Fast Fault Detection Challenge for Alienation Coefficient Based Bus Fault Discriminator

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***Abstract*—One of the latest fault discrimination algorithms used to supervise bus differential protection schemes, is Alienation Coefficient Algorithm (ACA). ACA uses alienation coefficient of current signals during first one-eighth cycle after fault inception to discriminate between internal and external faults. Therefore, the performance of ACA highly depends on fault detection speed. This paper examines the performance of ACA for currently used fault detection technique and the results reveal that ACA fails to detect external fault in case of fast current transformer (CT) saturation. This paper also proposes an alternative fault detection technique for ACA and presents a simulation study to validate the performance. Documented results show that ACA with the new fault detection technique performs better for fast CT saturation during close-in external faults.**

I. Introduction

Busbar is the most critical element of a power system, as it is the connection point of many transmission lines, transformers, generators and loads. The effect of a single bus fault is equivalent to many simultaneous faults and usually, due to the concentration of supply circuits, involves high current magnitude. Any incorrect operation of bus bar protection would cause the loss of all these elements. Therefore, protection of busbar demands high speed, reliability and stability. Failure-to-trip on an internal fault, as well as false tripping of a busbar during service or in case of an external fault, can both have disastrous effect on the stability of the power system, and may even cause a complete blackout of the system. So, it is very essential to incorporate precision and reliability factors in the design of a busbar protection scheme.

It was a very old practice in small substations to be cost effective by providing simply over-current relays for the protection of a busbar without a dedicated protection scheme. With the increase in substation equipment and feeder complexity, it became necessary to use reliable busbar protection schemes.

Recently, micro-processor based low impedance differential protection scheme has become popular for busbar protection. Low impedance differential protection scheme works based on operating current which is the summation of all CT secondary currents. Practically summation of the secondary current is not zero even for normal operating conditions because accurate matching of characteristics of current transformer cannot be achieved. Hence there may be spill current flowing through the relay in normal operating conditions. Moreover, there may be a probability of mismatching in cable impedance from CT secondary to the remote relay panel. These uneven pilot cables capacitance causes high current through the relay operation coil when external through fault occurs. This operating current is known as false operating current and it becomes high during high loading conditions or high system congestion. To overcome these issues, various restraint characteristics [1-3] have been adapted with low impedance differential scheme. Under normal and through fault conditions, operating current is less than a percentage of restraining current therefore relay remains inactive. During an internal fault, the operating current becomes greater than a percentage of restrained current and the relay operates.

The main application issue with this modified differential protection is mal-operation in response to the CT saturation during close-in external faults. The CT saturation during close-in external faults creates high operating (differential) current which can cause the undesired operation of the relay. The primary reason of these mis-trips is that the traditional percentage differential principle works based on current magnitude rather than directionality for tripping decisions. Hence, proper discrimination of external and internal faults becomes the main concern for the performance of busbar differential protection.

Numerous fault discrimination techniques [4-13] were proposed by exploring various aspects of busbar faults. One of the latest proposed techniques of busbar fault discrimination is based on Alienation Coefficient Algorithm (ACA) [14-16]. The technique uses alienation coefficient of two current signals from two-terminal equivalent busbar configuration to determine the location of the faults. The algorithm declares internal fault if alienation coefficient becomes greater than zero during first one-eighth (1/8) cycle time-window from fault inception. The technique has two major challenges: i) the fault discriminator can enter a non-deterministic state due to the change in system topology which is addressed by introducing Dynamic Current Allocation Algorithm (DCAA) [17] and ii) the delay in detecting fault inception to trigger one-eighth (1/8) cycle window of fault discrimination can affect the algorithm performance. The existing fault detection technique works on traditional over-current principle using the phasor magnitude of the through current of a differential zone. The phasor quantity does not change instantaneously with fault inception which may cause potential mis-trips during external faults when CT becomes saturated. This paper examines the performance of the fault detection technique used in ACA in various CT saturation conditions during external faults. An alternative fault detection technique is proposed using first-derivative of instantaneous current signal to prevent potential mis-trips initiated by delayed fault detection.

