International Drive Distribution Loop Protection

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***Abstract*—Designed and installed in the late 1990s, the International Drive (I-Drive) system was one of the first examples of distribution designs that provide high reliability and availability for critical business customers.**

After years of successful operation, aging equipment and unintended consequences of maintenance updates contributed to a few misoperations and unwanted outages for these customers. This was the driving factor in taking a critical look at these systems to evaluate the current state and determine appropriate upgrades and operational changes.

This paper will cover the history and background of the I-Drive design, motivations for the modifications that have been implemented, and the events and their causes/solutions. It will also go into detail about how the special scheme works, and what work has been done to keep the I-Drive system as reliable as possible over that past twenty years.

***Index Terms*—Distribution, Distribution Automation, Event Analysis, Lessons Learned, Power, Power Distribution Faults, Protection and Control, Reliability, Smart Grid, Distribution Loop, Directionality**

I. Introduction

The I-Drive distribution grid is a unique design engineered to meet the high reliability requirements of customers along International Drive in Orlando, FL. After a string of misoperations, the current configuration was engineered and commissioned in 1999-2000 and is considered to be one of the most reliable and innovative distribution designs of its time.

This reliability is due to the fact that the system was designed to very quickly (sub 10 cycle) isolate faults on the underground cables. With a total of 85 relays and 33 switchgear, the system is divided into several zones of protection that can be removed from service with little to no impact on the rest of the system. This is achieved via a Directional Comparison Blocking/Permissive Overreaching Transfer Trip (DCB/POTT) scheme. Since each of the 85 relays is communicating with every adjacent relay, there are over 160 communication channels required to monitor the integrity of the 12.47kV cables and quickly isolate faulted sections.

Years after the 2000 era design and installation, faults on the system and subsequent root-cause analysis (RCA) reports indicated numerous problems due to equipment malfunctions or failures, and relay setting/wiring inconsistencies. The I-Drive system has since been upgraded and changed several times since its initial installation. While the core features (loops, DCB/POTT) have remained the same, the relays, settings, and communications have all been upgraded since 2000, and incremental improvements have been made several times since to fine-tune the operation of this critical distribution service area.

This paper is an update on the changes to the I-Drive system and does not go into full detail on the original system. For more information on that topic, please refer to International Drive Automation and Protection, by James R. Fairman, Karl Zimmerman, Jeff W. Gregory, and James K. Niemira [1] and Energizing International Drive, by Barry Pagel [2]

A. Abbreviations and Acronyms

I-Drive: International Drive
DCB: Directional Comparison Blocking
POTT: Permissive Overreaching Transfer Trip
SCADA: Supervisory Control and Data Acquisition

II. History

Pre-1999, before the loop system and communications backbone was put in place, a combination of two overhead and four underground lines were used to feed the growing and highly-critical electrical needs in the area. The feeders were radial, feeding fused loops between 33 pad-mounted switchgear units, each with multiple lines, to supply the near 100 pad-mounted transformers in the service area. In the year preceding the installation of the current I-Drive design (1998), the I-Drive area had 16 feeder-level outages. This was the latest in a trend of more frequent and severe service issues, and the decision was made to engineer a new scheme to solve the major issues and increase service reliability.

In 2000, the new design removed the overhead lines and added four more underground feeders, making a total of eight underground lines. These feeders were paired into four loops, with both ends of the respective loops terminating at the same substation.

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The relays on the feeder breakers and pad-mounted switchgear were upgraded to microprocessor directional overcurrent relays, and a communications system was set up using a multiplexed fiber optic network. This allowed each section of the I-Drive loops to be protected by a special POTT/DCB scheme, which will be explained in detail in section III.

There are two configurations of switchgear: 2 Way and 3 Way. The I/O for the two different configurations is quite different, and thus relays use separate logic.

The most common setup is a 2 Way scheme utilizing lines 1 and 3 for connection to adjacent switchgear, and lines 2 and 4 for load connections. The 3 Way scheme is utilized when a third feeder connects to an adjacent loop, with either the local or remote end opened. In this application, the line 1 and line 2 (as opposed to line 1 and line 3) are used in the typical method, while line 3 connects to the adjacent loop, which again is normally open either at the local or remote switchgear.

