Wavelet Based Transient Directional Method for Busbar Protection

N. Perera, A.D. Rajapakse, D. Muthumuni

***Abstract*-- This paper investigates the applicability of transient based fault direction identification method for busbar protection. In this method, the wavelet transform is used to extract traveling wave fronts originating from a fault. By comparing the polarity of the wave fronts, busbar zone faults are identified. Custom modules required to simulate the proposed protection scheme were implemented on an electromagnetic transient (EMT) type simulation program. Investigations were carried out using a high voltage transmission system simulated in the EMT simulation environment. Performance of the wavelet based method was compared against a conventional differential protection scheme. Effects of current transformer (CT) saturation, CT ratio error and fault impedance were also investigated. Results presented in this paper showed the capability of implementing a fast busbar protection scheme using the proposed approach.**

***Keywords*: wavelets transform, busbar protection, differential protection, electromagnetic transients**

I. Introduction

TRANSMISSION system protection is provided by dividing the system into different zones/areas typically based on the protected components such as transmission lines, busbars, power transformers, etc.. Although the occurrence of faults inside a busbar zones is rare, they could sustain significant damages to the system due to high current levels associated with the busbar faults. Clearing a busbar fault usually involves tripping of several branches, leaving the system vulnerable to instabilities. Therefore priority is always given to clear the faults inside the basbar zones. These faults must be cleared as soon as possible to avoid system instabilities that could evolve into blackouts with severe economic consequences [1].

Conventionally, the busbar zones are protected using phasor based differential current elements in which power frequency (50/60Hz) components of the measurements are extracted using the Fourier Transform [2]. Although this method is normally being used in almost all busbar protection schemes, it involves a significant computational delay which introduces a limitation on the speed of operation of the busbar protection. On the other hand, the conventional differential protection can malfunction during external faults due to the measurement errors caused by current transformer saturation [3-4].

In contrast to the conventional phasor based methods, transient based protection methods are faster in operation. Their performances are generally not affected by the measurement errors and CT saturation. Furthermore, their operation is less affected by the fault impedance [5-6]. The applicability of transient based protection methods for high speed protection has been investigated since early 70's [7]. In recent research, wavelet transform has become a popular tool for analyzing high frequency transients in power system [8-9] due to its aptness in extracting high frequency transients that are submerged in voltage and current signals of the power system. Transient based methods that use wavelet transform can be based either on the traveling wave principle or on the transient directional principle [10-12].

This research investigates the applicability of transient directional type protection method for busbar protection. The transient directional method developed in [13], which uses the wavelet coefficients of the current transients, is applied to develop a fast busbar protection method. In this method, the three-phase current signals observed on each of the branches connected to a given bus are transformed into the modal domain and the wavelet coefficients of modal components are obtained. The fault directions determined using wavelet coefficients on each branch are compared to identify the faults inside the busbar zone. Use of only the current measurements circumvents the bandwidth problems associated with voltage measurements obtained using capacitive voltage transformers. In addition, use of only initial transients enables fast operation irrespective of possible saturation of current transformers. Furthermore, this method is capable of identifying the fault directions during high impedance faults, regardless of the fault inception angle and CT saturation.

In this paper, the concept of the busbar protection scheme using wavelet coefficients of current transients and its implementation on PSCAD/EMTDC electromagnetic transient (EMT) simulation software is described. The performance of the protection scheme is evaluated and compared against the conventional differential protection using a simulated high voltage power system.

II. Proposed Busbar Protection System

A. Structure

Figure 1 shows the structure of the proposed protection system. A typical bus requires several 'directional' units

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depending on the number of branches connected and a 'decision making' unit. The inputs to the directional units are three-phase current measurements. Fault directions determined by the directional units using the current transients are sent to the decision making unit. The decision making unit combines these directional information to determine the busbar faults and generates necessary trip signals. The algorithms for directional unit and decision making unit are described below.

