A. R. van C. Warrington

Protective Relays

Their Theory and Practice

Protective Relays

THEIR THEORY AND PRACTICE

VOLUME TWO

THIRD EDITION

by

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Foreword

The addition of this Volume II by Mr. Warrington provides, in the two volumes together, an exhaustive study of the development and present status of protective relaying, particularly in relation to the transition from electromagnetic to static relays using semiconductors. Volume II attempts, among other things, to explain their theory in a manner understandable to non-electronic engineers, as well as dealing more thoroughly with some of the subjects touched on in Volume I.

It gives me much pleasure to recommend this book and its counterpart Volume I to all interested in protective relaying, as they have been written by one of the country's outstanding specialists in this particular field. As Chief Engineer of the English Electric Company in the years 1948–1954, I was closely connected with Mr. Warrington's Forward Development Programme and I am particularly pleased, from his success in this field, that my confidence in his forward judgment has been amply justified. I am sure that the industry will greatly benefit from his putting down in writing the product of his many years of experience in the design and application of protective relaying.

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Author's Preface

In modern protective relay design transistor circuits are replacing electromagnetic movements. Since this is a new technique for many protective relay engineers it was felt that an explanation of static protective relays, written by a relay engineer for relay engineers, would be useful.

This Volume also supplements Volume I by providing additional information on c.t's and p.t's, fault incidence, transients and sources of relay error.

For those interested only in static relays, an attempt has been made to make this Volume self-contained by summarizing the basic principles of protective relaying in Chapter 1.

As in Volume I, the space devoted to each subject was determined by its importance and novelty.

A. R. van C. Warrington

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I wish to thank the English Electric Co. Ltd. for their permission to publish this book, my colleagues in the Relay Department for engineering assistance, Dr. W. D. Humpage of the M.C.O.S.T. for editorial and technical checking of the manuscript, Mr. F. H. Birch of the C.E.G.B. for his assistance in forecasting future trends of protective relaying and Dr. J. Rushton of the C.E.G.B. for contributing Chapter 15 which summarizes recent work in the U.K. on Pilot Differential Systems; also Mr. M. C. S. Simpson of G.E.C. Measurements Ltd. for revising Chapter 3 to bring it up to date.

A. R. van C. Warrington

APOLOGY

Since this book was first written the international symbol for a resistor has been changed from a saw-tooth to a rectangular shape. This has been used in the revision of Chapter 3, but the cost of changing all the other diagrams would have made the price of the book excessive.

A. R. van C. Warrington

List of Symbols

A	area; amperes
B	susceptance; magnetic flux density
C	capacitance
D	discrimination factor; diameter
E	e.m.f. (usually at power source)
F	force
G	conductance
H	magnetizing force
I	current
J	angular moment of inertia
K	a constant
L	self-inductance
M	mutual inductance; numeric ratio or constant
N	number of turns; numeric ratio or constant
O	origin of a graph
P	point on a graph; general constant
Q	steady-state amplitude of charge q; general constant
R	resistance; ratio
S	spacing or displacement
T	temperature; transistor
V	voltage
W	power
X	reactance
Y	admittance
Z	impedance

A and B are also used as unspecified quantities or ratios, real or complex

a	a $\underline{/120^\circ}$ operator $\left(-\frac{1}{2}+\mathrm{j}\frac{\sqrt{3}}{2}\right)$
b	susceptance per mile
c	capacitance per mile
d	diameter
e	instantaneous value of potential difference
f	frequency
g	conductance per mile
h	height

