

**Near Real-Time Analysis of Operating Conditions Affecting
Protective Equipment Reliability**

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Abstract

This paper describes a tool used by TVA to perform near real-time monitoring and analysis of certain system operating conditions that can affect the performance of relays and current transformers (CTs). The tool is a link between TVA's SCADA and State Estimator (SE) systems, and data stored in a software protection simulation environment that TVA uses for short-circuit and relay setting calculations.

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 2 minutes, the SCADA system generates a snapshot of the TVA network (161 kV and higher). The SE system generates similar output for the TVA base case network, and from running hundreds of branch contingency studies. The data output includes bus voltages, branch flows in amperes, MW, MVAR and branch identification information.

The monitoring and analysis tool described in this paper continually reads the SCADA and SE output files and compares (a) the recorded line current with the continuous current ratings of relays, (b) the recorded line current with the continuous current ratings of CTs, (c) the ohmic value of the recorded load flows against the reach of phase distance relays at the actual power factor angle and (d) the recorded bus voltage against the base voltage of a bus. Equipment rating violations and distance element reach violations are flagged.

The information required for the analysis – CT and relay continuous current ratings, distance element reach at any angle and base voltage of the bus – is stored within the protection simulation environment.

In its present form, the analysis function is running continuously on a “development server” at TVA. It has not been deployed in a production environment yet, pending some implementation issues.

Keywords

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 determine 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 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 the branch flow data recorded by the SCADA system and generated by a contingency analysis based on the state estimator model of the TVA network are compared with the protection equipment ratings to identify problem areas. The comparison and analysis is performed in near real-time; i.e. every 2 minutes. An off-line (interactive) version of this analysis is described in [1].

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

II. 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 [2].
- A library of detailed relay models [3]. 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 code for each relay model interprets the setting names. 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, so that the relay model is “set” in the same way as the physical device.
- 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 [4].
- Import/export facilities to communicate with a physical relay through the relay vendor’s database or setting software.

The real-time 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 analysis and, for each condition, what data it gathers from the database of the protection simulation environment.

III. Implementation

A. Input Data from the SCADA and State Estimator Systems

The analysis function reads as its input, data files supplied by the SCADA and State Estimator systems. A data 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. Magnitude of the current flowing in the branch in amperes.
3. Values of MW (real power flow) and MVAR (reactive power flow) measured flowing from the from-bus to the to-bus.
4. Voltage magnitude at the from-bus in kV, and its angle, if available.

The data in the file represents the state of the system at the time the file was written. An example of how this file is organized is shown below:

```
"F_Bus_No", "F_Bus_Name", "T_Bus_No", "T_Bus_Name", "Ckt", "AMPS", "MW", "MVAR", "kV_Mag", "kV_Ang"
"334", "Sumr Shad5-1", "6013", "Paddys RunT", "1", "436.29", "123.68", "21.35", "168.75", "0.00"
"2186", "Watauga 3", "2188", "Winner T", "1", "33.79", "4.01", "0.49", "0.00", "0.00"
"1462", "RogersvilleA", "274", "Ardmore AL 5", "1", "27.16", "4.76", "5.20", "166.55", "0.00"
.
.
.
```

Each branch is identified by a “from-bus”, “to-bus” and “circuit number”. Both the number and the name of the buses are included. Then follows the measured line current in amperes, MW, MVAR and the magnitude and angle of the voltage at the from-bus of the branch. A typical SCADA or SE output file will contain data for around 1000 branches.

The state-estimator is also used to run hundreds of branch contingency studies. The results of these studies – namely for each type of contingency, any branches that violate the loading criteria set by TVA – are written to a separate file. This data file has the format shown below:

```
"Contingency : 1", "KINGSTON- ROANE -FT LOUDN 161KV #2", "", "", "", "", "", "", "", ""
"F_Bus_No", "F_Bus_Name", "T_Bus_No", "T_Bus_Name", "Ckt", "Amps", "MW", "MV", "kV_Mag", "kV_Ang"
"438", "DOE K-27 5", "443", "DOE X-10 5", "1", "768.5", "185.59", "12", "161", "0"
"1232", "Bear Creek", "4321", "Kingston 1-1", "1", "892.5", "215.53", "14", "161", "0"

"Contingency : 2", "KINGSTON-FORT LOUDON 161KV LINE", "", "", "", "", "", "", "", ""
"F_Bus_No", "F_Bus_Name", "T_Bus_No", "T_Bus_Name", "Ckt", "Amps", "MW", "MV", "kV_Mag", "kV_Ang"
"438", "DOE K-27 5", "443", "DOE X-10 5", "1", "802.0", "193.68", "12", "161", "0"
"442", "Elza 5", "443", "DOE X-10 5", "1", "-779.0", "-188.1", "12", "161", "0"
```

Each contingency analyzed by the state estimator is identified by the keywords “Contingency : 1” etc., and the name of the contingency. This line is followed by information about those branches that violate TVA’s branch loading criteria, for that contingency. For

example, in contingency 1 above, two branches – “438 – 443 – 1” and “1232 – 4321 – 1” – are reported. These are the only two branches that violate TVA’s branch loading criteria.

