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March 29, 1966 J. BAUDE 3,243,656

CIRCUIT INTERRUPTER CONTROL RESPONSIVE TO WAVE FORM

Filed Sept. 9, 1963 2 Sheets-Sheet 1

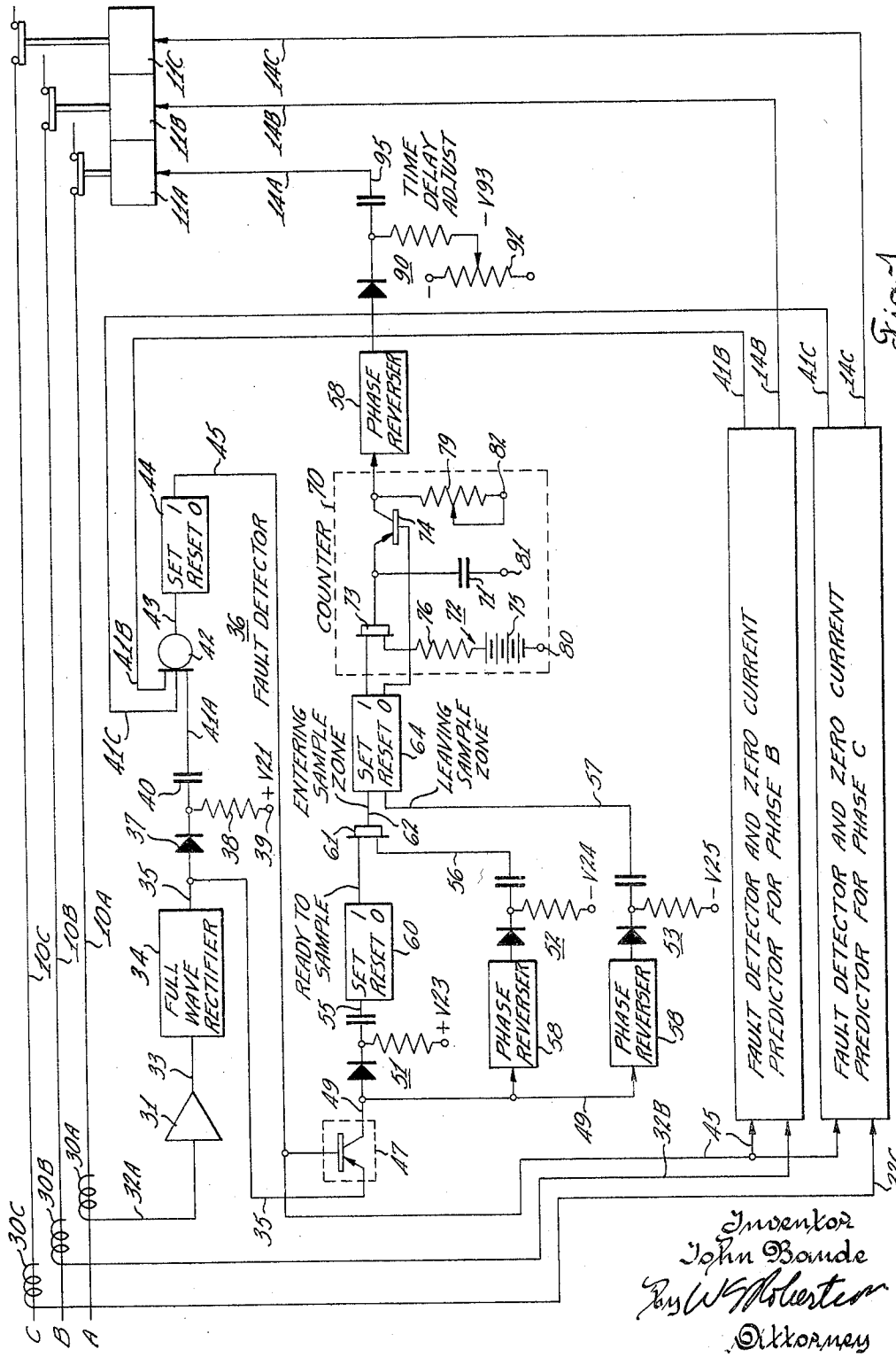


Fig. 1

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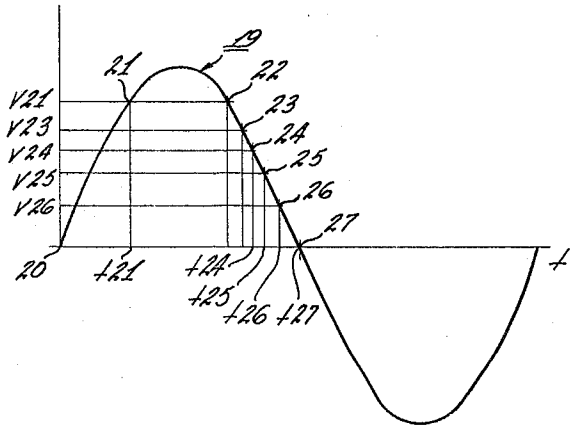


Fig. 2

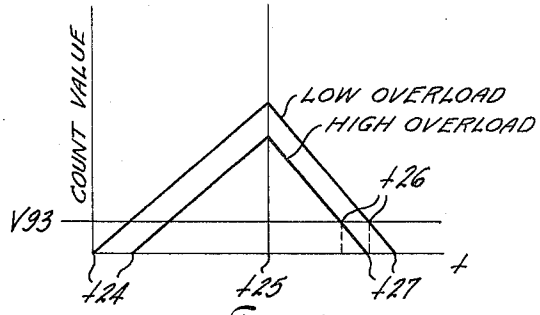


Fig. 3

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CIRCUIT INTERRUPTER CONTROL RESPONSIVE TO WAVE FORM

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2 Claims. (Cl. 317—11)

This invention relates generally to circuit interrupters; more specifically to a control for actuating a circuit interrupter to open at a preselected point in the current or voltage wave form of the electrical system that the circuit interrupter is connected in.

In the conventional circuit interrupters, interruption takes place in two steps. First the contacts separate and form an arc of hot ionized metal from the contacts and gases from the dielectric medium. This ionized medium maintains conduction between the separated contacts until it cools and deionizes sufficiently to withstand the voltage between the contacts. In the second step of conventionally interrupting the circuit, devices such as arc chutes operate on the arc medium to restore its dielectric strength. In an alternating current circuit the arc stops conducting at each current zero, and circuit interrupters are usually designed to interrupt the circuit by preventing reconduction after some current zero. If the contacts happen to be separated at a current zero, an arc would not form and the circuit would simply not start conduction on the following half cycle.