In 2008, in response to increasing reliability issues, relay settings work was completed to address automatic closing of the normally open tie between loops, as well as loss of source conditions that led to misoperations. When a fault occurred and the correct breaker opened, the original settings would view this as a loss of source condition and close the normally open tie onto the fault.

In 2012, it was decided that the original microprocessor relays had reached the end of their reliable life and required replacement. This relay upgrade project was done in two phases: Phase 1 saw the change from the original multiplexed communications scheme to a new one utilizing cutting-edge fiber multiplexing technology. Phase 2 was a complete replacement of all 85 microprocessor relays with new relays of the same model.

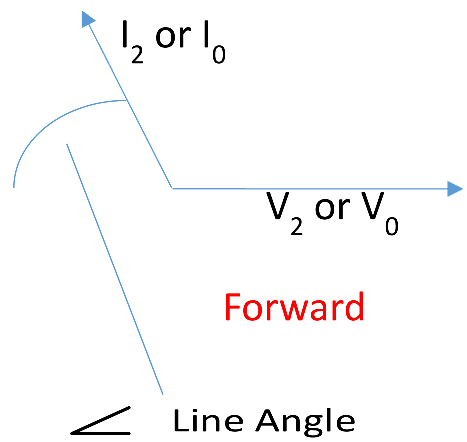
In 2016, after some communications inconsistencies where the relays were communicating with the incorrect remote relay, the settings were again upgraded to include much more robust communication alarming. This will be discussed further in the Analysis section.

III. Directionality

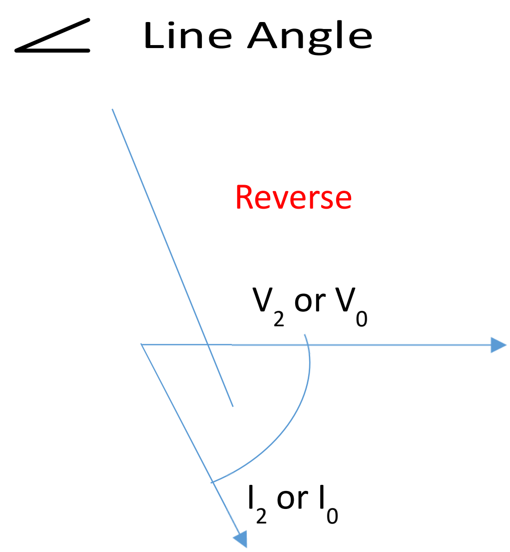
As previously stated, this system's protection uses a primary POTT scheme and a secondary DCB scheme. It is essential to have both schemes reliably trip for both looped and radial configurations of the feeders. As the devices involved do not have distance (21) functionality, torque-controlled overcurrent elements provide directionality.

The torque is made of directional negative-sequence and zero-sequence supervision; negative sequence directional elements get priority.

Both negative and zero sequence current have a predictable angle relationship between voltage and currents. For forward faults, the current is leading the voltage by 180 degrees minus source impedance angle.

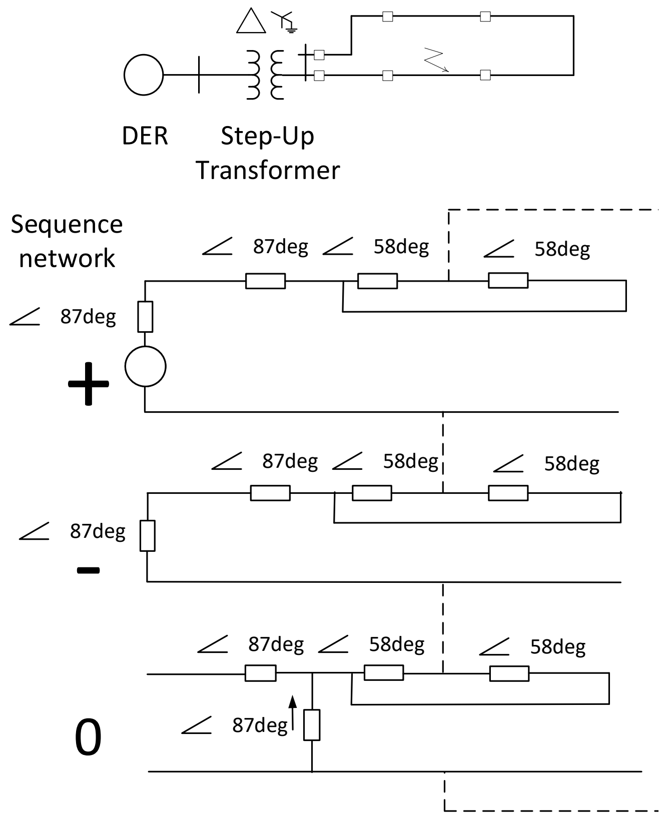


In the reverse direction, voltage is leading the current by the source impedance angle.