Some points to be noted are:

1. The SCADA measurement and the state estimator output are provided only at those locations where there are real circuit breakers in the TVA network.
2. Every transmission line will have as many records in the data file as it has line terminals. So, a three-terminal line will have three sets of measurements, and therefore three records in the data file.
3. The measurements reported in the data file automatically combine multiple circuit breakers at a line end. That is, if a line terminates on a ring bus, the measurements from both the relevant breakers are combined and made available as one measurement, in the data file.
4. The network model used by SCADA, the state estimator and the protection simulation tool all use the same bus numbers and circuit numbers to identify the branches in the network. That is, a branch going from bus number 1 to bus number 2, with circuit number 3 in the SCADA or state estimator output 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 network models in synchronism.
5. In the contingency analysis output, we make the assumption that the voltage at the from-bus of the branch is the same as the base kV of the bus. We also make the assumption that the load-angle is 30°. These assumptions are necessary because the program that performs the contingency analysis provides only the branch current in amperes and the branch MVA. It does not provide an output of the actual bus kV, nor does it provide the real and reactive power components.

B. Operating Conditions Checked by the Analysis Tool

The reliability analysis function uses the data in the SCADA and state estimator input files to check four conditions described below. To check these conditions, the analysis function needs to be able to access information that is contained in the database of 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.

- **Does the actual voltage at the from-bus of the branch exceed the base voltage of the bus by a user-specified percentage?**

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. Figure 1 shows part of a form that contains this data.

Bus Number	232	?
Bus Name	Sturgis 5	
Base kV	161	▼
Type	(Real) Conventional	

Figure 1: Base voltage of a bus shown in kV (highlighted). This information is used to perform the bus voltage check.

- Does the magnitude of the actual branch current exceed the continuous current rating of any CT that is used on that branch?

The continuous current rating of a CT in primary amperes 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). Figure 2 shows the CT information as contained in the integrated database of the protection simulation environment.

Style	2000/5amr (6 tap)
Manufacturer	
KV Rating	0
Accuracy Class	
CT Rating Factor	1
Burden Impedance	0
Burden PF	0
Secondary Wdg ohms	0
Saturation Curve No	
Secondary Tap	5

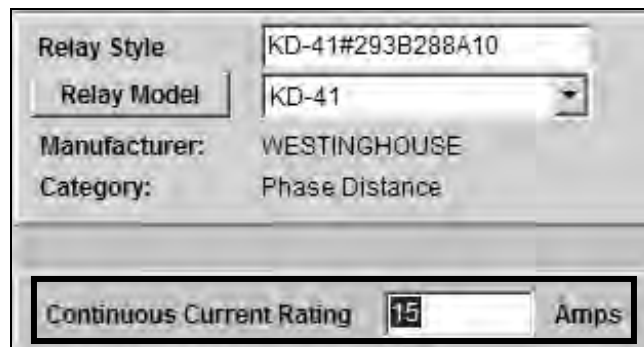
Primary Taps	
Number of Taps	6
Tap 1	300
Tap 2	500
Tap 3	800
Tap 4	1200
Tap 5	1500
Tap 6	2000

Figure 2: CT information for performing the CT rating check. CT rating factor, CT secondary tap and the available primary taps are outlined. The CT can be applied at any 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 equation (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.

- **Does the magnitude of the actual branch current exceed the continuous current rating (in primary amperes) of any relay that is used on that branch?**

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. Figure 3 shows the nominal continuous current rating for a KD-41 type electromechanical relay.



Relay Style	KD-41#293B288A10
Relay Model	KD-41
Manufacturer:	WESTINGHOUSE
Category:	Phase Distance
Continuous Current Rating	15 Amps

Figure 3: Relay information for performing the relay continuous current rating check. The nominal value of the rating, in secondary amperes, is outlined. The actual rating is computed based on the tap settings the relay uses.

