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A New Approach to High Impedance Fault Detection Based on Correlation Functions

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Abstract. Detection of High Impedance Fault (HIF) that is mainly occurred in MV power systems has been a challenge due to its low current magnitude. A new HIF detection approach based on correlation functions is applied on the voltage and current signals in this paper. Twelve indices based on correlation functions are implemented and tried on a lot of cases. Some of them which have clearly different values for no-fault and HIF conditions are chosen. Simulation results prove the efficiency of proposed method for HIF detection.

Keywords: high impedance fault detection (HIF), auto correlation function (ACF), partial auto correlation function (PACF), SACF, SPACF.

1 Introduction

The high impedance fault (HIF) is an abnormal electrical condition which may affect human lives wherever the feeders and the living areas have any overlaps. The HIF is usually occurred in the distribution feeders because of their low height in comparison with high voltage transmission lines. This fault is happened when an unexpected connection appears between a feeder and the ground by a high impedance object. Most of the time, it is generated by falling a broken conductor of an energized line on the ground or connection between tree branches to the line. In electrical point of view if a high impedance object produces a parallel loop with the load in a circuit while the line is loaded as much as nominal current, then the over-current which is imposed by fault would be low in contrast to load current. So, this phenomenon is called HIF. Since the basis of operation for conventional relays is current magnitude, HIF flow cannot be detected by mentioned relays.

A review of many approaches on HIF detection from classical to heuristically algorithms is done in [3] that is a useful guideline.

Operating principle of HIF detection is reviewed and possible future technologies is discussed in [5]. Discrete wavelet transformer technique in [2], [6] and [7], artificial neural network in [4] is used to detection of HIF. Besides, some others such as [1] and [8] used low frequency harmonic analysis to detection.

In this paper, a new approach for HIF detection based on correlation functions is proposed. It is found that the values of correlation functions applied on voltage, current and also their derivations during the system healthy conditions are different from their values when high impedance fault occurs. To show the benefits of correlation functions in HIF detection, the paper will be continued with five sections. A brief summary of the correlation function theory and proposed indices for this purpose will be discussed in section 2. Then a case study system with using of two different models of high impedance fault is used for data collection in section 3. Simulation results of the case study system using PSCAD/EMTDC software are presented in section 4. The conclusion is given in section 5.

2 A brief theory of correlation functions

Auto correlation function (*ACF*) and partial auto correlation function (*PACF*) that are defined by equations 1 and 2 respectively are applied to detect any abnormal changes in a signal.

$$r_k = \frac{\sum_{t=1}^{n-k} (Z_t - \mu)(Z_{t+k} - \mu)}{\sum_{t=1}^n (Z_t - \mu)^2} \quad k = 1, 2, 3, \dots \quad (1)$$

$$r_{kk} = \begin{cases} r_1 & \text{if } k = 1 \\ \frac{r_k - \sum_{j=1}^{k-1} r_{k-1,j} r_{k-j}}{1 - \sum_{j=1}^{k-1} r_{k-1,j} r_j} & \text{if } k = 2, 3, \dots \end{cases} \quad (2)$$

where

$$r_{k,j} = r_{k-1,j} - r_{kk} r_{k-1,k-j} \quad j = 1, 2, \dots, k-1$$

r_k and r_{kk} symbolize ACF_k and $PACF_k$ respectively. n is time series window length and μ is the mean of time series. To get a good performance it's better to use summation of *ACF* and *PACF* components. So, in the present approach two more functions are defined to distinguish the normal case from HIF.

SACF: Summation of *ACF* components of a window including k number of samples that is called *SACF*. Related equation is as follows:

$$SUM_{ACF} = \sum_{k=1}^{k_{\max}} r_k \quad (3)$$

SPACF: This function is defined similar to *SACF* but the difference is that the *PACF* components have been used to make it. Equation (4) belongs to *SPACF*.