The remainder of this paper is as follows. Section II of this paper describes the basic principle of ACA based fault discriminator including existing fault detection technique. Simulation based performance analysis of existing fault detection technique is presented in Section III. Development of the proposed fault detection technique is described in Section IV. A simulation study is featured in Section V to verify the performance of modified fault discriminator including proposed fault detection technique. Concluding remarks are made in Section VI.

II. Fault Discriminating Principle

Fault discriminating technique illustrated in Fig. 1 comprises two main components including i) fault detector: detection of fault inception to trigger one-eighth cycle timer and ii) ACA: implication of discriminating logics based on calculated alienation coefficient. The output of fault detector and fault discriminator is denoted by FD_Φ and IFT_Φ, respectively.

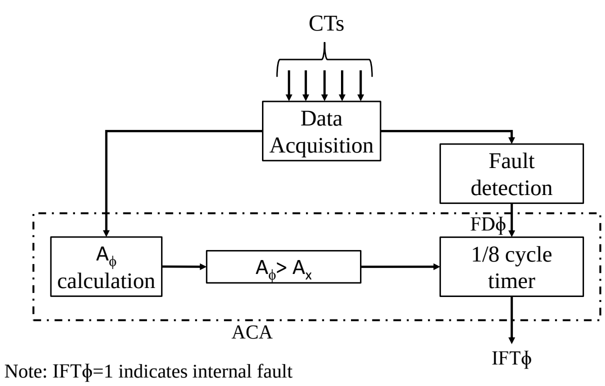

Fig. 1. Fault discriminating technique based on ACA

A. Fault Detection

The existing fault detection technique works on traditional over-current principle using the phasor magnitude of the through current of a differential zone. For phase-Φ (Φ = A, B, C), through current ($I_{\Phi t}$) is defined by Equation (1), where n is the number of terminals connected to the busbar.

$$I_{\Phi t} = \frac{1}{2}\sum_{k=1}^{n} I_{\Phi k} \tag{1}$$

The fault detector declares a fault when the change in through current ($\Delta I_{\Phi t}$) is greater than 20% of busbar nominal current (I_n).

B. Alienation Coefficient Algorithm (ACA)

The alienation coefficient (A_Φ) is the indicator of non-similarity between two current signals which is calculated from cross-correlation (r_Φ) shown in Equation (2).

$$A_\Phi = 1 - (r_\Phi)^2 \tag{2}$$

Correlation coefficient (r_Φ) between two equivalent currents $i_{\Phi E1}$ and $i_{\Phi E2}$ is calculated by Equation (3).

$$\begin{aligned} r_\Phi = (&\sum_{n=1}^{m} i_{\Phi E1} i_{\Phi E2} - (1/m)\sum_{n=1}^{m} i_{\Phi E1}\sum_{n=1}^{m} i_{\Phi E2})/ \\ &\sqrt{(}(\sum_{n=1}^{m} i_{\Phi E1}^2 - (1/m)(\sum_{n=1}^{m} i_{\Phi E1})^2)(\sum_{n=1}^{m} i_{\Phi E2}^2 \\ &\qquad -(1/m)(\sum_{n=1}^{m} i_{\Phi E2})^2)) \end{aligned} \tag{3}$$

In Equation (3), m represents sample size per cycle. The two-terminal equivalent representation of a busbar is obtained by using Dynamic Current Allocation Algorithm (DCAA). DCAA arranges all terminal currents of each phase into two groups, resulting in two equivalent currents $i_{\Phi E1}$ and $i_{\Phi E2}$.

