The Six Ways to Ensure Improper Operation of Microprocessor Relays

Kevin Donahoe (GE Grid Solutions)

***Abstract*—At the 44th Annual Conference for Protective Relay Engineers in 1991, Walt Elmore presented the paper "Ways to Assure the Improper Operation of Transformer Differential Relays." This paper applies the same approach to microprocessor relays. Relay designers work very hard to develop microprocessor relays that will be secure and dependable. However, a considerable amount of background and experience is required to apply them correctly. There is a limited number of correct ways to connect and apply a microprocessor relay and literally hundreds of ways to connect them improperly. Wrong connections or applications generally manifest themselves in an undesired trip or failure to trip. Often, unfortunately, this doesn't happen on first energization but rather during a fault when proper operation is most needed or during load periods when false operations are to be avoided. The six ways to ensure improper operation of microprocessor relays are presented with examples of each. The six ways are:**

1. **Fail to consider how the relay is set.**
2. **Fail to consider how the relay acts.**
3. **Fail to consider how the relay measures the power system.**
4. **Fail to consider how the relay operates the control system.**
5. **Fail to consider how the power system acts.**
6. **Fail to consider how the power system is operated.**

Applications of the Six Ways to design, testing and troubleshooting are discussed.

***Index Terms*—Power system protection, substation protection.**

I. Introduction

At the 44th Annual Conference for Protective Relay Engineers in 1991, Walt Elmore presented the paper "Ways to Assure the Improper Operation of Transformer Differential Relays."[1] The paper was a unique way of presenting lessons that were learned during the many instances of applying transformer relaying. This paper uses the same approach to microprocessor relays, not just transformer relays. The fundamental ways to ensure improper operation are presented along with examples. Since it is still applicable, the following presents the introduction from Walt's paper but applied to microprocessor relays.

Relay designers work very hard to develop microprocessor relays that will be secure and dependable. However, a considerable amount of background and experience is required to apply them correctly. There are a limited number of correct ways to connect and apply a microprocessor relay and literally hundreds of ways to connect them improperly. Wrong connections or applications generally manifest themselves in an undesired trip or failure to trip. Often, unfortunately, this doesn't happen on first energization but rather during a fault when proper operation is most needed or during load periods when false operations are to be avoided.

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II. Ways to Ensure Improper Operation

When it came to adapting the concept of Walt Elmore's paper to microprocessor relays, I started to consider the improper operations I have observed. I've devised a way of organizing them that reflected the approach I had seen over the years used to troubleshoot misoperations.

The first step is explaining what is meant by improper operation in the context of this paper. Whenever there are events with negative consequences where a relay could have done something different which would have avoided or limited the negative consequences, this is being referred to as an improper operation. The operation does not have to take place on a live power system, though those tend to have more negative consequences.

It starts with recognizing that when applying a microprocessor relay, it is easy to focus on the immediate connections to the device. However, ignoring the different ways the relay interacts will ensure its misoperation. Fig. 1 presents how the relay interacts and the different levels of relay interaction.

A. How the Relay Interacts

No matter the complexity of the device, the protective relay interacts in basically two ways:

1) The Relay Takes Actions
2) Based on Received Data

1) Relay Actions

An obvious relay action is to trip however to avoid an improper operation this action needs to be defined. When a microprocessor relay trips is it closing a contact, operating a solid state output or sending a message?

Another important relay action is the transmission of data, whether it is to other local devices or to a remote site. This data could be reporting analog values it is measuring or equipment status it is monitoring. This data could also be sent to other relays that will be used for protective action related decisions.

Note also, that when the relay decides that system conditions warrant no operation that is also an action.

What is crucial to consider is that the consequences of a relay's actions extend beyond the circuit it is connected to and beyond the location where the relay is installed. The relay interacts far beyond its immediate connections.