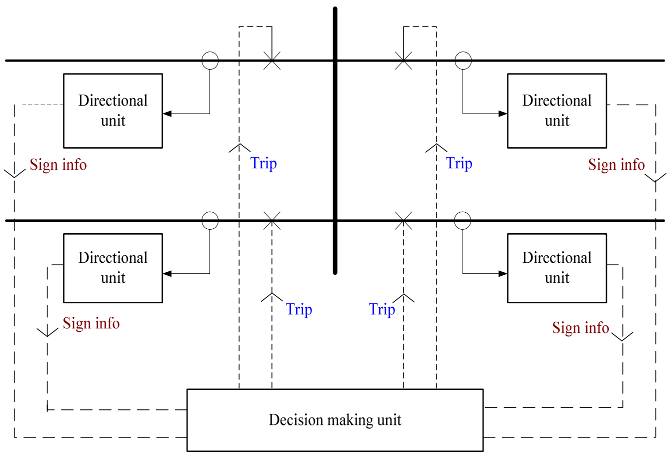

Fig. 1: Busbar protection scheme

B. Algorithm for Directional Unit

The algorithm for directional unit is shown in Fig.2. The signals were sampled at 20 kHz. This frequency was selected considering the upper limit of the bandwidth of conventional current transformers. The digitized three-phase currents are first transformed into modal components using the constant Clarke transformation [14] matrix given in (1).

$$\begin{pmatrix} I_0 \\ I_\alpha \\ I_\beta \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{pmatrix}\begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} \qquad (1)$$

Here, I_a, I_b, and I_c are the phase currents and I_α, I_β, and I_0 are the corresponding Clarke components. The purpose of using the modal transformation is to obtain propagation modes of the system characterized by vertical symmetry, which is the case of station busbars.

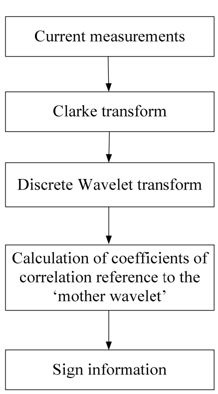

Fig. 2: Algorithm for directional unit

In the next step, traveling wave fronts of the modal currents were extracted using discrete wavelet transform. The mother wavelet used here is 'DB4' (shown in Fig. 3). A brief description about the discrete wavelet transform is given in the Appendix.

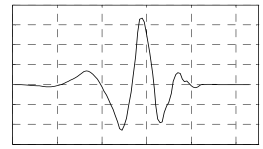

Fig. 3: The 'DB4' mother wavelet

The next step is to determine the polarity of the wave front (as indicated by the sign of the wavelet coefficient), with reference to the shape of the mother wavelet. The coefficients of cross-correlation between the mother wavelet and the (wavelet transform coefficients) WTCs are used to determine the sign if the transient. Since the WTC and the reference are not exactly aligned, the cross-correlation coefficient is calculated at different sample lags by advancing and retarding one signal with respect to the other signal. The mean removed correlation of coefficient (r), for a data sequence of x with reference to the mother wavelet y is given in (2).

$$r = \frac{1}{n}\sum_{i=0}^{n-1}\left(y_i - \bar{y}\right)\left(x_i - \bar{x}\right) \qquad (2)$$

where $\bar{y}$ and $\bar{x}$ are mean values of two data sequences and n is the size of the data set [15].

If the highest value of cross-correlation coefficients between two signals is positive, they are of the same sign; otherwise they are having opposite signs. When a fault situation is identified, WTC of all three modal components of the current signals are analyzed and the signal with the highest magnitude is used to determine the sign information.

C. Algorithm for Decision Making Unit

The decision making unit compares the signs of transients receiving from the directional units. If the sign information received from the all directional units is the same, the fault is declared as a busbar fault.

III. Modeling and Simulation

The modules required to simulate the wavelet based busbar protection scheme were implemented in PSCAD/EMTDC power system simulation program. Investigations were carried out using a test network. The performance of the proposed method was compared against the conventional differential protection method. The details of the simulation study are described below.

A. Implementation of Directional Unit

In order to implement the algorithm for directional unit, several custom simulation modules were developed. As a standard component to perform the cross-correlation is not available in the PSCAD/EMTDC master library, a custom model was developed. The discrete wavelet transformation (DWT) was performed using the simulation module developed in [16]. Figure 4 shows the implementation of complete algorithm for directional unit in PSCAD/EMTDC.

