Multi-Terminal Line Differential Protection

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Abstract

In a “perfect” world all transmission lines are two terminals with no tapped loads. Regrettably, the cost of circuit breakers, with their associated disconnects, foundations and buswork, frequently precludes this “perfection” for many transmission and subtransmission lines. These lines, with multiple terminals and tapped loads, must still be protected. Tripping speeds must be sufficient to maintain system stability and limit damage to transformers and other primary equipment feeding the fault.

While three terminal protection has been frequently applied it has been problematic to protect more, even with digital communications and microprocessor relays. Distance relays with communication assisted tripping can be applied, however settings are difficult when infeed and other factors are considered.

A new line current differential system is available and has been applied on a system with 5 terminals. A case study on this application, and the reason the installation was installed with this many terminals, is included. The paper discusses operating principles, application considerations, and performance of the installed system. Communication requirements and impact on protection are discussed as well as reliability and security considerations.

Introduction

There is no question that planners, operators, and protection engineers would all prefer to have a power system with all lines having two terminals. Economics and other factors may prevent this preferred approach for some applications. Two examples, one specific and one general, provide illustrations as to how this could be the case.

Example 1. Electricity of Vietnam (EVN) Phu My 3 Power Plant

The Phu My 3 generation station provides 720 MW as part of what will be a 3600 MW complex to meet the needs of the nearby industrial area and Ho Chi Minh City 570 km to the Northwest. The final configuration of the station is as shown in fig. 1.
Here we see main and backup protection with differential and distance for both the three-terminal and two-terminal lines. Generator step-up transformers are part of the line system (no line side breaker) but they are not included in the protected zone. Separate 500 kV lines are connected to GT 1 and GT2 and 3.

When it was time to commission the powerplant, some construction was behind schedule and the 500 kV system was not available. In order to have plant power available and perform output and unit testing, the system was configured as shown in fig. 2.
Here we see that the three generation units are connected in parallel and "bussed" to two 500 kV lines. These two lines are then stepped down to feed the 220 kV system. It was necessary to connect the lines in this manner as the 500 / 220 kV transformers could not individually carry the load from the plant.

The savings in this case was not directly money, but time (which may equate to the same thing). Delays in bringing a large powerplant on line incur costs which range from tens to hundreds of thousands of dollars per day. In this case the difference in equipment between figures 1 and 2 consists of the two additional 500 / 220 kV transformers and the line connections. The availability of the transformers were what mandated the connections as shown, but they were also what made the savings in time possible.

The system was tested at full load to ensure proper operation of the generation plants, and at the same time the protection. Note in figure 2 that the communications between relays is in a complete loop between all the terminals. The protection can also operate in a "chain" configuration (discussed in the operating principles section) and the communications was tested at the time of commissioning. During the months of operation in this configuration there was no incorrect tripping of the relays.
Example 2. Multiple Connections to a Transmission Line

In this case it was not an actual power system operation but a test configuration that was used to validate the protection [ref. 1]. Consider a simple line connection with 4 taps as shown in figure 3.

![Image of a 6 Terminal Line Configuration]

Fig. 3. 6 Terminal Line Configuration

The specific case simulated in this example was for an offshore wind farm. Because of the geographic considerations in either an offshore installation or one that might be on several ridges along a rolling terrain, the connections to a transmission line are problematic if a single connection is required.

In the case of multiple connections to the same line measured against splitting the line, the economics are clear and measurable. Using $150,000 as a rough figure to purchase a 230 kV transmission breaker (of course more at higher voltages and less for lower) and then doubling it for foundations and installation; doubling it again for disconnect switches, controls and accessories, we could reasonably estimate $600,000 per installed and commissioned breaker. Under the simplest conditions then, with three breakers required to split the line and add a tap we would be at $1.8 Million for a simple connection.

For a connected wind farm with the six connections as shown in figure 3 we would be adding 12 breakers to the 6 shown, or 12 * $600k = $7.2 Million dollars. It is well known in our industry that the economics of connecting any small generators to the grid is such that large added costs will generally make the project non-viable.

While the viability of a specific generation source may not be of interest, a potential connector (that is the human wanting to connect) may ask what is unique about a single tap being acceptable and one more tap being too many. If the case is the availability of high-speed protection, that is not the limitation any more.

