EARLY DETECTION OF TREE FAULTS

Amr Muhammad El-Hadidy
TU-Dortmund - Germany
amr.elhadidy@daad-alumni.de

Christian Rehtanz
TU-Dortmund - Germany
christian.rehtanz@tu-dortmund.de

ABSTRACT

Faults due to falling trees happen frequently. At the moment a tree falls on a transmission line, the impedance path of the tree is not fully conductive. Therefore, the tree resistance at these early stages is very high and hard to detect. As time passes, the conductivity of the tree increases (less fault resistance R_f) till the point where R_f is low enough for the protection algorithms to detect. This phenomenon could happen in both High Voltage and Medium Voltage networks.

This paper focuses on the application of the protection function proposed in [1] for early detection of faults; especially tree faults. Tree faults with fault impedances up to 10^6 Ω can be detected. This very high value of impedances corresponds to very early stages of formation of the fault. Another important feature of the function in addition to detection of High Impedance Faults (HIF) is its security against non-fault phenomena like power swing, voltage instability and load encroachment. A comparison between the proposed function and conventional percentage differential relays shows superiority of the proposed approach. Other advantages are discussed throughout the text.

INTRODUCTION

In the era of smart grids power systems are expected to be highly loaded. A more reliable protection system is therefore a basic requirement. Reliability of protection system has two parts; dependability and security. A phenomenon that can threaten the first part (dependability) is the high fault path resistance; especially faults due to tree faults. The relay could be dependable in case of faults with low fault path resistance but insensitive to high fault path resistance. On the other hand, other phenomena like power swing, voltage instability and load encroachment can threaten the second part (security). Another interesting phenomena, although it rarely happens, is that a HIF can enter a protected zone and stays there for a long time before it evolves into a solid fault [2]. Such an event could be interpreted as unstable swing [2] which could lead the relay to be blocked from tripping. Therefore, early detection of tree faults, or generally speaking HIF, is required. Fig. 1 [3] shows that tree faults could reach very high values of about 20 to 60 kΩ [3]-[4], or more [5]-[6].

Many methods are used to handle the issue of HIF [7]. Reference [7] categorize the methods used in HIF detection into different groups: impedance-based methods; traveling-based methods; artificial-intelligent-based methods; distributed devices-based methods; and hybrid methods. Generally speaking the methods lack to study some important effects. Of these effects is how secure is the proposed algorithm in case of other non-fault phenomena like voltage instability, power swing or load encroachment. In addition to this, in many references it is not mentioned how high the maximum detectable R_f is. Other factor like the effect of measurements errors, especially errors due to Voltage or Current Transformers (VT's and CT's), must be also considered in design of the protection function.

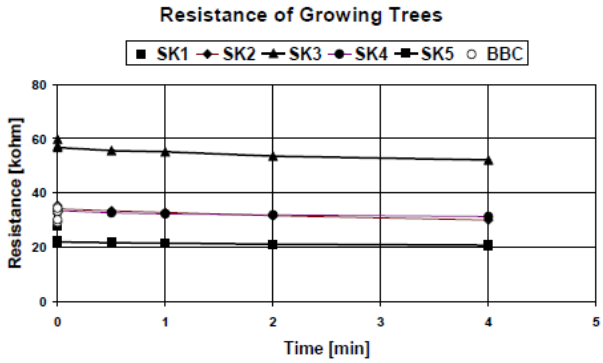

Fig. 1 Practical values of R_f of tree faults[3]

This paper introduces a new concept based on the previously illustrated concept in [1]. The new concept incorporate the effect of errors of VT and CT in a way that enables the function to detect fault resistances up to 10^6 Ω. This enables detection of tree faults at very early stages of occurrence of the fault. The function is then compared to conventional percentage differential relays. The proposed concept remains secure against the previously mentioned non-fault phenomena.

DESCRIPTION OF THE OLD FUNCTION

In [1], a new protection function has been proposed. The basic idea behind the function is to use directly the value of the fault resistance as indicator for occurrence of a fault. Fig. 2 illustrates this concept.

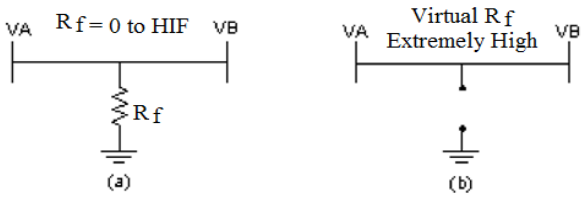

Fig. 2 R_f and virtual R_f

At non-fault conditions, R_f could be imagined to be virtually existing but with extremely very high value (theoretically ∞). At fault conditions, R_f drastically changes to be equivalent to the value of the fault path resistance.

Based on Fig. 3, the basic equation used for calculation of R_f is given in (1) [1]. Synchronised Phasor Measurements (SPM) are used to measure all variables in (1).

