cycles with switch 140 being conductive during the positive polarity half cycle (i.e., when terminal 50*a* of source 50 is positive with respect to terminal 50*b*) and switch 142 during the negative polarity half cycle (i.e., terminal 50*a* negative relative to terminal 50*b*). The firing circuits 144 and 146 respectively for each switch 140 and 142 are identical except that the firing circuit 144 for switch 140 is arranged to render switch 140 conductive on positive half cycles while firing circuit 146 which is associated with switch 142 is arranged to render that switch conductive on negative polarity half cycles. Common to both firing circuits 144 and 146 is the primary coil 150 of a transformer 148. However, the secondary coils 152 and 154 of transformer 148 are associated only with firing circuit 144 while the coils 156 and 158 are associated solely with firing circuit 146. Coils 152 and 156 are respectively electrically connected in phase shifting circuits 162 and 160 respectively. The phase shifting circuits 160 and 162 comprise capacitors 164 and 166 respectively and variable resistors 168 and 170 respectively. Thus, each phase shift circuit is a series LCR circuit, the resistance of which is adjustable to vary the phase of the current relative to the phase of the voltage induced in the secondary coil. Resistors 168, 170 are adjusted so that the gating signals to switches 142, 140 will gate switches 142, 140 on at the beginning of the respective half cycles of current supplied to coil 60. The two secondary coils 154 and 158 are electrically connected in individual gating circuits 174 and 172 respectively. Each gating circuit comprises a first solid state switch 176, 178 respectively, a second solid state switch 180, 182 respectively and a transformer 184, 186 respectively. The associated primary coil 188, 190 of each transformer 184, 186 is connected in series with the associated secondary coil 158, 154, the associated first solid state switch 176, 178 and the associated second solid state 180, 182. Each secondary coil 192, 194 is connected to its associated solid state switch 142, 140 respectively. Each phase shift circuit 160, 162 is electrically connected to its associated gating circuit 172, 174 by applying the voltage developed across its resistor 168, 170 as a triggering signal for the first solid state switch 176, 178. Each second solid state switch 180, 182 is electrically connected to an error signal circuit; for example, the error signal circuit shown in FIG. 7. Thus, the error signal developed at line 128 of FIG. 7 is applied as a triggering signal for each second solid state switch 180, 182.

Operation of firing circuit 146 during the negative polarity half cycle is now described and it is to be understood that circuit 144 operates correspondingly during the positive half cycle. Therefore, assuming circuit 146 in proper adjustment and assuming that an error signal is being applied to second solid state switch 180, then at the beginning of the negative half cycle, the voltage developed across resistor 168 triggers switch 176 for conduction. Simultaneously, the voltage across secondary coil 158 is such that a current flows through switches 176 and 180 to develop a voltage across primary coil 188 of transformer 184. In turn, the voltage across the transformer primary induces a voltage in the secondary 192 which operates to trigger switch 142 into conduction. Therefore, current flows in secondary coil 60 of flux amplifier 54 to control the magnitude of the flux waveform of the flux amplifier in the fashion previously described. Flux amplifier 54 is of the subtractive flux type in the preferred embodiment of FIG. 10 so that this current flow in secondary coil 60 reduces simultaneously the reactance and voltage of primary coil 58 and hence permits increased power to flow from source 50 to load 52. So long as a positive error signal is applied to the two firing circuits 144 and 146, flux amplifier 54 operates as if it were directly connected to source 50 and load 52; for example, as if it were connected as in FIG. 3. When the positive error signal ceases, switches 180 and 182 cannot be operated and hence the gating circuits are ineffective to trigger the switches 140 and 142. Under this condition, secondary coil 60 is effectively disconnected from the circuit and as a result, reactance of and the voltage across coil 58 increase thereby reducing the flow of power from source 50 to load 52.