Alienation coefficient (A_Φ) calculated between two current signals found from the two-terminal equivalent representation of a busbar for each phase, is used to determine busbar fault type whether internal or external to make a trip or no trip decision for a relay [14-16]. It is known that during normal operation or external faults without CT saturation $i_{\Phi E1}$ is equal to $i_{\Phi E2}$; therefore, A_Φ is zero. During internal faults, the alienation coefficient between $i_{\Phi E1}$ and $i_{\Phi E2}$ becomes high instantaneously after fault inception [14-16]. During external faults with CT saturation, the alienation coefficient between $i_{\Phi E1}$ and $i_{\Phi E2}$ could become high; however, it remains very low (close to zero) during the first one-eighth (1/8) cycle after fault inception. The algorithm declares internal faults if $A_\Phi > A_x$ within 1/8 cycle after fault detection; otherwise, fault is external to the protection zone, where A_x is equal to 0.05 [14-16].

III. Perforamnce Evaluation of Existing Fault Detector

As mentioned above ACA works on instantaneous current signals; however, fault detector works on phasor magnitudes. The phasor quantity does not change sharply at the inception of faults. The rate of change of phasor quantity depends on the change in instantaneous signals and sampling rate. Time difference between fault detection and CT saturation can be less than 1/8 cycle or 2.084ms (in 60Hz system) due to delayed fault detection. The above scenario during external faults can cause a mis-trip as A_Φ becomes high instantaneously with CT saturation. A simulation study is conducted to examine the performance of the alienation coefficient-based fault discriminator including existing fault detector for above-mentioned external fault scenarios. The network shown in Figure 2 was simulated in EMTP for various external faults (faults applied at $F1$) by varying fault resistance (R_f) and fault inception time

TABLE I
PERFORMANCE ANALYSIS WITH EXISTING FAULT DETECTOR

Fault	Location	R_f (Ω)	Time (ms) T1	T2	T3	T3 - T2	Response of discriminator
AG	F1	0.1	47	48.56	50.23	1.67	**Internal fault**
AG	F1	5	47	48.64	50.56	1.92	**Internal fault**
AG	F1	10	47	48.73	50.98	2.25	External fault
AG	F1	0.1	49	50.15	51.77	1.62	**Internal fault**
AG	F1	5	49	50.23	52.10	1.87	**Internal fault**
AG	F1	10	49	50.31	52.52	2.21	External fault
ABG	F1	0.1	47	48.73	50.48	1.75	**Internal fault**
ABG	F1	5	47	48.81	50.77	1.96	**Internal fault**
ABG	F1	10	47	48.90	51.23	2.23	External fault
ABG	F1	0.1	49	50.23	51.90	1.67	**Internal fault**
ABG	F1	5	49	50.31	52.19	1.88	**Internal fault**
ABG	F1	10	49	50.40	52.60	2.20	External fault

considering fast CT saturation. Bus1 is the targeted differential protection zone and the value of I_n is considered 2000A.

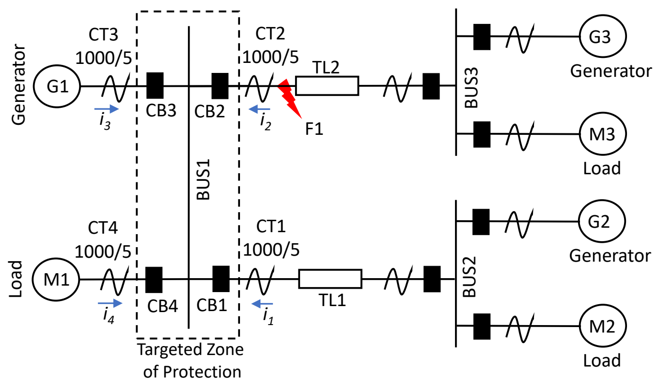

Fig. 2. Test System

The results are documented in Table I. T_1 & T_2 represent fault inception time and fault detection time, respectively. T_3 is the time instant when A_Φ becomes high. For external faults, A_Φ becomes high instantaneously with the start of CT saturation. The results show that the existing fault detector needs 1.15ms to 1.9ms after fault inception to detect faults, which results in $(T_3 - T_2)$<2.084ms or 1/8 cycle for some external fault events. Subsequently the fault discriminator responds incorrectly by detecting an external fault as an internal fault. A selected case study is discussed in detail in the following Subsection.

