Busbar Protection- A Solution to CT Saturation

P. Jena and A. K. Pradhan

Abstract: This work proposes a busbar protection scheme based on phase changes in positive sequence current of incoming and outgoing line current transformers (CTs). The angle differences of during fault and prefault current signals of incoming and outgoing CTs are the indicators of external or internal faults for bus bar protection. The advantage of the method is that it does not use magnitude information of the current and thus overcomes the CT saturation issues. The performance of the technique was investigated for a variety of operating conditions, for CT saturation, CT ratio mismatch, different fault inception angles, for different type of faults and for several bus-bar configurations.

Keywords- Digital busbar protection, phasor estimation, CT saturation, DFT, Fault

I. INTRODUCTION

Differential protection schemes are applied for high voltage busbars. Failure-to-trip on an internal fault, as well as false tripping of a busbar during load service, or in case of an external fault, both have disastrous effects on the stability of power systems [1]–[2]. The challenge of bus differential protection is the issue of false differential current due to CT saturation and ratio mismatch [6]. The busbar protection can be classified as high impedance and low impedance types. High impedance relays are used to provide low cost bus protection, but have limitations due to complex arrangements and use of multi-ratio current transformers. The low impedance measuring principle employs the zone-selective differential current as the operating quantity and the sum of the current magnitudes as the stabilizing signal. The measuring principle must ensure protection with CT saturation on external faults. A low-impedance busbar protection operates during CT saturation by using a principle, which discriminates between saturated and unsaturated waveforms [5]. Recently, many novel differential techniques have been proposed to overcome CT saturation. For external faults, the differential current should be zero, but errors caused by CT saturation can result in a nonzero value. To prevent maloperation, the operating threshold is raised by increasing the bias setting. Raising the bias threshold has a detrimental effect on the relay sensitivity as it prevents the detection of in-zone resistive faults [4]. The impact of CT ratio-mismatch is countered by using percentage-bias characteristics that reduces the sensitivity of the relay [6]. In [7] Kang proposed a bus-bar current differential protection relay suitable for use with measurement type current transformers. A fault direction based techniques using a combined signal derived from prefault voltage and fault current signals [8]. A wavelet transform based technique has been used to derive significant information from the observed current and voltage signals, which is then suitably employed for protection. In [9], a technique is proposed which is based on a feature signal extracted from the original current value using the wavelet packet transform method. Jiang used a protection scheme based on wavelet filter banks to extract the windowed average energy spectrum of fault-generated transients so as to distinguish between an internal fault and an external fault [10]. In [11] Chen proposed a directional differential bus-bar protection scheme, which employed a wavelet-transform-based polarity detector. Kumar and Hansen [12] developed a technique that uses multiprocessing and utilizes the relationship between restraining and differential voltages and a restraining factor. The above discussed algorithms do not have inherent immunity to CT saturation.

This work proposes a digital relaying technique for busbar protection using phase change in sequence current of incoming CT currents and outgoing CT currents. The fundamental of the phase change in sequence current is given in [3]. The angle differences of during fault and prefault current signals of incoming and outgoing CTs are the indicators of external or internal faults for bus bar protection. The phasor concept is used to overcome the current transformer saturation. The major advantage of the proposed technique is that it does not require additional voltage signal for discriminating internal and external faults. Another advantage of the method is that it does not use magnitude information of the current and thus overcomes the CT saturation issues. The proposed algorithm has the potential to overcome the CT ratio mismatch problem discussed in section IV. The positive sequence component is used as such a component is available for both unbalanced and balanced faults. The performance of the technique is investigated for a variety of operating conditions; for CT saturation, CT ratio mismatch, different fault inception angles, for different type of faults and for several busbar configurations.

II. PROPOSED METHOD

(i) The Basics

To demonstrate the principle a single phase power system is considered as shown in Fig. 1. The bus to be protected is bus-B. CT1 and CT2 are the two current transformer for the differential protection. Ground faults are created at different locations of the system; (Fx, Fy and Fz). The current waveforms as shown in Fig. 2 are obtained through the 100:5 CTs. Other three current waveforms are measured by CT1 are for faults initiated at Fx, Fy or Fz at 0.3sec. The current magnitudes are high for the three fault cases but the fault currents change differently in phase. Similar phase change is observed for different fault inception angles. The corresponding phasor diagrams are shown in Fig. 3. Similarly the currents measured by CT2 are shown in Fig. 4. It is observed that for faults at Fx and Fz (external faults with respect to the bus-bar B), the the phases of the currents measured by the two CTs change in negative and positive direction respectively with respect to the pre-fault current. Whereas for fault at Fy (internal fault or bus fault) the phase change in current is positive for CT1 and negative for CT2. The corresponding phasor diagrams are shown in Fig. 5. From the phasor diagram it is clear that for any external fault the phase change in sequence component of incoming and outgoing current is either positive or negative. Whereas for an internal fault the phase change for
incoming line current is positive and negative for outgoing line current.

