# EXPERIENCE WITH THE R-RDOT OUT-OF-STEP RELAY

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## ABSTRACT

A new out-of-step relaying concept has been previously reported. Appendix A is provided for a review of previously reported information. The concept involves augmenting apparent resistance (R) measurement with rate-of-change of apparent resistance (Rdot) computation. The new R-Rdot relay thus has more intelligence for control decisions.

This follow-up paper presents the following new information: large scale simulation results, including use of relay outputs for discrete supplemental control action; additional details on design and testing of the microprocessor based relay; and experience during an extensive monitoring period at Malin Substation on the Pacific AC Intertie. The relay is expected to be energized for tripping in October 1984.

## INTRODUCTION

Reference 1 describes a new out-of-step relay developed at the Bonneville Power Administration. The conventional apparent impedance measurement is augmented by rate-of-change of apparent impedance computation. In the actual implementation, however, apparent resistance and the rate-of-change is used. The device is termed the "R-Rdot" relay. The tradeoffs between impedance and resistance implementations are discussed in Reference 1.

An output or trip of the R-Rdot relay occurs when the out-of-step swing trajectory crosses a switching line on the R-Rdot phase-plane. Examples from large scale stability simulations, for several types of disturbances, are provided in Reference 1.

The R-Rdot relay was installed at Malin Substation on the Pacific 500kV AC Intertie in February 1983. Prior to commissioning for tripping, the relay performance was monitored for about 1 1/2 years.

This paper supplements Reference 1 by providing the following new information: final relay settings, including use of auxiliary outputs for other discrete supplemental control action; additional details on design and testing of the microprocessor-based relay; and experience during the monitoring period.

## DISCRETE SUPPLEMENTARY CONTROLS FOR STABILITY [2]

The primary purpose of the R-Rdot relay is for initiation of controlled separation (termed a discrete supplementary control in Reference 2). By use of auxiliary switching lines, other discrete supplementary control actions can be initiated. Examples include generator tripping, series capacitor switching [3,4], dynamic braking [5], and shunt reactor or shunt capacitor switching.

The R-Rdot phase-plane is analogous to the angle difference-speed difference phase-plane of an equivalent two-machine system. The nonlinear relationships for an elementary model are given by equations 15 and 16 of Reference 1.

Many mostly academic papers have been written on use of the angle-speed phase-plane for discrete supplementary control stabilization [4,5,6]. (Reference 6 contains many additional references.) The control method can be either open-loop or closed-loop (bang-bang). Examples of open-loop control include generator tripping, series capacitor insertion without automatic high speed bypass, and dynamic brake insertion with fixed energization time.

The R-Rdot relay provides a practical means to implement phase-plane control techniques. Only local measurements and elmentary computation is required. In addition to controlled separation initiation, the R-Rdot relay will initiate hydro-generator tripping to stabilize severe disturbances. To date, no need has developed for closed-loop control -- if first swing transient stability, post disturbance conditions, and small signal damping are all satisfactory; then damping for severe disturbances has been satisfactory.

The following section provides an example of R-Rdot initiated generator tripping. The generator tripping is only required for rare multiple contingency disturbances. For example, it provides a backup for failure of other discrete supplementary controls.

## RELAY SETTINGS, SIMULATION EXAMPLE

Figure 1 shows present relay settings. The Pacific AC Intertie will be tripped at 40 ohms apparent resistance for marginally stable swings and at 50 ohms for strongly unstable swings. A three segment, piecewise linear switching line will be used. Trajectories moving from right to left across the switching line will cause Intertie separation.

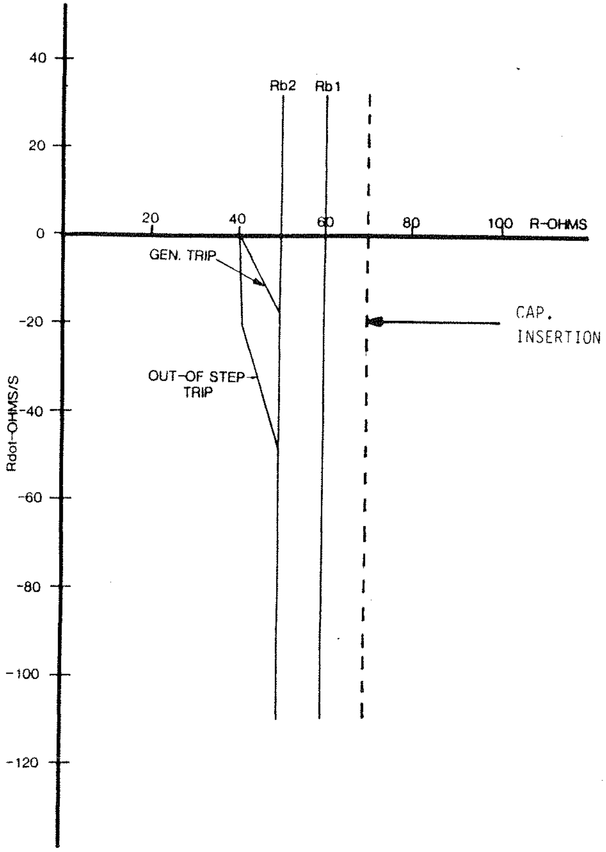

Figure 1 Present R-Rdot Out-of-Step Relay Settings. Previous conventional based out-of-step protection was set at 50 ohms.