A general object of this invention is to provide a new and improved control for opening a circuit interrupter at a predetermined point in the current or voltage wave form where arcing should be prevented. Although the terms "zero crossing" and "current zero" will be used to describe this point, the control can be set to open the breaker at some other point that may be appropriate for a particular circuit interrupter or for a particular electrical system. Opening the circuit interrupter only at a current zero gives several advantages. It reduces contact erosion and thereby simplifies maintenance of the circuit interrupter. It could also permit using smaller circuit interrupters than before. Furthermore, there are advantages in the electrical system in addition to the advantages to the circuit interrupter. Interrupting only at the current zero reduces the transients on the system that are caused by conventional switching. Zero current switching is faster than conventional switching which requires several half cycles to complete. It could also simplify the problems of coordinating a succession of switches in a system.

One of the problems of actuating a circuit interrupter to open at a current zero is that the control must allow for the delay between the time that the interrupter is signaled to open and the time that the contacts separate. Some present day circuit breakers can be made to open in about one millisecond, a rather short time for mechanical devices, but still about 21° in the sinusoid of a sixty cycle per second electrical power system. For a power system that has a sixty cycle pure sinusoidal current wave form, circuits have been proposed that use phase shifters to provide a sinusoidal tripping signal that crosses zero appropriately ahead of the expected current zero in the line. After first receiving an actuating signal, and then receiving the phase shifted current zero signal, the control trips the switch with the proper lead time to open the breaker at current zero.

