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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. 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 now energized for initiating controlled separations at several locations within the Western North American Power System.

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 its rate-of-change are 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.

Relay operation initiates controlled separation of the Pacific AC Intertie, controlled separation of the Utah/Colorado-Arizona/New Mexico areas, and generator tripping in the Pacific Northwest. The large western North American interconnection is thus split into two islands by operation of the R-Rdot relay.

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.

85 SM 322-3 A paper recommended and approved by the IEEE Power System Relaying Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1985 Summer Meeting, Vancouver, B.C., Canada, July 14 - 19, 1985. Manuscript submitted February 1, 1985; made available for printing April 22, 1985.

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 elementary computation are required. In addition to controlled separation initiation, the R-Rdot relay can initiate hydro-generator tripping to stabilize severe disturbances and prevent out-of-step tripping. To date, no need has developed on the Pacific Intertie 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.

As shown, a two segment piecewise linear switching line can initiate about 600 MW of hydro-generation tripping. Again, a swing trajectory moving from right to left across the switching line would 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.)

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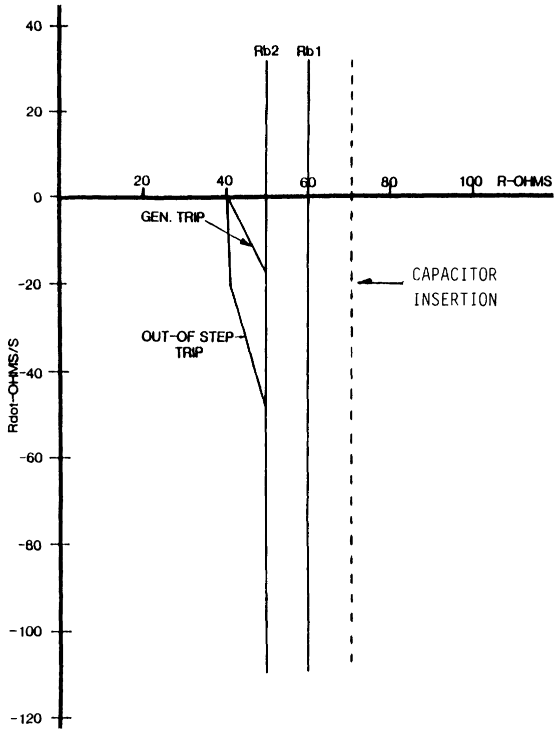

Figure 1 Present R-Rdot Out-of-Step Relay Settings. Previous conventional based out-of-step protection was set at 50 ohms.

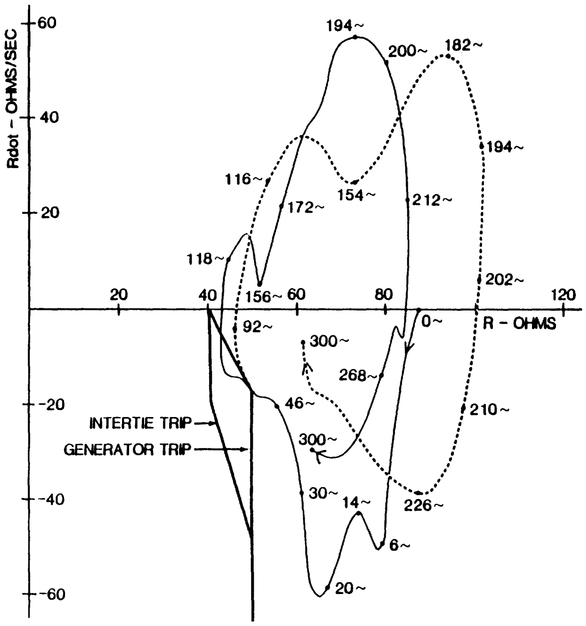

Figure 2 R-Rdot phase-plane for loss of Pacific HVDC Intertie (2000 MW). Time values in cycles indicated along trajectories. Series capacitors inserted along Pacific AC Intertie at 14 cycles. NW generator tripping (2000 MW) at 26 cycles. Solid trajectory without additional generator tripping; dashed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

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

Figures 2 and 3 show 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 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. For this case, failure of the dynamic braking is assumed.

Figure 2 shows the R-Rdot phase-plane. 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.