i	instantaneous value of current, unit vector
j	a $\underline{/90^\circ}$ operator
k	a constant
l	length
m	mass; unspecified number
n	an unspecified number
p	in-phase component
q	quadrature component or electric charge
r	resistance per mile
s	modulus of attenuation
t	time
v	velocity
x	unknown quantity or reactance/mile
y	admittance per mile
z	impedance per mile
α	an angle
β	an angle
γ	attenuation factor (complex)
δ	an increment
ε	base of Naperian logarithms
η	efficiency
θ	characteristic angle; angle between source e.m.f's
λ	an angle
μ	permeability or prefix micro
π	radians in 180°
ϱ	resistivity
$\mathcal{R}$	reluctance
σ	conductivity
ϑ	phase angle of a relay characteristic
Φ	magnetic flux
ϕ	phase angle, generally the angle by which the current lags the voltage in a protected circuit
Ψ	an angle
ω	frequency in radians/sec; ohms
Σ	summation
Ω	ohms
$\overline{\lvert 60^\circ}$	lagged 60°
$\underline{\lvert 60^\circ}$	led 60°
$\lvert V \rvert$	scalar value
$\hat{V}$	peak value

α is also used as the complex ratio of two currents and β their inverse ratio.
ϕ and G on circuit diagrams refer to phase and ground relays respectively.

List of Subscripts

A, B, C	the terminals of a protected line
a, b, c	the three phases
d	difference; direct axis
e	general suffix
f, F	fault
g, G	ground
h, i, j	general suffixes
l	load
L	line
m	magnetizing
n	neutral; nominal
o	a basic value; operating quantity; offsetting quantity
p	in-phase component; primary; polarising
r	replica; restraint
R	relay; relay (to distinguish in the case of a secondary quantity); receiving end.
s, S	source; secondary; sending end.
t	suffix denoting quantity variable with time
res	residual
max	maximum
min	minimum
1	positive sequence
2	negative sequence
0	zero sequence

Abbreviations

B.S.S. British Standard Specification (put out by the British Standards Institution)

C.E.G.B. Central Electricity Generating Board of Great Britain

Suffixes used in Chapter 3

a	anode
b	base
c	collector
d	drain
e	emitter
f	feed-back
g	gate
s	source (F.E.T.); supply
z	zener
cm	common mode
in	input
out	output

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1
Basic Principles of Protective Relays

Operating characteristics and equations–Types of protection Level detectors, timing circuits and comparators–Duality of phase and amplitude comparators

VOLUME I of this book was a self-contained treatise on electromagnetic protective relays. This second volume deals with semiconductor protective relays and contains further information on the following subjects: power system faults, transient overvoltages, c.t's and p.t's, steady-state and transient sources of error in relay measurement and some new principles of protection.

Because some readers may be interested only in static relays, an attempt has been made to make Vol. II self-contained also. In this first chapter the general principles of protective relays have been summarized and thus duplicates some of the material in Vol. I. To those who possess Vol. I the author offers apologies and suggests that they now turn to Chapter 2.

1.1. THE ROLE OF PROTECTIVE RELAYS

In order to generate electric power and transmit it to customers a vast amount of money must be spent on equipment [36], so that it is important to run it at peak efficiency and protect it from accidents. Unfortunately, a certain number of accidents are inevitable as insulation deteriorates or unforeseen things occur, such as strokes of lightning or the entry of birds or animals into the equipment.

Insulation breakdowns are called 'faults' by relay engineers. When one occurs it is liable to be very expensive because of the damage that can be done by the tremendous amount of electrical energy in modern power systems; furthermore there is a loss of revenue due to the shutdown of the damaged circuit or equipment.

Protective relays minimize this damage and expense by locating the fault immediately and opening the correct switches to isolate the faulted circuit. Hence it is obvious that *reliability*, *speed* and *selectivity* are the most desirable qualities of a protective relay.

Figure 1.1 shows how the relays are arranged to trip only the breakers which isolate the faulted circuit and yet to overlap their zones of operation so as to leave no unprotected spots. Figure 1.2 shows how the speed of clearing faults affects the stability of a typical power system. The curves show the maximum time permissible for clearing each type of fault (relay plus breaker) versus system loading prior to the fault; the system will become unstable if these faults clearing times are exceeded.