If the line current wave form is not a pure sinusoid, the control described in the preceding paragraph will trip the breaker too soon or too late. In fact, a circuit breaker is most likely to be opened during a fault condition when the line current wave form becomes non-

sinusoidal, the frequency changes and the next zero crossing cannot be predicted in the circuit just described. A more specific object of this invention is to provide a new and improved control that responds to the slope of the current wave form to produce the proper tripping signal for the adverse conditions that usually exist during a fault.

The control of this invention responds to a first predetermined magnitude on the peak going slope of the wave form to indicate that the maximum allowable instantaneous current has been exceeded; when this magnitude is reached, circuits are set up to sample the slope magnitude on the zero going slope and predict the next zero crossing. The control responds to second and third preset current values on the zero going slope of the wave form and generates a count value proportional to the time between these points. The control waits a related time (which may be substantially zero) and then produces a tripping signal for the circuit interrupter of the line with the approaching current zero.

An important feature of the control is that for a three phase system a fault sensing and slope sampling control is provided for each phase; the three controls are interconnected so that a peak going current that passes the first point on any phase signals the controls for all three phases to start sampling the slope between the second and third points. Since one other phase will usually cross zero before the phase where the fault was first detected, this interconnection improves the speed of response of the control. After the first line to reach zero is opened, the controls for the other two lines open their circuit interrupters at current zeros. (These two lines may be tripped together or at different times, depending on whether there are ground currents.)

The detailed description of the invention will suggest other problems in zero current switching and the associated advantages and objects of this invention.

The drawing

FIG. 1 is a single line schematic diagram of a three phase electrical power system, a circuit interrupter, and the control of this invention;

FIG. 2 shows a current wave form of the electrical system of FIG. 1 and illustrates how the control operates to predict a zero crossing; and

FIG. 3 shows two wave forms of the control of FIG. 1.

The three phases of the electrical system of the drawing are designated A, B and C. The control for phase A is shown in detail and similar controls for phases B and C are shown by boxes with the interconnections to the electrical system and between the phase controls. Where components that are identical except for their association with a particular phase are shown in the drawing, they are distinguished by the letter suffix of the associated phase.

The electrical system and circuit interrupter

The electrical system of FIG. 1 has three lines **10**A, **10**B and **10**C, and a circuit interrupter **11** with three independently operable switch units **11**A, B and C. Each unit **11**A, B and C responds to a tripping signal **14**A, **14**B, **14**C to open after a time delay that is inherent in the switch. Preferably, switch units **11**A, B, C are quick opening; for example, they may be vacuum switches.

The control of this invention produces tripping signal **14**A, B, C ahead of a predicted zero crossing by the inherent delay of circuit interrupter operating mechanism for the contacts to open at the predicted current zero. In the embodiment of the invention that is shown in the drawing, the control generates its own fault indicating signal in response to overcurrent in any line **10**A, B or C.

Later the description will explain how the control can be actuated with a manual trip signal and with trip signals generated by independent fault sensing devices.

Predicting a current zero

FIG. 2 shows a wave form **19** for one of the lines **10** that illustrates the principles that the control of this invention uses in predicting a current zero. FIG. 2 will be easier to understand if it is first thought of as describing a single phase system. During a fault, wave form **19** may be aperiodic and nonsinusoidal and it may have a D.C. component. A succession of points **20** through **27** on wave form **19** illustrates the operation of the control. The corresponding times along the horizontal axis are identified by the letter *t* with the subscript of the associated point, and the voltages along the vertical axis are identified by the letter V with the subscript of the associated point. The vertical axis is labeled voltage because the components of the control that will be described later are voltage sensitive and the control transforms the current wave form of lines **10**A, B, C into a corresponding voltage wave form.

At the first zero crossing **20** in FIG. 2 the electrical system is operating normally and the wave form is undistorted. Shortly after time t_{20}, a fault occurs that causes the current magnitude to rise above its normal peak value into the region above point **21**. Point **21** is a selected magnitude where it is desirable for the control to begin operating to open the breaker. Point **22** on the zero going slope of the curve corresponds in magnitude to point **21**.