2) Received Data

Data received by the relay includes the voltage and current measurements of the connected analog circuits, whether the analog to digital conversion is done at the relay or performed

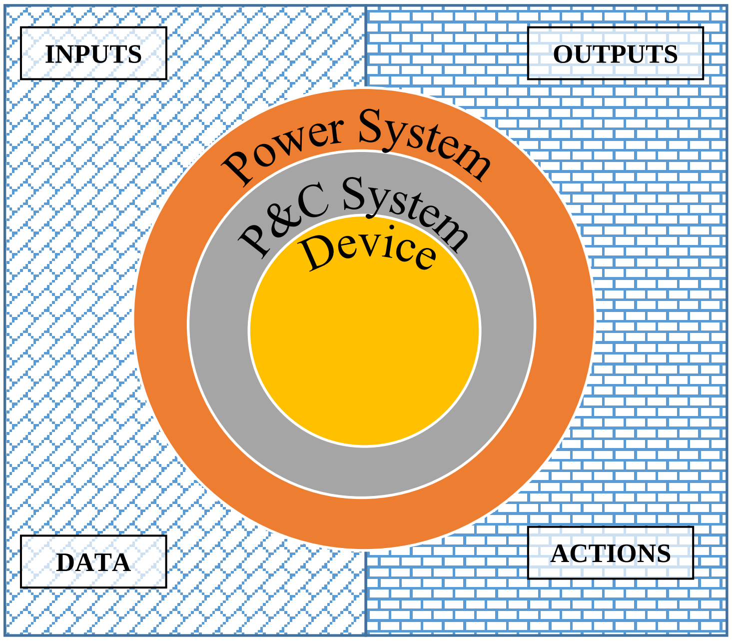

Figure 1 Relay Interactions

at a merging unit and the analog values communicated to the relay. Consider, though, that these analog values affect the relay actions beyond how the coulombs and electromotive force are measured by the relay. The source of the amps and volts has just as important a role. The input from voltage and current transformers is dependent on configuration (delta vs. wye), ratio, saturation conditions and how it is installed.

But it even goes beyond that. Assumptions about how the power system acts have an enormous effect on how a relay will operate in a given scenario. This is reflected in the models used for fault studies but also in other ways. For example, power system are not only expected to deliver a certain amount of fault current but also particular levels of positive, negative and zero sequence currents. The power system is also assumed to contain a certain amount of harmonics and operate at a certain level of stability. If these aspects of the power system are not adequately considered then the relay may not act properly when needed.

But if we are looking at what the relay needs in order to take action then received data includes more than just the analog information. It also includes the digital inputs connected to the control system through which the relay gathers status information. This would include data received through messages.

Furthermore, consider that the relay receives data even before it is put into service. The programming or setting of the relay defines how it will act given the data measured and received.

But the terms "data" and "actions", while helpful in visualizing how a relay interacts, ignore an important consideration. When evaluating whether a relay has misoperated you may need to look at the relay interactions beyond its immediate connections. When looked at this way, the terms "inputs" and "outputs" are more comprehensive and are included in Figure 1.

B. Levels of Interactions

When you consider all relay interactions, they can be organized into three levels.

1) Device Level Interactions

This level addresses how the device interacts directly with adjacent devices, in terms of both output and input. This would include the relay ratings and the ability of a relay to communicate. Since the relay setting defines what the relay will do with the device inputs and outputs, this is considered a device level interaction. By necessity, it includes the ratings and abilities of the adjacent devices. Failing to consider how a relay interacts at the device level may lead to an improper operation.

2) P&C System Level Interactions

An improper operation can occur even when the relay successfully collects inputs and correctly actuates outputs. Sometimes misoperations are based on how the relay interacts with equipment or other systems at the same location.

3) Power System Level Interactions

Interactions between local power systems can also lead to misoperations. A power system interaction refers to how events on remote power system elements can affect a P&C system and in other situations how the actions of a P&C system can affect remote power system elements.

C. The Six Ways to Ensure Improper Operation

When the two ways that relays interact (inputs and outputs) are considered at each of the three levels we arrive at the six ways to ensure improper operation (Six Ways).

1) Fail to consider how the relay is set.
2) Fail to consider how the relay acts.
3) Fail to consider how the relay measures the power system.
4) Fail to consider how the relay operates the control system.
5) Fail to consider how the power system acts.
6) Fail to consider how the power system should be operated.

