An Off-line Analysis of System Operating Conditions Affecting Relay Reliability

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***Abstract* – This paper describes a link between the Supervisory Control and Data Acquisition (SCADA) system of the Tennessee Valley Authority (TVA) and a software protection simulation environment developed by Electrocon International Inc. Using this link, four operating conditions that can affect protective relay reliability are checked and any violations of the conditions are flagged and reported. Every 5 minutes, the SCADA system generates a file that contains branch flows and bus voltages at 161kV and higher. A special process within the protection simulation environment reads this file, analyses the four operating conditions, and reports any violations. In its present form, this analysis is run in an off-line interactive mode. It is being extended to run in a near real-time mode with new data from the SCADA system every 5 minutes. Also planned is the analysis of hundreds of contingency cases from a State Estimator solution of the TVA network every 5 minutes.**

***Index Terms* – Overreaching distance, protection simulation, relay loadability, relay reliability, SCADA, zone 3.**

I. Introduction

The operations department and the protection engineering department of electric utility companies typically do not interact very much. The operations department is concerned with the daily operation of the network, monitoring of the actual load flows and possible re-routing, remedial action during emergencies, etc. One of the important factors that determines how much load a particular line can carry is the protective relay circuit (current transformers and relays). The limit may be determined by a current transformer, a relay's continuous current rating, or a relay's set point. This information is obtained from the protection department.

Protection engineers are generally interested in the fundamental frequency behavior of the network in the zero- and positive-sequence. They perform detailed fault studies to determine the settings for the protective relays on the network. They also need to know the maximum load a particular line might carry, so that they can set the relay with adequate margin to avoid tripping on load.

As the operating conditions of the system change and more current flows through the lines in the network, protection equipment on those lines such as relays, current transformers etc. can be stressed to or beyond their design operating limits. For example, the actual current in the line might be very close to or exceed the continuous current carrying capability of the relays and instrument transformers. Also, the increasing line loading might bring the protective relays on the line very close to operation such as might be the case with an overreaching distance element.

The SCADA system continuously monitors the branch flows and bus voltages on the system. However, it does not have access to protective equipment data like the reaches of the impedance relays or their current ratings. Such data are usually available within the protection engineering group and not easily accessed by the SCADA system. If the recorded SCADA data can be compared with the protection equipment ratings and settings in real-time, the relay engineers can quickly identify any equipment that is close to or over its operating limit. Remedial action can be then be taken to replace that equipment with a higher rated one if it is over-stressed for extended periods of time. This ensures that the equipment is available for operation under real emergency conditions like a fault and does not fail because of previous over-stressing.

On the operations side, knowing when a relay is close to operation because of increasing load current allows the operator to take action before the relay actually trips. This can prove especially useful in avoiding loss of load over a wide area, or blackouts.

In this paper, we describe a method by which branch flow data recorded by the SCADA system are compared with the protection equipment ratings and settings to identify problem areas. In its present form, this comparison in done in an off-line, interactive mode – the user (either a relay engineer or a system operator) has to start the analysis. The subsequent sections of this paper explain in detail the conditions that are checked and the types of exception reports that are generated.

The analysis itself is part of a protection simulation environment that is used by TVA for short-circuit fault analysis, relay settings calculation, relay settings storage and relay coordination analysis. We first describe the components of this environment.

II. The Protection Simulation Environment

The protection simulation tool can be used to compute relay settings and send them to a relay, or to read settings from a relay and test them in the system that is modeled. The main components are:

- An integrated database that contains all the network equipment (buses, generators, lines, shunts, transformers) and protection equipment, including instrument transformers, relays, reclosers and fuses.
- Short-circuit analysis with high-level commands for faults and outage contingencies. Currents and voltages are treated as steady-state phasors. Calculations are performed on the network model that is contained in the database [1].
- A library of detailed relay models [2]. A relay model consists of instantaneous overcurrent, time overcurrent, directional, current differential, distance, voltage, timer and recloser elements with auxiliary elements for internal logic and teleprotection schemes. Special operational equations are coded for each relay model, to comply with the comparator equations developed by the relay manufacturer. Further, the user works with the actual named settings of the relay, instead of an abstraction of the device characteristics.
- A library of instrument transformers – CTs, VTs, auxiliary CTs and auxiliary VTs.
- A simulation tool that evaluates the response of the entire protection system from the time a fault occurs to the time it is cleared by the last circuit breaker operation [3].
- Import/export facilities to communicate with a physical relay through the relay vendor's database or setting software.