As shown, a two segment piecewise linear switching line will initiate about 600 MW of hydro-generation tripping. Again, a swing trajectory moving from right to left across the switching line will initiate control action. As described in Reference 1, $Rb_1$ and $Rb_2$ elements distinguish between faults and swings as in conventional out-of-step relays. The series capacitor insertion element is from a conventional out-of-step relay, which supervises the R-Rdot relay. (Series capacitor insertion by out-of-step relays has been in service on the Pacific Intertie since 1976.)

Figure 2 shows results from a large scale transient stability simulation. High stress conditions for spring 1985 are represented. The disturbance is bi-polar loss of the parallel Pacific HVDC Intertie (2000 MW) with restart failure on both poles. Normal discrete controls for this event include generator tripping equal to the DC schedule, series capacitor insertion initiated from the DC terminal, and Chief Joseph dynamic brake energization.

The model for the stability program for R-Rdot computations is shown on Figure 4.

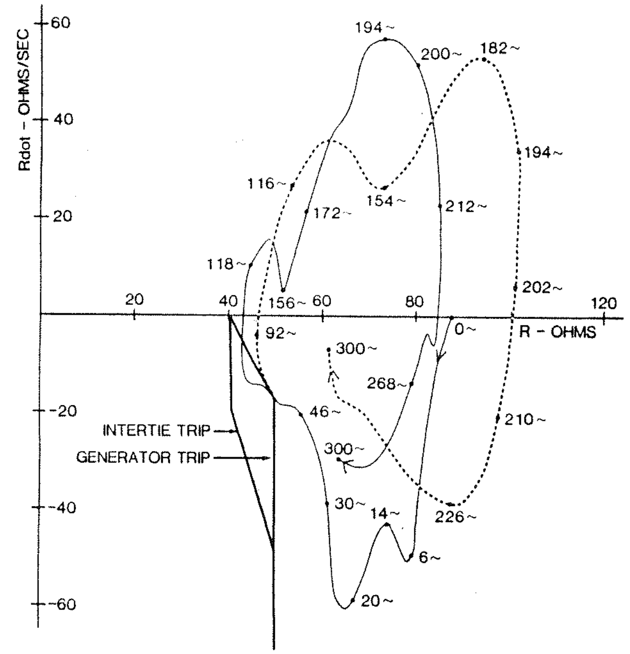

Figure 2 R-Rdot phase-plane for loss of Pacific HVDC Intertie (2000 MW). Time values in cycles indicated along trajectories. Series capacitors inserted along Pacific AC Intertie at 14 cycles. NW generator tripping (2000 MW) at 26 cycles. Solid trajectory without additional generator tripping; dashed trajectory with additional 600 MW of NW generator tripping initiated by R-Rdot relay.

For this case, failure of the dynamic braking is assumed. Without additional R-Rdot initiated generator tripping, the case is marginal -- close to the trip characteristic. With generator tripping, adequate margin is obtained. Note the R-Rdot generator tripping provides a degree of "self-protection" against Intertie instability and separation.

Figure 3 shows an angle-speed phase-plane for the same disturbance. The angle and speed differences are between Grand Coulee generators in the Pacific Northwest and the Mohave generators in the Southwest. The effect of local modes are evident. Ideally, an average of Northwest and Southwest angles and speeds is desired. The R-Rdot phase-plane inherently provides this with strictly local measurements.