III. Examples of the Six Ways

A. Fail to Consider How the Relay is Set

At the device level, all relay actions are determined by how the relay is set. The relay is set considering how it will receive analog input and digital signals. These considerations include analog values within the rating of the relay's current and voltage inputs. The format of the digital signals needs to be considered, whether it is a voltage based input or data received through specific communication protocols. In addition, the inputs to a relay must be properly documented so those who must install and maintain the relay can do so reliably.

But the orchestration of these inputs is managed by the logic functions and equations programmed into the relay. How the relay is set for an intended operation must be fully considered.

For example, referring to the portion of a power system in Fig. 2, the connection between the transformer low side bushing and the main breaker is not in the transformer differential zone though it is protected by overcurrent functions. Shortly before putting the station into service, it is decided to add a fast trip overcurrent function to the 11T1 relay with a directional block coming from the 11M1 relay. The intent is to get a fast trip to limit exposure to arc flash but is blocked for faults past 52M1 so it still coordinates with the 34kV feeder protection.

The relay communication was installed, the fault detecting element was set up on 11T1 and the directional function looking in the correct direction was enabled. Yet when a fault occurred on the connection between the transformer and main breaker the fast trip did not occur. Upon review it was found

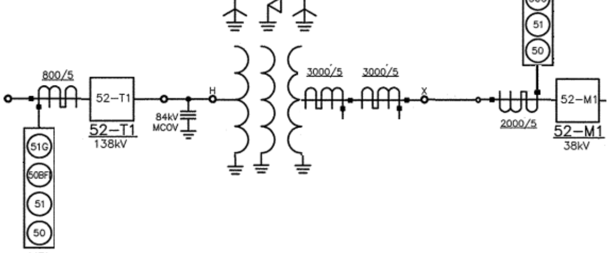

Figure 2 Blocking Scheme

that there is also a setting for the order in which directionality is determined which had been left off. With this setting the blocking signal would never be sent.

Though the relay measured the current properly and was able to communicate properly, the failure to fully consider how the relay was set led to an improper operation.

B. Fail to Consider How the Relay Acts

At the device level, the only way a fault can be cleared is if the relay successfully acts to operate equipment sufficient to isolate the fault. These actions rely on adequately rated outputs that initiate the fault clearing. Alternatively, the actions might rely on properly formatted messages to other devices. Regardless of how it is done, the devices that the relay acts upon must be able to work with these actions. Device ratings or communication protocols have to be known to ensure proper operation.

In addition, these outputs of the device need to be documented and clearly and completely communicated in order that those who must install and maintain the relay can fully consider how the relay acts.

For example, during routine testing of a line protection package, the line was taken out of service. Since it was on a ring bus, the line was isolated with the line disconnect and the ring restored with the line breakers. With schematics in hand, all line relay output test switches were opened and testing commenced. On the first relay operation, breaker failure was initiated and three breakers on the ring bus opened. Though the breaker failure initiation and its test switches were shown on the schematic, it was located on the drawing away from all the other outputs and was overlooked.

Though the relay was able to be isolated and was able to operate correctly, the failure to fully consider how the relay acted led to an improper operation.

C. Fail to Consider How the Relay Measures the Power System

At the P&C system level, the inputs to the relay must be able to accurately reflect what is happening on the power system. The digital input from the status of local equipment must match what the relay is expecting. Getting the analog inputs is more complicated and therefore requires significant consideration. The ratio of the CTs and VTs are crucial to the proper operation of the relay along with the capabilities of the transformers to reliably reflect the primary values. Saturation of these transformers can result in bad data getting to the relays. Even something as fundamental as the polarity of the analog inputs must be fully considered in order to understand how the relay measures the power system.

