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Secured Busbar Differential Protection Using A Computationally Efficient Dot Product Technique

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Abstract

The use of low impedance bus differential protection has increased over the recent years because of its versatility and cost effectiveness.
Low impedance bus differential schemes can take advantage of the use of current transformers that can also be used for other protections. Use of low impedance bus protection also has some issues that must be overcome such as current transformer saturation and DC current offsets that must be considered in the differential calculations. This paper discusses one way that these nuisance error quantities can be controlled. Use of phase angle measurement between current inputs of a bus protection scheme is presented here using an efficient Dot Product Technique.

Introduction

Low impedance bus differential protection takes advantage of Kirchoff's law in that the sum of current flow into a zone of protection must balance. The balance needs to include current magnitude as well as angle . The resultant vector additions must therefore sum to zero for a protection zone in which no fault is present.
Currents flowing into and out from a protection zone are measured using current transformers that provide electrical isolation and effectively reduce the large primary currents into 1A or 5A nominal values that can be handled by protective relays.
The traditional approach to measure differential currents is to sum the vector quantities. This sum is typically called an Operating current, **Io**. If this measurement is done accurately, the Io current vector summation should be zero. In practice, however, the primary currents measured by current transformers can result in secondary currents supplied to protective differential protections that is affected by factors such as:

1. CT errors during loading and during nearby faults.
2. CT errors due to CT saturation.
3. CT errors due to DC offsets
4. CT ratio, setting and wiring errors.

CT saturations or can be affected on a steady state basis due to CT design errors. The traditional way that differential relays were made to be more secure, has been to sum the arithmetic sum of the input currents to provide a restraint quantity , often called an **Ir** quantity. In addition, the Ir quantity is typically the arithmetic current summation divided by two. The resulting Io and Ir quantities are then arranged in a configuration as is shown in Figure 1.

TYPICAL TWO SLOPE CHARACTERISTIC

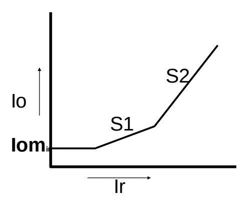


Figure 1

The typical two slope differential characteristic used provides a minimum pickup level defined as Iomin for conditions where bus loading is low, then a Ir area under slope S1 where typical bus loading occurs. This slope allows for some error from the CTs during normal load conditions. Finally the characteristic provides a S2 slope to allow for CT errors during fault conditions near the bus.

In summary, therefore, any factors that may cause improper transformations of the primary bus currents can cause the Io quantity to cross into the trip region above the S1-S2 slope lines.

CT Saturation

If a CT is subjected to currents on the primary side that cause the secondary currents to saturate, these secondary currents will not be representative of the primary currents and therefore could cause improper differential operation. An example of CT saturation is shown in Figure 2.

Example Of CT Saturation

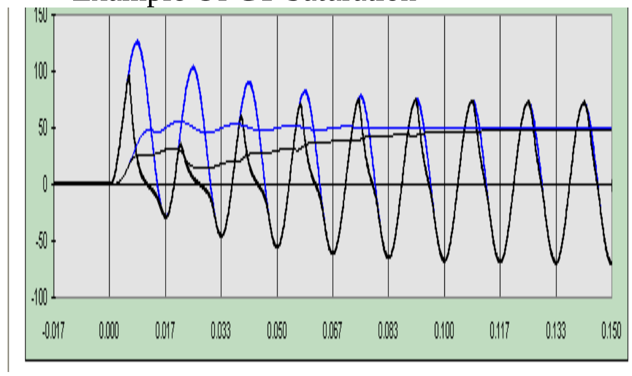


Figure 2

It can be seen in Figure 2 the primary current sine waveform is distorted for several cycles . This error in secondary current can create an Io quantity for an external fault and a false bus trip as a consequence.

Various techniques are used to detect CT saturation to block the bus relay from false tripping.

DC Current Offset

It can be seen that in Figure 2 that DC offset can accommodate CT saturation . This DC offset can occur on the CT secondary even if saturation does not occur. Some bus protection relays use software techniques to reduce or remove the DC offset by use of filtering. Introduction of a filter may however introduce current phase shifts and time delays in recreating the currents.