Relays leverage this relationship to determine the direction of the fault. For example, the real part of the vectors' cross product after rotation of the current phasors by the source impedance angle is used in the International drive loop relays. If the result is negative, the fault is in the forward direction, and if it is positive, the fault is in the reverse direction.

An important setting is the line angle, which is used in the directional logic as the source impedance angle when rotating the current phasors. Because the loops are underground cable, the reactance is smaller in relation to the resistance when compared to the source impedance at the distribution bus. The source impedance angle near the bus is almost 87 degrees while the impdance angle of the cable is 58.5 degrees.



Additional supervision is used to disable directional checks when the measured quantities are too small to be trusted.

Negative sequence directionality offers a few advantages. First, negative sequence elements are insensitive to zero-sequence mutual coupling. Second, if the zero-sequence impedance behind the device is small, as is the case when there is a zero-sequence "source" nearby, the negative-sequence voltage is higher than the zero-sequence voltage [3]. Both devices should register a forward fault for a fault between the two devices and send trip permissives in the POTT scheme. Neither device will register a reverse fault, so no block will be issued in the DCB scheme. If a branch in the feeder is removed, there will no longer be a source behind one of the devices. In this scenario, the device without a source behind it will likely not issue a trip permissive, but neither will it issue a block signal. The fault is still cleared. There is also an additional time inverse overcurrent element that will trip if neither the POTT nor DCB schemes operate.

If a fault occurs in one switchgear on the loop, the remote device will register it as a reverse fault, issuing a block signal. However, because each device in the system communicates with the device "2 buses away", in addition to the device remote from it, communications assisted tripping will occur using input from the device "2 buses away".

IV. Events

When a complication that could impact protection or reliability begins, an alarm is sent to SCADA so said complication can be taken care of before a future fault occurs. Some of these alarm systems include:

- Phase rotation inconsistencies: The relays report 3-phase MW and MVAR. The values are compared against the reported values from the remote terminal and should match.
- Loss of Voltage: The relays report a major error if the undervoltage element asserts. The undervoltage element is set to 80% of nominal voltage. There are undervoltage elements on each phase. This output is assigned to a programmed variable which is reported to SCADA.
- Battery issues: Loss of power will result in communication failure observed by a remote terminal relay.
- Communication Bit (Comm. Bit) inconsistencies: Substation feeder breaker relays use different communication bits from the switchgear relays for POTT/DCB communications. This has led to complications during expansion projects.
- Port Connection inconsistencies: The port on one relay must be confirmed to be wired to the correct port on the remote relay(s).

The above are all examples of events that have occurred over the 20+ year life of the I-Drive system and have provided valuable learning experiences. Some of the causes for these previous examples could have been monitored and corrected prior to the faults. Phase rotation issues can be ascertained by comparing the real power flows reported by the relays on each end of underground cable between switchgear.

V. Analysis

In 2016, a new project was started to correct some of the communication errors that had occurred in previous years, as well as to examine the relay setpoints to confirm their validity. The existing relay setting files for all eighty-five switchgear and feeder relays were compared and tabulated. The approach to validating relay settings primarily focused on the ability of the relays to operate as intended and designed and identify opportunities for improvement based on historical fault data collected. An examination of the results showed great consistency between the many relays and no major settings concerns.

A shortcoming discovered on the system was that all relays use communication bits for communications assisted trip schemes, and all port settings to transmit or receive were set to the same or similar values. Depending on mistakes in wiring or within the multiplexor, it was possible for one relay to communicate with another relay unintentionally, and this problem was dormant on the system for some time until it was discovered after a fault had caused a misoperation.

A method to avoid miscommunication and to verify *exactly* that Port A on relay B is communicating with Port C relay D is to transmit an address along with the protection-related communication bits. This address is unique to each port on each relay, and thus each relay can verify it is communicating with the correct port on the correct remote relay.