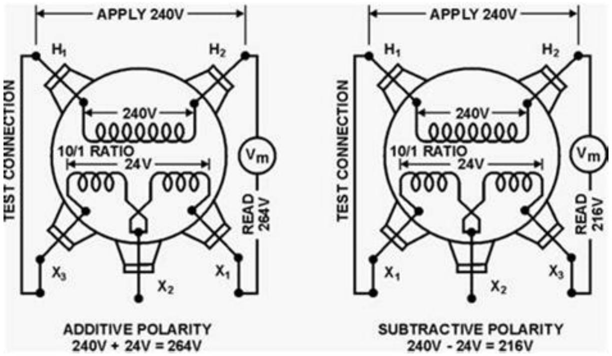

Figure 3 Voltage Transformer Polarity

For example, the installation of an anti-motoring function was scheduled for the outage of a generator with a long history of service. Installation was completed and confirmed to the design. Power system conditions led to a decision to end the outage early. The function was energized without in-service checks. As soon as power was generated the anti-motoring function operated.

Current transformer polarity was the first suspect but after investigation it was found that it was in fact the voltage transformers (VTs) polarity that was misidentified in the design and not confirmed during testing. The assumption was that the VTs were subtractive polarity when they were actually additive (refer to Fig. 3) [2]. With the voltage polarity opposite of expectations, the function operated on generation instead of motoring.

Though the relay was installed per the design, failure to consider how the relay measured the power system ensured an improper operation.

D. Fail to Consider How the Relay Operates the Control System

At the P&C system level, interactions between a relay and other relays and systems can be easier to overlook because they are so numerous and not obvious. If relay operations aren't time coordinated, this will ensure an improper operation. But P&C system interactions are both operational and physical. Ensuring the physical separation between critical systems is a physical interaction between relays on the P&C system. Simply having access to the relays in a proper environment (e.g. HVAC, lighting, etc) is an interaction between the P&C system and the objects around it. An additional form of P&C system interaction is in communications. Whether it is by propagating frequencies or employing protocols, how relays communicate to other relays and other P&C systems must be fully considered.

For example, an IEC61850 substation network was designed and built to maximize redundancy, refer to Fig 4. The intent was for any switch or path failure that all data would throw over to the alternate path/switch and on return of the path/switch, the default data flow would be restored. A conformance limit for protection data convergence was set at 100ms. Note that during convergence the data is black holed or lost. For the loss of TS-SW-A, a root switch, convergence was measured at 500msec. It was observed that 100msec may not have been realistic for the design so the conformance limit was going to be reevaluated. However, on return of TS-SW-A, convergence was measured at 3.5sec. There was no debate that this was unacceptable and the network had to be redesigned.

Even though all the devices worked as they should, failure to consider how the relay operates the control system led to an improper operation.

E. Fail to Consider How the Power System Acts

At the power system level, interactions between equipment determine how power flows affecting what is measured therefore affecting what the relay sees and what the relay acts upon. This interaction is usually modelled and, when necessary, modelled at both a steady state and a transient state. To address the changing state of the power system, it will be modelled under multiple contingencies to ensure proper operation under as many credible scenarios as possible. But the accuracy of the predictions is a function of the accuracy of the model. Sometimes changes to the power system are unknown or not expected and therefore the power system interactions are not fully considered.

For example, the transformer differential relay protecting the step-up transformer at a processing plant tripped when a nearby large unit transformer at a power plant was energized from the high side. The trip was due to sympathetic inrush current flowing through the step-up transformer. Refer to Fig 5.[3]

The relay was set to restrain operation if the 2nd harmonic differential current is 20% or more of the fundamental. The 20% setting was an effective past practice. The current that the relay operated on was captured in a fault record and the ratio