The reliability analysis function makes use of the information contained in the integrated database to perform its calculations. In the next section, we will see what operating conditions are checked by the reliability analysis, and for each condition, what data it gathers from the protection simulation environment.

III. Operating Conditions Checked By The Reliability Analysis Function

A. Input Data from the SCADA System

The analysis function reads as its input, a file supplied by the SCADA system. This file contains the following information for each branch in the TVA network (161kV and above):

1. From-bus number and name, to-bus number and name, circuit number.
2. Voltage magnitude at the from-bus in kV.
3. Magnitude of the current flowing in the branch in amperes.
4. Values of MW (real power flow) and MVAr (reactive power flow) measured flowing from the from-bus to the to-bus.

The data in the SCADA input file represents the state of the system at the time the file was written.

B. Operating Conditions Checked

The reliability analysis function uses the data in the SCADA input file to check the following conditions for each branch:

1. Does the actual voltage at the from-bus of the branch exceed the base voltage of the bus by a user-specified percentage?
2. Does the magnitude of the actual branch current exceed the continuous current rating of any CT that is used on that branch?
3. Does the magnitude of the actual branch current exceed the continuous current rating of any relay that is used on that branch?
4. Does the actual load flow at the actual power factor angle lie within a user-specified margin of the reach characteristic of any distance relay element on that branch?

To check the above conditions, the analysis function needs to be able to access information that is contained in the protection simulation tool. Some of that information is within the integrated database, while the remaining information has to be computed (on-the-fly) while the analysis is being done.

C. Information Required to Perform the Analysis

We now consider each of the four operating conditions, and the information that is needed to check that condition against the actual recorded data.

1) Bus voltage check:

For this check, the analysis function needs to know the base voltage of the from-bus of the branch that is currently being analyzed. This information is stored in the integrated database. Fig. 1 shows part of a form that contains this data. The analysis function accesses this data to perform the bus voltage check.

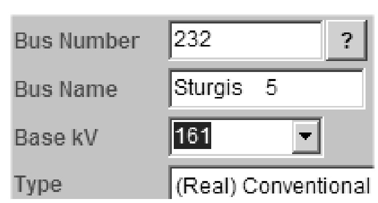

Fig. 1. Base voltage of a bus shown in kV (highlighted). This information is used for performing the bus voltage check.

2) CT continuous current rating check:

The continuous current rating of a CT is given by the following expression:

$$CT\ RATING = CTR \times CT\ RATING\ FACTOR \times CT\ SECONDARY\ TAP \quad (1)$$

where *CTR* is the CT ratio of the CT, *CT RATING FACTOR* is a factor ≥ 1, supplied by the CT manufacturer and *CT SECONDARY TAP* is the secondary tap at which the CT is applied (1A or 5A). Fig. 2 shows the CT information as contained in the integrated database.

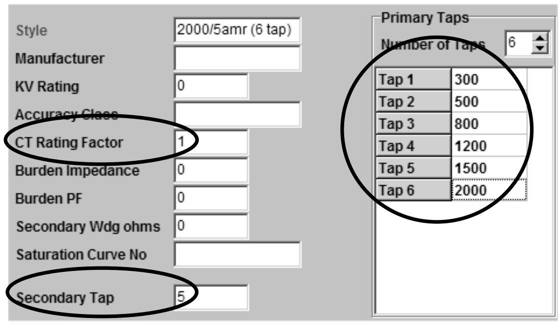

Fig. 2. CT information for performing the CT rating check. CT rating factor, CT secondary tap and the available primary taps are circled. The CT can be applied at any one of the 6 available primary taps. The CTR is the ratio of the primary tap to the secondary tap.

The actual line current magnitude is compared against the CT rating computed using (1). There may be more than one CT applied on the branch. The analysis function will check the CT rating for every CT and flag violations of the rating.

3) Relay continuous current rating check:

The continuous current rating of a relay is specified in the integrated database. It is a fixed number for most relays, and is available from the relay manufacturer. However, the rating of some electromechanical relays varies with the settings that are made for the relay. So, while the relay might have a nominal current rating of 15A secondary, the actual setting taps selected on the relay might reduce this to 8A secondary. The protection simulation environment accounts for this change automatically. Fig. 3 shows the nominal continuous current rating for a KD-41 type electromechanical relay.