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

- **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?**

One of the outcomes of the August 14, 2003 blackout in the Eastern United States is the requirement imposed by the North American Electric Reliability Council (NERC) on transmission system operators to ensure that so-called “Zone 3” relays (any distance relay that provides remote backup protection) be secure against emergency line loading conditions. What constitutes an emergency condition and other details are part of the NERC Recommendation 8a, [5, 6]. Transmission system operators are required to verify compliance with Recommendation 8a on a periodic basis. This is performed in an “off-line” mode, without consideration of actual network conditions.

Using the real-time analysis tool, we can now check whether the actual loading condition on a line encroaches into the characteristic of a distance element, on a real-time basis. As network conditions change – opening of breakers, line or machine outages etc. – the system operator gets immediate feedback on how distance relay elements are going to react to those changes.

The MW and MVar information, which is part of both the SCADA and state estimator outputs, is used to determine the ohmic value of the load at the power factor angle. Thus,

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

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 element at the power-factor angle θ_{PF} that is applied on the branch under consideration. Figure 4 shows a MHO-shaped characteristic, with “X” marks identifying the reach of the relay at $\theta_{PF} = 30^\circ$ and the Z_{LOAD} .

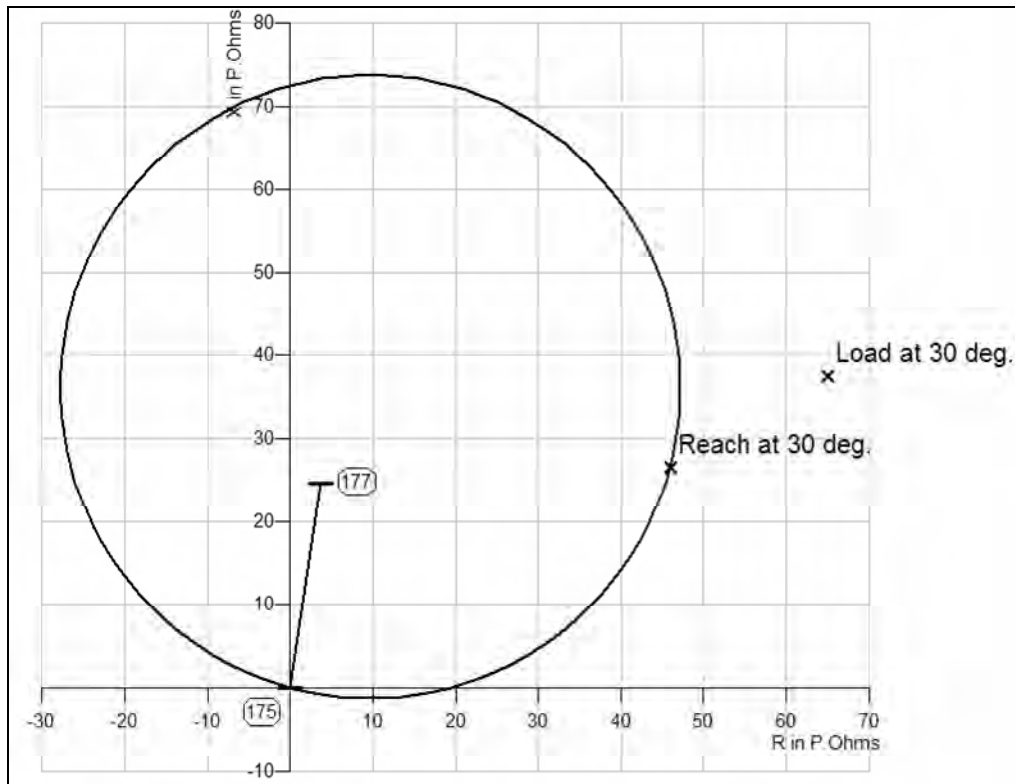


Figure 4: The reach of the relay element at 30° and the load on the relay branch at 30° are shown. The real-time analysis function compares these two numbers and flags a violation if the reach is within a user-specified margin of the actual load at the actual power factor angle.

The analysis function compares the reach of the relay element at the actual power-factor angle with the load impedance at that same angle. If the reach is within a user-specified margin, a violation will be reported.

C. Other Data Considerations

It was stated earlier that all the information needed for the real-time analysis is either present in the integrated database used by the protection simulation tool, or is computed as needed. It should be pointed out that this integrated database is a real database with conventional data structures, tables and fields. The database uses the open-source Interbase database structure. As can be imagined, accessing the data from the database is a time consuming process.