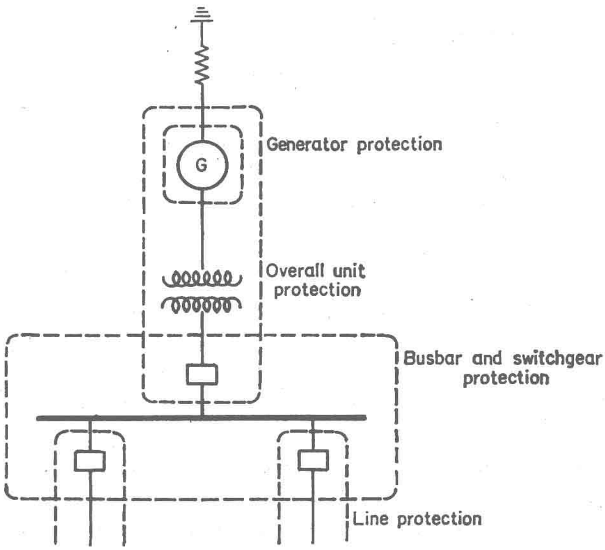


Fig. 1.1. Zones of protection

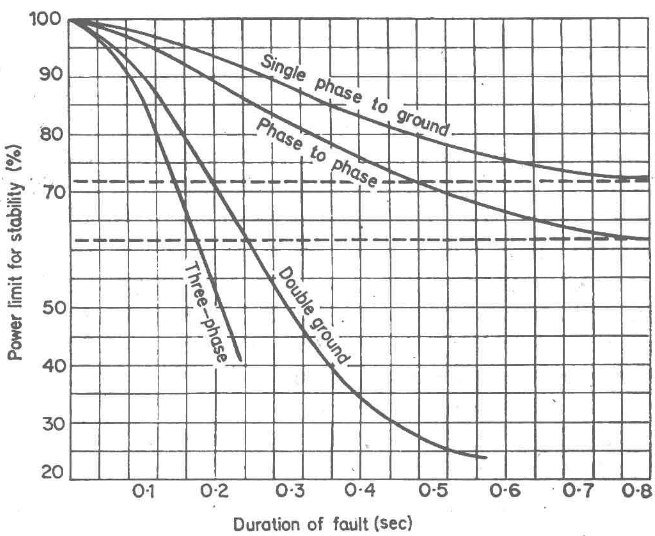


Fig. 1.2. Fast clearing of faults preserves stability

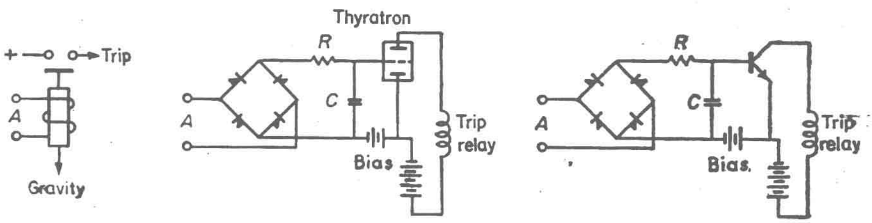
Relays recognize and locate faults by constantly measuring electrical quantities of the system, which are different during normal and abnormal conditions. The basic electrical quantities which may change when a fault occurs are current, voltage, phase-angle (direction) and frequency. It is generally necessary to provide relays responding to more than one of these conditions because, for instance, the current during a fault with minimum generation may be less than load current during maximum generation and power-factor may be as low during a power swing as during a fault.

Two sets of relays are used, main and reserve (back-up) [25]. The main relays clear faults in the protected section as fast as possible. The back-up relays operate if the others fail and usually protect not only the local section but the adjoining section also; they usually have a time delay long enough to permit the main relays to operate if they can.

1.2. LEVEL DETECTORS AND COMPARATORS

A relay operates when the measured quantity changes, either from its normal value or in relation to another quantity. The operating quantity in most protective relays is the current entering the protected circuit. The relay may operate on current level against a standard bias or restraint, or it may compare the current with another quantity of the circuit such as the bus voltage or the current leaving the protected circuit.

