Challenges Testing Low Impedance Bus Differential Relays

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Abstract – Low impedance bus differential protection provides fast, intelligent operation for bus faults, but may introduce a unique set of challenges to test personnel when commissioning the system. This paper explains some of the challenges and proposes solutions to test low impedance bus protection relays. Challenges discussed include security algorithms that make traditional slope testing difficult, high pickup settings that make lower portion of the slope differential characteristic flat, large differences in CT ratio require high currents, and large buses can make for large test plans.

Introduction

A low impedance bus differential measures the current flowing through each breaker that is connected to the bus and vectorially sums these currents together. The sum will be the differential current. In an idealized world the differential current would be zero during non-fault conditions and would sum to some value during fault conditions. The differential current is never zero because of inherent inaccuracies of the current transformers. Not only are there small inaccuracies to deal with in the steady state but large inaccuracies can occur when an out of zone fault occurs and current transformers may saturate. To deal with both the steady state and through fault inaccuracies, the sloped differential algorithm has been developed. The characteristic of this algorithm is shown in Figure 1. In Figure 1, the horizontal axis is the restraint current and the vertical axis is the differential current. The differential is the magnitude of the vector sum of all currents in the differential zone and the restraint is either the magnitude of the maximum current in the zone or the magnitude of the average of the currents. The curve shown in Figure 1 defines the operate region of the characteristic. If the differential restraint point graphs above the curve the algorithm will operate and if the point graphs below the curve the algorithm will restrain.

The settings that define the differential characteristic allow the algorithm to accommodate small CT errors during the steady state as well as some CT error due to saturation during through faults. The characteristic does this by using a low slope and a high slope for the characteristic. The low slope occurs below the setpoint for the low breakpoint and is graphically shown as the slope on the lower portion of the characteristic. The low slope allows for small unequal CT performance during the steady state. The high slope is shown graphically as the upper slope above the upper breakpoint and is meant to accommodate unequal CT performance during through faults.

The slope settings are usually given as a percentage and define the ratio of differential to restraint to operate. For example, if the slope is 25% and the restraint current is 1 per unit, the element would operate when the differential exceeded 0.25 per unit.

Beyond the upper and lower slope and the upper and lower breakpoint, the last setting that defines the characteristic is the minimum pickup of the element. This setting defines the minimum differential current necessary to operate.

Testing the sloped differential algorithm involves finding several operation points to build the characteristic shown in Figure 1. It is not difficult to calculate the quantities necessary to test this characteristic because the mathematics are simple. It does become more challenging because the algorithm may use settings that are unexpected, the current transformers connected to the IED may have multiple ratios, and the IED may employ extra security algorithms. Strategies to deal with these types of issues are discussed in the following sections. The result should be that the tester understands the algorithms well enough to conclude that the settings applied will protect the bus from in-zone faults and provide security during through faults.

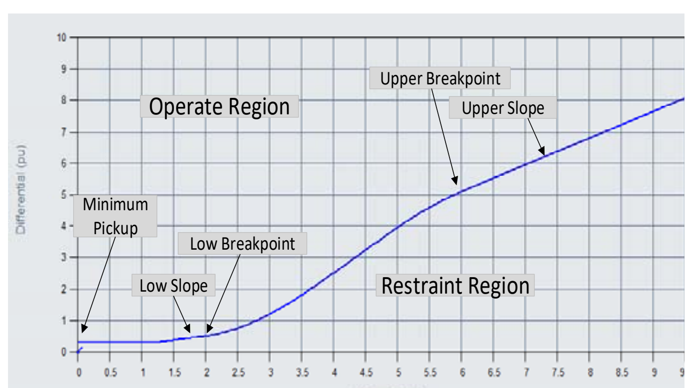

Figure 1: Sloped Differential Characteristic

I. Basics of Testing sloped Differential

Testing bus differential will require injecting current into at least two relay current inputs and varying the magnitude and angle until operation is achieved. Operation points should be tested to build the operation characteristic in Figure 1. Since multiple CT inputs are involved in the bus differential zone, each of the CT inputs would need to be tested. It overly complicates the test to test each CT input with every other CT input. The recommendation is to test a single CT input with every other CT input. To demonstrate this, consider a bus that has eight breakers connected to it. If the combination of every CT input is tested against every other CT input, this requires 28 different tests verses just 7 different tests if a single CT input is tested against every other CT input.