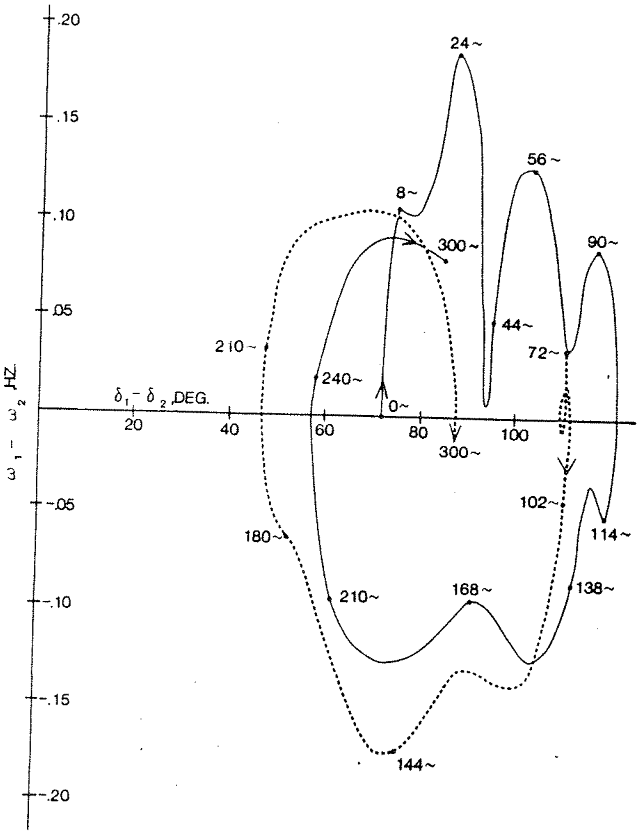

Figure 3 Angle difference-speed difference phase-plane for loss of Pacific HVDC Intertie (2000 MW). Angle, speed differences are between Grand Coulee and Mohave. Series capacitors inserted along Pacific AC Intertie at 14 cycles. NW generator tripping (2000 MW) at 26 cycles. Solid trajectory without additional generator tripping; dashed trajectory with additional 600 MW of NW generator tripping initiated by R-Rdot relay.

Regarding Figure 3, the R-Rdot initiated generator tripping is at Chief Joseph powerplant, which is electrically close to Grand Coulee. This accounts for the strong negative swing in speed difference following the 600 MW of generator tripping at 70 cycles.

## R-RDOT OUT-OF-STEP RELAY ARCHITECTURE

The R-Rdot out-of-step relay was developed using microprocessor technology. The relay consists of three separate 8-bit microcomputer systems - one supervisor and two identical algorithm processors. The supervisor is tied to each of the algorithm processors via asynchronous communications links.

### The Supervisor Unit

The supervisor unit is responsible for a majority of the operator interface functions. Algorithm parameter setting, relay calibrating, and information requests are verified and input to the processors through a keyboard located on the front panel. A printer, located on the supervisor front panel, provides a hard copy of operator-requested information, relay trouble diagnostics, and relay operation diagnostics. Indicator lights are also provided to indicate relay enable status, error status, and algorithm processor status. The supervisor verifies proper operation of itself through self-checking routines and verifies proper operation of each of the algorithm processor units. The supervisor removes a unit from service if one has failed.

### The Algorithm Processor Units

The algorithm processor units perform the out-of-step algorithm based upon the apparent resistance and apparent resistance rate of change computations. These computations are based on measurements from active and reactive power transducers along with voltage transducers. Figure 4 shows the computation and filtering algorithms programmed into the algorithm processor and the estimated transducer response model. Filtering of the resistance and resistance rate quantities was necessary due to the differentiation. During a relay operation, the algorithm processors print out time tagged records of significant relay events (fault/swing determination, tripping events, etc). Each processor also dumps into memory each measured and calculated value for a period of ten seconds following detection of a disturbance. This information is then printed out through the printer on the supervisor front panel.