$$SUM_{PACF} = \sum_{k=1}^{k_{\max}} r_{kk} \quad (4)$$

Here six signals are used instead of Z in equations (1) and (2) which are as follows:

$$di_n = i_n - i_{n-1} \quad (5)$$

$$dv_n = v_n - v_{n-1} \quad (6)$$

$$d^2i_n = di_n - di_{n-1} \quad (7)$$

$$d^2v_n = dv_n - dv_{n-1} \quad (8)$$

where i and v are the current and voltage at relay placement. d and d^2 denote the first and second differences. Both *SACF* and *SPACF* functions are applied to all six above signals to obtain 12 indices as follow:

$$sacfi = \sum_{k=1}^{k_{\max}} r_k(i) \quad (9) \quad sacfv = \sum_{k=1}^{k_{\max}} r_k(v) \quad (10)$$

$$spacfi = \sum_{k=1}^{k_{\max}} r_{kk}(i) \quad (11) \quad spacfv = \sum_{k=1}^{k_{\max}} r_{kk}(v) \quad (12)$$

$$sacfdi = \sum_{k=1}^{k_{\max}} r_k(di) \quad (13) \quad sacfdv = \sum_{k=1}^{k_{\max}} r_k(dv) \quad (14)$$

$$spacfdi = \sum_{k=1}^{k_{\max}} r_{kk}(di) \quad (15) \quad spacfdv = \sum_{k=1}^{k_{\max}} r_{kk}(dv) \quad (16)$$

$$sacfd^2i = \sum_{k=1}^{k_{\max}} r_k(d^2i) \quad (18) \quad sacfd^2v = \sum_{k=1}^{k_{\max}} r_k(d^2v) \quad (19)$$

$$spacfd^2i = \sum_{k=1}^{k_{\max}} r_{kk}(d^2i) \quad (20) \quad spacfd^2v = \sum_{k=1}^{k_{\max}} r_{kk}(d^2v) \quad (21)$$

where $r_k(v)$ denotes k th component of voltage's *ACF*. Other equations are similarly defined.

3 Case Study system

One case study system with two different HIF models is implemented in figures 1 and 2. Case study system belongs to a radial cable feeder of a medium voltage (25 kv) system. Single line diagram of the case study system with the HIF model 1 is given in

figure.1. V_s and I_{st} are the relay voltage and current which are used for sensing the HIF. The connected load to the feeder is assumed to be constant at the end of the line. HIF model 1 is explained through equation (22) and figure.1.

$$L_f = 3mH, R_f = R_{f0} \left(1 + \alpha \left(\frac{i_f}{i_{f0}}\right)^\beta\right) \quad (22)$$

Where $R_{f0} = 20$, $i_{f0} = 70$, $\alpha = 0.6$, $\beta = 2$, $V_{L-L} = 25 kV$, $f = 60 Hz$

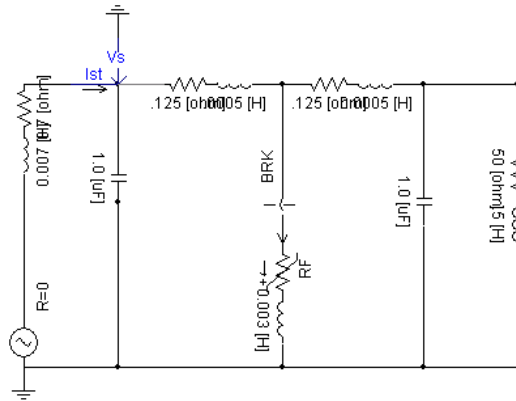


Fig. 1. The case study system with HIF model 1

The model circuit with the description of second HIF model is given in figure.2. Figure.3 shows the case study system used in figure.1 which applied HIF model 2 in figure.2. Where $i(t)$, u_p , R and l_p represent arc current, constant voltage parameter per arc length, resistive component per arc length and arc length respectively. It is considered that R ($R=9\Omega/cm$) and l_p ($l_p=10 cm$) are constant. The fault is occurred in the middle of the feeder.