The Delta Phase Dot Product Technique

It was observed that, to a large degree, preservation of current phase angle will always take place even if CT saturation or DC offset conditions occur. As a result, if the phase angle of the current waveforms is compared with phase angles of each of the bus element currents, a decision can be made if a fault is external or internal to the protected bus zone. By comparing phase currents in near real time, a comparison can be made between currents that are entering the bus and those currents that are leaving the bus. If little CT saturation occurs, for an internal bus fault phase angle currents will be nearly in phase while for an external fault, one or more phase angles of the currents will be near 180 degrees from the other currents. This is intuitively true as well since Kirchoff's law also applies to phase angles as well as to current magnitudes. The phase angle comparison is used in conjunction with a slope characteristic The key challenge in the delta phase technique is to rapidly measure phase angle between all current phase angles. In the technique utilized, the DOT PRODUCT is calculated between input phase currents. If **A** and **B** are vectors, the DOT product of **A*B =** AB Cos theta where A and B are scalars and theta is the angle between the vectors. The DOT product of vectors **A** and **B**

where **A=** $a_1 + j\, a_2$

And **B=** $b_1 + j\, b_2$

A * B = $a_1 b_1 + a_2 b_2$ ----Eq. 1

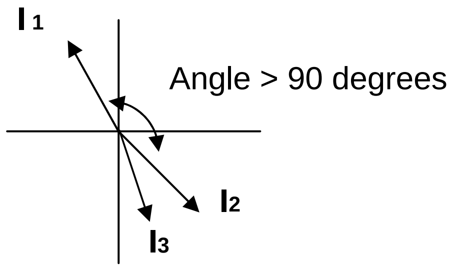
The calculation of **A*B** using Eq.1 has the advantage in that the Cosine function does not need to be used. Implementation of a trig function is a laborious process when done by a microprocessor, whereas multiplication and summation is easy to do with small resource requirement.

The delta phase algorithm looks at the phase angles of each of the similar phase currents to determine their phase relationships. If a fault is external to the protected zone for instance, the phase angles will be approximately equal and opposite. If a fault is internal to a protected zone, the current phasors will be approximately in phase.

Comparing the phase angles of the currents at every sample point of time allows the slope characteristic algorithm to be supervised by the delta phase function. This technique works because current phasors that are heavily saturated have DC offset or are otherwise distorted in magnitude will still retain their correct phase angle relationships. This information can then be used to provide correct operation of the overall differential protection by supervising the slope characteristic. The phase angle difference for discrimination of fault/no fault conditions is fixed at 90 degrees, so if all current phasors are within less than 90 degrees from each other, slope tripping is allowed. If the measured current phasors are within an angle greater than 90 degrees, this is recognized as an external fault and tripping is blocked. If only one current input is present, tripping will be permitted if the slope characteristic operates. The delta phase logic is shown in Figure 3 & 4 showing three inputs from elements connected to the protected bus zone.

The calculation of the current phase angles is done for every time that the current vectors are measured. Relays typically sample waveforms from 32 to 96 samples per cycle and current vectors for protection purposes are typically calculated every 2 ms or so.

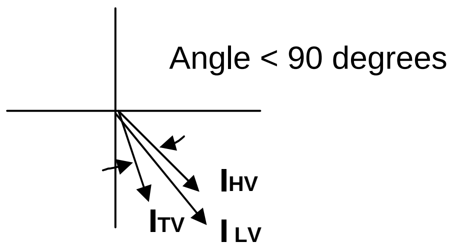
Current Vectors For No Fault In Protected Zone



Phase angles between currents Greater than 90 degrees, delta Phase BLOCKS differential trip.

Figure 3

Current Vectors For Fault In Protected Zone



Phase angles between currents Less than 90 degrees, delta Phase ALLOWS differential trip.

Figure 4

It can be seen from Figures 3 & 4 that the phase angles of the input currents of the elements connected to the protected bus are either about 180 degrees apart or approximately in phase . In the Dot product technique, the current vectors are measured to determine if vectors are within 90 degrees of each other . If all input vectors are within 90 degrees of each other, it is an indication of an internal fault. The Dot product of two vectors is ZERO. So in the calculation of phase angle the actual phase angle does not need to be measured. If the Dot product is greater than zero, angle coincidence is less than 90 degrees. If the Dot product is negative, the coincidence angle is greater than 90 degrees.

It should be noted that if the protected zone has only one source connected to it, a phase comparison cannot be made. At least two current vectors are required to make a phase angle decision. If only one current vector is available, the phase angle control defaults to a trip condition. In those cases, the slope characteristic is the only logic that is used. Also, if input currents are too low to be measured accurately, these vector currents are not used. The measurement of phase angle can typically be done down to 0.05 A for a 1 A nominal input relay, or .25 A for a 5 A relay.

Overall Transformer Differential Performance

The phase comparison Dot product function operates to supervise the operation of the slope characteristic. In many ways, the setting of the slope characteristic function becomes less critical because of delta phase supervision. The Iomin setting determines the amount of unbalance or fault current that can be present in the transformer zone before the slope characteristic tries to trip. The delta phase supervision will then allow or block the trip based on current angle measurement. Setting the slope characteristic to avoid tripping for current measurement errors can be a timely and laborious task. This is because CT performance and application parameters need to be known to provide these studies. With phase supervision, phase angles are largely preserved even if CT saturate or if DC offset quantities occur.