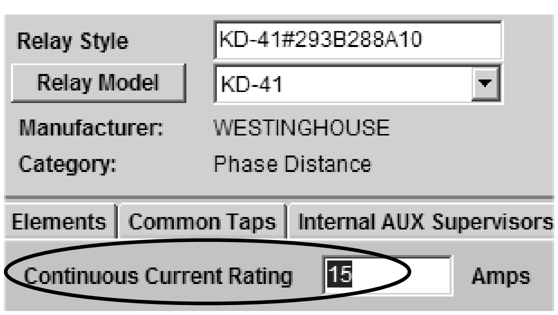

Fig. 3. Relay information for performing the relay continuous current rating check. The nominal value of the rating is circled. The actual rating is computed based on the settings that the relay uses.

The relay rating check is performed on every relay that is applied on the branch being studied. Violations of the rating are reported.

4) Distance element reach check:

The actual MW and MVAr measured for the branch under consideration are used to determine the ohmic value of the load at the power factor angle. Thus,

$$Z_{LOAD} = \frac{V_{L-L}}{\sqrt{3} \cdot I} \cdot \exp\left(j\theta_{PF} \right) \quad (2)$$

where Z_{LOAD} is the impedance of the load at the power-factor angle θ_{PF}. The angle θ_{PF} is the 4-quadrant arctangent of Q and P, which are the measured reactive and active power respectively. V_{L-L} is the line-to-line voltage measured at the from-bus of the branch (not the base voltage) and I is the magnitude of the measured line current.

Z_{LOAD} is checked against the reach of every distance relay at the power-factor angle θ_{PF}, that is applied on the branch under consideration. Fig. 4 shows a MHO-shaped characteristic, with "X" marks identifying the reach of the relay at $\theta_{PF} = 30°$ and the Z_{LOAD}.

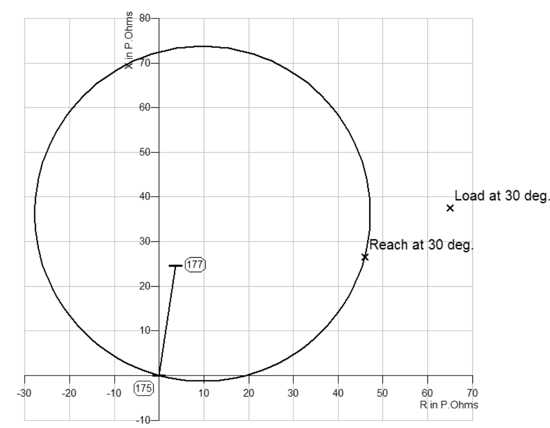

Fig. 4. The reach of the relay element at 30° and the load on the relay branch at 30° are shown. The analysis function will compare these two numbers and flag a violation if the reach is within a user-specified margin of the actual load at the actual power factor angle.

The analysis function compares the reach of the relay at the actual power-factor angle with load impedance at that same angle. If the reach is within a user-specified margin, a violation will be reported. This comparison is performed for every distance relay element that is used on the branch under consideration.

D. Other Data Considerations

It was not stated explicitly before, but it is very important that the model of the network used by the protection simulation environment and the operations group use the same bus numbers to identify branches. That is, a branch identified as going from bus number 1, to bus number 2 with circuit number 3 in the

SCADA data file must map to the same branch in the network model of the protection simulation environment. At TVA, this mapping has been thoroughly checked and the necessary corrections have been made. Periodic maintenance of the data is also performed to keep the two network models in synchronism.

IV. Performing The Study & Exception Reports

We now turn our attention to actually performing a reliability analysis on the data contained in the SCADA input file. As explained before, the analysis is performed in an off-line mode. A user has to initiate the study from within the protection simulation environment. In its final implementation, no user intervention will be required.

Upon starting the analysis, the user will be prompted to supply some parameters, shown in Fig. 5.

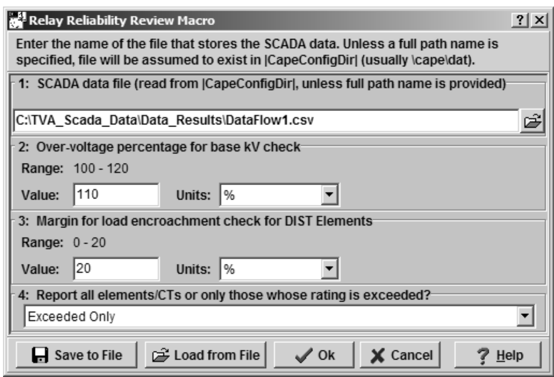

Fig. 5. Setting up the reliability analysis function. The user has to enter a few parameters before the study can commence.

