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PILOT-WIRE PROTECTION OF TRANSMISSION LINES

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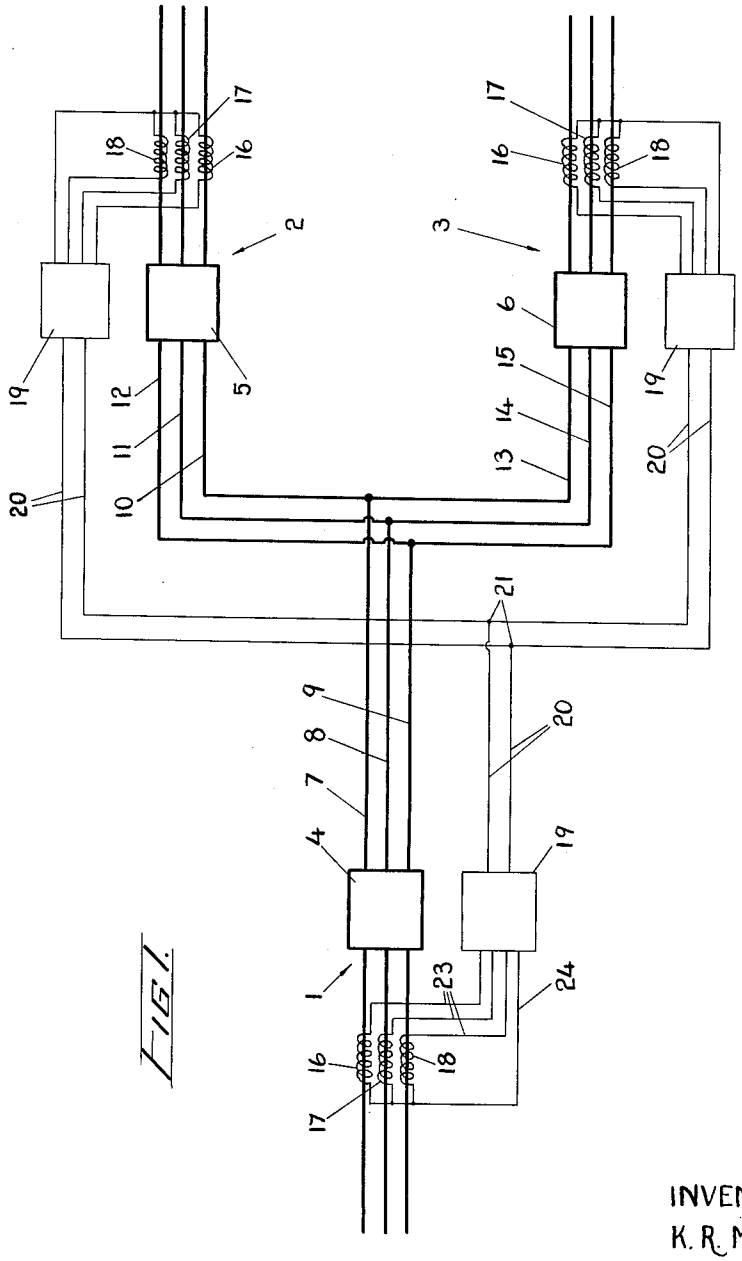


FIG. 1.