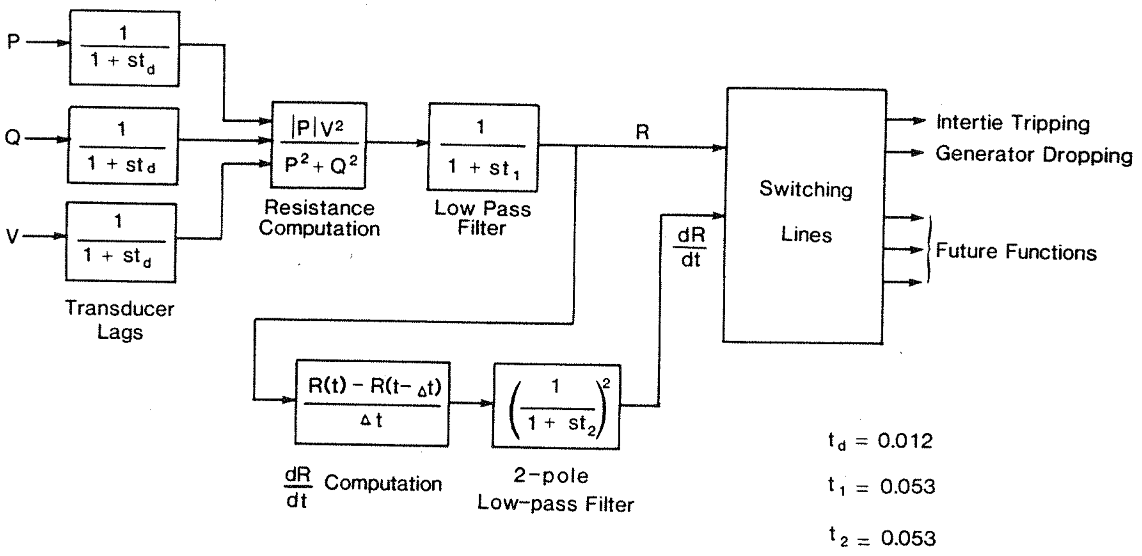

Figure 4 R-Rdot out-of-step relay filter model. This model was incorporated into the large scale simulation studies.

Other diagnostic information provided by the algorithm processors includes switching line enable status, tripping status, and error status. This information is indicated by lights on the algorithm processors front panels.

### Interposing Relays and Test Interface

Located on the relay are interposing relays which interface with external input and output stability controls. Relays also provide target information. Test handles allow isolation of the input and output functions for testing.

### Bench Testing and Field Monitor Performance

Stage tests were performed in two parts. Part one of the test simulated the current transformer and the potential transformer outputs expected during swings. These were used as inputs to the relay's transducers. Transducer response and proper relay operation were then verified. The main purpose of the AC portion of the staged tests was to check the filtering characteristics of the transducers and their effect on the algorithm. Part two simulated the DC outputs of the voltage, real power, and reactive power transducers. These DC signals were input to the relay's analog to digital converters to further verify proper relay operations.

In each part of the testing the R-Rdot relay was subjected to a number of swings ranging from very slow, with no relay operations expected, to very fast, simulating an unstable power system swing. Swings in every sector of the R-Rdot phase-plane were simulated at least twice for both parts of the stage tests. Faults were also simulated in a similar manner.

In each test case, the relay performed as expected and the algorithm processors agreed to within 2% of each other, and within 2% of expected values. Figure 5 shows a bench test swing plotted in the R-Rdot phase-plane as measured by the relay.

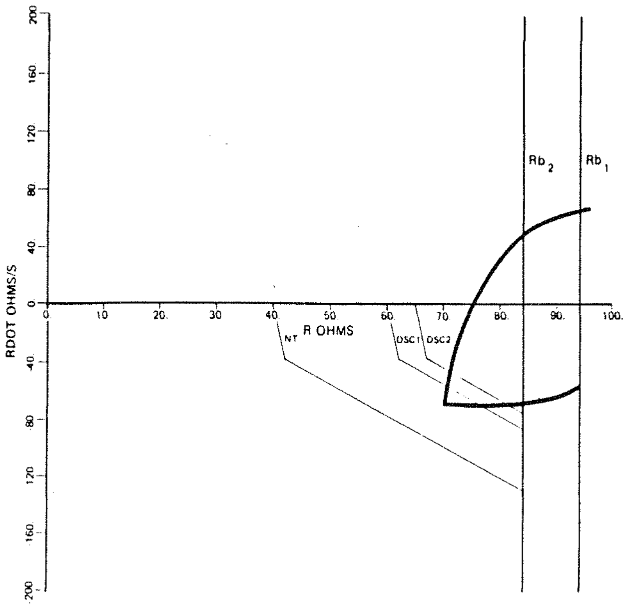

Figure 5 R-Rdot out-of-step relay bench test simulation.

For field experience, the R-Rdot relay was installed at the Malin Substation for on-line monitor testing without trip circuit connections. During the evaluation period which began in February 1983, approximately 150 power system swings or faults were recorded by the R-Rdot relay. Most of these were swings which did not require any action by the relay. Over 65% of these swings occurred between June and September of 1983. In each case, the R-Rdot relay operated properly.

Figure 6 shows a typical swing measured by the R-Rdot relay. This swing was detected on July 28, 1983 at 07:37:21 hours. The cause of this disturbance was blocking of one pole on the HVDC Intertie. Series capacitor insertion was initiated from the DC terminal for stabilizing the power system.