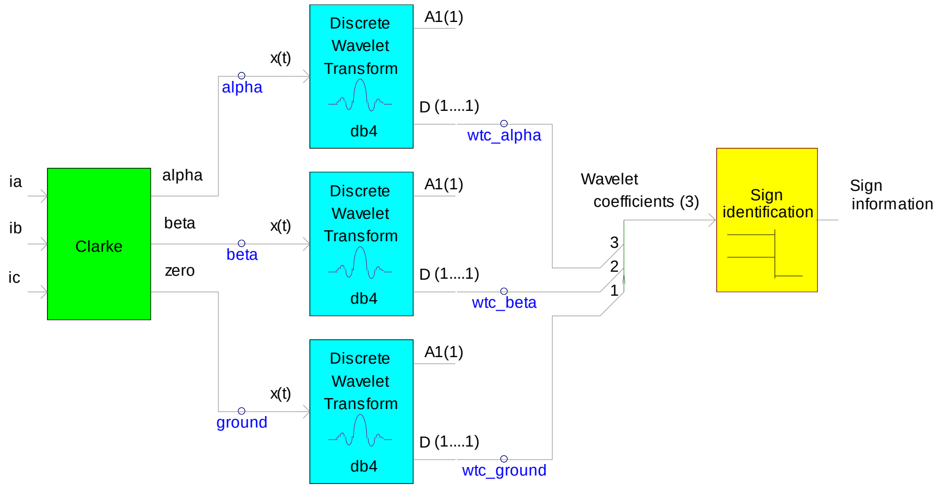

Fig. 4: PSCAD/EMTDC implementation of directional unit

B. *Implementation of Decision Making Unit*

The implementation of decision making unit is straight forward. The output signals of the directional units are combined to obtain the trip signal. If all output signals of the directional units are equal in sign, the trip signal is generated.

C. *Test System*

In order to investigate the performance of the proposed method, the network configuration used in [3] to study the conventional differential busbar protection scheme was used. Fig.5 shows the topology of the transmission network in this study. The transmission lines were modeled using the frequency dependent overhead line models available in PSCAD/EMTDC master library. The generators were modeled as voltage sources. The effects such as the capacitance of busbars were not modeled since the highest frequency of the signals used for protection was limited to 20 kHz. The proposed protection scheme was simulated using the custom modules (given in Section II) as shown in Fig. 5.

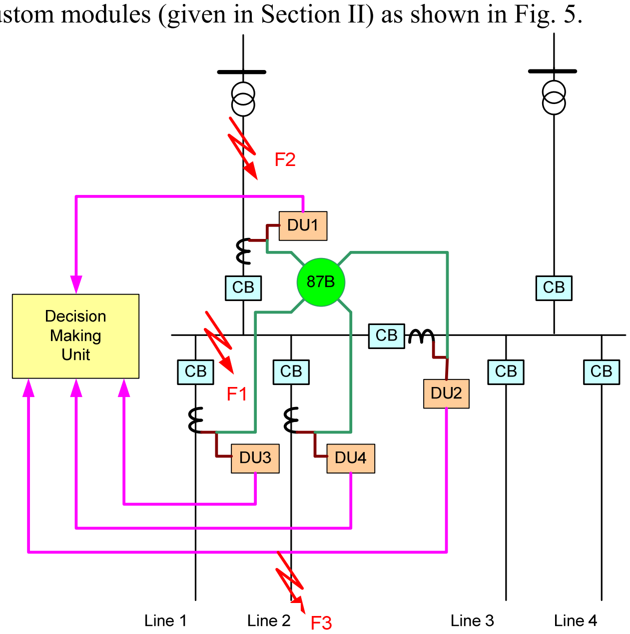

Fig. 5: Protection scheme

The conventional differential busbar protection scheme (87B) was also simulated using a custom model. In this, current phasors are extracted using the Fast Fourier Transform (FFT) module in PSCAD/EMTDC with a base frequency of 60 Hz, which is equivalent to the one cycle Discrete Fourier Transform (DFT) used in most conventional relays. The current transformers were simulated using a detailed simulation model [18]. The standard C400 current transformers were assumed at 2000:5 ratio. A simulation time step of 5 μs was used and the current signals were sampled at 20 kHz.

The performance of the proposed method was compared against the covenantal method, in terms of both speed and reliability and results are summarized below.