Thus, the control circuit shown in FIG. 10 is essentially an on-off type control for energizing secondary coil 60. However, it is to be noted that the linear operation of flux amplifer 54 is entirely unimpaired because switches 140, 142 are on for their entire respective half

cycles of current supplied to coil 60 when a positive error signal is present. Hence, coil 60 is energized only by substantially sinusoidal currents as the embodiments previously described. This is because the operation of switches 140 and 142 is substantially coextensive with their respective half cycles. Thus, in any given half cycle, the net flux waveform is a half cycle of a sinusoid.

Although specific embodiments of the present invention have been described hereinabove for purposes of illustration, it will be understood that various modifications can be made. Any one of the various different embodiments of the flux amplifiers 54 illustrated in FIGS. 3, 4 and 7 could be used to control the voltage and reactance of the stator windings in the manner illustrated in FIG. 5 or the voltage and reactance of the rotor windings in the manner illustrated in FIG. 6. As indicated earlier, although the flux amplifiers 54 are preferably operated as subtractive flux amplifiers, the present invention also contemplates operation as additive flux amplifiers and, moreover, operation as a combined additive and subtractive flux amplifier in the manner illustrated by the circuit of FIG. 3. Although the high torque embodiment as described in connection with FIG. 6 incorporates capacitor 116 connected directly in series with the motor windings, a similar result could be achieved by connecting a capacitor in circuit with the secondary coil 60 of the flux amplifier 54 so that when the secondary coil 60 is energized, the capacitance is reflected into the primary coil 58 and hence in the circuit of the motor windings. Moreover, the high torque capacitors 116 can be used without the flux amplifiers 54, although the combination of the flux amplifiers 54 and the high torque capacitors 116 would be useful in a wide variety of control applications. Although the use of solid state switches 140, 142 has been described hereinabove in connection with the flux amplifier 54 of FIG. 10, it will also be understood that similar solid state circuits could be used to control the application of sinusoidal current to the secondary coils 60 in the other embodiments illustrated, for example, the three-phase embodiments illustrated in FIGS. 5 and 6. Additionally, switches 140, 142 could be connected in parallel with coil 60 to serve as a shunt control rather than the series control illustrated in FIG. 10.

It will also be understood that the flux amplifier circuits for controlling induction motors and the like have been described hereinabove for purposes of illustration and are not intended to indicate limits of the present invention, the scope of which is defined by the following claims.

What is claimed is:

1. In an induction motor control circuit the combination comprising an induction motor having a stator winding and a rotor winding, a source of sinusoidal current at a fundamental frequency and flux amplifier means electrically connected in circuit with said source and said motor for adjustably controlling power flow from said source to said motor, said flux amplifier means comprising a primary coil electrically connected with one of said motor windings for conducting primary sinusoidal current at said fundamental frequency during operation of said motor to thereby develop a sinusoidal primary magnetic flux at said fundamental frequency, a secondary coil, means for causing a sinusoidal secondary current at said fundamental frequency having an amplitude parameter and a phase parameter to flow in said secondary coil to thereby develop a corresponding sinusoidal secondary magnetic flux at said fundamental frequency having amplitude and phase parameters correlated to said amplitude and phase parameters of said secondary current, a magnetic circuit operatively coupling said two coils and conducting said primary and said secondary magnetic fluxes, said magnetic circuit having a magnetic characteristic that causes said primary and secondary magnetic fluxes to be linearly combined with each other to develop a sinusoidal resultant flux in said magnetic circuit at said fundamental frequency having an amplitude parameter and a phase parameter and adjustment means having selectable adjustment positions for adjusting at least one of said parameters of said secondary current over a selected range to thereby correspondingly adjust at least one of said resultant flux parameters so that for all adjustment positions of said adjustment means said resultant flux is maintained sinusoidal whereby reactance and voltage at said primary coil can be varied to thereby operate said motor at selected motor speeds and motor torques as determined by said adjustment means.

2. The combination of claim 1 wherein said primary coil of said flux amplifier means is electrically connected between said source and said stator winding and said primary sinusoidal current flows from said source to said motor via said primary coil.