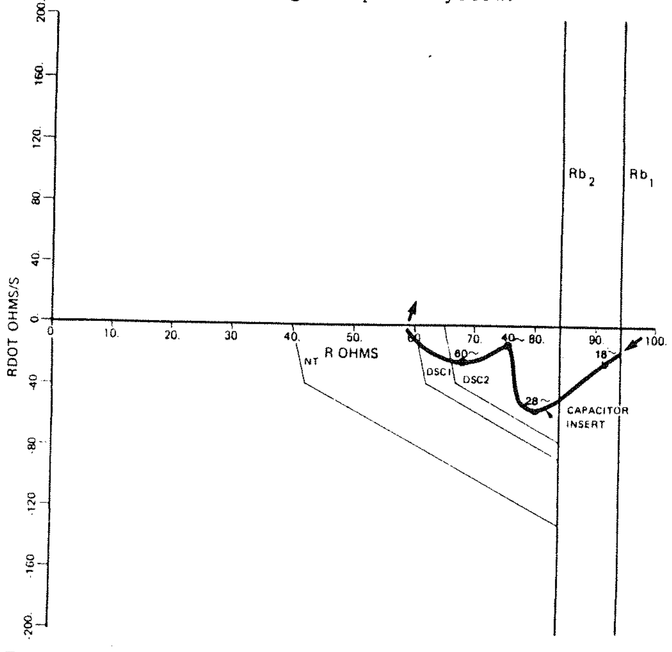

Figure 6 Swing detected by the R-Rdot relay on July 23, 1983, at 07:37:21 hours. Swing was caused by a disturbance on the HVDC Intertie.

It should be noted that the relay settings used for monitoring were different than the final relay settings. This was so more relay operations could be monitored during the test phase.

Figure 7 shows a line separation response as measured by the R-Rdot relay. This disturbance was detected on August 11, 1983, at 23:02:56 hours. The very rapid change inapparent resistance was due to a false trip and opening of one of the Intertie lines during staged fault tests at another substation. This caused one of the two processors to lose its potential supply and the event was detected as a fault. As indicated by the vertical $Rb_1$ and $Rb_2$ lines, only apparent resistance is used in fault (as opposed to swing) detection.

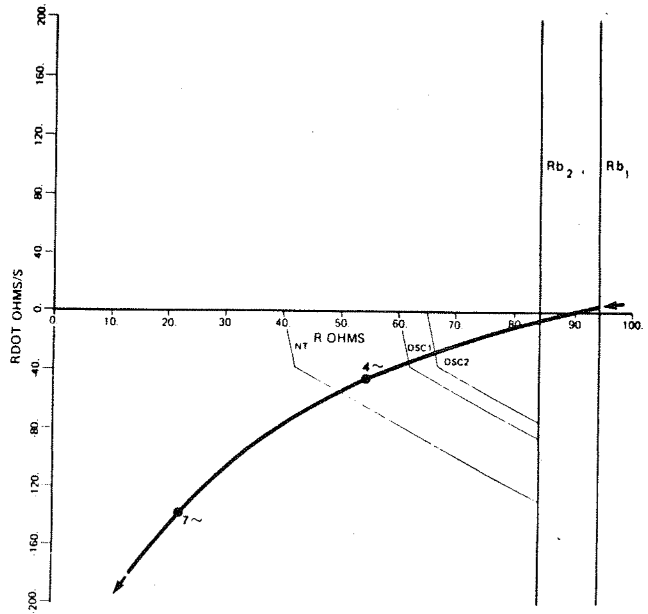

Figure 7 Disturbance detected by the R-Rdot relay on August 11, 1983 at 23:03:56 hours. Operation was due to stage fault tests at Summer Lake and a Malin breaker opening a line on the AC Intertie.

## CONCLUSIONS

The R-Rdot out-of-step relay concept has several advantages over conventional impedance-based relays. The principle advantage is that more information is available to avoid tripping on recoverable swings while initiating early tripping for non-recoverable swings. Worst case considerations will then not dictate relay settings and associated Intertie performance. The R-Rdot relay has been extensively tested and is suitable for Pacific Intertie tripping service.

The R-Rdot relay may be used to initiate discrete supplementary control actions such as generator tripping. The relay is a practical method to implement phase-plane control methods.

## Acknowledgements

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M. A. Albrecht, Intel Corporation

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4. R. H. Webster, A.P. Mane, and O. J. M. Smith, "Series Capacitor Switching to Quench Electromechanical Transients in Power Systems", Ibid, Vol. PAS-90, March/April 1971, pp. 427-433.

5. M. L. Shelton, P. F. Winkelman, W. A. Mittelstadt, and W. J. Bellerby, "Bonneville Power Administration's 1400MW Braking Resistor", Ibid, Vol. PAS-94, March/April 1975, pp. 602-611.

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# APPENDIX A

The information in this appendix is available in detail in Reference 1, and is provided here as a summary for the reader.

The Pacific Northwest-Southwest Intertie consists of two 500kV series and shunt compensated AC lines and a parallel ± 400kV HVDC line which are approximately 850 miles long. The electrical center of the Intertie is generally close to Malin Substation near the Oregon-California border. BPA has used conventional out-of-step relaying (impedance-based trip on the way in) at this location. Since the energization of the AC Intertie in 1967, there have been a number of AC Intertie separations due to out-of-step relaying. These separations have occurred during stressed operating conditions and multiple contingency disturbances. None of these have been due to severe short circuits such as a three phase fault near a major generating station.