IV. Simulation Results

A. *Internal Fault Identification*

In order to investigate the performance of the proposed protection scheme during the internal faults, the fault F1 (shown in Fig. 5) was considered. Simulations were repeated for different types of faults (L-G, LL-G, LLL-G, LL, LLL, etc) at different fault impedances. Fig. 6 shows the Level-1 wavelet transform coefficients (WTCs) observed by each directional unit and the corresponding output signals during a phase-to-phase fault.

As it can be seen from Fig.6, all the wavelet coefficients are of the same sign. Thus the output signals determined by all the directional units are the same. Based on this information the protection scheme can correctly recognized this situation as an internal fault. The operation of the conventional differential protection scheme during this fault is shown in Fig. 7. As it can be seen from Fig.7, the operating point has moved into operating/trip region during the fault disturbance. Thus the differential protection scheme was also able to correctly identify the internal fault situation.

The response times of the two protection methods are compared in Fig. 8. The fault was occurred at 0.513 s. As it can be seen from Fig.8, the response time of the wavelet based method was less than 2 ms whereas that of the conventional method was close to 5 ms. Similar response was observed during the other types of internal faults simulated at different fault impedances with different fault inception angles.

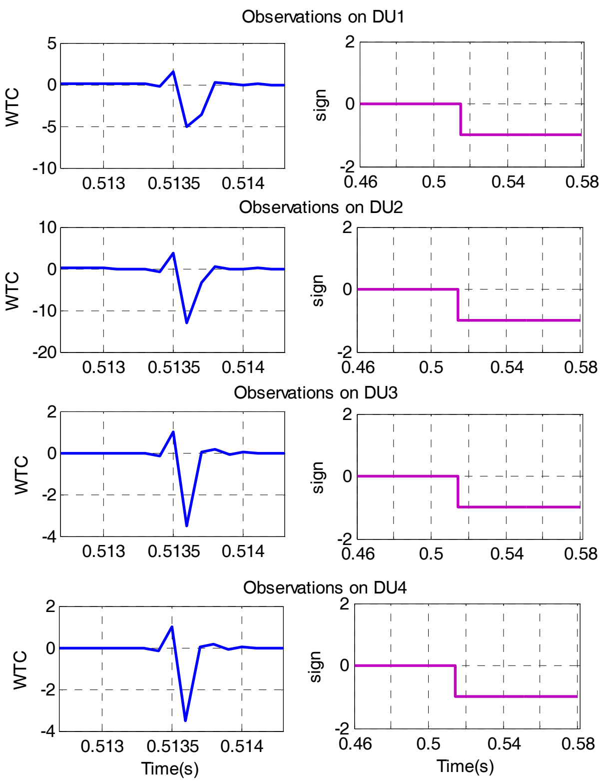

Fig 6: WTCs observed by the directional units and their output during the internal fault, F1

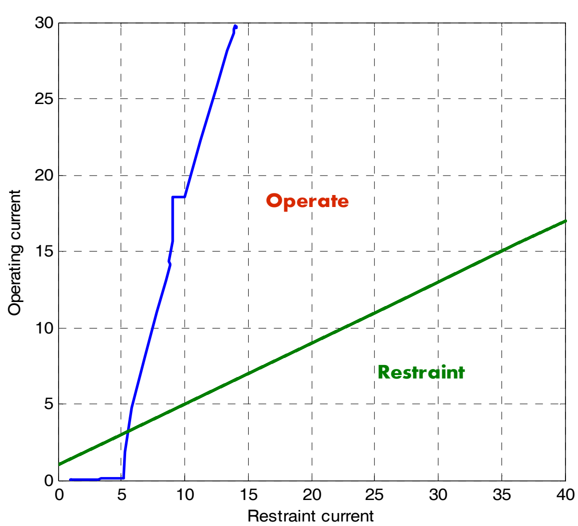

Fig 7: Operation of the differential protection scheme during the internal fault, F1

In order to investigate the response of the proposed protection scheme under external fault situations, simulations were carried out for different types of external faults simulated with different fault impedances at different locations of the network. Figure 9 shows the WTCs observed by different directional units and their output signals during the external fault F2 shown in Fig. 5.