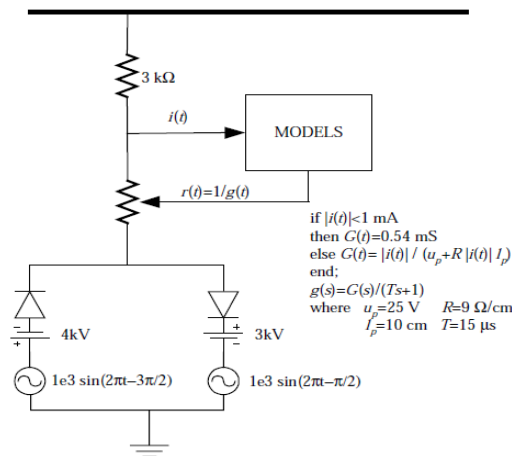


Fig. 2. Circuit and description of HIF model 2 [2]

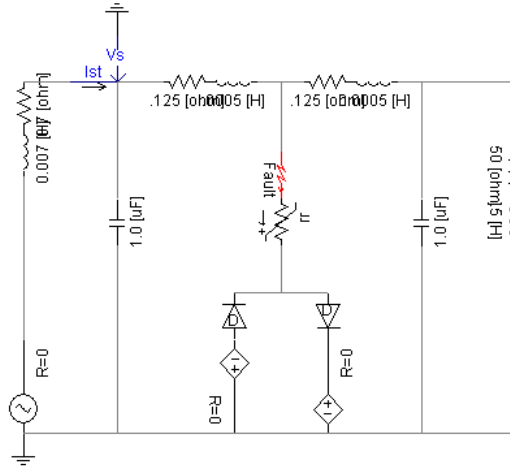
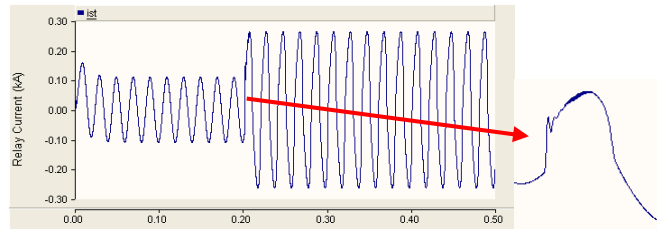


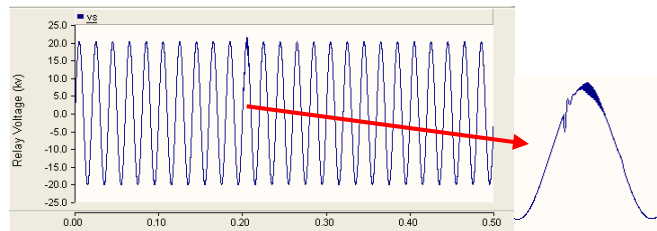
Fig. 3. The case study system with HIF model 2

The voltage and current curves of the case study system with both of HIF models which are simulated in PSCAD/EMTDC software are shown in figures 4 and 5. In these simulations, the time duration is 500 ms, the fault occurs in 202 ms and the sampling time is 50 μ s.

As can be seen in figure.5, no sign of any events for model 2 is visible in both current and voltage of relay.

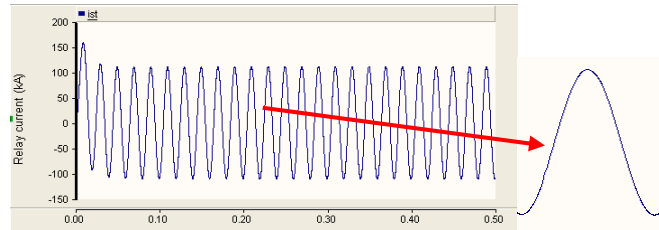


(a)

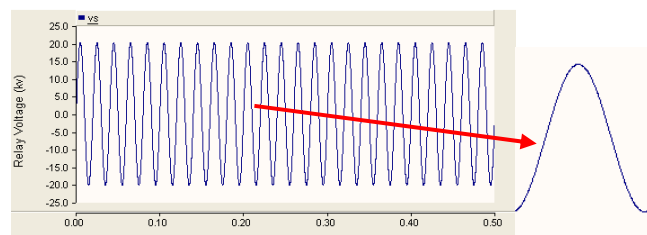


(b)

Fig. 4. (a) current and (b) voltage results of case study system with HIF model 1



(a)