Conventional out-of-step relaying, using impedance relays, has generally performed satisfactorily. A problem with this type of relay is the inability to distinguish between various types of disturbances. On major EHV systems, out-of-step separation should occur before the voltage at the electrical center swings to a minimum value, therefore, the out-of-step relays are generally set to insure adequate protection for worst case conditions.

To maximize power system performance, tripping on recoverable swings should be avoided. The R-Rdot relay was designed to initiate early tripping for non-recoverable swings while avoiding tripping on recoverable swings to improve transient stability performance.

The R-Rdot relay decides on an out-of-step condition on the basis of the generator angle and the rate-of-change of generator angle. By adding this ability to use the rate-of-change of generator angle, the Intertie can be kept intact for the maximum length of time during slow swings. For faster (more severe) swings, the R-Rdot relay can initiate tripping more quickly than the existing out-of-step relays, thereby allowing the system to begin recovering sooner. The R-Rdot relay uses resistance and rate-of-change of resistance to approximate generator angle and rate-of-change of generator angle. Resistance is approximately proportional to generator angle in the region of interest. A resistance measurement is used to approximated generator angle because sensing at one location can yield the desired angle information. (A rigorous angle measurement would require sensing at two locations, with communications between.) These calculations are based upon measurements from active and reactive power transducers along with voltage transducers where:

$$R=|P|V^2/(P^2+Q^2),\quad Rdot=R((n)T)-R((n-1)T)/\Delta T.$$

A sample period of about 20 milliseconds is used to measure and compute power system quantities. Figure A-1 shows, on the R-Rdot phase-plane, the multiple switching lines and swing/fault detection lines. Apparent resistance values $Rb_1$ and $Rb_2$ are used to distinguish between swings and faults in much the same way as conventional out-of-step relays.

$Rb_1$ and $Rb_2$ are spaced such that, for the largest negative value of dR/dt expected during a swing, there will be at least two samples taken as R passes between $Rb_1$ and $Rb_2$. The time, $\Delta$ T, between $Rb_1$ and $Rb_2$ crossings is computed. The computed value of $Rdot=(R_2-R_1)/(t_2-t_1)$

where: $R_1$ = first sample of resistance after crossing $Rb_1$
$t_1$ = first sample of time after crossing $Rb_1$
$R_2$ = first sample of resistance after crossing $Rb_2$
$t_2$ = first sample of time after crossing $Rb_2$

is compared to a resistance rate setting. If the computed value is negative and greater than the setting, the relay determines a swing is in progress. If the computed value is negative and less than the setting, the relay determines a fault is in progress. The relay is reset when the resistance is greater than $Rb_1$.

As shown in Figure A-1, two segment piecewise linear switching lines are used for out-of-step tripping and auxiliary outputs. If $dR/dt$ is positive, tripping will not occur. Also, the reactive reach of the controller is limited by computing apparent impedance and requiring that the apparent impedance is less than a set value. The following is the equation of one segment of an R-Rdot relay switching line:

$$U = (R-R_1) + T_1 \frac{dR}{dt}$$

Each switching line will consist of one or two segments (see Figure A-2). $R_1$ and $T_1$ are programmable constants. $R_1$ will determine where the switching line will cross the R axis. $T_1$ determines the amount of anticipation or slope of the line.

There are four, two segment switching lines used to initiate out-of-step tripping. The switching line that is enabled for out-of-step tripping will be determined by manual input or other stability control inputs.

These inputs can adapt the relay out-of-step characteristic for disturbances involving intertie outages, failure of series capacitor insertion, etc.

The relay will also have two auxiliary R-Rdot switching lines to control generator dropping, load tripping, dynamic brake insertion, out-of-step blocking, capacitor insertion, and other stability controls. If used, the outputs from these will precede the out-of-step tripping in an attempt to stabilize the system and avoid unnecessary Intertie separations. If these schemes and other regional stability control action are unable to stabilize the intertie system, out-of-step tripping, controlled by the R-Rdot relay, will separate the intertie.

To evaluate this relay concept, large scale simulations with stressed operating conditions were run. The western interconnection was modeled with about 1500 busses and 300 generators. The AC Intertie was heavily loaded north to south for all simulations. Figures A-3 through A-6 are representative of these studies. Benefits of delayed tripping for stable disturbances and advanced tripping for strongly unstable disturbances are obvious.