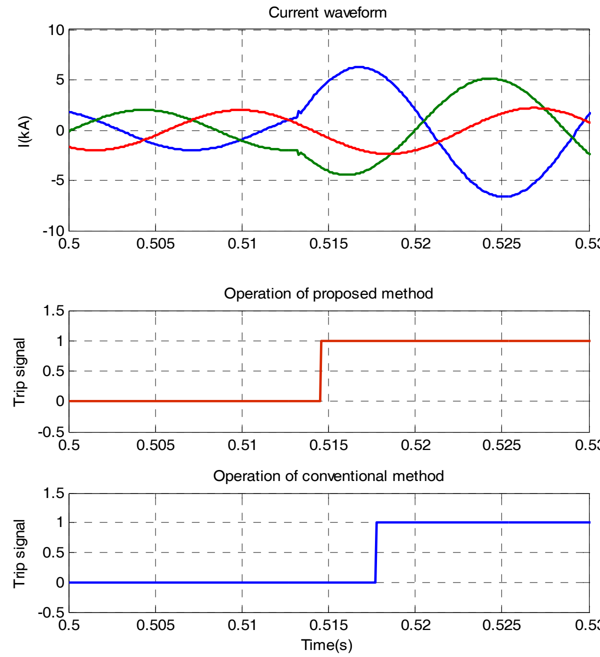

Fig 8: Speed comparison for internal fault, F1

B. *External Fault Identification*

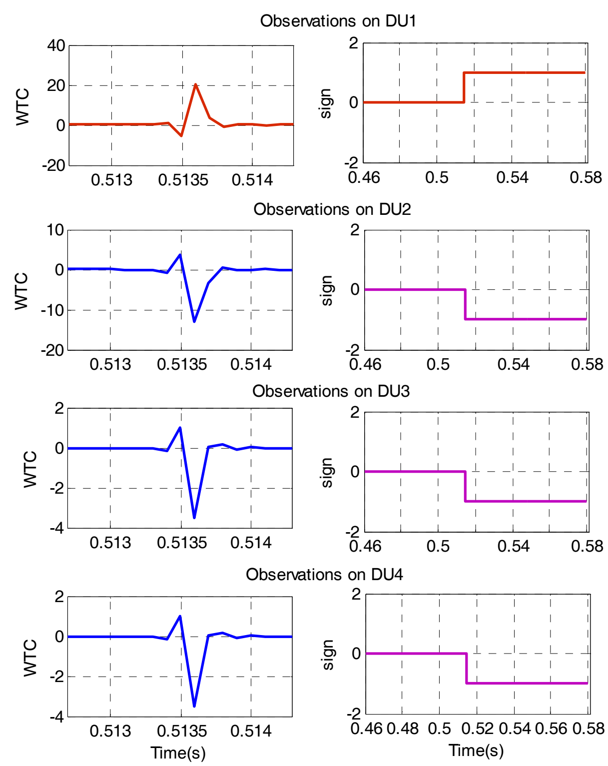

Fig 9: WTCs observed by the directional units and their output during the external fault F2

As it can be seen from Fig. 9, the WTCs determined on the faulted branch (DU1) is having a sign opposite to those of the others. Based on this information, the protection scheme can correctly recognize this situation as an external fault. The operation of the conventional protections scheme during this fault was also investigated and results are shown in Fig. 10. As it can be seen from Fig. 10, the operating point was restrained outside the operating/trip area as intended.

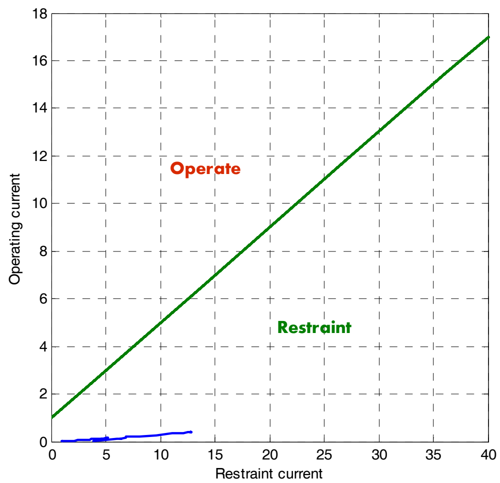

Fig 10: Operation of the conventional differential protection scheme during the external fault, F2