![Fig. 1. Single phase two-source system](image1)

Fig. 1. Single phase two-source system

The current waveforms for external faults (Fx and Fz) the phase change is either zero (for Fx case) and phase change in negative direction (for Fz) with respect to the pre-fault current. But at the same time the phase change in current for internal fault Fy is negative for incoming current measured by CT1 and zero for CT2 measured current, with respect to the pre-fault current. The corresponding phasor diagram for the three cases are shown in Fig. 8. From the phasor diagrams it is clear that for external fault (Fx) the phase change in CT1 and CT2 current is zero and negative for Fz as the fault position is downstream to both CT1 and CT2. Whereas for internal fault (bus-B fault), the phase change of CT1 current is negative and the phase change in CT2 current is zero as the CT2 does not see any fault current for fault at Fy. This information is useful to differentiate the external and internal fault with respect to the concerned bus bar relay by deriving a directional feature as described above.

![Fig. 2. Current waveforms for external and internal faults at t=0.3 sec in different directions of relay location, measured by CT1](image2)

Fig. 2. Current waveforms for external and internal faults at t=0.3 sec in different directions of relay location, measured by CT1

![Fig. 3. Phasor diagram showing different currents, I_{Fx}, I_{Fy}, and I_{Fz} - fault components only and I'_{Fy} and I''_{Fy} – fault currents (including load current) for CT1](image3)

(a) fault at Fx

(b) fault at Fy and Fz

Fig. 3. Phasor diagram showing different currents, I_{Fx}, I_{Fy}, and I_{Fz} - fault components only and I'_{Fy} and I''_{Fy} – fault currents (including load current) for CT1

![Fig. 4. Current waveforms for external and internal faults at t=0.3 sec in different directions of relay location, measured by CT2](image4)

Fig. 4. Current waveforms for external and internal faults at t=0.3 sec in different directions of relay location, measured by CT2

![Fig. 5. Phasor diagram showing different currents, I_{Fx}, I_{Fy}, and I_{Fz} - fault components only and I'_{Fy} and I''_{Fy} – fault currents (including load current) for CT2](image5)

(a) Fault at Fx and Fy

(b) Fault at Fz

Fig. 5. Phasor diagram showing different currents, I_{Fx}, I_{Fy}, and I_{Fz} - fault components only and I'_{Fy} and I''_{Fy} – fault currents (including load current) for CT2

![Fig. 6. Single phase radial system](image6)

Fig. 6. Single phase radial system

![Fig. 7. Current waveforms for external and internal faults at t=0.3 sec in different directions of relay location, measured by CT1](image7)

Fig. 7. Current waveforms for external and internal faults at t=0.3 sec in different directions of relay location, measured by CT1
Similarly the currents measured by CT2 are given in Fig. 9 and the corresponding phasor diagram is provided in Fig. 10. From the phasor diagram it is clear that for external faults (Fx, Fz) the phase changes of CT1 and CT2 positive sequence currents are either zero or negative and for internal fault (Fy) the above said phase changes are negative and positive. For three phase system the analysis has been done and the corresponding rule base is given in Table 1.

The positive sequence network of a three phase system being similar to its single phase model, the phasor diagrams as depicted earlier are valid for positive sequence components of current for similar three phase system. Thus the rule enumerated in Table 1 is valid for positive sequence current of any three phase system. To implement the scheme, flow diagram of Fig. 11 is used. A fault detector unit triggers the phasor estimation technique to provide prefault and fault positive sequence phasors and the power flow direction. The power flow direction helps to decide on the incoming and outgoing current.

Table 1: Rule base for discriminating external and internal fault

<table>
<thead>
<tr>
<th>Fault zone</th>
<th>Sign of phase change in current measured by incoming current</th>
<th>Sign of phase change in current measured by outgoing current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fx (external faults)</td>
<td>Positive/ zero</td>
<td>Positive/zero</td>
</tr>
<tr>
<td>Fz (external faults)</td>
<td>negative</td>
<td>negative</td>
</tr>
<tr>
<td>Fy (internal fault)</td>
<td>negative</td>
<td>Positive/zero</td>
</tr>
</tbody>
</table>

Fig. 11. Flow diagram for finding external and internal fault for bus bar B

III. RESULTS

Three systems are considered to evaluate the performance of the proposed protection algorithm. In the simulation nonlinear model of CT is considered. In all the cases one-cycle DFT is applied to estimate the phasors with 1 kHz sampling rate. Positive sequence components are estimated with phase-A as reference. In the proposed method the phase angle is estimated using arctan function for four-quadrant option; $-\pi$ to $\pi$ (atan2 function in MATLAB). The phase angle difference of fault and prefault phasors,
as discussed in the phasor diagrams, is limited to $-\pi$ to $\pi$. In some cases this angle difference calculated by this way will exceed the mentioned limit. In that case $2\pi$ should be subtracted or added to the difference if it exceeds $\pi$ or $-\pi$ limit respectively.