3. The combination of claim 1 wherein said primary coil of said flux amplifier means is electrically connected in series with said rotor winding.

4. The combination of claim 1 further including means for causing series resonance of the current flow from said source to said motor at said fundamental frequency and at a predetermined speed.

5. The combination of claim 4 wherein said means for causing resonance comprises a capacitance electrically connected in series with said primary coil of said flux amplifier means.

6. The combination of claim 5 wherein said capacitance has an electrical reactance at said fundamental frequency which is equal and opposite to the equivalent electrical reactance of the motor at said fundamental frequency and at a predetermined speed.

7. The combination of claim 1 including automatic control means for automatically adjusting the position of said adjustment means as a function of a selected control parameter.

8. The combination of claim 1 wherein said motor is a plural phase motor having a respective stator winding and a respective rotor winding for each phase and a respective flux amplifier means is connected in circuit with each winding in either the stator or the rotor.

9. The combination of claim 1 wherein said adjustment means comprises solid state switch means electrically connected to said secondary coil and means for operating said solid state switch means coextensively with half cycles of said secondary current to thereby cause said secondary current to be conducted to said secondary coil in units of half cycles.

10. The combination of claim 9 wherein said solid state switch means comprises first and second solid state switches electrically connected to said secondary coil and means for operating said first solid state switch coextensively with positive half cycles of said secondary current and means for operating said second solid state switch coextensively with negative half cycles of said secondary current.

11. The combination of claim 1 wherein said magnetic circuit comprises air.

12. The combination of claim 11 wherein said two coils are closely magnetically coupled by said magnetic circuit.

13. The combination of claim 1 wherein said adjustment means comprises means for varying the amplitude of said secondary current.

14. The combination of claim 1 wherein said adjustment means comprises means for varying the phase of said secondary current.

15. The combination of claim 1 wherein said adjustment means comprises means for adjusting the amplitude and the phase of said secondary current.

16. The combination of claim 1 wherein said means for causing sinusoidal current flow in said secondary coil comprises a load connected across said secondary coil to complete an electric circuit path with said secondary coil so that voltage induced in said secondary coil by said primary flux causes said secondary current to flow in said secondary coil and said load wherein said adjustment means comprises means for adjusting said current flow through said load and said secondary coil.

17. The combination of claim 16 wherein said adjustment means comprises means for adjusting the magnitude of said load to thereby adjust said current flow through said load and said secondary coil.

18. The combination of claim 17 wherein said load comprises an adjustable resistance.

19. The combination of claim 16 wherein said load comprises an autotransformer electrically connected across said secondary coil.

20. The combination of claim 1 wherein said means for causing secondary current flow comprises means for conducting a portion of said primary current into said secondary coil and wherein said adjustment means comprises means for adjusting the portion of said primary current which is conducted through said secondary coil.

21. The combination of claim 20 wherein said means for conducting a portion of said primary current into said secondary coil comprises a load connected across said secondary coil and a tap connection to said load intermediate its points of connection to said secondary coil and wherein said adjustment means comprises means for adjusting the position of said tap on said load.

22. The combination of claim 21 wherein said load comprises an autotransformer.

23. In an electric control circuit the combination of a source for supplying sinusoidal current at a fundamental frequency, a load electrically connected to said source and flux amplifier means electrically connected in circuit with said source and said load for controlling power flow from said source to said load comprising a primary coil electrically connected in circuit between said source and said load which conducts said sinusoidal current from said source to said load and which develops a sinusoidal primary magnetic flux at said fundamental frequency, a secondary coil, means for causing a sinusoidal secondary current at said fundamental frequency having an amplitude parameter and a phase parameter to flow in said secondary coil to thereby develop a sinusoidal secondary magnetic flux at said fundamental frequency having amplitude and phase parameters correlated to said amplitude and phase parameters of said secondary current, a magnetic circuit operatively coupling said two coils which conducts said primary and secondary magnetic fluxes and which has a magnetic characteristic for causing said primary and secondary magnetic fluxes to be linearly combined with each other to develop a resultant flux in said magnetic circuit which is sinusoidal at said fundamental frequency, and adjustment means having selectable adjustment positions for adjusting at least one of said parameters of said secondary current over a selected range to thereby correspondingly adjust at least one of said resultant flux parameters so that for all adjustment positions of said adjustment means said resultant flux is maintained sinusoidal whereby reactance and voltage at said primary coil can be varied to thereby control power flow from said source to said load.