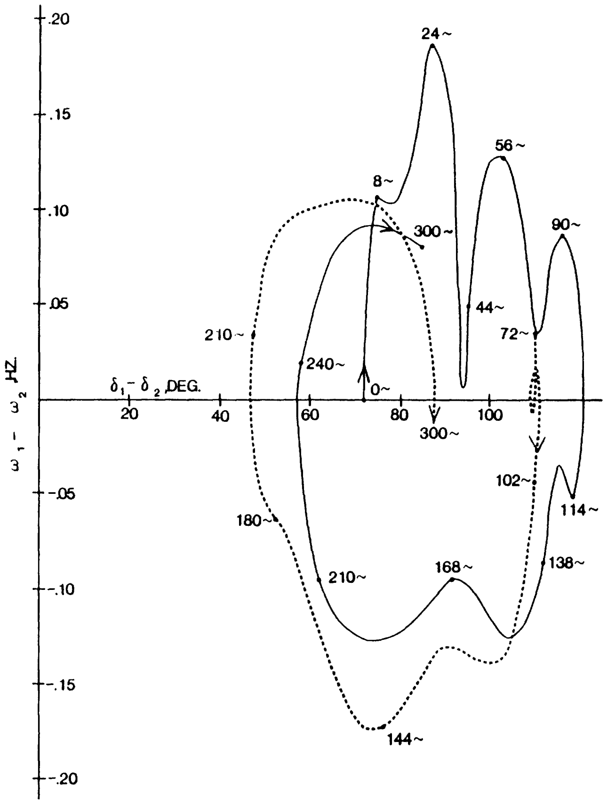

Figure 3 Angle difference-speed difference phase-plane for loss of Pacific HVDC Intertie (2000 MW). Angle, speed differences are between Grand Coulee and Mohave. Series capacitors inserted along Pacific AC Intertie at 14 cycles. NW generator tripping (2000 MW) at 26 cycles. Solid trajectory without additional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

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 operation.

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.

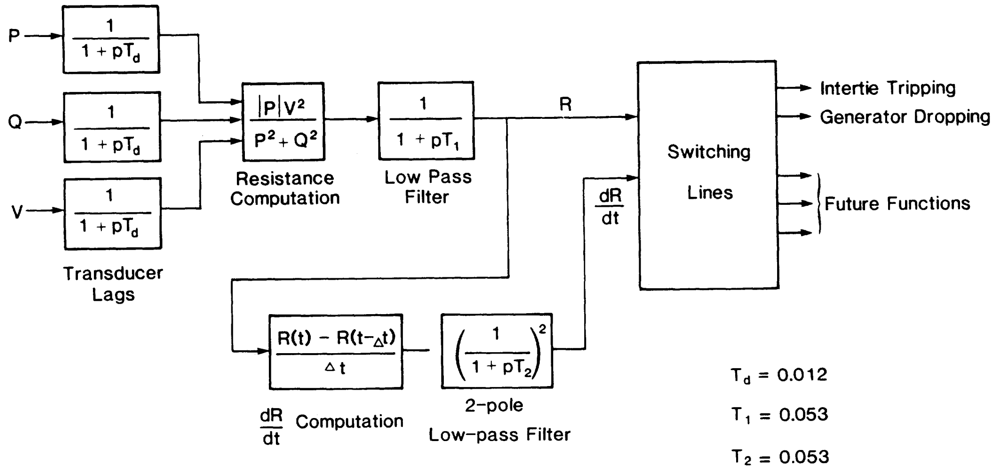

Figure 4 R-Rdot out-of-step relay filter model. This model was incorporated into the large scale simulation studies.

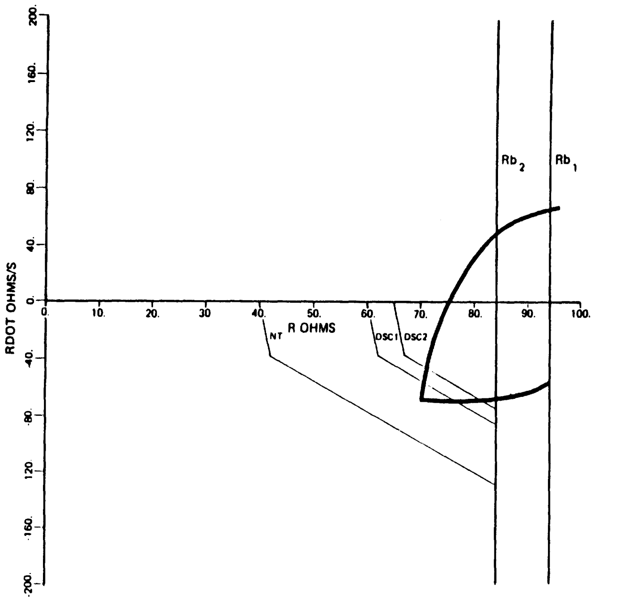

Figure 5 R-Rdot out-of-step relay bench test simulation.

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.

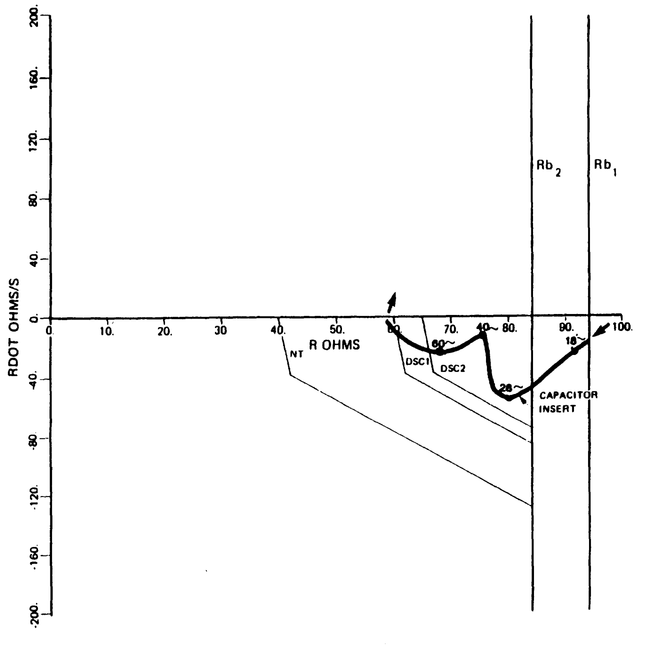

Figure 6 Swing detected by the R-Rdot relay on July 23, 1983, at 07:37:21 hours. Swing was caused by a disturbance on the HVDC Intertie.