C. *Effect of CT Saturation*

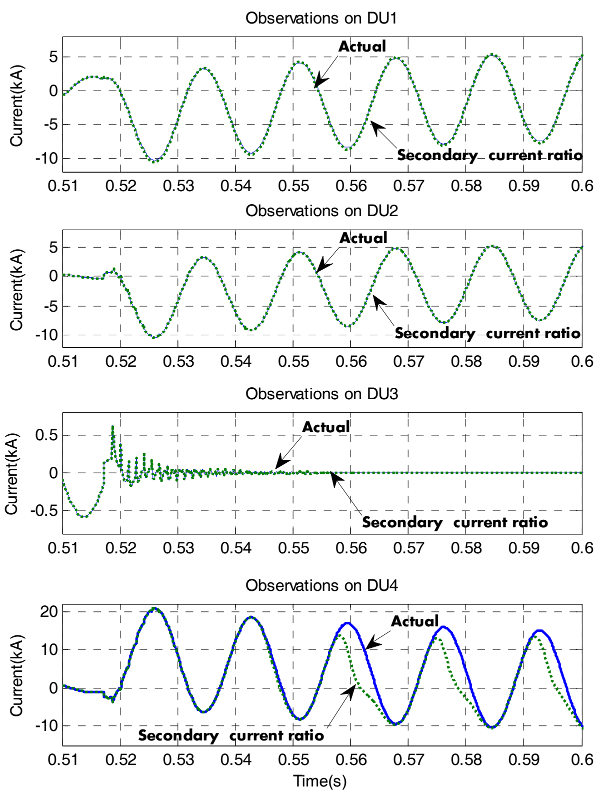

Fig 11: CT secondary current waveforms during the external fault F3

Malfunctioning of the conventional differential protection method during external faults due to the measurement errors caused by current transformer (CT) saturation is a common problem. In this study, simulations were carried out to investigate the behavior of the proposed protection method during such situations. The external F3 (shown in Fig. 5) was simulated with a high dc offset that results in saturation of CTs on line-2 (DU4). The phase-A CT secondary current waveforms observed during this fault on all the CTs are shown in Fig. 11. As it can be seen from Fig.11, the CT on faulted branch (DU4) has gone into a late saturation while the other CTs are not saturated. This ultimately leads to erroneous operation of the conventional differential protection scheme as shown in Fig.12.

The proposed protection scheme operates based on the initial transient originating form the fault which is observed well before the occurrence of the CT saturation. Thus the proposed method is capable to correctly identifying the faults irrespective of CT saturation. The WTCs observed by the directional units and their output signals during this fault are shown in Fig.13.

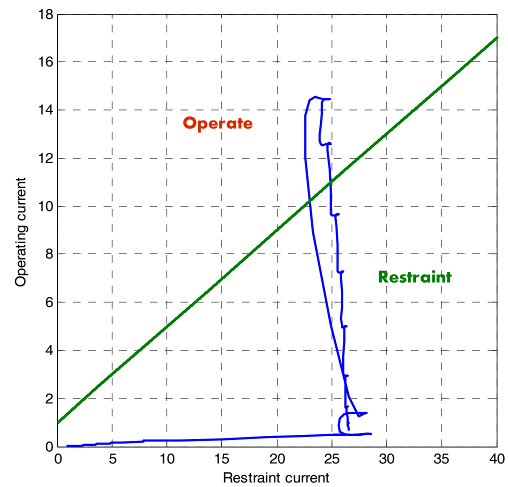

Fig 12: Operation of the conventional differential protection scheme with CT saturation during the external fault, F3