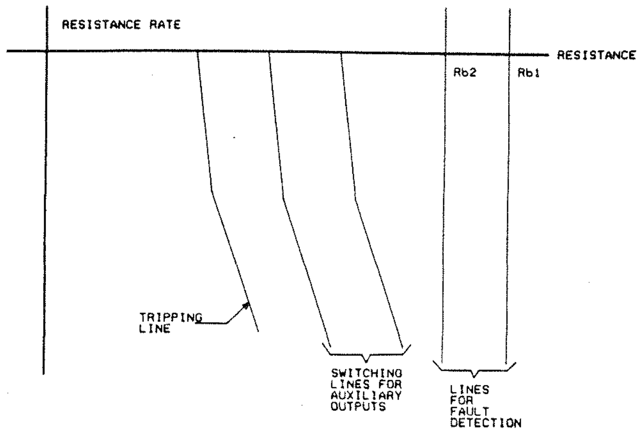

Figure A-1 Switching and swing/fault detection lines.

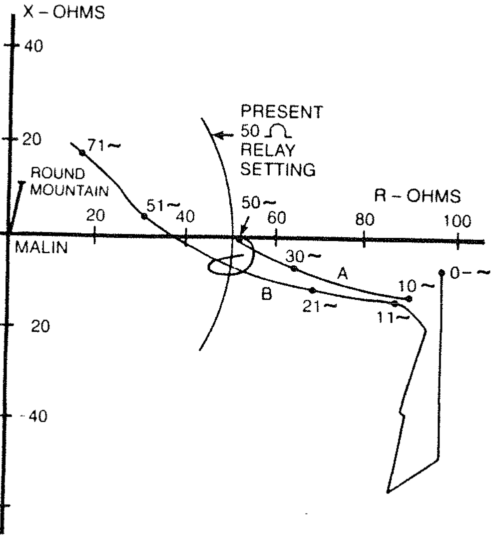

Figure A-3 Apparent impedance plot for three-phase fault at Grand Coulee on Hanford 500kV line. Curve A--clear Grand Coulee terminal at 2.5 cycles and Hanford at 3.5 cycles. Curve B--clear Grand Coulee at 4 cycles and Hanford at 5 cycles. Present out-of-step relay trip setting is 50 ohms.

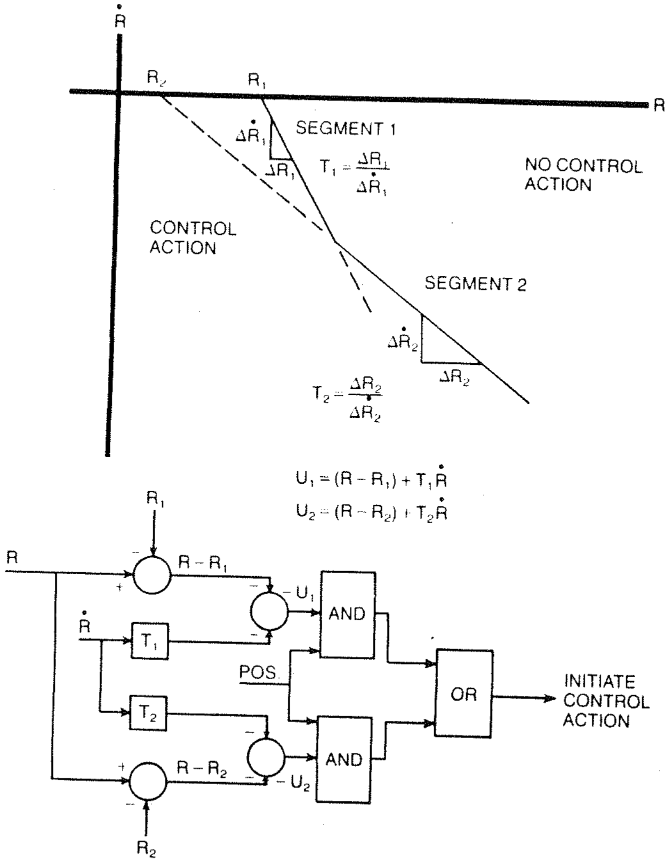

Figure A-2 Phase-plane and block diagrams illustrating concept of a rate augmented out-of-step relay.