Operating Principles

The general operating principle of current differential is well known. An operating signal is created, most simply as the vector sum of the currents at each terminal. This is compared to a restraint, or stabilizing signal in order to provide security against external faults. The stabilizing signal is usually some summation of the magnitudes of the currents at each terminal. This general characteristic is shown in figure 4.
There are many considerations in the exact selection of operating and stabilizing quantities but they are beyond the scope of this paper. The principle is simple if all the information is available at each terminal. This is done with a single relay for a multi-winding transformer; where of course, all the data is available at the same time from every terminal.

With line relays at each terminal, the total current, that is the values from each terminal, must be available to all of the relays in order to provide high-speed tripping of each terminal. For a two terminal line, this is simple; the two relays exchange information and they both can process the complete current feeding the line. For a three terminal line the complication grows in that each relay must now build operate and restraint quantities by summing currents from two remote locations. This can be simplified back into a two terminal solution using partial summing as shown in figure 5 [ref. 3].

Figure 5. Multi-terminal communication with partial summing
In a multi-terminal arrangement we can avoid the complication of comparing all of the currents by using a partial summation received from the neighboring relays. In the case of the three terminal line with chain communications shown in figure 5, terminal 1 sends the sum of its current with terminal 3 to terminal 2. It also sends the sum of its current with terminal 2 on to terminal 3. In this way all of the relays have all of the information necessary to determine the line status. We can expand this to more terminals (the present practical limitation is 6) and use this partial summing to provide all information to all terminals. Reliable and secure operation of all terminals is assured by having all terminal currents available to each of the terminals. Tests [ref 1.] show that for severe faults the complete system relay operation time is from 16 – 19 ms including time required to make the summation calculations and pass that to a neighbor over fiber communications.

In figure 5 we see an example of “chain” communications, but adding a link from terminal 3 to terminal 2 will convert this to a “loop” system. Looped communications provides an added layer of communication reliability by using path monitoring to instantly convert to a chain on loss of any channel between terminals.

Application Considerations and Communication Requirements

Line current differential protection has very few physical constraints. It is not impacted by line loading or infeeds that can compromise distance protection. Series capacitors do not impact the line current and as such do not change the application. One of the advantages of line current differential for distributed generation connection is the capability to include transformers in the protected line as shown in figure 6.

Figure 6. Multi-terminal line with transformer in the protected zone
The only changes necessary to the settings is to compensate for ratio differences and phase angle shift at the terminal with the transformer. The information received by the remote terminal(s) includes the transformer impact on currents and so no changes are necessary at any of the other terminals.

Of course the first requirement for a line differential scheme is communications. Digital communications is required to send the information on terminal current between relays. This is optimally done using direct relay to relay fiber but any system providing 64kb or higher speed is acceptable. This includes everything from a twisted pair of wires to leased phone lines to modern SONET systems. This flexibility in communications opens the possibility of using radio for some of the connections [ref. 4]. While this may not be ideal for all applications, in a loop communications scheme with monitored paths and high-speed reversion to chain, radio may be a viable solution for low cost protection.

Direct fiber has a limitation of about of 100 km, which is probably sufficient for most tapped line applications. SONET systems or creation of a digital path has virtually no limit on length, so application can be extended to very long lines or systems.

**Backup During Communication Outage**

During a communication outage some form of local protection must provide tripping for faults on the line. Most effective would be distance relaying that could reach to cover the line beyond the connected tap but not overreaching beyond the nearest remote terminal. This limitation may result in sequential tripping. This may not be a serious issue. Sequential tripping will almost always trip the largest infeed first. This can remove the system stability problem caused by a fault with a high speed trip. Other infeeds would be cleared as their reach was extended by clearing the largest first.

**Conclusions**

Connection of multiple terminals to a transmission line need not compromise the overall integrity of a transmission system. Taking into account overall exposure of each tap, the benefit of adding connections to a line may exceed the added trips.

1. Up to six terminal lines may now be protected with 1 – 1.5 cycle operating times.
2. Modern digital communications options provide flexibility for optimizing the communications with the terminal conditions.
3. Communication failures are mitigated using "loop" to "chain" failback for overall protection reliability.

Reliable protection schemes can reduce costs for distributed generation, providing for more options in the overall mix of power sources. Mixed communications, different terminal arrangements, and accommodation of communication failure provides protection engineers with necessary options to improve overall system operation.

**References**
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