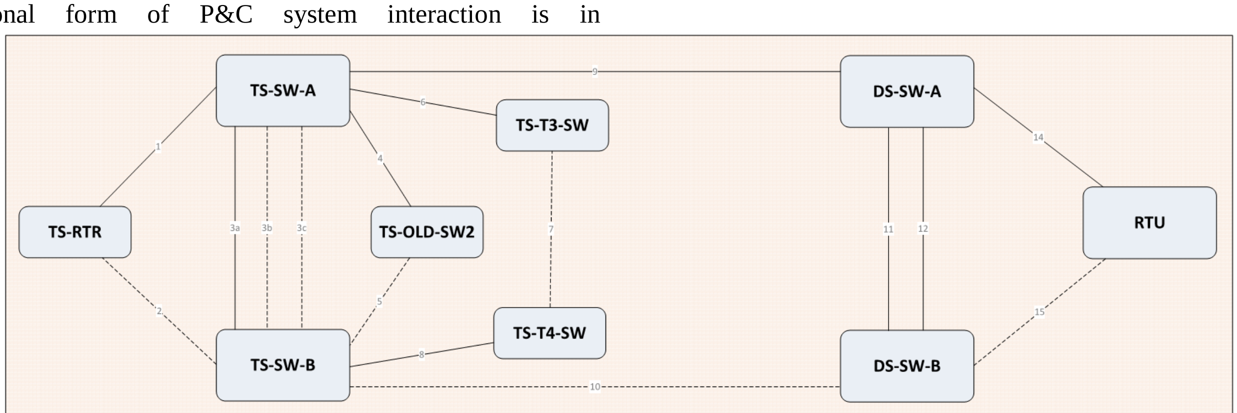

Figure 4 Substation Network

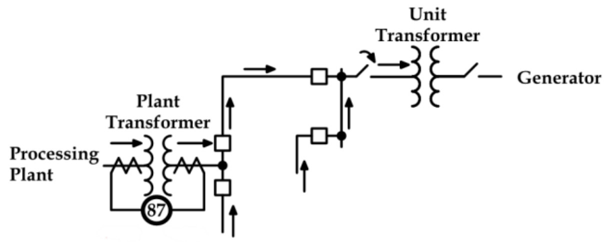

Figure 5 Transformer Livening

was measured at 13-17%. Transformer manufacturers have started making transformers that use less material and were designed with smaller tolerances. Therefore, modern laminated sheet core transformers will not reliably produce 20% 2nd harmonic current during inrush. The setting was revised.

Though the P&C systems at the processing and power plants were installed per legitimate past practices regarding what to expect from the power system, how the power system acted was not fully considered.

F. Fail to Consider How the Power System is Operated

At the power system level, coordination of the operation of power system equipment is a necessity. This includes isolating and restoring the system, aware of how all effected equipment will react to these system events. But it also refers to the rating of the individual pieces of power system equipment and how long they can bear fault currents. How a relay operates and its effect on the rest of the power system must be considered.

For example, wildlife contact on a 12kV feeder initiated a fault, unfortunately the feeder breaker failed to open. This required the fault to be cleared by overcurrent bus backup. This prolonged the fault and led to the burndown of several spans of conductor along a busy street at the height of rush hour at dusk. This type of burndown is very noticeable. Though the P&C system operated as designed, there were no injuries, and restoration was very quick, it was still considered an improper operation.

Investigation found that the conductors had annealed which reduces the conductors' strength and flexibility. It is likely that this was the state of the conductors before the fault. The overcurrent backup was designed to coordinate with the conductor melt curve and most of the conductor anneal curve. The only exposure to annealing was at the lower fault current levels which occur during high impedance faults or an extended fault operation when back up protection clears the fault. It was decided that though the scheme had operated effectively in the past and that burndowns were rare, the increase in load density increased the exposure to this type of misoperation and therefore the overcurrent backup would be changed to operate quicker.

In spite of the fact that the relay operated per design and the material costs of event were limited, the fact that the power system had changed (increased load density, increased consequences from burndowns) had not been considered fully. This resulted in an improper operation due to how the power system operated.

IV. Application of the Six Ways

There are three times when consideration of the Six Ways will be beneficial.

1) Design of the P&C System
2) Testing of the P&C System
3) Troubleshooting the P&C System

A. Design of the P&C System

The design of a dependable and secure P&C system requires a significant knowledge base that can address all three levels of protective relay interaction. It might be easier to find device experts but finding expertise in the interactions within a P&C system and its interactions with the power system can be challenging.

Processes can be put in place to enable a successful design. The use of standards can leverage expertise though there are often assumptions built into standards that need to be documented, communicated and reviewed periodically. The use of subject matter expert reviews is another way to leverage expertise.

The most effective way to make sure all levels of interaction are addressed is to plan out where the expertise will come from and when it will be applied at the beginning of a project.