The parameters that the user has to supply are:

1. Name and location of the file that contains the SCADA data.

2. For the bus voltage check, specify the over-voltage percentage that will flag a violation report. If the user enters 110%, a violation report will be generated if

$$\frac{V_{ACTUAL}}{V_{BASE}} \cdot 100 \geq 110 \quad (3)$$

where V_{ACTUAL} is the measured voltage at the from-bus and V_{BASE} is the base voltage at the from-bus of the branch under study.

3. For the relay reach check, specify the minimum allowed margin between the load impedance and the distance element reach. A margin less than this number will flag a violation report. If the user enters 20% as the margin, a violation report will be generated if

$$\frac{|Z_{LOAD}|}{|Z_{RELAY}|} \cdot 100 \leq 120 \quad (4)$$

where Z_{LOAD} is the ohmic value of the load at the power factor angle, and Z_{RELAY} is the reach of the distance element at the same angle.

4. Should the analysis function report all buses, CTs and relays that were studied or only those that either exceed their ratings or otherwise violate the checking conditions? The default response for this parameter is "Exceeded Only", which will generate an exception report.

On clicking "Ok" in the form in Fig. 5, the analysis begins. Given below are examples of the reports that the analysis produces.

A. Bus Voltage Violation Report

```
---------------------------------------------------------------------------------------------
FROM BUS NAME NUMBER TO  BUS  NAME NUMBER CKT  AMPERES    MW      MVAr    kV MAG   kV ANG
------------- ------ ------------ ------ --- -------- -------- -------- -------- --------
Great Fa 5-1    3991 E. McMinvi T    1062   1   250.78    73.50    -1.64   180.66     0.00

   Bus voltage violation - Actual kV / Base kV >=  1.10
   ----------------------------------------------------
     BUS NAME   NUMBER BASEKV ACT.kV kV/BkV
   ------------ ------ ------ ------ ------
   Great Fa 5-1   3991 161.00 180.66   1.12
   ----------------------------------------
```

The actual bus voltage is 180.66kV. The base voltage is 161kV. The study was run with a user-specified overvoltage percentage of 110%.

B. *CT Continuous Current Rating Report*

FROM BUS NAME	NUMBER	TO BUS NAME	NUMBER	CKT	AMPERES	MW	MVAr	kV MAG	kV ANG
Paradi 2-3 5	581	Lost City 5	5400	1	920.64	-258.85	3.67	165.78	0.00

CT Continuous Rating Check

CT TAG	CT NAME	CT DESIGNATION	CT STYLE	CT RATING PRI.AMPS	DOES LINE AMPS EXCEED CT RATING ?	PERCENT LOADING
260	pcb_948	line	3000/5amr	2000.00	NO	46.03

In the cases tried so far, no CT continuous current rating violations were reported. The output above simply shows the format in which a violation might be reported. The actual line current is 920.64A. The CT continuous rating is 2000A (3000/5 CT set on 2000/5 tap). This gives a percent loading of 46.03% on the CT.

C. *Relay Continuous Current Rating Violation Report*

FROM BUS NAME	NUMBER	TO BUS NAME	NUMBER	CKT	AMPERES	MW	MVAr	kV MAG	kV ANG
Cumberland 8	40	Marshall 8	15	1	734.43	-595.38	169.45	0.00	0.00

Relay Continuous Rating Check

LOCAL ZONE OF PROTECTION	RELAY STYLE	RELAY RATING PRI.AMPS	DOES LINE AMPS EXCEED RELAY RATING ?	PERCENT LOADING
5024 Marshall Cumb 50264	12PJC11AV1A	450.00	YES	163.21

The actual line current of 734.43A exceeds the relay rating of 450A.

D. *Relay Reach Report*

FROM BUS NAME	NUMBER	TO BUS NAME	NUMBER	CKT	AMPERES	MW	MVAr	kV MAG	kV ANG
Paradi 2-3 5	581	Lost City 5	5400	1	907.94	-256.12	8.03	166.09	0.00

DIST Element Load Encroachment Check

LOCAL ZONE OF PROTECTION	TAG	DESIGNATION	Z	U	LINE AMPS IN OHMS	DIST REACH	MARGIN RATIO	MARGIN VIOLATED?
948 Lost City Para 9421	3464		3	1	105.62	24.06	4.39	NO

In the cases we have tried so far, no relay reach violations have been detected. The output above shows an example of how the relay reach violation might be reported, if there was one. The MW and MVAr measured on the line are used to compute the power-factor angle. The ohmic value of load is determined using the line current and the magnitude of the voltage at the from-bus of the branch. This works out to 105.62Ω. The reach of the distance element at the same angle is 24.06Ω. The ratio of the load impedance to the relay element's reach is 4.39. The threshold for declaring a violation is a margin ratio ≤ 1.2 (assuming that the user-specified margin in the form in Fig. 5 was 20%).