In applying any differential protection, it is important to determine that wiring connections and connection settings are made correctly. This can be done during the commissioning by viewing the metering screen on the relay metering screens. If current magnitude errors are present in the initial installation, the slope characteristic will operate and can annunciate a high MISMATCH indication to draw attention to the fact that something is amiss. Tripping will largely be prevented even in this condition if no actual fault on the protected zone is present.

Examples Of Protected Bus Zone Operations

For An External Fault

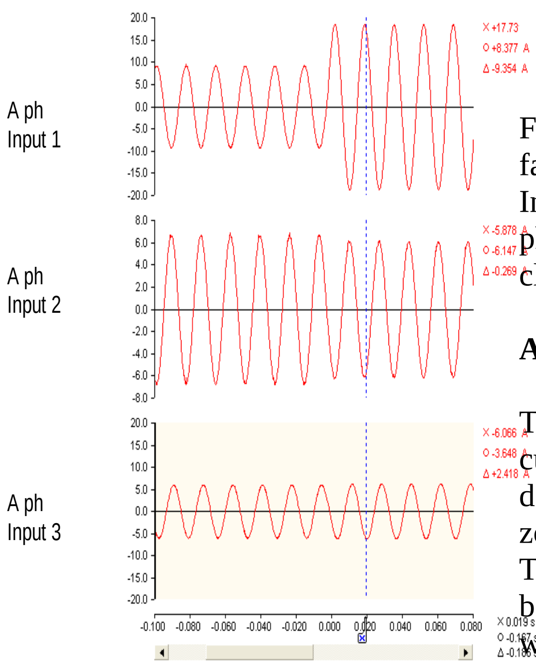


Figure 5

It can be seen from this example, that the phase angles of the three input A phase currents are 180 degrees from each other with currents 2 and 3 in phase and these 180 degrees out of phase with current 1.

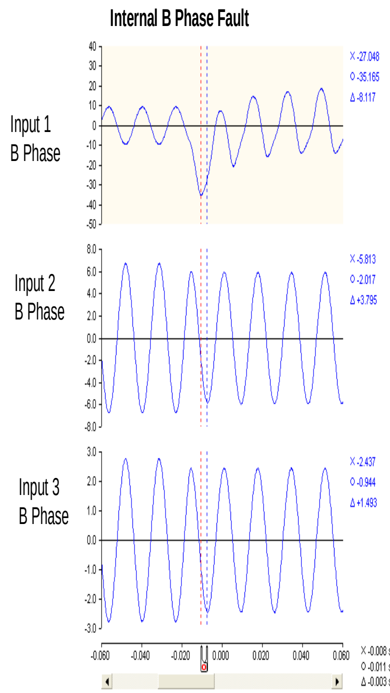


Figure 6

Figure 6 displays an internal B phase bus fault . It can be seen that even though Input 1 has a DC offset amount, the phase angles of the input currents come close to coinciding.

Application To Device 87N

The previous Figures showed how phase current phase angles can be compared to determine if faults are within a protected zone or whether they are external faults. The same phase angle comparison can be done on zero sequence currents as well. For this case Kirchoff's rule equally applies to 3Io currents over a protected zone. Current transformers can ebe used to summate the phase currents to generate 3Io , just as these same CTs can be used to measure the individual phase currents.

Observations Of The Use Of The Dot Product For Bus Protection Enhancement

The Dot product phase angle comparison of current inputs for a bus has been verified through hundreds of tests using the RTDS simulator. In fact, the phase angle comparator has shown to be equally effective when used with differential protection for other applications such as transformer protection as well.
The use of the phase angle comparison along with the slope detection method in combination has proven to be a very stable combination especially for external faults where severe input current saturation or DC offsets can occur.

Benefits Of The Dot Product Phase Angle Comparison

1. The addition of phase angle comparison to a differential function provides excellent security for all external faults where current quantities into the differential relay could be corrupted due to DC offsets, CT saturation or other CT errors.
2. The addition of the Dot angle comparison simplifies differential relay application as the stability of the CT phase angles makes possible fault discrimination and lessens the emphasis put on the slope characteristic requirements.
3. Use of the rapid Dot product computation allows for phase angle measurement without time to operate speed penalties.
4. Use of the Dot phase angle comparison can compliment the slope characteristic in that it can provide a zone checking function to prevent false relay trips that might otherwise take place because of wiring or application errors.