Both the SCADA and the state estimator systems write new measurement data files every 2 minutes. If the real-time analysis tool were to access the database to gather the data required for the analysis, it would have been impossible to finish analyzing a new input file every 2 minutes. So, we used a separate program to create what is called the “mini-database” file. This file is a text file, which contains data extracted from the main database – and more importantly, *only* data that is needed by the real-time analysis function. Accessing the mini-database text file is extremely fast, and allows the 2-minute turnaround time to be satisfied easily.

The structure of the mini-database file is as follows:

```

Line,      3,      493,      1,161.0,2000.0,2000.0
Relay,    8226,"854 C33-McCracken 161kv","ShFP 8521AZ1","KD-10#719B195A13", 4000.00
Relay,    8228,"854 C33-McCracken 161kv","ShFP 8521AZ2","KD-10#719B195A13", 4000.00
Relay,    8229,"854 C33-McCracken 161kv","ShFP 8521AZ3","KD-11#719B196A09", 2800.00
Relay,    8230,"854 C33-McCracken 161kv","ShFP 8521BZ2","KD-10#719B195A13", 2000.00
Relay,    8231,"854 C33-McCracken 161kv","ShFP 8521BZ3","KD-11#719B196A09", 3200.00
CT,      2256,"pcb 854"," ", "2000/5amr", 2000.00
DIST,    8226," ", "1","1"
-60,0.0
-55,0.0
-50,0.0
-45,0.0
-40,0.0
-35,0.0
-30,0.0
-25,0.0
-20,0.0
-15,0.0
-10,0.3
-5,0.6
.
.
.
x

```

The data corresponding to a given branch is identified by the keyword “Line”. Next to this keyword are printed out:

1. From-bus number: 3 in this example
2. To-bus number: 493 in this example
3. Circuit number: 1 in this example.
4. Base kV of the from bus: 161kV in this example.
5. Worst case (smallest) continuous relay rating among all relays applied on this line: 2000A in this example.
6. Worst case (smallest) continuous CT rating among all CTs applied on this line: 2000A in this example.

The keyword “Relay” identifies the relays that are applied on this line, and the continuous current rating of each one of them.

The keyword “CT” identifies all the CTs that are applied on this line, and their continuous current rating. In this example, there is only one CT.

Next, the keyword “DIST” identifies all distance elements that are applied on this line. For each distance element, the file stores a set of <angle, reach> points. These points denote the reach of the distance element in primary ohms at the given angle. In the example above, we see that at an angle of -60° , the reach is 0Ω . At -5° , the reach is 0.6Ω and so on. The list of points is terminated by the character “x”. The reach is stored in two angular ranges – between -60° and $+60^\circ$, and between 120° and 240° . A step-size of 5° is used.

The actual power factor angle, as recorded by the SCADA or state estimator is expected to lie in one of these two ranges. The reach of the relay at the actual power factor angle is obtained by interpolating between two of the nearest stored points.

Additional relay data is stored in a similar fashion.

IV. Starting the Real-Time Analysis and Display of Violations

The real-time analysis function is implemented as a special process that is started automatically by the operating system of the computer on which the analysis tool is to be run. It can also be run manually as a program, which would require the user to specify certain input parameters. Figure 5 shows the initialization screen that a user would see if the program were started manually.