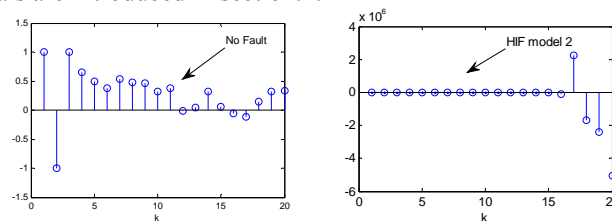


(b)

Fig. 5 (a) current and (b) voltage results of case study system with HIF model 2

4 Implementation of new approach

After utilizing correlation functions on voltage, current and also their derivations samples, it is specified that both $SACF$ and $PSACF$ can be acceptable factors for HIF detection. For better perception, stem diagrams of some indices for both HIF models are shown in figure.6. k on the horizontal axis is plotted against ACF and $PACF$ values. In this case, k_{max} is equal to 20. As can be seen, the majority of $pacfi$ ($PACF_i$) and $pacfdv$ ($PACF_{dv}$) values and all of $acfdv$ (ACF_{dv}) values are positive in no fault condition while in HIF phenomenon there are both positive and negative. Briefly, feature pattern of three indices show differences for both conditions. If in each diagram the summation of all 20 data is calculated, the summation result will be a big positive number in no fault condition while it will be approximately zero in HIF event. So, it can be used for HIF detection. $SACF$ and $SPACF$ functions for all six of relay-side signals are introduced in section.2.



(a)

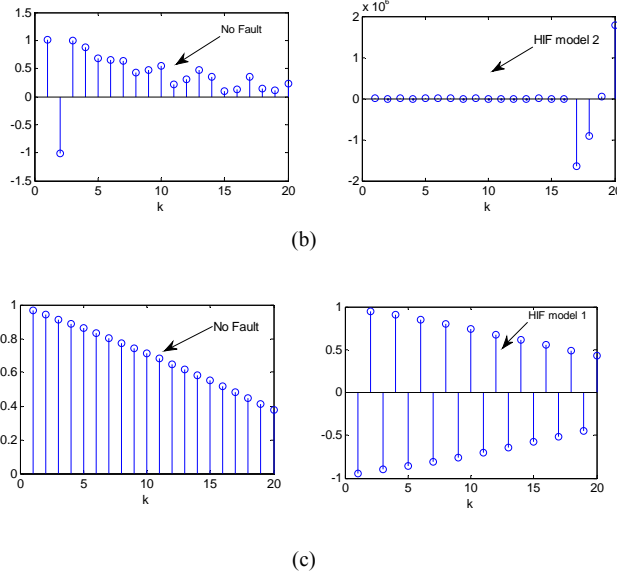


Fig. 6. comparing feature pattern of (a) *pacfi* (b) *acfd2v* (c) *acfdv* for both no-fault and HIF conditions ($n=100, k=1, \dots, 20$)

On the first step, the time window (including N samples with sampling time equal to $50 \mu\text{s}$) is assumed. Two different windows are considered.

The two windows are assumed to have the same length.

The indices values are experimented for $n=40, 80, 100, 200$ and $k_{max}=10, 20, 40$ in both HIF and no fault states. The values of all 12 mentioned indices for $n=40$ and $k_{max}=10$ are given in tables I to IV.

Table 1. Current's *ACF* results for static window in no fault condition ($n=40$ and $k_{max}=10$)

<i>Fault time</i> (s)	<i>Current</i>					
	<i>sacfv</i>	<i>sacfdv</i>	<i>sacfd²v</i>	<i>spacfv</i>	<i>spacfdv</i>	<i>spacfd²v</i>
0.200	6.5900	6.5085	6.3878	4.0011	4.5190	4.6588
0.201	6.6192	6.4370	6.4153	4.0940	4.4195	4.6484
0.202	6.6264	5.3030	6.4222	4.5049	4.9448	5.1292
0.203	6.6248	6.2117	6.4206	4.2429	4.7193	5.0486
0.204	6.6116	6.4814	6.4083	4.4522	4.6284	4.7855
0.205	6.5568	6.5176	6.3564	4.4555	4.8640	5.0938
0.206	5.9560	6.5267	5.7754	4.3321	4.6874	4.8726
0.207	6.1057	6.5263	5.9225	4.1080	4.4797	4.7678
0.208	6.5651	6.5162	6.3643	4.5088	4.6646	4.8468
0.209	6.6134	6.4754	6.4099	3.8506	4.3387	4.6272
0.210	6.6252	6.1363	6.4210	3.5469	4.3965	4.6285