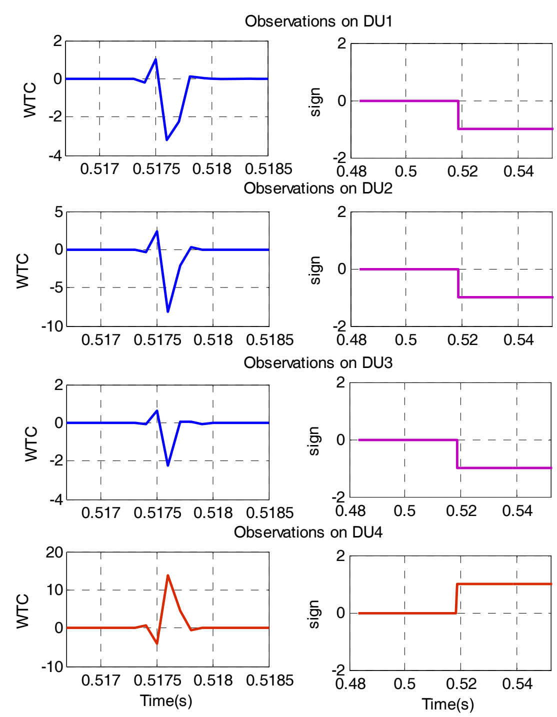

Fig 13: The WTCs observed by the directional units and their output signals during the fault F3

Simulations were carried out to investigate the effect of the CT ratio errors on the performance by introducing random ratio errors (up to 5%) on CTs. Results showed that the proposed method is capable of operating correctly irrespective of the ratio errors, while the conventional differential relay malfunctions at some instances.

D. Effect of Mother Wavelet

In order to investigate the robustness of the proposed protection scheme with reference to the type of the mother wavelets, simulations were carried out for different types of mother wavelets such as 'db1', 'db2', 'db4', 'db8', etc.. The results obtained using the wavelets 'db1' and 'db2' found to be erroneous. Increase in sampling frequency up to 100 kHz showed accurate results for 'db1' and 'db2'. Further the studies were carried out to investigate the effectiveness of different mother wavelets under different noisy conditions. The mother wavelets 'db4' and 'db8' were found to be more accurate under noisy conditions.

E. Computational Latencies

Computational latency of the proposed protection scheme is mainly depends on the time delays involve in calculation of wavelet coefficients and coefficients of cross-correlation. The calculation of detail-1 'db4' discrete wavelet coefficient involves time delays equivalent to 8 samples. The calculation of coefficients of cross correlation involves a time delay equivalent to 14 samples. The calculations were repeated after each 8 samples. Thus a minimum time delay equivalent to 30 samples is involved in this implementation. This is equal to 1.5 ms for 20 kHz sampling frequency.

F. Other Considerations and Future Work

The effect of mutual coupling between the transmission lines may affect the performance of the proposed protection method when double circuit transmission lines are connected to the same busbar. In order to investigate the effect of mutual coupling on the performance of the protection scheme, transmission lines 1 and 2 were simulated on the same corridor. Operation of the protection scheme was tested during the different types of external and internal faults with different fault impedances. The results obtained so far showed that the proposed protection scheme operates correctly irrespective of the effect of mutual coupling between the transmission lines. Further studies are being carried out to investigate the effects of mutual coupling using a more complex actual transmission network configuration.

Furthermore, laboratory prototype of the proposed protection scheme is being implemented. The Texas Instrument TMS32^{TM} family floating point DSK [19] is used for the implementation. A test setup based on the power system waveform generator, Real Time Playback (RTP) [20] is under development for investigating the operation of the prototype using the recorded transient waveforms. The RTP unit is capable of playing back the simulated waveforms as well as actual waveforms obtained from fault recorders.

V. Conclusion

A protection scheme based on transient directional principle was proposed for busbar protection. The wavelet transform was used to extract the traveling fronts of the current transients originating from the faults. The models required to simulate the protection scheme was implemented in an EMT type simulation program. The performance proposed method was compared against the conventional differential protection method using a test network simulated in the EMT simulation environment. Simulation results showed that proposed method can recognize faults in the busbar zone in less than a quarter of a power cycle and confirmed its robustness against CT saturation and other conditions that pause problems to conventional bus differential protection. Further investigations are being carried out to study the performance of the proposed method using a laboratory prototype.

VI. Appendix

The discrete wavelet transformation (DWT) of discrete function *f(k)* is defined as,

$$DWT_{\psi} f(m,n) = \sum_{k} f(k)\psi^{*}_{m,n}(k)$$

where, $\psi_{m,n}$ is the discretized mother wavelet given by,

$$\psi_{m,n}(k) = \frac{1}{\sqrt{a_0^m}}\psi\left(\frac{k - nb_0 a_0^m}{a_0^m}\right)$$

where a_o (>1) and b_o (>0) are fixed real values and *m* and *n* are positive integers.

VII. References

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