B. Testing of the P&C System

The Six Ways lay out a broad approach to testing a P&C system. The IEEE PSRC paper "Commissioning Testing of Protection Systems" mirrors the levels of interactions within its eight core elements of commissioning testing when it lists the following three elements in this order:

- Equipment and device acceptance testing (device level).
- Functional testing (P&C system level)
- Operational (or in-service load) checks (power system level). In reality, it is for the most part impossible to "test" how the relay interacts with the power system. In-service checks observe this interaction but in the system normal state. It is beneficial to regularly review even correct operations (including non-operations) following system events to check that the interactions are acceptable.

C. Troubleshooting the P&C System

The different levels of interaction also reflect the likelihood of where to look for the cause of an improper relay operation. They also reflect the ease in confirming the cause.

Device level interactions are more likely to cause an improper operation because of the number of devices, the number of settings and the complexity of settings because all of these contribute to the number of opportunities for failure. Add to these opportunities for failure those of a physical nature, including device failures and inadequate connections. Note though that once a device level failure is identified, it is easier to confirm and address due to its limited scope.

P&C system level interactions are the next most common cause of misoperation. These are less common because these are so well addressed by the use of standards. That's why they need to be reviewed when new devices or new equipment are implemented.

Power system level interactions are the least common and are a challenge to identify. The most definitive approach to identifying the cause of an improper operation at this level is through analysis of fault records. It can sometimes be difficult to reliably confirm the solution for an improper operation due to a power system interaction because it is usually undesirable to recreate the initial power system scenario.

The reality of the situation that requires troubleshooting is that there is an urgent need to identify the cause so it is unlikely that one can start at the device level and work up the levels. Rather, all levels should be considered initially and a few likely causes, possibly at different levels of interaction, investigated.

V. Conclusion

Six ways to ensure the improper operation of microprocessor relays were identified:

1) Fail to consider how the relay is set.
2) Fail to consider how the relay acts.
3) Fail to consider how the relay measures the power system.
4) Fail to consider how the relay operates the control system.
5) Fail to consider how the power system acts.
6) Fail to consider how the power system is operated.

It should be noted that once you go beyond the device level, many of the same interactions that cause an improper operation of a microprocessor relay can affect any relay. Therefore, the Six Ways encompass the two ways all relays interact at three levels. Illustrations of the Six Ways were provided. How the Six Ways could be applied to design, testing and troubleshooting were described. The Six Ways provide a base for approaching analysis of protection and control systems.

VI. References

[1] W.A. Elmore, "Ways to Assure Improper Operation of Transformer Differential Relays," presented at *44th Texas A&M Relay Conference,* College Station, TX, April 15, 1991.

[2] Image from "Understanding Transformer Polarity," Sept. 23, 2011. [Online]. Available: http://electrical-engineering-portal.com/understanding-transformer-polarity.

[3] S. Turner, "Catastrophic relay misoperations and successful relay operation," 2017 70th Annual Conference for Protective Relay Engineers (CPRE), College Station, TX, 2017, pp. 1-21.

[4] IEEE PES-PSRC, Working Group I-25, "Commissioning Testing of Protection Systems," May 10, 2017. [Online]. Available: http://www.pes-psrc.org/kb/published/reports/WG%20I-25%20Commissioning%20_Testing%20of%20Protection%20Systems%205-10-2017.pdf

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He started with Commonwealth Edison in 1981. From 1981 to 1983, he was an Engineer in the distribution engineering department. From 1983 to 1991 he installed, tested, maintained and troubleshot power equipment and protective relaying as a Principal Engineer. From 1991 to 2001, he worked in the System Protection and Control Department planning, specifying and setting protective relaying on the Commonwealth Edison T&D system, generating stations and customer systems. In 2001, he moved to General Electric in Oakbrook Terrace, IL where from 2001 to 2004 he was the Manager of Protection and Control where he led the team designing P&C systems for utility substation projects. Since 2004, he has been the Lead Protection Engineer acting as a technical lead for the team designing P&C systems for substation projects. Over his career, he has co-authored a number of works including the article "The True Vision of Automation" in the May/June 2007 issue of IEEE Power & Energy Magazine and conference papers including "Application of an Integrated Distance Relay to a Resistively Grounded 69kV Transmission System" at the American Power Conference, April 1994, Chicago, IL.

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