A. Case Study: Phase-ground external fault

Fig. 3 shows instantaneous A-phase current signals of terminals connected to Bus 1 in the event of an A-phase to ground (AG) external fault applied at F_1. The fault inception time T_1 is 47ms. The CT at terminal 2 started saturation at 50.23ms. The corresponding through-current of the bus ($I_{\Phi t}$), calculated alienation coefficient (A_Φ), and responses of the existing fault detector (FD_Φ) as well as fault discriminator (IFT_Φ) are illustrated in Fig. 4. The fault detector delayed 1.56ms to detect fault. The 1/8 cycle timer was started by fault detection at 48.56ms (T_2=48.56ms). The expiration time

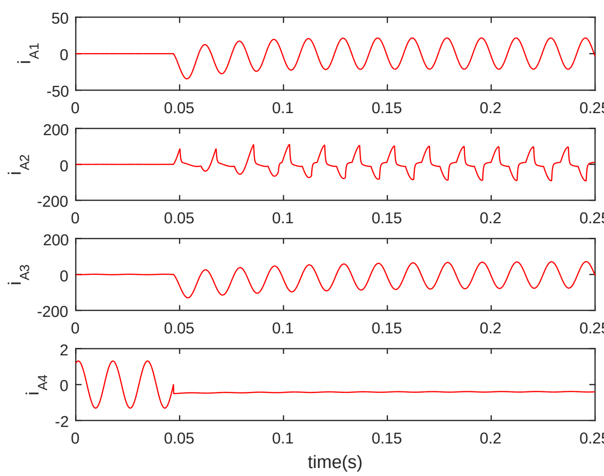

Fig. 3. Instantaneous terminal currents for the event of AG external fault

of 1/8 cycle timer is 50.644ms. However, A_Φ became high at 50.23ms (T_3=50.23ms) instantaneously with the starting of CT saturation at terminal 2 before expiration of 1/8 cycle timer, forcing fault discriminator to identify the fault incorrectly as internal to the protection zone.

The above results indicate that an alternative fault detection method is essential that is able to detect fault inception instantaneously. A new fault detection method is proposed in this paper which is described in the following Section.

IV. PROPOSED FAULT DETECTOR

A. Mathematical Development

The steady-state instantaneous current of k-th terminal ($i_{\Phi k}$) connected to the bus can be expressed as Equation (4).

$$i_{\Phi k}(t) = \sqrt{2} I_{\Phi km} \cos(\omega t + \theta_k) \tag{4}$$

In Equation (4): $I_{\Phi km}$ is rms value of the current, ω is angular frequency and θ_k is phase shift.

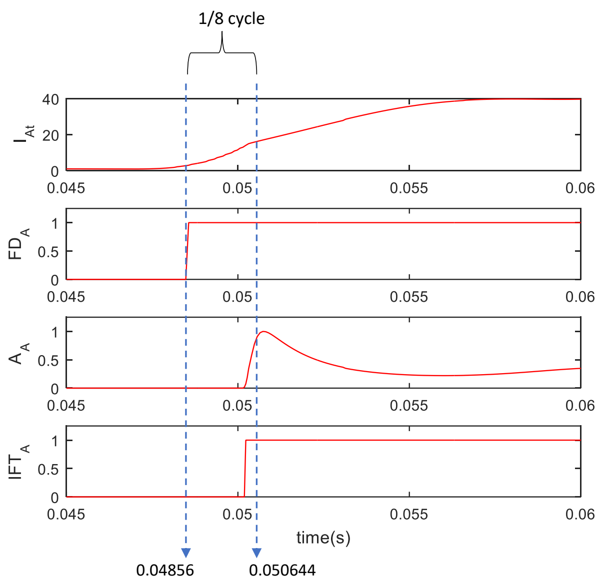

Fig. 4. Responses of the fault discriminator with existing fault detector during AG external fault