INVENTOR
K. R. McCLYMONT
BY
Maybee & Legris
ATTORNEYS

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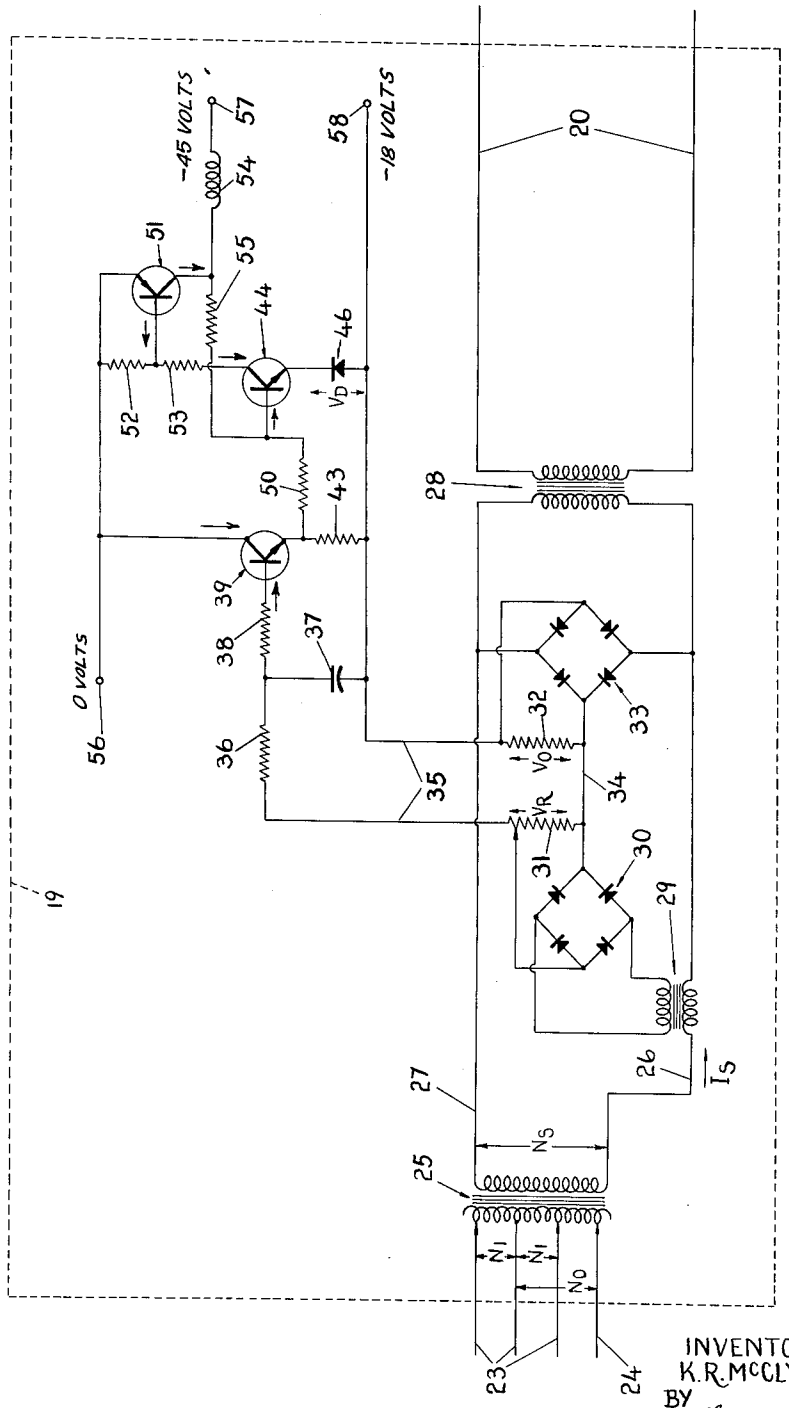
FIG. 2




INVENTOR
K. R. McCLYMONT
BY
Maybee & Legris
ATTORNEYS.

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# PILOT-WIRE PROTECTION OF TRANSMISSION LINES

Kenneth R. McClymont, 29 Abinger Court, Islington, Ontario, Canada

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This invention relates to the protection of electrical transmission lines by a pilot-wire arrangement.

Pilot-wire protective arrangements presently in use are subject to incorrect operations which arise in part because of the unpredictable characteristics of these arrangements. The lack of reliability of such arrangements has specially hindered their use for the protection of three-terminal transmission lines where the requirements are much more severe than for two-terminal lines.

According to the present invention there has been devised a pilot-wire arrangement which has improved performance on a two-terminal transmission line and the behaviour of which lends itself to analytical solution and to the application of the arrangement to lines having three or more terminals.