Point **27** is the next zero crossing where the contacts might be advantageously separated. Point **26** corresponds to time t_{26} which is ahead of time t_{27} by the delay in operating the circuit breaker **11**. The object of the control is to establish the relationship between point **26** and one of the preceding points (specifically point **25**). In the region between points **24** and **25** the control samples the slope of the wave form. Point **24** corresponds to a predetermined voltage V_{24} and point **25** corresponds to a predetermined voltage V_{25}. The corresponding times t_{24} and t_{25} are unknown in relation to each other or to the other points, but time t_{25} can be thought of as a reference time in the sequence of operating the control. Point **23** is located just ahead of the sampling region and is defined by a predetermined voltage V_{23}. Thus, points **24, 25** and **27** are related by known voltage magnitudes and points **26** and **27** are related by a known time interval.

As FIG. 2 shows, the wave form **19** is approximately a straight line between points **24** and **27** and the voltages and times in this region are related by similar triangles; the sides of these triangles are known except for V_{26} and the intervals t_{24} to t_{25} and t_{25} to t_{26}. As the detailed description of the control will explain, the control measures the interval t_{24} to t_{25} and in effect determines the required interval t_{25} to t_{26}. Notice that in this analysis the half period t_{20} to t_{27} has been undefined and the peak voltage has been undefined; thus the simple sine wave of FIG. 2 illustrates the operation of the control with complex current wave forms.

As the wave form of FIG. 2 has been described for a single phase system, the control would sense the overcurrent condition at time t_{21} and then trip the breaker at time t_{26}. In a three phase system, at least one of the other lines will usually cross zero in this interval; the control responds to the overcurrent condition at time t_{21} to cause any one of the three lines that goes through the sequence of points **23** through **27** to trip at its zero crossing. In other words, for the three phase system the rising slope of FIG. 2 can be thought of as describing the line where the fault is first detected and the descending slope can be thought of as the line that first goes through zero.

It would give a false reading to begin a slope sample within the interval t_{24} to t_{25}. As the sequence of points **20** through **27** has been described for a single phase system (or three independently controlled phases), wave form **19** would not enter the sampling period t_{24} to t_{25} unless it had already crossed point **22**; but this is not necessarily true when the controls are interconnected, and point **21** on one line may occur between points **24** and **25** of the first line to go through zero. To prevent starting a slope sample in the middle of the sampling period, the control first senses the point **23** just ahead of the sampling period. Crossing point **23** sets up the circuitry for the sampling operation.

In the control that will be described next, voltage V_{25} is made high enough so that in the shortest operating time between points **25** and **26** the highest current amplitude that the control is intended to respond to will cross the line of V_{25} ahead of time t_{26} sufficiently to produce the tripping signal. Voltage V_{24} is made as close as possible to voltage V_{25} within the limitations of the accuracy of the control in distinguishing small signals. Point **23** may be made to coincide with point **24** but is preferably somewhat ahead of point **24** to allow for delays within the control; it may be made as early as point **21** but this slows the speed of response of the control; preferably point **23** occurs later than point **22**. Point **22** is shown only as the zero going slope counterpart of point **21**; none of the components that will be described respond specifically to point **22**.

The control

The control includes some digital devices; with exceptions mentioned later a zero or negative voltage is considered to be a **0** and a predetermined positive value is considered to be a 1.

The control includes a current transformer **30**A, B, C for each line of the system. The control for phase A has an amplifier **31** connected to receive the output **32**A of current transformer **30**A and to produce at its output **33** a voltage that corresponds to the current wave form. The wave form at output **33** contains any D.C. term and both the positive and negative polarity portions of the current wave form. A full wave rectifier **34** is connected to receive the voltage wave form **33** and to produce a full wave rectified wave form at its output **35**. By full wave rectifying the wave form at output **33**, the peak going slopes of FIG. 2 are made positive going and the zero going slopes are made negative going. The control components that will be described later respond to the slope polarity of the rectified wave form and thereby respond to the peak going and zero going slopes of the wave form of FIG. 2. In other respects the wave form at output **35** is equivalent to the wave form **19** of FIG. 2 and the two wave forms will be described as though they were identical.