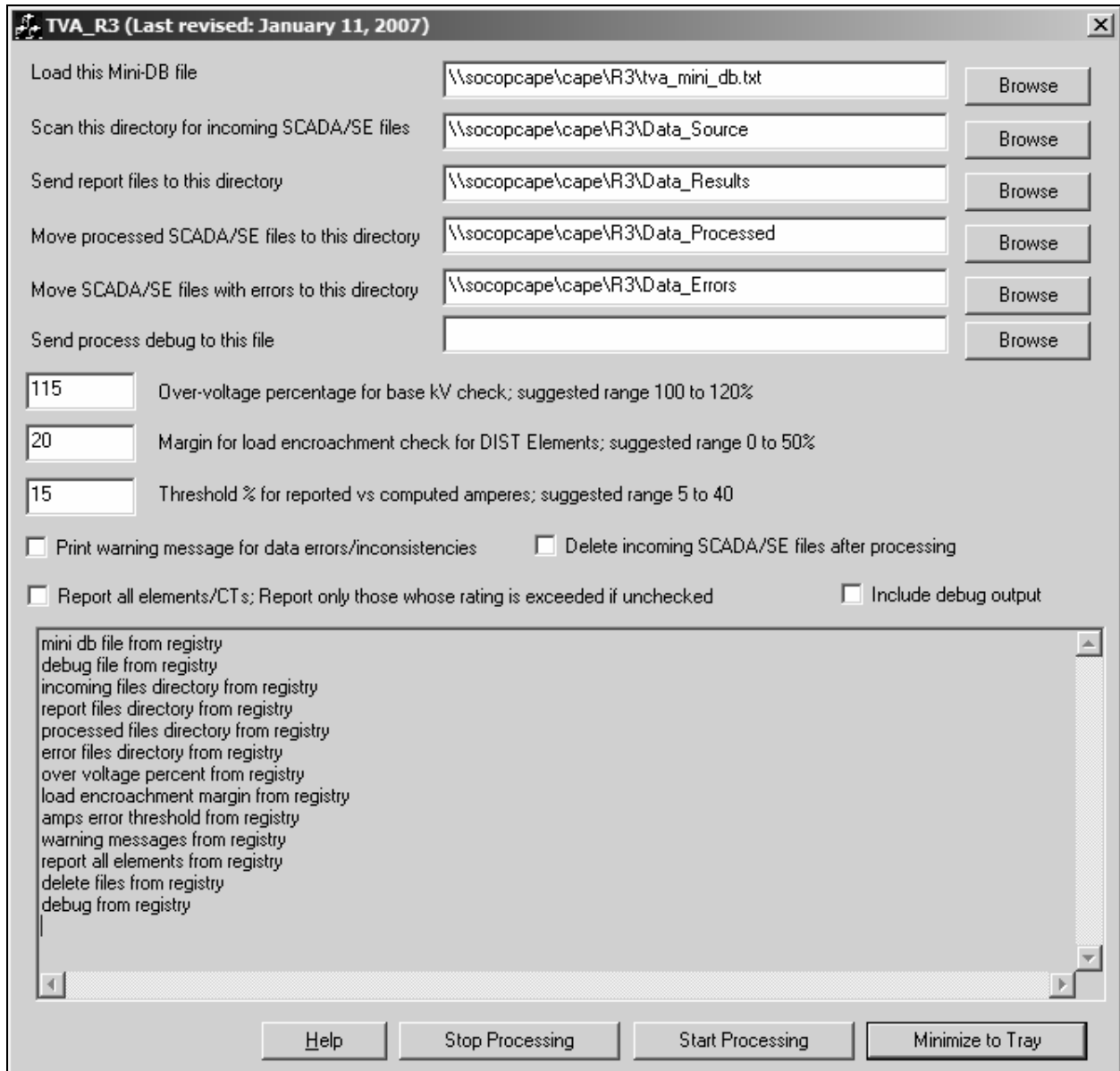


Figure 5: Setting up the Real-Time Analysis Function.

Each of the parameters above is explained in Table 1.

Table 1: Initializing the Real-Time Analysis Function.

Load this Mini-DB file	File that is the mini-database for the analysis. This file must have been created beforehand by the user. Network path names are allowed. For example: \\socopcape\cape\R3\TVA_Mini_DB.txt.
Scan this directory for incoming SCADA/SE files	Directory in which files from the SCADA/SE process are stored. For example: \\socopcape\cape\R3\Data_Source.

Send report files to this directory	Directory in which the files resulting from the R3 analysis are stored. For example: \\socopcape\cape\R3\Data_Results.
Move processed SCADA/SE files to this directory	Directory in which the processed SCADA/SE files are stored. For example: \\socopcape\cape\R3\Data_Processed. Files from the incoming directory are moved to this directory.
Move SCADA/SE files with errors to this directory.	If an input file has errors (corrupt file or data not in the proper format), they will be moved to this directory. For example: \\socopcape\cape\R3\Data_Errors.
Overvoltage percentage for base kV check	Range is from 100 to 120% of the base kV of the from-bus of the branch being studied. If the actual kV exceeds the base kV by the specified percentage, the analysis program will flag it in the output file.
Margin for load encroachment for DIST elements	Range is from 0 to 50%. The ohmic value of the load at the actual load angle is computed as Z_{LOAD} . The reach of the distance element under study is computed at the same angle as Z_{DIST} . If $(Z_{LOAD} - Z_{DIST})/Z_{DIST} \times 100$ is less than the specified percentage, the analysis program will flag it in the output file.
Threshold % for reported vs. computed amperes	Data check threshold. The load current in amperes, as recorded by SCADA or SE is compared against the current computed separately from the recorded MW, MVAR and kV. If these currents are different from each other by more than the specified percentage, the R3 process will flag it as a data inconsistency (if the following option is checked).
Print warning messages for data errors/inconsistencies?	Cases where the computed amperes differs from the recorded amperes by more than a specified percentage will be flagged in the output file if this option is checked.
Delete incoming SCADA/SE files after processing?	If checked, input files (generated by the SCADA and SE processes) will be deleted, instead of being moved to the "Processed" directory.
Report all elements/CTs	If checked, all the studied elements, CTs and relays will be reported. If not, only those that fail the various checks will be reported in the output file.