The scope of the invention is defined in the appended claims, but one embodiment of the invention will be described in detail by reference to the accompanying drawings in which:

FIGURE 1 is a schematic diagram of a three-phase transmission line having three terminals protected by a pilot-wire arrangement; and

FIGURE 2 shows in detail, for a typical terminal, the control circuit that is indicated by one of the blocks of FIGURE 1.

The transmission line of FIGURE 1 has three terminals generally indicated by reference numerals **1**, **2** and **3**, each terminal including a circuit breaker **4**, **5** and **6** respectively. Three wires **7**, **8** and **9** of the transmission line are connected to terminal **1** and to wires **10**, **11** and **12** leading to terminal **2** and to wires **13**, **14** and **15** leading to terminal **3**.

In the transmission line at each terminal is a set of current transformers **16**, **17** and **18**, and the current transformers of the three terminals are connected through control circuits **19** to pilot-wires **20**, the pilot-wires having a common junction at points **21** and thus providing an electrical path between the terminals of the transmission line.

Details of a typical control circuit **19** are shown in FIGURE 2. Let it be assumed that the circuit **19** shown in FIGURE 2 is the one associated with terminal **1** in FIGURE 1. The three-phase leads **23** and neutral lead **24** of the current transformers **16**, **17** and **18** are connected to the primary winding of a mixing transformer **25**. The mixing transformer acts as a current source and has a two line output **26**, **27** to which it delivers a sinusoidal output current $I_s$ the value of which is given by the expression

$$I_s=\frac{N_1}{N_s}\left[\left(\frac{3N_0}{N_1}\right)I_0+(1\alpha)I_1+(1-\alpha^2)I_2\right]$$

where $N_0$, $N_1$ and $N_s$ are the numbers of turns indicated in FIGURE 2 (taps on the primary winding permitting variation of $N_0$ and $N_1$), $I_0$, $I_1$ and $I_2$ are respectively the zero, positive and negative sequence components of current input to the transformer **25**, and $\alpha$ is the vector operator $1 \angle 120°$. It will be seen from the above expression that $I_s$ is independent of the impedances in the circuits to which the mixing transformer is connected.

The output lines **26**, **27** of the mixing transformer **25** are connected through an insulating transformer **28** to



the pilot-wires **20**. The purpose of the insulating transformer is to ensure that high voltages (relative to ground) which may fortuitously occur on the pilot-wires **20** are isolated there. Insofar as the operation of the pilot-wire and control circuits is concerned the lines **26**, **27** may be considered to be continuations of the pilot-wires **20**. The current transformers at each terminal are connected with the same polarity as the current transformers at the other terminals so that a current normally circulates through the pilot-wires and the lines **26**, **27**, the current $I_s$ of terminal **1** being the sum of the currents $I_s$ of terminals **2** and **3**.

A transformer **29** in the line **26** has its secondary winding connected through a full-wave rectifier bridge **30** to a potentiometer **31**, and across the resistance of the potentiometer there appears a unidirectional restraint voltage $V_R$ proportional to the line current $I_s$. The potentiometer setting may be varied to vary $V_R$ over a wide range and false operations caused by undesired saturation of one or more of the current transformers can be prevented by proper setting of the potentiometer **31**. A shunting resistance **32** is connected across the lines **26**, **27** through a full-wave rectifier bridge **33**, and across the resistance **32** there appears a unidirectional operating voltage $V_0$ proportional to the voltage across the pilot-wires.

Normally the restraint voltage $V_R$ is much greater than the operating voltage $V_0$. If, however, a fault should occur between the terminals, the currents in the pilot-wires will subtract rather than add and $V_0$ will become large compared to $V_R$. By means of a line **34** the voltages $V_R$ and $V_O$ are connected in opposition so that the difference voltage appears across leads **35**; ripple in this difference voltage is substantially filtered out by a series resistance **36** and shunt capacitance **37**. The time constant of the filter **36**, **37** is made small enough so as not to delay significantly the operation of the control circuit, but there can be sufficient time delay in the filter to prevent operation on sharp transient peaks.