The control for phase A also includes a fault detector **36**. The fault detector is illustrated as part of the control connected to rectifier output **35** but it may be an entirely separate unit. Fault detector **36** is illustrated as a voltage responsive gate comprising a diode **37** having its anode connected to receive the positive potential of rectifier output **35**, a resistor **38** connecting the cathode of diode **37** to a reverse biasing potential point **39** having the positive potential of V_{21}, and a capacitor **40** that is connected to block the potential of point **39** from the output **41**A of fault detector **36**. A positive going voltage change at output **41** means that the current in line **10**A has exceeded the fault level defined by voltage V_{21}.

An OR gate **42** is connected to receive the outputs **41**A, **42**B and **41**C of the fault detectors **36** for each of the three phases. When a fault occurs on any phase, OR gate **42** energizes its output **43** and sets a flip-flop **44**. When flip-flop **44** is set, it energizes its one output **45** in the proper polarity (negative) to signal each of the three slope sampling circuits to begin sampling the slope at the appropriate time to operate the switch units. When flip-flop **44** is set, it closes a switch **47** in the control for phase

A, and switch **47** conducts the full wave rectified wave form **35** to its output **49**. Switch **47** is illustrated somewhat schematically as a transistor having its emitter and collector terminals connected to conduct between points **45** and **49** and having its base terminal connected to flip-flop **44** to receive the proper polarity with respect to the emitter terminal to be turned on when flip-flop **44** is set.

In the control for phase A, three gates **51**, **52**, **53** are connected to receive output **49** and to produce a positive pulse at their outputs **55**, **56**, **57** in response respectively to the three points **23**, **24** and **25** on the wave form. Each gate is similar to the fault detector **36** except that gates **52** and **53** for points **24** and **25** each include a phase reverser **58** that makes the wave form negative and causes gates **52** and **53** to indicate when the magnitude of wave form **19** is less than voltage V_{24} and V_{25} respectively. Gate **51** produces a positive pulse at its output **55** when rectified wave form **19** is higher in magnitude than voltage V_{23} and switch **47** is turned on. Output **55** is connected to set a flip-flop **60** when the voltage magnitude of wave form **19** reaches point **23**. When flip-flop **60** is set, it energizes its 1 output to indicate that the control for phase A is ready to begin sampling the slope, or conversely that the fault was not detected by the control for phase B or C within the sampling interval, t_{24} to t_{25} of the phase A wave form. When the voltage magnitude of wave form **19** becomes as low as V_{24}, gate **52** opens and produces a positive going pulse at its output **56**, and AND gate **61** is connected to respond to the presence of a signal at the 1 output of flip-flop **60** and a 1 output of gate **52** to energize its output **62**; a 1 at output **62** indicates that the wave form is entering the sample zone t_{24} to t_{25}. Output **62** is connected to set a flip-flop **64** which energizes its 1 output. Energizing the 1 output of flip-flop **64** indicates that the wave form is in the sample zone and that the control should begin counting the time between t_{24} and t_{26}.

At time t_{25} the voltage magnitude V_{25} at output **49** causes gate **53** to open and produce a positive going pulse at its output **57**. Output **57** is connected to reset flip-flop **64** to indicate that the count period is over and that the reverse count interval has started.

A counter **70** is connected to be counted up during the sampling period and to be counted down after the sampling period. As the drawing illustrates the counter, it comprises a capacitor **71**, a source **72** for charging the capacitor, an AND gate **73** operable in response to the 1 output of flip-flop **64** to connect capacitor **71** to be charged, and a switch **74** that is operable in response to the 0 output of flip-flop **64** to connect capacitor **71** in a circuit to be discharged. Source **72** is illustrated as a voltage source **75** and a resistor **76** that make up approximately a current source for charging capacitor **71** linearly; this is the simplest circuit to explain but the capacitor may be charged nonlinearly as will be explained later. The discharge circuit is illustrated as a variable resistor **79** that switch **74** operates to connect across the terminals of the capacitor. Source terminal **80**, capacitor terminal **81**, and resistor **79** terminal **82** are reference potential points in counter **70**.