The absolute value of first-derivative of $i_{\Phi k}(t)$ is found as Equation (5).

$$|\frac{di_{\Phi k}(t)}{dt}| = \sqrt{2}\omega I_{\Phi km}|\sin(\omega t + \theta_k)| \tag{5}$$

Equation (6) can be derived from Equation (5) since $|\sin(\omega t + \theta_k)|_{max}$ =1.

$$|\frac{di_{\Phi k}(t)}{dt}|_{max} = \sqrt{2}\omega I_{\Phi km} \tag{6}$$

In steady-state rms value remains constant over time which means $I_{\Phi km}(t) = I_{\Phi km}(t-T)$, where T = time period. Therefore, Equation (6) can be re-written as Equation (7).

$$|\frac{di_{\Phi k}(t)}{dt}|_{max} = \sqrt{2}\omega I_{\Phi km}(t-T) \tag{7}$$

However, with the inception of any transient condition (i.e. fault), $i_{\Phi k}(t)$ changes abruptly which results a huge value of $|\frac{di_{\Phi k}(t)}{dt}|$ and the relation of Equation (8).

$$|\frac{di_{\Phi k}(t)}{dt}| >> \sqrt{2}\omega I_{\Phi km}(t-T) \tag{8}$$

Based on Equation (8), a new fault detection algorithm is proposed in the following Subsection.

B. Proposed Fault Detection Algorithm

Figure 5 shows the proposed fault detection algorithm, where n is the number of terminals connected to the bus. The proposed fault detection algorithm works phase-wise as it is used to supervise bus differential protection. Based on Equation (8), the condition of fault inception can be equated as in Equation (9). In Equation (9), S is a marginal constant to avoid mis-detection of fault inception in case of the change in terminal current during normal operating condition (i.e. load change). The value of S must be greater than 1 but not very large. The large value of S can affect the sensitivity of fault detector. In this study, S is set to 2.0.

$$|\frac{di_{\Phi k}(t)}{dt}| > S\sqrt{2}\omega I_{\Phi km}(t-T) \tag{9}$$

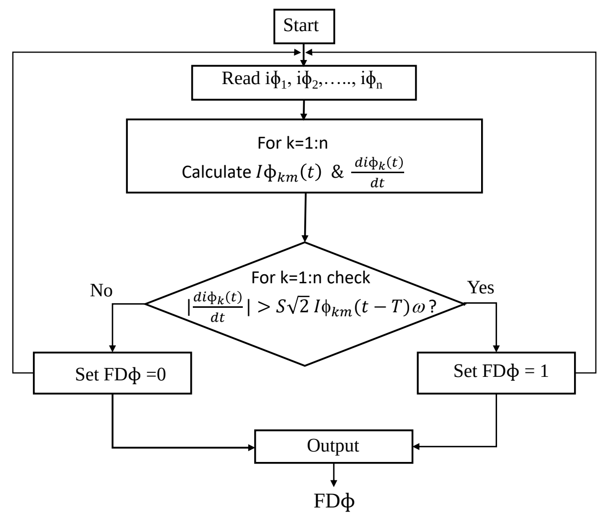

Fig. 5. Proposed fault detection algorithm

V. Performance Validation

The performance of the modified fault discriminator including proposed fault detection algorithm is evaluated for the faults listed in Table I. The results are shown in Table II. The documented results indicate that the proposed fault detector is capable of detecting faults almost instantaneously (maximum time delay is 0.11ms). The fast fault detection results in $(T_3 - T_2)$>2.084ms or 1/8 cycle for all simulated faults and consequently, fault discriminator correctly detects external faults. A fault case is discussed in detail in the following Subsection.