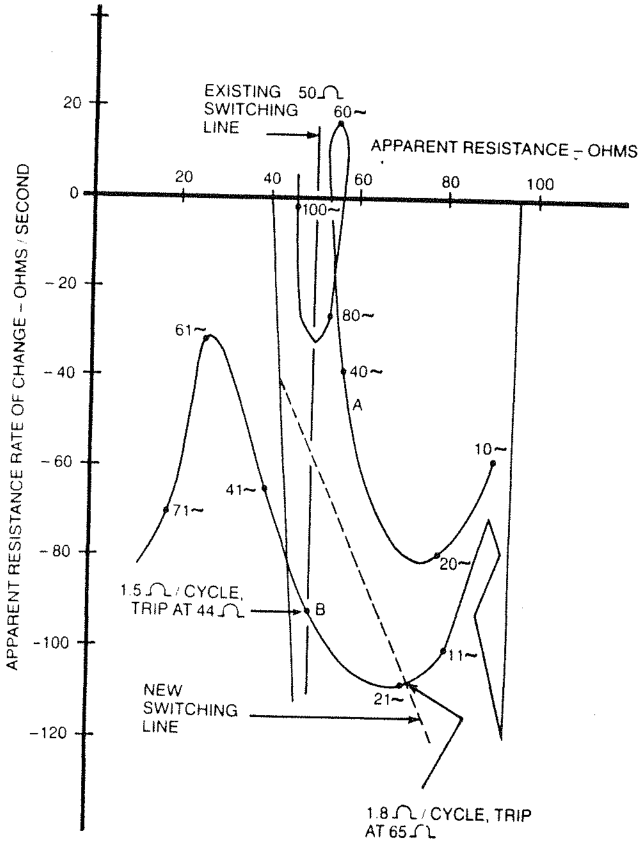

Figure A-4 Apparent resistance phase-plane plot for three-phase fault at Grand Coulee on Hanford 500kV line. Curve A--clear Grand Coulee terminal at 2.5 cycles and Hanford at 3.5 cycles. Curve B--clear Grand Coulee at 4 cycles and Hanford at 5 cycles.

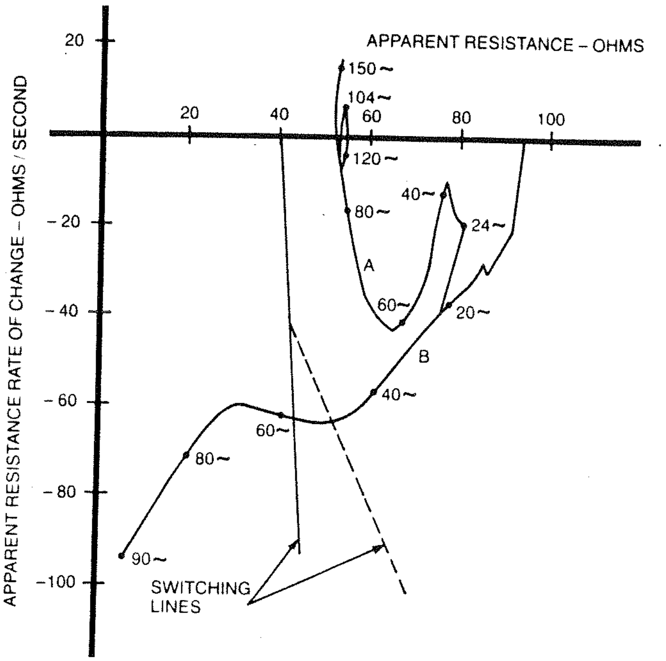

Figure A-5 Apparent resistance phase-plane plot for loss of HVDC Intertie (1600 MW). Curve A--1600 MW generator dropping at the Dalles and Chief Joseph at 22 cycles. Curve B--failure of generator dropping controls.

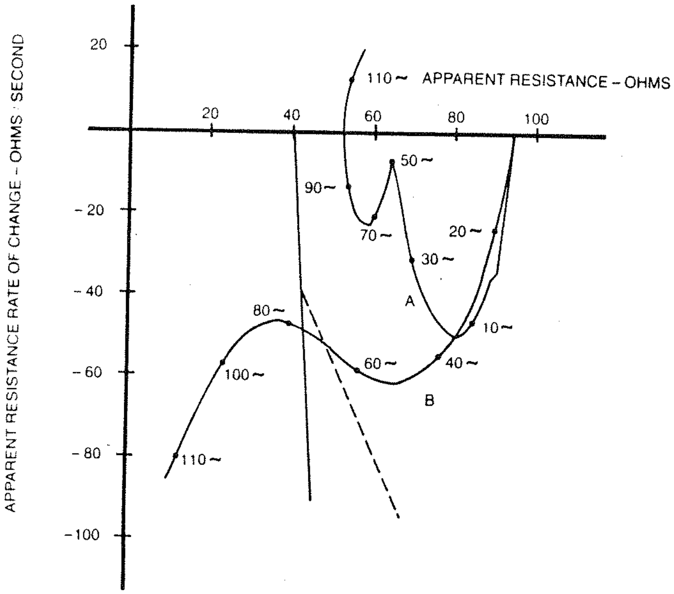

Figure A-6 Apparent resistance phase-plane plot. Curve A--lose 951 MW at Rancho Seco nuclear plant. Curve B--false operation of Southwest Separation Scheme.