The unidirectional voltage from the filter **36**, **37** is applied through a resistance **38** to a transistor **39** which does not conduct unless $V_0$ exceeds $V_R$. If $V_0$ exceeds $V_R$ the transistor **39** receiving the difference between these voltages begins to conduct. The transistor **39** when conducting produces across a resistance **43** an output voltage of nearly the same magnitude as the input voltage to the transistor, the output voltage thus being indicative of a fault between the terminals of the transmission line. The transistor **39** acts as a power amplifier, providing a high and substantially nonvarying input impedance as seen from the filter **36**, **37**. A second transistor **44** is normally rendered nonconductive by a reference voltage $V_D$. It is important that the voltage $V_D$ be held at a value which remains stable over a long period of time, and the provision of a Zener diode **46**, across which $V_D$ appears, ensures such stability.

The transistor **44** is rendered conductive when the fault indicating voltage across the resistance **43** exceeds $V_D$, the difference being supplied to the transistor **44** through a resistance **50**. Conduction through the transistor **44** causes conduction and power amplification through a third transistor **51**, the latter having its base connected between voltage dividing resistances **52**, **53**. Voltage is thus built up across a relay coil **54**, and the relay is actuated, opening the circuit breaker at the associated terminal.

To ensure stable operation of the amplifying circuit through the transistors **44** and **51** a regenerative feedback circuit is provided through a resistance **55**. Thus, when the transistor **51** conducts, the potential of its collector rises, and the base of the transistor **44** goes more positive, en-

suring that the transistor **44** remains conductive so that the relay **54** does not vibrate. As a result, the feedback circuit ensures fast operation of the line protective relay **54**, of the order of one cycle on a sixty cycle system, when the fault indicating voltage exceeds the reference voltage $V_D$.

The transistors and the relay **54** are supplied from a D.C. power supply indicated in FIG. 2 by its output terminals **56, 57, 58**. This power supply is independent of the current transformers **16, 17** and **18**: that is to say, it is not supplied from the current transformers and thus places no burden on them. The input impedance of the transistor **39** is high, and there is a high impedance in the circuits connected across the lines **26, 27** to produce the restraint and operating voltages $V_R$ and $V_0$. Thus very little power is required from the current transformers to operate the relay. The transformer **29** offers low series impedance to the circulating currents $I_s$. The nature of the components in the control circuit **19** is such that the performance of the pilot-wire arrangement can be predicted from a mathematical analysis.

The relay control circuit **19** is so arranged that its operation is substantially independent of large changes in the characteristics of the transistors. The transistor **39** is connected as a cathode follower, so that changes in the gain of the transistor with time have negligible effect on its output voltage. The feedback circuit through the resistance **55** makes the gain very high, so that changes of gain of the transistors **44** and **51** are unimportant. Of primary importance is the stability of the reference voltage $V_D$. The relay **54** is caused to operate when the fault indicating voltage across the resistance **43** exceeds the reference voltage $V_D$, and very little difference between these voltages will operate the relay. Thus, the point at which the relay is operated is as accurate as the accuracy of $V_D$, relay operation being dependent upon a comparison of the fault indicating voltage with $V_D$. As an example, if $V_D$ is 5 volts, and a fault indicating voltage of 5.1 volts will operate the relay, a loss, with time, of fifty percent of the gain through the transistors **44** and **51** would necessitate an increase in the fault indicating voltage to only 5.2 volts to operate the relay.

The reference voltage $V_D$ provides a sharp point of operation for the relay **54**. Whereas the voltage at which a given relay will pick up can vary substantially, the control circuit for the relay operates precisely and then provides ample power, not drawn from the current transformers, to operate the relay coil. It will be noted that the voltage $V_D$ is not provided through the current transformers; rather the means for supplying $V_D$ are the D.C. power supply and the Zener diode **46** which are independent of the electrical output of the current transformers.