Case-1 A three phase two-source system

A 132 kV, 50 Hz three phase two-source system as shown in Fig. 12 is considered to evaluate the performance of the proposed protection algorithm; system simulated through PSCAD. The CT ratio considered in this case is 1000:5. Here the sampling frequency is considered 1 kHz. A three-phase fault has been created at $t=0.3$ sec at three positions ($F_x$, $F_y$ and $F_z$) with respect to the relay placed at bus B. The corresponding results are given in table 2. Here for external faults ($F_x$, $F_z$) the phase change in sequence component of CT1 and CT2 group currents is either positive (i.e. 1.67 rad. for $F_x$) or negative (i.e. -1.16 rad. for $F_z$) and for internal fault($F_y$) for CT1 group is negative(i.e. -1.16 rad) and for CT2 group is positive(i.e. 1.67 rad). So the results obtained here obey the rule base given in table 1. The current waveforms shown in Fig 13 are distorted because the CT 1 is being saturated.

Results given in table 2 depicts that even with severe CT saturation the results obtained obey the rule base given in table 1.

CASE-2 multi-input multi-output radial system

A 132 kV, 50 Hz three phase radial system as shown in Fig. 14 is considered to evaluate the performance of the proposed protection algorithm; system simulated through PSCAD. The CT ratio considered in this case is 1000:5. Here the sampling frequency is considered 1 kHz. A three-phase fault has been created at $t=0.3$ sec at three positions ($F_x$, $F_y$ and $F_z$) with respect to the relay located at bus B. The corresponding results are given in table 3. Here for external faults ($F_x$, $F_z$) the phase change in sequence component of CT1 and CT2 group currents is either zero (i.e. 0.03 rad. , for $F_x$) or negative (i.e. -1.10 rad. for $F_z$) and for internal fault($F_y$) for CT1 group is zero(i.e. -0.06 rad.) and for CT2 group is negative(i.e. -1.20 rad.). Form the result it is clear that the rule base given in table 1 holds good.

Table 3 Results for three-phase fault at $F_x$, $F_y$ and $F_z$, $t=0.3$ sec.

<table>
<thead>
<tr>
<th>Fault/ sensor</th>
<th>Fault current phasor</th>
<th>Prefault current phasor</th>
<th>Angle Difference (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x$/CT1 group</td>
<td>Mag (A) 4.04</td>
<td>Angle (rad) -2.12</td>
<td>Mag (A) 7.59</td>
</tr>
<tr>
<td>$F_x$/CT2 group</td>
<td>Mag (A) 4.04</td>
<td>Angle (rad) -2.12</td>
<td>Mag (A) 7.59</td>
</tr>
<tr>
<td>$F_z$/CT1 group</td>
<td>Mag (A) 17.88</td>
<td>Angle (rad) 3.03</td>
<td>Mag (A) 7.59</td>
</tr>
<tr>
<td>$F_z$/CT2 group</td>
<td>Mag (A) 17.88</td>
<td>Angle (rad) 3.03</td>
<td>Mag (A) 7.59</td>
</tr>
<tr>
<td>$F_y$/CT1 group</td>
<td>Mag (A) 42.73</td>
<td>Angle (rad) 2.93</td>
<td>Mag (A) 7.59</td>
</tr>
<tr>
<td>$F_y$/CT2 group</td>
<td>Mag (A) 42.73</td>
<td>Angle (rad) -2.21</td>
<td>Mag (A) 7.59</td>
</tr>
</tbody>
</table>

CASE-3 A multi-input multi-output system

A 132 kV, 50 Hz three phase multi-source system as shown in Fig. 15 is considered to evaluate the performance of the proposed protection algorithm. The CT ratio considered in this case is 1000:5.
The corresponding results are given in table 4 for power flow from bus-A to bus-C. The phasor angle differences for both the CT groups are positive (1.53 rad.) for fault at Fx. For external fault at Fz, the phase changes for both the CT groups are negative(-1.44 rad.). Whereas for internal fault the phase change of CT1 group current is negative(i.e. -1.44 rad.) and for CT2 group current is positive(i.e. 1.53 rad.) as shown in table 4, which clearly discriminates the external and internal fault with respect to the relay bus. Here the rule base given in table1 holds good.

Table-4 Results for three-phase fault Fx, Fy and Fz, t=0.3 sec.