24. In combination an electric motor having a stator winding and a rotor winding, alternating current source means for supplying to said stator winding a first sinusoidal current having a predetermined fundamental frequency, and series controller means connected in circuit with one of said windings to control power transferred from said source to said motor, said controller means comprising first coil means connected in series with said one winding, second coil means, magnetic flux coupling means operatively associated with said first and said second coils to provide a common flux path therebetween, and circuit means connected in circuit with said second coil means to provide a path for a second alternating current at said predetermined frequency through said second coil means, said flux coupling means being operable according to predetermined B-H characteristics which are substantially linear over a predetermined range of flux densities in said flux coupling means and wherein said first and said second alternating currents have amplitudes and phases correlated to each other and to said B-H characteristics so that said flux coupling means operates only on said predetermined characteristics without substantially saturating said flux coupling means in response to said first and said second currents.

25. The combination set forth in claim 24 wherein said first and said second coil means are a sole means supplying flux to said flux coupling means.

26. In the method of controlling the speed of an alternating current induction motor having a rotor winding and a stator winding and wherein current flow through one of said windings at a predetermined frequency is controlled by first coil means connected in circuit therewith, second coil means, and flux coupling means magnetically coupling said first and said second coil means and being operable according to predetermined B-H characteristics which are substantially linear over a predetermined range, that improvement wherein primary current through said first coil means is controlled by applying to said second coil means a second sinusoidal current whose phase and amplitude are correlated to the phase and amplitude of said primary current and to said B-H characteristics to cause said flux coupling means to operate only on said predetermined linear range of said B-H characteristics without substantially saturating said flux coupling means.

27. In the method of controlling power flow from a source of sinusoidal current at a fundamental frequency to a load electrically connected to said source through flux amplifier means wherein said flux amplifier means comprises primary coil means electrically

connected in circuit between said source and said load, a secondary coil, and magnetic circuit means having predetermined magnetic characteristics and magnetically coupling said primary coil means with said secondary coil means, the steps of establishing in said primary coil means a primary sinusoidal current from said source which causes a sinusoidal primary magnetic flux at said fundamental frequency to be developed in said magnetic circuit means, simultaneously establishing in said secondary coil means a secondary sinusoidal current at said fundamental frequency which causes a sinusoidal secondary magnetic flux at said fundamental frequency to be developed in said magnetic circuit means, and correlating respective phase and amplitude parameters of said primary sinusoidal current with respective phase and amplitude parameters of said secondary sinusoidal current and with said predetermined magnetic characteristics of said magnetic circuit means so as to cause said primary and secondary magnetic fluxes to be linearly combined with each other in said magnetic circuit means to thereby develop a resultant flux in said magnetic circuit means which is sinusoidal and at said fundamental frequency.

28. The method set forth in claim **27** wherein said flux amplifier means is operated by primary sinusoidal current and secondary sinusoidal current correlated to each other and to said predetermined magnetic characteristics so that said magnetic coupling has a substantially constant permeability over an anticipated operating range of said primary and said secondary currents.

29. The method set forth in claim **27** wherein said predetermined magnetic characteristic is a B-H characteristic which is substantially linear over a predetermined range and wherein said primary sinusoidal current and said secondary sinusoidal current have phases and amplitudes correlated to each other and to said B-H characteristic such that said flux amplifier means operates only on said predetermined linear range of said B-H characteristic.

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