In a simple electromagnetic relay, used as a level detector, gravity or a spring can provide the fixed bias or reference quantity, opposing the force produced by the operating current in an electromagnet. The spring is thus a means of calibration of the relay pick-up. In static relays the equivalent is a d.c. voltage bias, as shown in Fig. 1.3a.



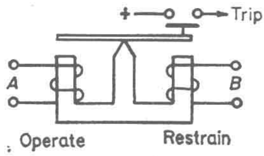
(i) Electromagnetic (ii) Thermionic (iii) Semiconductor

Fig. 1.3a. Inherent level detectors

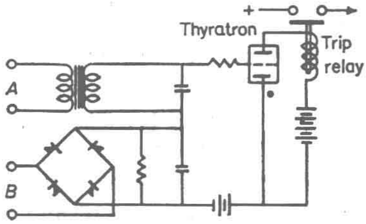
Since the fault current level changes with generating conditions, it is seldom possible to obtain selectivity on the basis of current magnitude alone. Usually a time function is added so that the relay nearest the fault, which sees the most current, will trip before relays in the unfaulted circuits.

It is difficult to obtain selectivity by measuring one quantity such as current, potential, phase-angle, etc., without using time delay. Hence most high-speed relays measure a derived quantity which is a combination of several simple quantities; for example, impedance, current-ratio, etc., in which two simple quantities are compared in magnitude and/or phase relation.

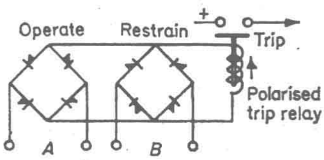
Figure 1.3b shows, in a very much simplified form, inherent amplitude comparators of the electromagnetic, electronic and semiconductor types; Fig. 1.3c shows inherent phase comparators. These comparators are discussed in more detail in Chapter 4.



(i) Electromagnetic

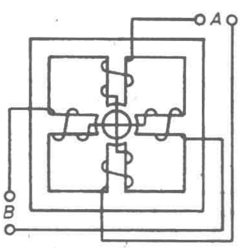


(ii) Electronic

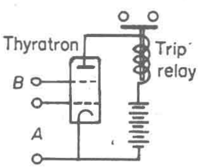


(iii) Semiconductor

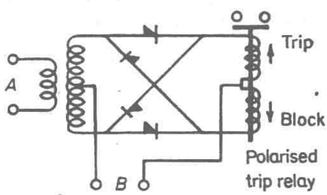
(b) Inherent amplitude comparators



(i) Electromagnetic



(ii) Electronic



(iii) Semiconductor

(c) Inherent phase comparators

Fig. 1.3. Basic electromagnetic and static relays

1.3. OPERATING CHARACTERISTICS [22, 41]

The most important operating characteristic of a single-input relay (level detector) is the relation between the input magnitude and the operating time, e.g. the time-current curve of a time-current relay.

Modern amplitude and phase comparator relays are virtually instantaneous but a curve of time versus the ratio of the inputs is of interest even though the time scale is in milliseconds; for example, a time-impedance curve of a distance relay. In such relays the most important characteristic is the ratio of the two input quantities at the threshold of operation for varying phase between them.

This operating characteristic is plotted on a polar graph whose ordinates are the real and imaginary components of A/B or B/A where A and B are the two quantities compared. The ordinates of the graph are $\left|\frac{A}{B}\right| \cos\phi$ and $j\left|\frac{A}{B}\right| \sin\phi$, where ϕ is the angle by which A leads B; this can be abbreviated as $\left|\frac{A}{B}\right| p$ and $\left|\frac{A}{B}\right| q$.

An example is the distance relay, where A is voltage and B is current, so that the ordinates of its operating characteristics are $\left|\frac{V}{I}\right| \cos\phi = R$ and $\left|\frac{V}{I}\right| \sin\phi = X$. This is generally referred to as the $R - X$ diagram or the impedance diagram. Similarly, the components of I/V give an admittance (G versus jB) diagram.