Table 2. voltage's *acf* results for static window in no fault condition ($n=40$ and $k_{max}=10$)

<i>Fault time</i> (s)	<i>Voltage</i>					
	<i>sacfv</i>	<i>sacfdv</i>	<i>sacfd2v</i>	<i>spacfv</i>	<i>spacfdv</i>	<i>spacfd2v</i>
0.200	6.6228	6.3595	6.4187	5.0753	5.9513	7.0459

Fault time (s)	Voltage					
	sacfv	sacfdv	sacfd2v	spacfv	spacfdv	spacfd2v
0.201	6.6040	6.4967	6.4011	4.2844	4.8190	5.2745
0.202	6.5153	6.5213	6.3171	4.0917	4.5285	4.8304
0.203	4.8080	6.5273	4.5936	4.3407	4.6798	5.0479
0.204	6.3758	6.5249	6.1840	4.3514	4.7660	5.1581
0.205	6.5861	6.5103	6.3841	4.3868	4.9144	5.4635
0.206	6.6182	6.4469	6.4144	4.0035	4.2751	4.5497
0.207	6.6263	5.5800	6.4220	4.6931	5.3362	5.6569
0.208	6.6251	6.1491	6.4210	9.7443	9.7535	10.0218
0.209	6.6131	6.4764	6.4097	4.3266	4.7334	5.4211
0.210	6.5639	6.5164	6.3632	4.2424	4.8392	5.1792

Table 3. Current's acf results for static window in hif condition (n=40 and kmax=10)

Fault time (s)	Voltage					
	sacfv	sacfdv	sacfd2v	spacfv	spacfdv	spacfd2v
0.200	6.3466	3.0206	1.6699	0.3590	0.2429	0.6375
0.201	2.6460	0.8672	-1.0995	-0.0993	1.0627	0.1453
0.202	0.1420	0.1680	-0.4644	-0.8723	2.4235	0.1064
0.203	-0.9982	0.0624	-0.1323	0.2219	1.8844	-0.3442
0.204	-1.4295	-0.0277	-0.1417	0.2232	1.8580	-0.2611
0.205	-1.5050	0.0226	-0.3410	-0.6238	1.7768	-0.1060
0.206	-0.1160	0.2922	-1.0224	-0.3133	1.2205	0.5994
0.207	4.8707	1.6456	-0.9479	-0.0176	0.6933	0.2696
0.208	7.2593	2.4569	2.1355	-0.1606	0.4349	0.0973
0.209	3.8737	1.6491	-1.0497	0.0396	0.8800	0.2729
0.210	0.8931	0.2576	-1.0511	0.1691	0.8014	0.5908

Table 4. voltage's acf results for static window in hif condition (n=40 and kmax=10)

Fault time (s)	Voltage					
	sacfv	sacfdv	sacfd2v	spacfv	spacfdv	spacfd2v
0.200	6.9339	1.6671	-0.4695	0.2669	0.1739	0.0934
0.201	5.4783	-0.9503	-0.2817	0.5827	0.0167	0.7039
0.202	3.4873	-0.4204	-0.2167	0.6335	0.0104	0.2035
0.203	0.9900	-0.0886	-0.0216	0.7565	-0.4900	-0.1591
0.204	0.5949	-0.0708	-0.0063	0.6957	-0.5060	-0.8871
0.205	3.2958	-0.1868	-0.0500	0.5217	-0.3864	-1.9170
0.206	5.4064	-0.8062	-0.5091	-0.1666	0.6426	-0.8450
0.207	6.5456	-1.2097	-0.8134	0.5620	0.1342	0.6332
0.208	7.0033	0.8362	-0.0565	0.4719	0.1510	0.6231
0.209	6.0259	-0.7936	0.2544	0.5499	0.0080	0.5214
0.210	4.2548	-0.8951	-0.3937	-0.0565	0.5887	0.1744

These tables clearly show that all indices values are positive and almost large for both current and voltage in no-fault case, while most of them are around zero in HIF phenomenon. In this stage, *sacfv*, *sacfi* and *sacfdi* indices are put aside because their values in HIF are far from zero and they are not suitable for fault detection.