Typical components for the relay control circuit are as follows:

| | |
|---|---|
| Rectifier **30** | 1N2071. |
| Rectifier **33** | 1N2071. |
| Capacitance **37** | ½ microfared. |
| Resistance **31** | 100 kilo-ohms. |
| Resistance **32** | 15 kilo-ohms. |
| Resistance **36** | 22 kilo-ohms. |
| Resistance **38** | 27 kilo-ohms. |
| Resistance **43** | 8.2 kilo-ohms. |
| Resistance **50** | 30 kilo-ohms. |
| Resistance **52** | 1.5 kilo-ohms. |
| Resistance **53** | 2.2 kilo-ohms. |
| Resistance **55** | 320 kilo-ohms. |
| Terminal **56** | 0 volt. |
| Terminal **57** | −45 volts. |
| Terminal **58** | −18 volts. |
| $V_D$ | 5.0 volts. |
| Transistor **39** | 2N365. |
| Transistor **44** | 2N365. |
| Zener Diode **46** | 1N750A. |
| Transistor **51** | 2N251. |

Transformer **25** may be a current transformer for which $N_1$=5 amps., $N_0$=1 amp. and $N_s$=0.01 amp. Insulating transformer **28** may have a 1:1 ratio, and transformer **29** a 1:27 ratio. The relay **54** may be a 350 ohm relay rated to operate at 24 volts.

Vacuum tubes could of course be used instead of transistors, and in the appended claims the term "valve" will be understood to include a vacuum tube or a transistor. Protective and compensating devices of conventional design will normally be provided. For example, to compensate for the capacitance of the pilot-wires adjustable reactors can be connected across the junction points **21** and across the lines **26, 27** at the insulating transformers **28**, and it may also be desirable to provide potentiometers across the lines **26, 27** at the transformers **28** to balance the open circuit transfer impedances of the pilot-wires. To limit the voltages applied between the pilot-wires **20**, voltage regulating gaseous discharge tubes can also be provided across the lines **26, 27** at the insulating transformers **28**.

What I claim as my invention is:

**1.** A pilot-wire arrangement for protecting a three-phase electric transmission line having a plurality of terminals, comprising a line circuit breaker at each terminal, a relay for each terminal for opening the circuit breaker of the terminal, current transformers in the line at each terminal, pilot-wires providing an electrical path between the terminals, and a relay control circuit for each terminal with connections between the pilot-wires and the current transformers of the terminal of such polarity that a current normally circulates in the pilot-wires, the connections of each control circuit including a mixing transformer having an input from the current transformers of the terminal and a two line output for delivering a current which is a function of the positive, negative and zero sequence components of the currents from the current transformers and is substantially independent of the impedance of the pilot-wires, and an insulating transformer connected between the two line output and the pilot-wires, means connected across the two line output for providing an operating voltage dependent on the voltage across the pilot-wires, a transformer in one line of the two line output and means connected across the last mentioned transformer for providing a restraint voltage dependent on the current in the pilot-wires, means responsive to a predetermined difference between the operating voltage and the restraint voltage to provide a voltage indicative of a fault between the terminals of the line, a power supply independent of the current transformers, means providing a stable reference voltage, and an electronic amplifier for operating the relay of the terminal from the independent power supply in response to a predetermined difference between said indicative and reference voltages, thus opening the circuit breaker of the terminal.