<table>
<thead>
<tr>
<th>Fault/ sensor</th>
<th>Fault current phasor</th>
<th>Prefault current phasor</th>
<th>Angle Difference (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fx/CT1 group</td>
<td>56.28 (-0.38)</td>
<td>4.96 (-1.91)</td>
<td>1.53</td>
</tr>
<tr>
<td>Fx/CT2 group</td>
<td>56.28 (-0.38)</td>
<td>4.96 (-1.91)</td>
<td>1.53</td>
</tr>
<tr>
<td>Fz/CT1 group</td>
<td>56.76 (2.93)</td>
<td>4.96 (-1.91)</td>
<td>-1.44</td>
</tr>
<tr>
<td>Fz/CT2 group</td>
<td>56.76 (2.93)</td>
<td>4.96 (-1.91)</td>
<td>-1.44</td>
</tr>
<tr>
<td>Fy/CT1 group</td>
<td>56.76 (2.93)</td>
<td>4.96 (-1.91)</td>
<td>-1.44</td>
</tr>
<tr>
<td>Fy/CT2 group</td>
<td>56.76 (-0.38)</td>
<td>4.96 (-1.91)</td>
<td>1.53</td>
</tr>
</tbody>
</table>

IV. DISCUSSIONS

Here the proposed algorithm is tested for different fault types, at different fault inception angles, at severe CT saturation and CT ratio mismatch conditions.

(i) Fault type

For different types of faults the proposed algorithm is verified and it is found that the above mentioned rule base holds good for both balanced and unbalanced faults. In the system as shown in Fig. 13, a A-G type fault is created in external and internal zones at t = 0.2 sec. The corresponding results are given in table 5. The phasor angle differences for both the sensors are equivalent to zero (-0.02 rad.) for fault at Fx. For external fault at Fz, where the phase changes for both the sensors are negative(-0.33 rad). Whereas for internal fault the phase change of CT1 group current is negative(i.e. -0.54 rad.) and for CT2 group current is equivalent to zero (i.e. 0.05 rad.). The results show that even with severe CT saturation the proposed algorithm works well. Here the A-G type fault is considered, where the rule base given in table 1 holds good.

(ii) Effect of Severity of CT Saturation and CT ratio mismatch

With severe CT saturation and CT ratio mismatch, the proposed algorithm is tested by taking the system given in Fig. 13. A-B-G fault is created at 0.2 sec. The corresponding results are given in table 6. From the results it is clear that for both the cases the rule base holds good. The phasor angle differences for both the CT groups are equivalent to zero( 0.00 rad.) for fault at Fx. For external fault at Fz, where the phase changes for both the CT groups are negative(-0.84 rad). Whereas for internal fault the phase change of CT1 group current is negative(i.e. -1.11 rad.) and for CT2 group current is equivalent to zero (i.e. 0.03 rad.).

Table-5 Results for A-G fault

<table>
<thead>
<tr>
<th>Fault/ sensor</th>
<th>Fault current phasor</th>
<th>Prefault current phasor</th>
<th>Angle Difference (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fx/CT1 group</td>
<td>6.9 (-2.17)</td>
<td>7.59 (-2.15)</td>
<td>-0.02</td>
</tr>
<tr>
<td>Fx/CT2 group</td>
<td>6.9 (-2.17)</td>
<td>4.96 (-2.15)</td>
<td>-0.02</td>
</tr>
<tr>
<td>Fz/CT1 group</td>
<td>9.43 (-2.48)</td>
<td>4.96 (-2.15)</td>
<td>-0.33</td>
</tr>
<tr>
<td>Fz/CT2 group</td>
<td>9.43 (-2.48)</td>
<td>4.96 (-2.15)</td>
<td>-0.33</td>
</tr>
<tr>
<td>Fy/CT1 group</td>
<td>14.07 (-2.69)</td>
<td>4.96 (-2.15)</td>
<td>-0.54</td>
</tr>
<tr>
<td>Fy/CT2 group</td>
<td>14.07 (-2.20)</td>
<td>4.96 (-2.15)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

V. CONCLUSION

This work proposes a digital relaying technique for busbar protection using phase change in sequence current of incoming CT currents (CT1 group currents) and outgoing CT currents (CT2 group currents). The angle differences of above said current signals are the indicator of external fault and internal fault. The phasor concept is used to overcome the current transformer (CT) saturation. The proposed technique is not using voltage signal for discriminating the internal and external faults. The proposed technique also overcomes the CT saturation and CT ratio mismatch problem.
VI. REFERENCES


Ashok Kumar Pradhan teaches at Indian Institute of Technology, Kharagpur. His research area of interest includes power system protection, wide area measurement technology and power quality.

Premalata Jena obtained her M. Tech. degree in Electrical Engineering from Indian Institute of Technology Kharagpur India in 2006 and presently she is pursuing for Ph.D at Indian Institute of Technology Kharagpur. Her research area is Power System Protection.