A new and improved addressing system was developed in order to update communications. Using all eight comm bits, each relay was assigned a unique binary address. The intent of the updated communication bit addressing system was to ensure that each relay is communicating with their adjacent relays as intended, and if there is an incorrect port connection or break in communication, that error would be detected and reported to SCADA. There are 3 important notes to make regarding this addressing system.

1. Using only a certain subset of the communication bits is insufficient for address assignment. For example, in loops 1-2, only bits 5-6 (Comm. Bit 5A, Comm. Bit 5B, Comm. Bit 6A, Comm. Bit 6B) are all set to 0 in every relay, and available for addressing. Thus, we must use the status of other bits that may be used for protection purposes. Under normal operation, the DCB blocking bit, the POTT keying bit, and the DTT transfer tripping bit will all be 0. We can use these bits and assign them a value of 0 in the remote relay.
2. Loops 1-2 and 3-4 are on different communication loops. So, an address used in Loop 1 may be duplicated in Loop 3, as cross-communication is not possible between these loop pairs.
3. Channel A and Channel B are local designations only. A relay using Communication Bit Channel A on one end may communicate with a relay set to Channel B on the remote end.

		Way	
		Existing	New
Port	Transmit	2,1	(1-4)
	Receive	1,2	(1-4)
Comm. Bit	Bit1	NA	0,1
	Bit2	NA	0,1
	Bit3	NA	0,1
	Bit4	NA	0,1
	Bit5	NA	0,1
	Bit6	NA	0,1
	Bit7	OC Elem.	OC Elem.
	Bit8	OC Elem.	OC Elem.
Alarm Variable		CH. FAIL	CH.FAIL*Bit1*Bit2*Bit3*Bit4*Bit5*Bit6*Bit7*Bit8

The alarm variable was modified to include Comm. Bits 1-8 received. All of the Remote Bits are AND'ed with the relays self-check alarm. Because of these setting changes, we can know with certainty that the relay is communicating with the correct remote relay and port.

Protection against malicious actors is something that should be considered as well. If one were to gain control over one of the devices on one of the loops, they could trip the device in an attempt to disrupt the system. However, because these feeders are looped, load would still be served.

The attacker could also trigger the device to send false trip permissives and blocks to adjacent relays. In this scenario, neither issuance would cause adjacent relays to trip without a fault present. A false permissive would result in "over-tripping" as the relay could trip for an out-of-section fault. A false block would cause a relay to restrain for an in-section fault, ultimately leading to delayed clearing of the fault or overtripping. This can be easily guarded against by monitoring these signals via SCADA. They should not be standing or frequently asserted, so system monitoring can flag unusual behavior.

Likewise, if an attacker were to decide to disable permissive and block issuing, the system would behave inversely. Relays would "over-trip" on the DCB scheme and fail to trip on the POTT scheme.

VI. Commissioning

The commissioning process for the updated communication settings was very involved. Relays had to first have the As-Found settings downloaded as a fallback reference. After this, the relay settings were upgraded in pairs and tested. Data was collected on all alarm statuses and phasors to confirm everything was functioning as intended. Finally, once all tests were completed and the new settings confirmed, the As-Left settings were downloaded and saved as the new record.

All of this was done while ensuring service continued to the area, and with the requirement that there could be zero alarms standing at the end of each day.

VII. Conclusion

The I-Drive system has been reliably serving customers for over twenty years. Throughout its life, it has seen multiple modifications and upgrades to maintain and improve this reliability. Events on the system provided valuable learning experiences that allowed the system to be made even more secure. The updated directional and communication systems continue to perform as intended, and have resolved the past inconsistencies that have caused misoperations.

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Mr. Billaut is an active contributor to IEEE PES PSRC, including the development of the P2800 performance standard on the interconnection of inverter-based resources, and with Commonwealth, he has applied for a US Patent on a method and apparatus for locating faults in an islanded microgrid. He currently Chair IEEE PSRC Working group D44, which aims at revising the C37.114 Guide on fault location in AC Distribution and Transmission systems. He also Chair the IEEE PSRC Working Group K29 which aims at revising the K3 report published in 2009 on reducing outage durations through improved protection and auto-restoration in distribution substations, and is a voting member of the IEEE PSRC Subcommittee D (Transmission Line Protection) and K (Substation Protection).

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