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 in apparent 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.

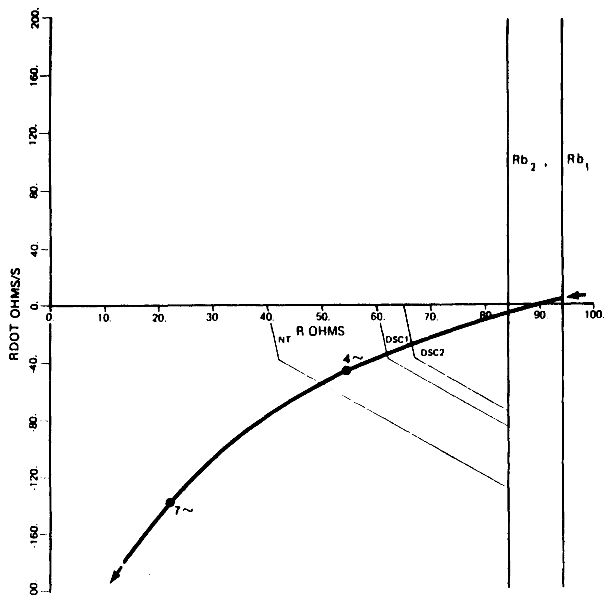

Figure 7 Disturbance detected by the R-Rdot relay on August 11, 1983 at 23:03:56 hours. Operation was due to stage fault tests at Summer Lake and a Malin breaker opening a line on the AC Intertie.

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 monitored in a substation environment. The relay is now in service for tripping on the Pacific Intertie.

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

Acknowledgements

The authors are pleased to acknowledge the following BPA engineers for their support in developing the R-Rdot relay:

G. R. Swoboda
L. A. Hill
M. A. Albrecht (now with Intel Corporation)

REFERENCES

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2. IEEE Committee Report, "A Description of Discrete Supplementary Controls for Stability", Ibid, Vol. PAS-97, January/February 1978, pp. 149-165.

3. E. W. Kimbark, "Improvement of System Stability by Switched Series Capacitors", Ibid, Vol. PAS-85, pp. 180-188.

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.

6. U. O. Aliyu and A. H. El-Abiad, "A Local Control Strategy for Power Systems in Transient Emergency State", Ibid, Vol. PAS-101, November 1982, pp. 4245-4262.

Discussion

Mohamed M. Mansour (Ain-Shams University, Cairo, Egypt): The authors have presented interesting informtion, especially about including use of their relay outputs for discrete supplemental control action for stability.

I am interested to know the motivation behind using a multiple microprocessor for realizing such a relay.

Is the task of performing the out-of-step algorithm being partitioned and distributed between the two algorithm processor units, or being done by each unit in parallel for the sake of backing up?

Which kind of transducers are being used for P and Q? Are they being generated digitally by processing the input current and voltage? I am interested to know the processing stages starting from the CT's and VT's to the A/D channels.

Finally, would the authors indicate the sampling rate being used and the processor type?

Manuscript received August 6, 1985.

M. M. Elkateb (Power Systems Studies, Abu Dhabi, U.A.E.): This paper uses a microprocessor to analyze the complex impedance source viewed by the relay into its real and imaginary components. Moreover, the rate of change of the resistive component trajectory is calculated to determine whether the case is a power swing or out-of-step condition.

Previous studies, given in the reference (a) below, showed that during a three-phase fault next to a capacitor bank located midway on a long EHV line with 50 percent compensation, a conventional power swing blocking relay may block tripping during the time the impedance trajectory settles into the exact fault impedance. This is seen due to the inherent electric phenomena during the lapse of time taken for current inversion. The trajectory took more than 80 m.s. within the power swing relaying region. Would the new R-RDOT technique cater to this problem and discriminate between a genuine fault and power swing or out-of step?

REFERENCE

[a] Elkateb M. and Cheetham W. "Problems in Series Compensated Lines," IEE Conf. #185 on Developments in Power System Protection, London, June 1980.

Manuscript received August 7, 1985.

J. M. Haner, T. D. Laughlin, and **C. W. Taylor**: Concerning Mr. Mansour's comments, multiple microprocessor parallel processing was used to realize increased redundancy over a single processing unit. Analog electronic transducers are used, with PT and CT inputs, to determine power, reactive power, and voltage quantities. These quantities are sampled at 20 msec. by an 11-bit A/D converter and processed by an 8-bit microprocessor unit.

Regarding Mr. Elkateb's comments, the R-Rdot relay uses absolute value quantities to compute resistance changes on an EHV line. We do not anticipate any problems as stated in his discussion.

Manuscript received September 10, 1985.