Now, it's time to go one step ahead and analyze the results of moving time window for different values of *n* and *k*. Finally, feature patterns of two indices for HIF with clear changes are shown in figure.7. These features belong to *spacfdv* and *spacfd²v* for HIF model 1.

Using a low-pass filter would be useful to make the curve flat to get a good and clear feature pattern for HIF detection. So, it is suggested that use a filter of degree 4 with equation number (23). Filtering of *SPACF* curve can be got similarly.

$$f_n(SACF) = \sum_{k=(n-3)}^n SACF_k \quad (23)$$

Some indices curves like $sacfd^2i$, $sacfd^2v$ and $spacfi$ for HIF model 2 before and after filtering are brought in figure.8.

Although voltage and current of relay don't show any problem in appearance, HIF can be detected easily by using of SACF and SPACF functions.

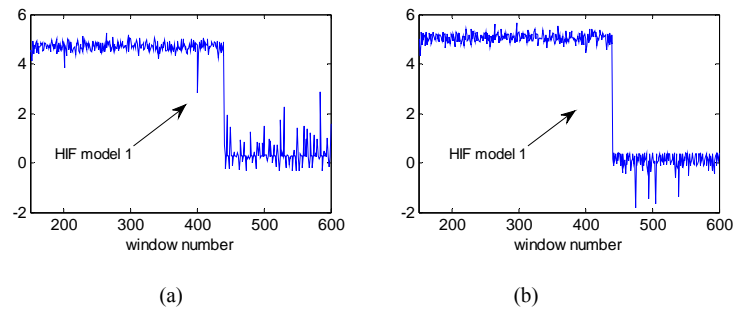


Fig. 7. Feature pattern of (a) spacfdv, (b) spacfd2v for HIF condition (time duration=3 s)

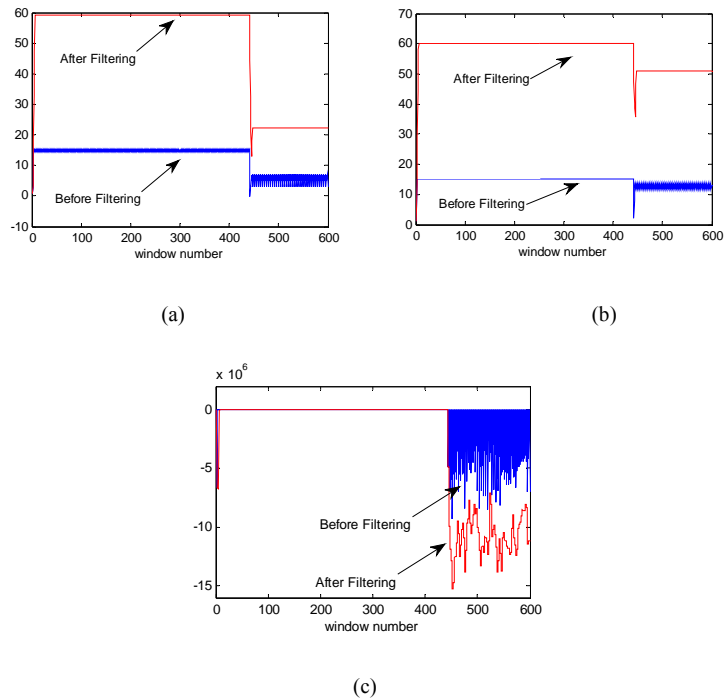


Fig. 8. Feature pattern of (a) sacfd2i, (b) sacfd2v and (c) spacfi for HIF (model 2) before and after using filter (time duration=3 s)

5 Conclusion

A new approach for HIF detection in distribution systems based on correlation functions is proposed in this paper. After simulating a sample system, *SACF* and *SPACF* functions were experimented on i , di , d^2i , v , dv and d^2v signals that resulted in twelve indices to HIF detection. After getting the results of both normal and HIF conditions for different values of variables, it was founded that *SACF* and *SPACF* operators can detect HIF phenomenon from voltage and current samples of relay.

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