Once injected currents are connected to the IED, testing falls into three basic categories: Below low breakpoint, above high breakpoint, and between breakpoint one and two.

Equation 1 below describes the operate condition of the differential element. Equation 1a solves the operate condition for one current if the second current is known. This allows the tester to confirm correct operation on the sloped characteristic. The test can then be performed by injecting two currents into the relay below the first breakpoint that are of equal magnitude and opposite angle. If CT settings are all the same, this should give a point of zero differential and a point of operation along the horizontal zero axis in Figure 1. To find operation, one of the currents can be ramped down until operation is achieved. Correct operation is then defined by Equation 1a where I_1 and I_2 are the injected currents and IR is the restraint current. If restraint is the maximum of the two injected currents, then IR will be the current that is not ramped down. If restraint is the average of the currents, then IR will be the average of the two-current injected. When testing the low slope, problems may arise with low restraint values and high pickup settings which is addressed in the next section.

$$\frac{\mathrm{I_1+I_2}}{\mathrm{I_R}} > \mathrm{Slope} \qquad \text{Equation 1}$$

$$I_1 > I_2(Slope - 1) \qquad \text{Equation 1a}$$

For values above the high breakpoint, Equation 1a is again used to test. The only difference being that the injected values must be above the high breakpoint and the high slope will be used instead of the low slope in Equation 1a.

The characteristic between the high breakpoint and the low breakpoint will be dependent on the relay algorithm and may be a straight line or may be a cubic spline. The straight-line testing will be a third slope between the high and low and can be tested using Equation 1a. The cubic spline gives greater security but complicates testing. To test in the cubic spline region, it is recommended to test at 1.05% of the low breakpoint and 95% of the high breakpoint. These values should be close to the low slope and the high slope respectfully.

An alternate method of testing is to “allow” the test set to “build” the characteristic. Most test sets will perform this task and consists of injected currents to find several operate points and build a characteristic of Figure 1. If the test set builds the characteristic, then the work of the tester is interpreting the results for correct operation. Correct operation can be verified using the technique previously discussed with equation 1a. Alternately, the settings software may be able to build a graph of the characteristic as seen in Figure 1. If a graph can be obtained, then correct operation can be verified from that graph and the characteristic given by the test set. If the relay set up software gives operate quantities in per unit, as in Figure 1, and the test set give actual injected currents, then the graph in Figure 1 can be converted to actual currents by multiplying by CT nominal. If all CT inputs are the same and have 5 amps nominal secondary, this means that the per unit values are multiplied by 5 amps to get actual injected current.

II. Low Restraint verses High Pickup Settings

For the differential characteristic to operate, both the minimum pickup and the sloped differential must be satisfied. This can cause testing problems for the technique discussed above because the minimum pickup was not addressed. The minimum pickup settings cause a portion of the low slope characteristic to be “flat” as shown in Figure 2. In this figure the minimum pickup is set to 0.3 per unit and the low slope is set to 25%. As can be seen from the figure, this causes a flat portion of the characteristic between pickup and the value of 1.2. The sloped differential doesn’t begin until the injected current is greater than 1.2 per unit. This causes testing issues if the tester is expecting to test the sloped differential characteristic below the value of 1.2 per unit.

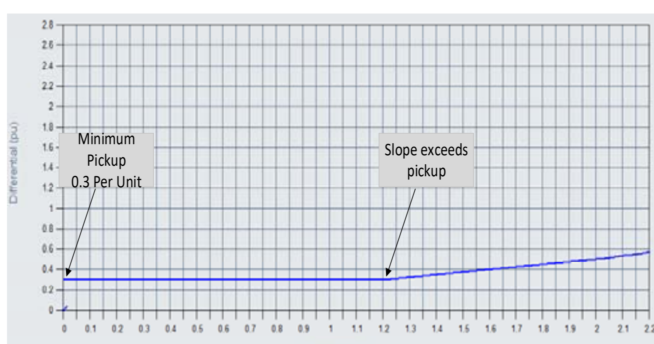

Figure 2: Flat low slope caused by high pickup settings.