A. Case Study: Phase-ground external fault

The performance of the proposed fault detector and modified fault discriminator is examined by the A-phase to ground (AG) external fault described in Fig. 3. The fault inception time T_1 is 47ms as mentioned earlier. Fig. 6 shows derivative of four terminals current, calculated A_Φ, and the responses of proposed fault detector (FD_Φ) and fault discriminator (IFT_Φ). The derivative of terminal currents became high with the inception of fault and the fault detector detected fault at 47.1ms (T_2 = 47.1ms). The fault detection delay of the proposed fault detector is only 0.1ms which is very small. The 1/8 cycle timer was started at T_2 = 47.1ms by fault detection. A_Φ became high at T_3 = 50.23ms after expiration time of 1/8 cycle timer which ended at 49.184ms. As A_Φ became high after expiration of 1/8 cycle timer, the fault discriminator expectedly identified the fault as an external fault.

TABLE II
PERFORMANCE ANALYSIS WITH PROPOSED FAULT DETECTOR

Fault	Location	R_f (Ω)	Time (ms) T1	T2	T3	T3 - T2	Response of discriminator
AG	F1	0.1	47	47.10	50.23	3.13	External fault
AG	F1	5	47	47.10	50.56	3.46	External fault
AG	F1	10	47	47.10	50.98	3.88	External fault
AG	F1	0.1	49	49.11	51.77	2.66	External fault
AG	F1	5	49	49.11	52.10	2.99	External fault
AG	F1	10	49	49.11	52.52	3.41	External fault
ABG	F1	0.1	47	47.10	50.48	3.38	External fault
ABG	F1	5	47	47.10	50.77	3.67	External fault
ABG	F1	10	47	47.10	51.23	4.13	External fault
ABG	F1	0.1	49	49.11	51.90	2.79	External fault
ABG	F1	5	49	49.11	52.19	3.08	External fault
ABG	F1	10	49	49.11	52.60	3.49	External fault

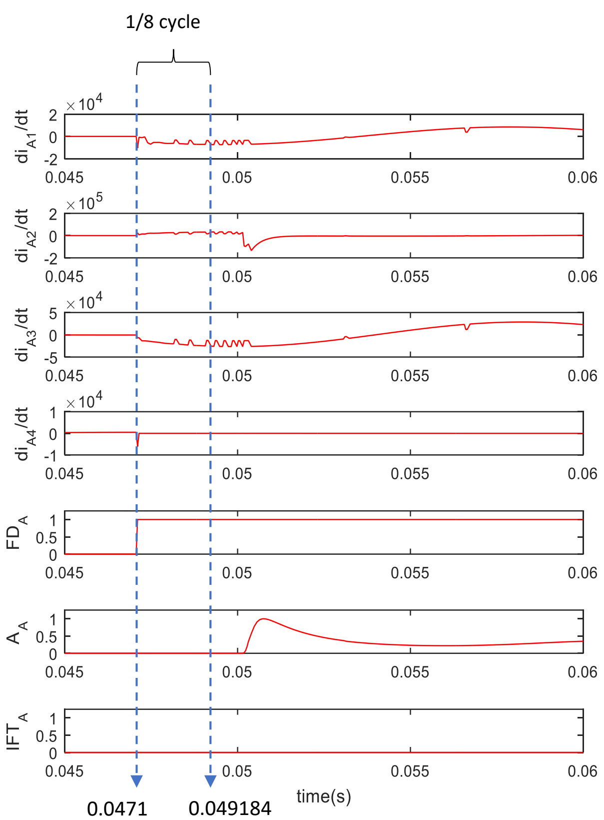

Fig. 6. Responses of the fault discriminator with proposed fault detector during AG external fault

VI. CONCLUSION

This paper examines the performance of alienation coefficient-based bus fault discriminator including existing fault detector by simulation study. The study suggests that existing fault detector can introduce mis-operation during external faults due to delayed fault detection. An alternative fault detection method is proposed based on the first derivative of instantaneous terminal current to overcome the aforesaid problem. The performance of the proposed fault detector is validated by simulation study. The results of the study indicate that the proposed method is able to detect fault inception almost instantaneously which addresses the risk of mis-operation of alienation coefficient-based bus fault discriminator.

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