Since there are no terms like impedance for the general case of A/B where A and B are, for example, two currents, the A/B diagram is referred to as the α-plane and the B/A diagram as the β-plane diagram [22]. For two-input comparators these characteristics have second-order equations and hence are straight lines, circles or sectors of circles. They represent the threshold of operation where the comparator has zero output; hence the output is positive (tripping) on one side of the characteristic and negative (blocking) on the other side.

It is interesting to note that, if the characteristic of the relay is a circle going through the origin when plotted on the α-plane, it is a straight line outside the origin when plotted on the β-plane and vice versa as shown in Fig. 1.4 . Also, circular characteristics not passing through the origin are orthogonal in the two planes.

1.3.1. General Equation of Operating Characteristics

If not more than two input quantities are involved, they can produce effects individually and by co-operation. Hence the equation of the operating

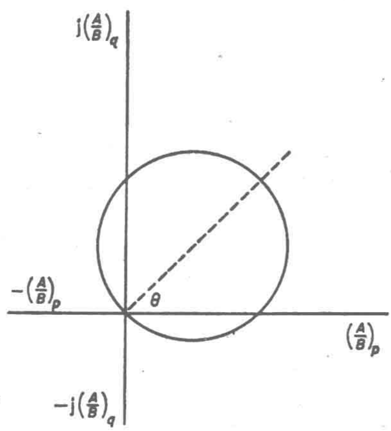


Fig. 1.4a. Typical relay characteristic plotted on α-plane

characteristic will [22] be of the form

$$K|A|^2 - K'|B|^2 + |A||B| \cos(\phi - \theta) = K'' \qquad (1.1)$$

where A and B are the two electrical quantities being compared, K and K′ are scalar constants, K″ is a constant representing a bias which would take the form of a mechanical restraint in an electromagnetic relay, ϕ is the phase angle between A and B and θ is the phase angle of the characteristic. θ is usually the value of ϕ which provides maximum relay torque in an electromagnetic relay or maximum output in a static relay.

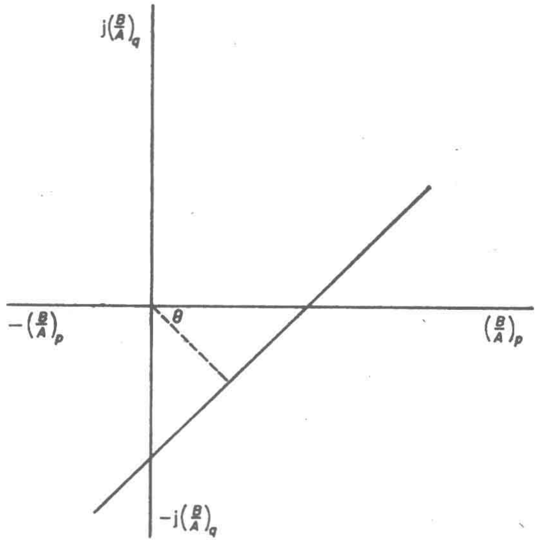


Fig. 1.4b. Typical relay characteristic plotted on β-plane

The Eq. (1.1) represents all the linear and circular characteristics which can be obtained from two-input relays. This equation is applicable to most of the common types of relay and simplifies the explanation of their operation and characteristic curves (as shown in Fig. 1.5, columns 3 and 4).