The differential current must be greater than pickup to operate as shown in Equation 2 below, where PU is pickup. Differential current is the sum of the two injected currents as shown in Equation 2a. Using Equation 2a, one of the injected values can be solved for to determine the value necessary for pickup, this is shown in Equation 2c.

To test pickup, inject current on one input with all other inputs at zero. This would give a value of 0.3 per unit for the injected value for the characteristic of Figure 2. Since these values are in per unit, the pickup should be multiplied by the nominal CT settings to determine the actual current. If all CTs are set the same and all have a nominal secondary of 5 amps this would result in an injected value of 5x0.3=1.5amps to test for minimum pickup.

$\mathrm{I_D} > \mathrm{PU}$ Equation 2

$\mathrm{I_D} = \mathrm{I_1} + \mathrm{I_2}$ Equation 2a

$\mathrm{PU} = \mathrm{I_1} + \mathrm{I_2}$ Equation 2b

$\mathrm{I_1} = \mathrm{PU} - \mathrm{I_2}$ Equation 2c

To test the slope characteristic, the operate point must move beyond the flat portion of the characteristic shown in figure 2. The operate point for two injected currents can be found from Equation 1a above. To determine where the sloped characteristic intersects with the minimum pickup characteristic, the point at which Equation 1a and Equation 2c are both satisfied. This is accomplished by solving Equation 2c for I_1 and solving for the two currents. Solving for the two currents are shown in Equation 3 through 5 below.

$PU - I_2 = I_2(Slope - 1)$ Equation 3

$I_2 = \frac{PU}{Slope}$ Equation 4

$I_1 = PU - \frac{PU}{Slope}$ Equation 5

In the characteristic in Figure 2 with a slope of 25% and pickup of 0.3pu, this would equate to injected values of I_2 = 1.2 (PU/Slope=0.3/0.25=1.2) and I_1 = -0.9 (pu-pu/sl=0.3-0.3/0.25= -0.9). Since these are in per unit values they will need to be converted to amps. If all CTs are the same, and nominal secondary current is 5 amps this would be I_2 = 6amps and I_1 = 4.5 amps. The case where the CTs are of different ratios will be discussed in the next section. For this characteristic, the sloped differential doesn't start until a value of 6 amps and 4.5 amps are injected into the IED. For injected values below 6 amps, the test is to determine the minimum pickup and operate will be governed by Equation 2c. For injected values above 6 amps, the sloped differential characteristic can be tested using Equation 1a.

The flat portion of the characteristic causes additional testing problems if the low breakpoint is set very low. In the characteristic of Figure 1 the low breakpoint is set to 2 per unit. This means that the lower slope of 25% is only active between 1.2 per unit and 2 per unit. If the low breakpoint were set lower, to 1.0 per unit, the lower slope would never be active, only the minimum pickup. In that case the only test that could be performed would be to test minimum pickup at several points on the characteristic using Equation 2c to determine the flat portion of the characteristic.

III. MISMATCHED CT SETTINGS.

Testing is simple when all the breaker CTs on the bus are the same ratio. A level of complexity is added when the CTs have mismatched ratios as in Figure 3 below. In the case where there are mismatched CT ratios, the algorithm will choose one of the CTs as a base quantity for all settings and will use the CT ratio settings to accommodate the fact that the CTs have different ratios. To illustrate this point, consider the bus in Figure 3 below. If it had 300 amps flowing into the bus on the right most breaker and 300 amps flowing out of the bus on the left most breaker, this would be zero differential current. But what the IED would see would be $5A\angle0$ from the breaker on the right and would see $500mA\angle180$ from the breaker on the left. The IED can accommodate this difference because the CT ratios are entered as settings and the IED can either divide the right current quantities by 10 or multiply the left current quantities by 10.

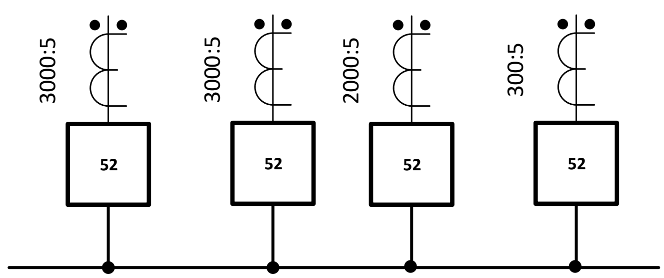

Figure 3: Bus with mismatched CT ratios.