Next, the user clicks "Start Processing" to put the program in the monitoring and analysis mode. In this mode, the program continuously looks for input data files in the specified directory. As files become available, they are analyzed, and violations if any are recorded in a special output file. The processed input files are then deleted or moved to another directory. A functional diagram of the analysis is shown in Figure 6.

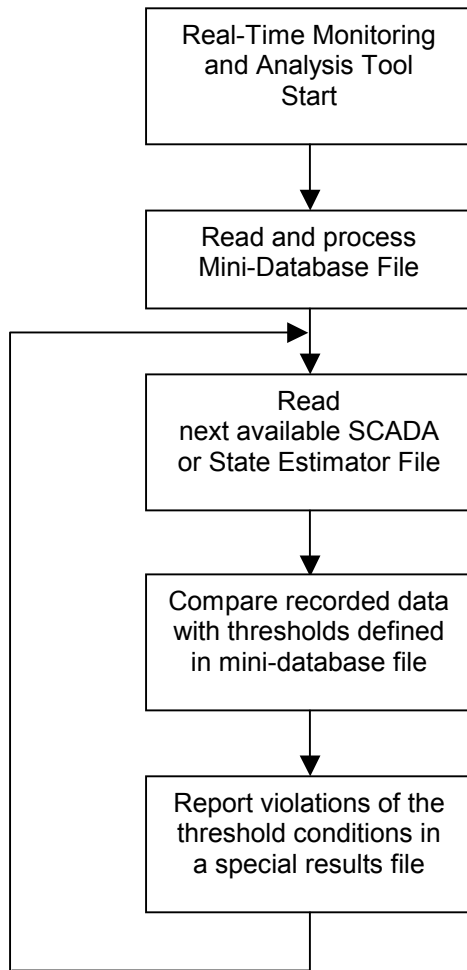


Figure 6: Flow-Chart of the Real-Time Analysis Tool.

Separate result files containing threshold violation information are written for the SCADA and state estimator files.

We will now take a look at how the violations are reported. The analysis tool writes information about the threshold violations into a text file. A separate web application reads the text file and displays the results in an Internet browser (like Mozilla Firefox or Microsoft Internet Explorer). The text file output is discussed first.