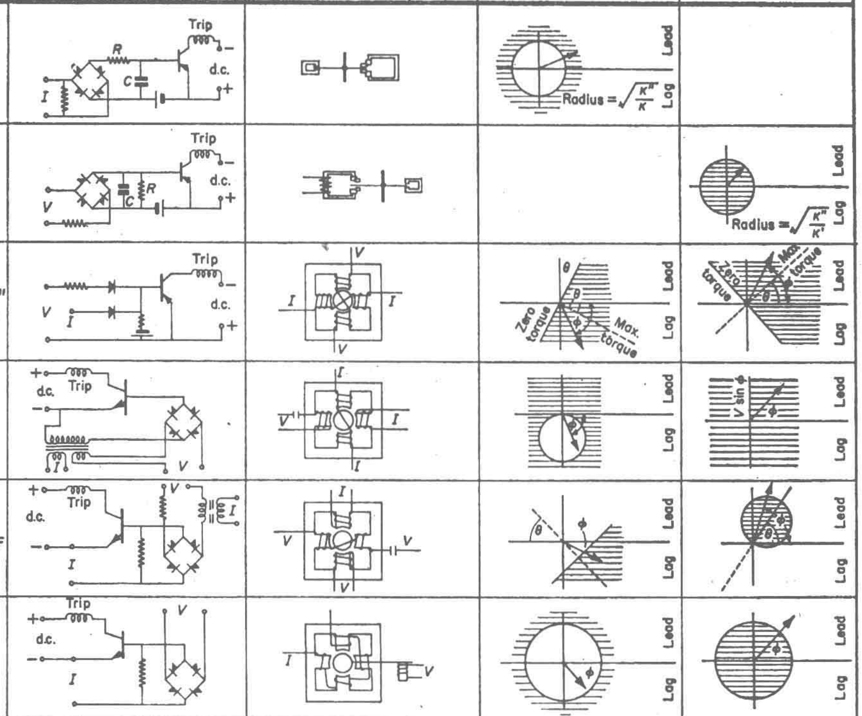
In Eq. (1.1) K″ is finite only in single-quantity relays where it is used as a level indicator; it is made substantially zero in relays that compare two input quantities and in this case the equation represents a circle or a straight line on a complex plane (polar diagram). This can be demonstrated by rewriting the equation (1.1) making K″ = 0 and dividing through by $K'A^2$:

$$\frac{K}{K'} - \left|\frac{B}{A}\right|^2 + \left|\frac{B}{A}\right| \frac{\cos(\phi - \theta)}{K'} = 0 \qquad (1.2)$$

Moving the K/K', term to the right-hand side and adding $\left(\frac{1}{2K'}\right)^2$ to each side, Eq. (1.2) becomes:

$$\left|\frac{B}{A}\right|^2 - \left|\frac{B}{A}\right| \frac{\cos(\phi - \theta)}{K'} + \left|\frac{1}{2K'}\right|^2 = \frac{K}{K'} + \left|\frac{1}{2K'}\right|^2 \qquad (1.3)$$

Type relay	Conditions	Resulting equation	Relay pick-up	Simplified relay static	Relay electro-magnetic	Polar diagrams: Admittance or current	Polar diagrams: Impedance or potential
Overcurrent	No potential windings hence no V^2 or VI terms	$KI^2 = K''$	$I > \sqrt{\frac{K''}{K}}$				
Undervoltage	No current windings hence no I^2 or VI terms K'' is neg.	$-K'V^2 = K''$	$V < \sqrt{\frac{K''}{-K'}}$				
Directional	$K = K' = 0$	$VI \cos(\phi - \theta) = K''$	$VI \cos(\phi - \theta) > K''$				
Reactance (ohm unit)	$K' = K'' = 0$ $\theta = 90°$	$KI^2 = VI \cos(\phi - \theta) = VI \sin\phi$	$Z \sin\phi < K$ i.e. $X < K$				
Directional impedance (mho unit)	$K = K'' = 0$ $\theta = 75°$	$-VI \cos(\phi - 75°) = K'V^2$	$\frac{Z}{\cos(\phi-\theta)} < \sqrt{\frac{1}{K'}}$				
Impedance (ohm unit)	V and I scalar or separate so no VI term	$KI^2 = K'V^2$	$Z < \sqrt{\frac{K}{K'}}$				



General relay equation = $KI^2 - K'V^2 + VI \cos(\phi - \theta) = K''$ (where all K's are torque constant)
All characteristics are loci of V or I for zero torque. In static relay column integration and level detection assumed incorporated in trip device

Fig. 1.5. Analogy of static and electromagnetic relay units