For the tester to accommodate unequal CT ratios, the equations mentioned above are still valid. The only thing that needs to be considered is the ratios of the CTs. For example, the Equations 2c and 1a from above become:

$$I_1 = PU - I_2 \frac{CTRatioI_2}{CTRatioI_1} \quad \text{Equation 6}$$

$$I_1 = I_2(Slope - 1) \frac{CTRatioI_2}{CTRatioI_1} \quad \text{Equation 7}$$

Extreme mismatches in current can lead to issues that must be dealt with in testing. To illustrate this extreme mismatch, consider the bus in Figure 3 and the combination of current of the 300:5 CT and the 3000:5 CT. These CTs have a mismatch of 10 which is well within the acceptable allowable mismatch of the IED. If in testing, a test point is chosen that is 10 times the nominal value of the left breaker, that would be 50 amps on that CT input. 50 amps is well within the range of most relays as well as most test sets. To achieve the zero-differential point with 50 amps injected into the CT inputs from the left breaker it would take 500 amps injected into the right breaker CT inputs. A quantity of 500 amps is beyond the output of most test sets, is beyond the cut off range of most IEDs, and could damage the IED. In this case, those points should not be tested. It will not compromise protection to avoid testing at these quantities because, if these quantities exist in the real world, the CT on the right would saturate to the point of having almost no output on the secondary. The test would not be applicable to real world conditions.

IV. Testing with Security Algorithms

Bus differential algorithms are required to be both secure and dependable. Secure in that the algorithm does not operate for an external fault and dependable in that it will operate for an internal fault. Security is needed because a mis-operation for an external fault will trip all the breakers on the bus. Dependability is needed because of the extreme fault currents seen during a legitimate bus fault. To accommodate the bus protection's need for both high dependability and security, security algorithms are employed to prevent mis-operation of the bus differential elements. These security algorithms will cause testing issues around the tests as described above because those tests don't represent real faults. The testing for bus differential should be broken into two phases: testing the sloped differential characteristics and testing the actual trip of the algorithm. The tests describe above are testing the sloped differential characteristic. Those tests don't represent real faults because the currents are in opposite directions. These tests are started by applying currents in opposite directions with zero differential current. Then, one current magnitude is ramped to move into the differential operate characteristic. This is unrealistic because a legitimate fault makes all breaker currents that are a source have currents that are into the bus differential zone and currents that don't have a source will have zero or very small magnitudes below the level to be used by the algorithm. To perform the test a relay operand must be used with an output contact that does not employ the security algorithm, like pickup of the bus differential.

To test the actual algorithm with the security algorithms in place, currents must be applied that represent a legitimate fault and an operand should be set to an output contact that includes the security algorithm. Legitimate faults will take the form of a pre-fault state with zero or little differential current and a fault state with differential current and the currents in opposite directions.

V. Conclusions

The main goals of the tester are to ensure that algorithms work as desired and that the settings controlling the algorithms are appropriate. Many modern test sets can automate the process of testing but often a human must interpret the results to determine if they are as intended. Knowledge of how the algorithms should work and how the IEDs should respond to injected quantities will be necessary to interpret the results and insure that IEDs are successfully tested.

It is only when the tester can be comfortable that the IED will trip the intended equipment for true faults that the equipment can be put into service. To insure the relay trips, the tester must test the algorithms and test for simulated faults. The test results must then be interpreted against the settings and the protective schemes to ensure that the IED as well as the system work as intended.

Biographies

Terrence Smith is the lead P&C Technical Application Engineer for GE Grid Solutions North American Commercial team. He has been with GE since 2008 supporting the Grid Solutions Protection and Control Portfolio. Prior to joining GE, Terrence has been with the Tennessee Valley Authority as a Principal Engineer and MESA Associates as Program Manager. He received his Bachelor of Science in Engineering majoring in Electrical Engineering from the University of Tennessee at Chattanooga in 1993 and is a professional Engineer registered in the state of Tennessee.

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