**2.** A pilot-wire arrangement for protecting a three-phase electric transmission line having a plurality of terminals, comprising a line circuit breaker at each terminal, a relay for each terminal for opening the circuit breaker of the terminal, current transformers in the line at each terminal, pilot-wires providing an electrical path between the terminals, and a relay control circuit for each terminal with connections between the pilot-wires and the current transformers of the terminal of such polarity that a current normally circulates in the pilot-wires, the connections of each control circuit including a mixing transformer having an input from the current transformers of the terminal and a two line output for delivering a current which is a function of the positive, negative and zero sequence components of the currents from the current transformers and is substantially independent of the impedance of the pilot-wires, and an insulating transformer connected between the two line output and the pilot-wires, a shunting resistance connected through a rectifier across the two line output for providing a unidirectional

operating voltage dependent on the voltage across the pilot-wires, a transformer in one line of the two line output and a resistance connected through a rectifier across the last mentioned transformer for providing a unidirectional restraint voltage dependent on the current in the pilot-wires, a D.C. power supply independent of the current transformers and of the pilot-wires, a D.C. electronic power amplifier supplied by the independent power supply, a filter delivering the difference between the operating and restraint voltages to the amplifier, the amplifier being responsive to a predetermined difference between the operating voltage and the restraint voltage to provide a D.C. output voltage indicative of a fault between the terminals of the line, means providing a stable D.C. reference voltage, and a D.C. electronic amplifier supplied by the independent power supply and operative in response to a predetermined difference between said indicative and reference voltages to operate the relay of the terminal and thus open the circuit breaker of the terminal.

3. A pilot-wire arrangement for protecting an electric transmission line between terminals of the line, comprising

(1) a line protective relay for each terminal;

(2) current transformers in the line at each terminal;

(3) pilot-wires providing an electrical path between the terminals; and

(4) a relay control circuit for each terminal, the relay control circuit comprising

(a) means so connecting the current transformers with the pilot-wires that the pilot-wires carry a circulating current dependent upon the currents in the line and substantially independent of the impedance of the pilot-wires,

(b) means for deriving from the circulating current a signal indicative of a fault between the terminals of the line,

(c) means for providing a reference signal,

(d) means for comparing said signals, and

(e) means responsive to a predetermined comparison between said signals for operating the relay for that terminal to protect the line.

4. A pilot-wire arrangement as claimed in claim 3, wherein the means connecting the current transformers with the pilot-wires comprise a mixing transformer having its input connected to the current transformers and having a two line output supplying the pilot-wires.

5. A pilot-wire arrangement as claimed in claim 3, wherein the means for providing the reference signal comprise means independent of the electrical output of the current transformers for producing a stable reference signal.



6. A pilot-wire arrangement as claimed in claim 5, wherein the means for deriving from the circulating curcurent a signal indicative of a fault comprise

(i) means for providing a voltage dependent upon the circulating current,

(ii) means for providing a voltage dependent upon the voltage across the pilot-wires, and

(iii) means for comparing said voltages to derive said signal indicative of a fault.

7. A pilot-wire arrangement as claimed in claim 6, wherein the means for providing a voltage dependent upon the circulating current comprise a transformer through the primary winding of which the circulating current flows and across the secondary winding of which the last mentioned voltage is developed.

8. A pilot-wire arrangement as claimed in claim 6, wherein the voltage comparing means (iii) comprise an electronic valve, said voltage-providing-means (i) and (ii) being connected in opposition at the input of said valve, said valve being responsive to an excess of one of said voltages over the other to provide said signal indicative of a fault.

9. A pilot-wire arrangement as claimed in claim 8, wherein the electronic valve comprises a power amplifier.

10. A pilot-wire arrangement as claimed in claim 5, wherein the means responsive to said predetermined comparison comprise an electronic valve having its input from said signal comparing means and normally biased off by the stable reference signal but rendered conductive by a predetermined difference between the signals, the relay being in an output circuit of the valve.

11. A pilot-wire arrangement as claimed in claim 10, including a feedback circuit from the output circuit to the input of the valve for maintaining the valve conductive.

12. A pilot-wire arrangement as claimed in claim 5, wherein the relay control circuit includes a power supply independent of the electrical output of the current transformers and wherein the relay operating means energizes the relay from the independent power supply.

13. A pilot-wire arrangement as claimed in claim 12, wherein the power supply is a D.C. power supply and said signals are D.C. signals.

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SAMUEL BERNSTEIN, *Primary Examiner.*