Since the voltage across capacitor **71** is proportional to its charge, the integral of current with respect to time, the capacitor voltage is a function of the time interval that the capacitor is charged. In the example of charging capacitor **71** linearly, the voltage is proportional to time. Similarly the capacitor voltage during discharge is some function of the interval remaining until the capacitor will have discharged to zero or to some other reference value. In this control the reference value corresponds to zero crossing point **27**. This relation between voltage and time depends on the discharge rate, which can be set by adjusting variable resistor **79**, and on the reference voltage which can be adjusted as will be explained later. Thus, as will be explained next, a preselected voltage can be made to correspond to point **26** where the breaker should be tripped.

An adjustable gate **90** is connected to receive the output of the counter **70** when switch **74** is closed and to respond to the preselected voltage level that corresponds to the time delay of operating the breaker (t_{26} to t_{27}). Gate **90** is similar to gate **36** which was described in detail with the phase reverser **58** of gates **52** and **53** except that its biasing potential is adjustable by means of a potentiometer **92** so that the time delay voltage V_{93} in FIGS. 1 and 3 and the corresponding time interval t_{26} to t_{27} can be set individually for each switch unit. When capacitor **71** has discharged to time delay voltage V_{93}, gate **90** produces a positive going pulse at its output **95** that trips the breaker **11A** for line **10A**.

In the description of counting down counter **70** in the interval t_{25} to t_{26}, it was assumed that the capacitor discharged linearly. For the simple counter of FIG. 1, time delay voltage V_{93} is made rather close to the capacitor voltage so that time is measured on a fairly linear part of the discharge curve of the capacitor. Equivalently the capacitor can be made to discharge into a current source (such as source **72**).

So far in this description it has been assumed that the curve of wave form **19** is a straight line between points **24** and **27**. This assumption is valid for most current wave forms on electrical transmission systems; however, it is more accurate for a short interval (high current overload) than for a longer interval (moderate current overload). The circuit as it has been described so far can be thought of as generating the first two terms in a Taylor's series; that is the control generates the curve of FIG. 3, capacitor voltage as a function of time, which corresponds in magnitude and slope to the wave form between points **24** and **25** but it does not necessarily have the same curvature. For more accuracy, additional terms of the series can be generated by the slope sampling techniques already described, or by making the count up or count down charge rate appropriately nonlinear, or by adjusting the timing voltage value V_{93} as a function of current overload magnitude. Generally the simpler control that FIG. 1 illustrates is preferable.

The control has been described in terms of rather specific components, and a variety of functionally equivalent components may be substituted in the control. A digital counter may be substituted for the analog counter **70** and a source of pulses substituted for current source **72**. A manual input to OR gate **42** may be provided to signal the control to open circuit interrupter **11**. The specific logic network of FIG. 1 can be transformed into different equivalent networks by well known design techniques. Those skilled in the art will recognize variations and modifications within the spirit of the invention and the scope of the claims.

Having now particularly described and ascertained the nature of my said invention and the manner in which it is to be performed, I declare that what I claim is:

1. A control for a circuit interrupter having a predetermined delay between receiving a tripping signal and separating its contacts, comprising,

means connected to receive a measure of a current wave form of the electrical system in which the circuit interrupter is connected and responsive to a first point of predetermined magnitude on the wave form to produce and maintain a signal indicating that a fault has occurred in the electrical system,

derivative means responsive to said fault indicating signal and responsive to said wave form in a region between second and third points of predetermined magnitude on the wave form to produce a signal value that is a function of the slope of the wave form in said region, delay means including a capacitor connected to receive said signal value to charge said capacitor to a level determined by the magnitude of said signal produced by said derivative

means, and means for discharging said capacitor at a predetermined rate, and

means responsive to the discharge of said capacitor to produce a trip signal delayed from said third point by a time that is a function of said signal before signal derivative, the magnitude of said third point, and the circuit interrupter delay to separate the contacts at a predicted point of predetermined magnitude in the wave form.

2. A control according to claim **1** in which said predicted point is a zero crossing of the current wave form.

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