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 PERCENT CT RATING ? LOADING
-----
260 pcb_948 line 3000/5amr 2000.00 NO 46.03
-----

```

The output above 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. Please note that this is not a violation of the threshold.

C. Relay Continuous Current Rating 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 PERCENT RELAY RATING ? 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 Load Encroachment Report

FROM BUS NAME	NUMBER	TO BUS NAME	NUMBER	CKT	AMPERES	MW	MVA _r	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	IN	OHMS	DIST REACH	MARGIN RATIO	MARGIN VIOLATED?	
948 Lost City	Para 9421	3464	3	1	105.62	24.06	4.39	NO		

The output above shows an example of how the relay reach violation might be reported, if there was one. The MW and MVA_r 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 Figure 5 was 20%).

E. Web Interface for Displaying the Results

A web interface for accessing the results of the analysis is available on the TVA intranet. Sample outputs from this interface are shown in Figure 7 and Figure 8. It should be pointed out that the threshold violations seen in these figures were created by artificially reducing the CT ratios of some of the CTs in the TVA system or by increasing the distance element reaches.

The “Status” area of the relay monitor (upper left) shows the time at which the most recent SCADA and State-Estimator output files were recorded and analyzed. The State Estimator files are identified by the acronyms RTNET (ReaT-Time Network Analysis) and RTCA (ReaT-Time Contingency Analysis).

The “Violation Status” area shows the number of violations in the most recently recorded set of data. Five violations are seen in the SCADA output, three in the RTNET (State-Estimator) output.

The “Health” area of the relay monitor displays the time it takes for one complete cycle of the monitor – writing of SCADA or state estimator data, processing of the data by the analysis tool followed by the result display. In the example below, the most recent cycle took 2 minutes to complete. Cycle times larger than 5 minutes will be shown in a different color and the user will be warned.

The “Selection” area of the relay monitor allows the user to selectively display results from SCADA, RTNET and RTCA analyses.

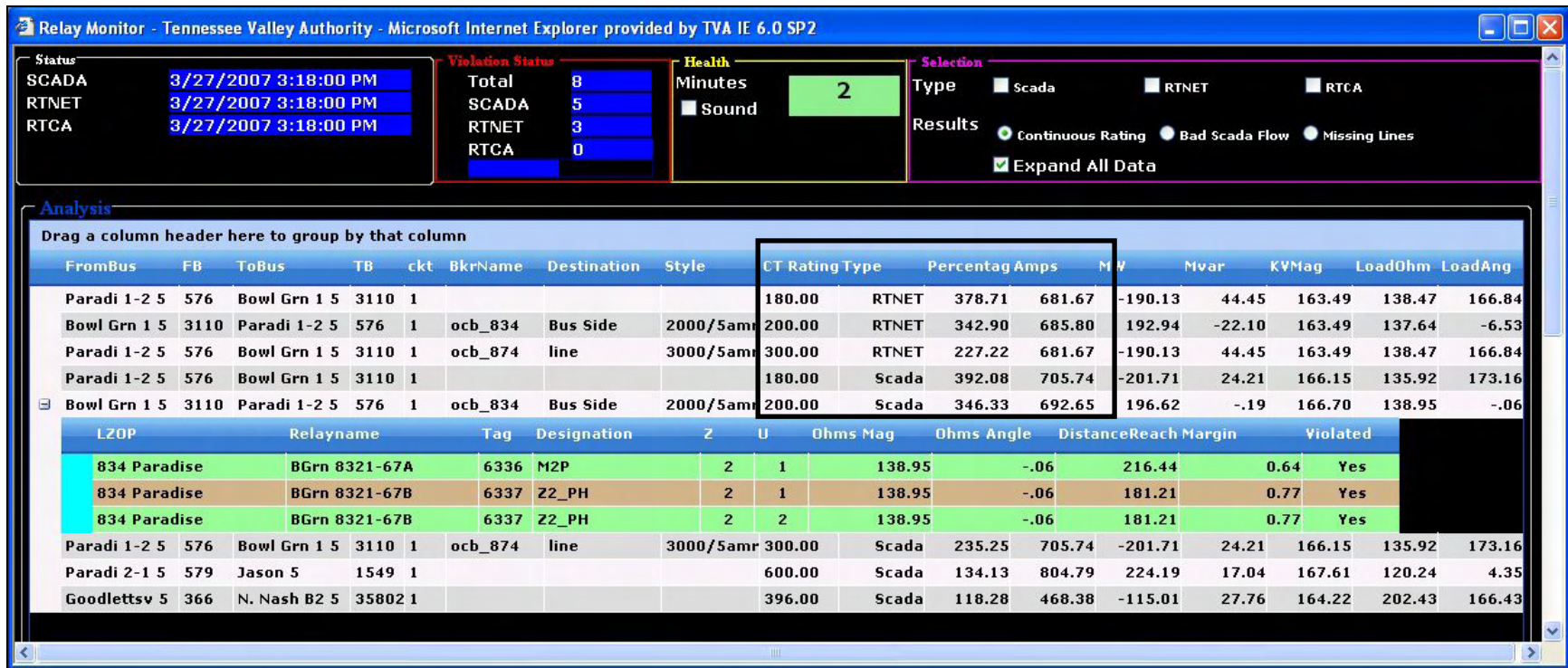


Figure 7: Monitoring the SCADA and State Estimator Outputs in Near Real-Time.

The “Results” radio-buttons allow the user to switch the display between

- (a) Violations to the 4 threshold conditions.
- (b) Bad Scada Flows – Inconsistencies in the recorded data.
- (c) Missing Lines – a branch is available in the SCADA output, but there is no record of it in the mini-database file.

Finally, the results of the analysis are printed out. In the example above, CT rating violations and relay reach violations are seen. Notice that the “Type” column shows three RTNET violations and five SCADA violations. On one of the lines, we see three relay reach violations also.

The “CT Rating” column shows the ratings of the CTs in primary amperes. The “Amps” column shows the actual amperes measured on the line on which the CT is applied. The “Percentage” column shows the ratio of measured amperes to the CT rating, expressed as a percentage.

Bowl Grn 1 5 3110 Paradi 1-2 5 576 1 ocb_834 Bus Side 2000/5amr 200.00 Scada 346.33 692.65 196.62 -.19 166.70 13												
LZDP	Relayname	Tag	Designation	Z	U	Ohms Mag	Ohms Angle	DistanceReach	Margin	Violated		
834 Paradise	BGrn 8321-67A	6336	M2P	2	1	138.95	-.06	216.44	0.64	Yes		
834 Paradise	BGrn 8321-67B	6337	Z2_PH	2	1	138.95	-.06	181.21	0.77	Yes		
834 Paradise	BGrn 8321-67B	6337	Z2_PH	2	2	138.95	-.06	181.21	0.77	Yes		

Figure 8: Relay Reach Violations.

In Figure 8 the relay reach violations are shown in more detail. The column labeled “Ohms Mag” is the ohmic value of the measured amperes. The column labeled “Ohms Angle” is the angle of the ohmic value of the measured amperes. It can be seen that the ohmic value of the load current is 0.64 times the “Distance Reach” for the distance element “M2P”. This means that the relay could have operated and isolated the line end, unless prevented from doing so by a load encroachment element.

V. Conclusions

In this paper, we have described an analysis function that compares the data recorded by the SCADA and State Estimator systems with data contained and computed within a protection system simulation environment. This comparison is performed in near real-time. It generates warnings under the following conditions:

1. If the actual bus voltage exceeds the base voltage of a bus by a user-specified amount.
2. If the actual line current exceeds the continuous current rating of CTs applied on the line.
3. If the actual line current exceeds the continuous current rating of relays applied on the line.
4. If 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 CTs and relays 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 to take remedial action like re-routing the load on other lightly loaded lines.

At present, this analysis is being performed on a “development server” and has not been deployed in a production environment. TVA will do so in the next few months.

In the three months or so that this tool has been running, it has not detected any major problems with either the SCADA data or with the state-estimator data. Under normal loading conditions, this is perhaps to be expected. The threshold violations seen in Figures 7 and 8 are due to an artificial reduction in CT ratios and distance element reaches on the TVA system.

The analysis of network contingencies using the state estimator model of the TVA network is an important part of this project. However, in analyzing the branch output with the real-time tool, we were restricted to using the base kV of the from-bus, and an angle of 30° for the power factor angle on the branch. This is because the state-estimator program, when running branch contingency analyses, does not provide the actual kV at the bus, nor does it provide the real and reactive power on the branch. Only the current in amperes and the branch MVA are available.

However, we believe that the tool is a useful one. As TVA gains experience with this tool, we expect to see real benefits in terms of “better” relay settings and newer protective equipment, which in turn implies a more reliable power system.

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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 Power 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

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S. Lee Goudelock is a Project Specialist in System Protection & Analysis for the Tennessee Valley Authority (TVA) in Chattanooga, TN. His responsibilities include: protective relay setpoint calculations for generation and transmission assets, relaying scheme scoping, field support, and oversight of CAPE projects. Previously he worked as an engineer with the R&D Department of Howard Industries, Inc., and with Westinghouse Savannah River Company - DWPF Technical. Lee earned the B.S.M.E from Mississippi State University in 1986 and the M.S.E.E. from Mississippi State University in 1993. He is a member of the IEEE Power Engineering Society and is a registered professional engineer in the state of Tennessee.

Harsha G. Sathyanarayana is a Software Analyst working with TVA's Transmission and Reliability Organization (TRO) since October 2003. He is responsible for maintenance and development of information models across TVA systems, which includes SCADA, Planning, Relaying, Asset Management (EMPAC), Advance Network Model (ANA), System Data Exchange (SDX), and Powerworld. At TVA, he has been responsible for development of applications which ensure flow of data across the system, including line rating, real time flow, and analysis from AREVA to monitor Reliability data, including protective equipment reliability.

Harsha earned his Masters degree in Computer Application from Bangalore University, Karnataka, India in 1999.

Tanya Mathur is a Senior Electrical Engineer working in Advanced Power Applications for the Tennessee Valley Authority (TVA, www.tva.gov) in Chattanooga, Tennessee. She is responsible for the development and maintenance of the state estimator and contingency analysis tools used by TVA to improve reliability. Her current research is in implementing Phasor Measurement Units (PMUs) into a real-time state estimator environment as a means to improve accuracy, robustness, and observability of the system. She earned a B.S.E.E. from the University of Tennessee at Chattanooga in 2002 and is a member of SWE and IEEE.

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 are 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.

Jeff Quada has been with Electrocon, and its predecessors, since 1975. In the early years, he developed energy control center applications for network topology, state estimation, power flow and contingency analysis. He subsequently turned his attention to the user interface and solution algorithms for Electrocon's CAPE product. He graduated from the University of Michigan with a BSEE and MSEE in 1974-75.