V. Conclusions and Future Work

In this paper, we have described an analysis function that compares the data recorded by the SCADA system with data contained and computed within a protection system simulation environment. This comparison yields four different reports:

1. Actual bus voltage exceeds the base voltage of a bus by a user-specified amount.

2. Actual line current exceeds the continuous current rating of CTs applied on the line.
3. Actual line current exceeds the continuous current rating of relays applied on the line.
4. The impedance of the actual load, measured at the actual power-factor angle, is within a user-specified margin of the reach (at the same power-factor angle) of distance relays applied on the line.

These reports give valuable information to protection engineers about how close to their actual rating, the various equipment in the power system are operating. Equipment that is over-stressed continually or on a frequent basis can be targeted for replacement with higher-rated equipment. This can prevent catastrophic failure of equipment, and ensure that they are available for operation during a real emergency like a fault.

System operators can quickly assess whether the actual load on a particular line will cause distance relays applied on that line to operate, thereby taking the line out of service. Such relay operations could quickly cascade into a blackout situation. With advance warning, operators can try and undertake remedial action like re-routing the load on other lightly loaded lines.

At present, the analysis function works only in an offline mode. A user has to start the analysis function by supplying it with some parameters. An exception report listing the violations is generated.

We are actively developing a real-time version of this analysis. The SCADA system will continually write data files into a computer dedicated for the real-time analysis, once every 5 minutes. The analysis function will not need to be invoked by a user. It will run in the background. As and when new files are written by the SCADA system, they will be analyzed and the results written into special files for subsequent viewing by system operators and protection engineers.

The real-time implementation will also work on output from a State Estimator solution of the TVA network. The state estimator solution will include the base case, as well as hundreds of contingency cases, with results immediately available to the TVA Reliability Authority.

VI. References

[1] F. L. Alvarado, S. K. Mong and M. K. Enns, "A fault program with macros, monitors and direct compensation in mutual groups," *IEEE Transactions on Power Apparatus and Systems*, vol. 104, pp. 1109-1120, May 1985.

[2] M. K. Enns and P. F. McGuire, "Data base organization for protection engineering," presented at the CIGRE Study Committee 34 Colloquium, Johannesburg, South Africa, October 1 – 3, 1997.

[3] P. F. McGuire, D. M. MacGregor, J. J. Quada and D. B. Coleman, "A stepped-event technique for simulating protection system response," presented at the 6th Technical Seminar on Protection and Control, Natal, Brazil, September 27 – October 2, 1998.

VII. Biographies

Russell W. Patterson is Manager of System Protection & Analysis for the Tennessee Valley Authority (TVA, www.tva.gov) in Chattanooga, Tennessee. Prior to this he was manager of TVA's Advanced Network Applications group where he was responsible for the maintenance and expansion of the state estimators used by TVA. As Manager of System Protection & Analysis he is responsible for the setting of all protective relays in the TVA transmission system and at Hydro, Fossil and Nuclear generating plants. He is responsible for ensuring that TVA's protective relays maximize the reliability and security of the transmission system. This includes setting and ensuring the proper application and development of protection philosophy for the TVA. Prior to this role Russell was a Project Specialist in System Protection & Analysis and was TVA's Power Quality Manager responsible for field and customer support on PQ related issues and disturbances. He has performed transient simulations using EMTP for breaker Transient Recovery Voltage (TRV) studies including recommending mitigation techniques. Russell is an active member of the IEEE Power System Relaying Committee (PSRC) and a prior member of the Protection & Controls Subcommittee of the Southeastern Electric Reliability Council (SERC). He earned the B.S.E.E. from the Mississippi State University in 1991. Russell is a registered professional engineer in the state of Tennessee and is a Senior Member of IEEE. His website is http://webpages.charter.net/rwpatterson357/ and he can be e-mailed at rwpatterson@tva.gov.

Ashok Gopalakrishnan joined Electrocon International, Inc., in May 1999. He is involved in the development of digital relay models, breaker duty functions and other protection and coordination tools. He received the M.S. (1995) and Ph.D. (2001) degrees, both in Power Systems from Texas A&M University. His interests lie in the fields of transient simulation of power systems, digital simulators for relay testing and transmission line fault location. He is a member of the IEEE.