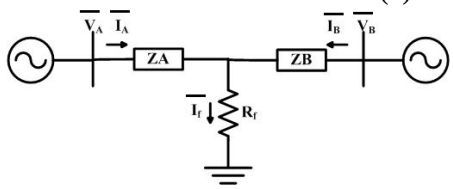

Fig. 3 System for calculation of R_f

$$R_f = abs\left(real\left[\underbrace{\left(\frac{\overline{V}_A}{\overline{I}_A} + \frac{\overline{V}_B}{\overline{I}_B} - \overline{Z}_{T.L.} \right)}_{Term1} \underbrace{\left(\frac{\overline{I}_A \overline{I}_B}{\overline{I}_f^{\,2}} \right)}_{\text{Term 2}} \right] \right) \quad (1)$$

Where : $I_f = I_A + I_B$

Extensive simulations have been carried out. A sample result is shown in Fig. 4. The result corresponds to single line to ground fault with a fault path resistance of 1Ω from time 4 to 6 sec. Base loading at bus 6 is P_6=90 MW and Q_6=30 MVAr. The result has been found to confirm the concept. Deeper explanation of the function and further results can be found in [1]. The results as in Fig. 4, shows that the function can detect up to 10^{10} Ω. The fault is carried out on line 4-6 of the WECC network. The network is not shown in the paper but all network details and parameters can be found in [1]. It is assumed that Bus 4 is Bus A and Bus 6 is Bus B.

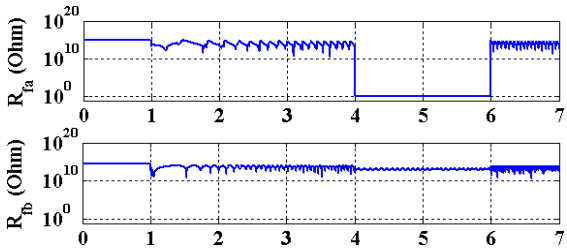

Fig. 4 R_f in case of single line to ground fault

Effect of measurements errors

As seen in Fig. 4, at non-fault conditions, although virtual R_f is extremely high, it fluctuates between 10^{20}Ω and 10^{11}Ω which is very high fluctuation. Furthermore, exploration of the function using SPM from actual field measurements have revealed that (1), at non-fault conditions, can have average values of about 10^6Ω and at the same time fluctuates between relatively small values like 10^7Ω, 10^6Ω, 10^4Ω,10Ω and some times ∞ or undefined value (NaN). Values like ∞, NaN or even 10^6Ω can be interpreted as non-fault condition. However, at non-fault conditions, the problem is the appearance of values like 10Ω or less which for sure represent a fault case. Therefore, a conflict between non-fault and fault condition could happen.

Inspection of (1) shows that at non-fault conditions (where I_A=I_B), Term1 and denominator of Term2 of (1) have a value of zero. Division of both of them results in NaN as illustrated in (2) where 0_n and 0_d represent zero of the nominator and zero of the denominator. If a very small error is introduced in any of the parameters of denominator of Term2 while Term1 is 0, at non-fault conditions, equation (3) holds causing R_f to be 0. The contrary of that is right as given in (4). Therefore, depending on errors in measurements and depending on how near to zero is Term1 or denominator of Term2, R_f could be near zero or near ∞ respectively. This explains the existence of high fluctuations in the function as in Fig. 4.

$0_n * I_A^2 / 0_d$ = NaN	(2)	if 0_n and 0_d are pure 0
$0_n * I_A^2 / 0_d$ = 0	(3)	if 0_d changed to 0.0000001
$0_n * I_A^2 / 0_d$ = ∞	(4)	if 0_n changes to 0.0000001

It is also noted that the denominator of Term2 of (1) normally has less errors than those of Term1. Term2 has some kind of control how high the level of virtual R_f is.

Study of combined errors of voltage and current

The main source of errors in measurements is caused by Current and Voltage Transformers (CT and VT). CT and VT are classified according to their accuracy class. Table 1 shows two different accuracy classes for CT's and VT's used for testing of the function performance. All variables in (1) are subjected to all possible errors of different combinations of CT's and VT's according to Table 2. In this section, only results due to CT and VT combination 1 is shown. Fig. 5 shows the histogram of different magnitude and phase angle errors (ε_m and ε_a) for voltages and currents at bus A. Similar distributions are assigned to voltage and current at bus B. Fig. 6 shows the corresponding Cumulative Density Function (CDF) of virtual R_{fa} due to CT and VT combination 1. All CDF's of other phases behave the same way as CDF of R_{fa}. Fig. 6 shows also the CDF of R_{fa} at different fault conditions.

Table 1 Used VT's and CT's

Accuracy Class VT	% ratio error	Phase Displacement (Minutes)	σ mag	σ ang
1) 0.1	± 0.1	± 5	0.00029	0.00044
2) 3P	± 3	± 120	0.008	0.009
Accuracy Class CT				
1) 0.1	± 0.1	± 5	0.00029	0.00044
2) 5P	± 1	± 60	0.0015	0.005

Execution of many tests using CT and VT combination 1 (also all other combinations) and according to Fig. 6, two properties of virtual R_f and actual R_f at fault conditions are obtained:

1- Median (μ) of virtual R_f has tendency to be high and in the vicinity of 10^5 to 10^6 Ω
2- Virtual R_f has high variance (σ^2) compared to the variance of R_f at fault conditions

Table 2 Numbering of Combinations of VT's and CT's

Combination	Number
VT1 CT1	1
VT2 CT1	2
VT1 CT2	3
VT2 CT2	4

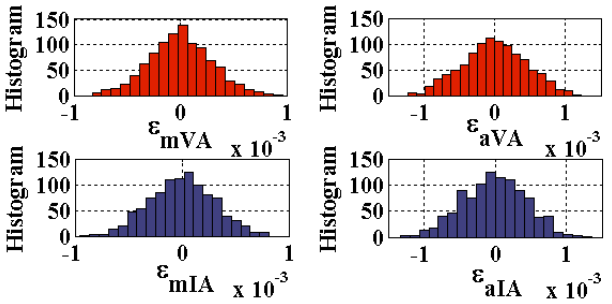

Fig. 5 Example of error distribution

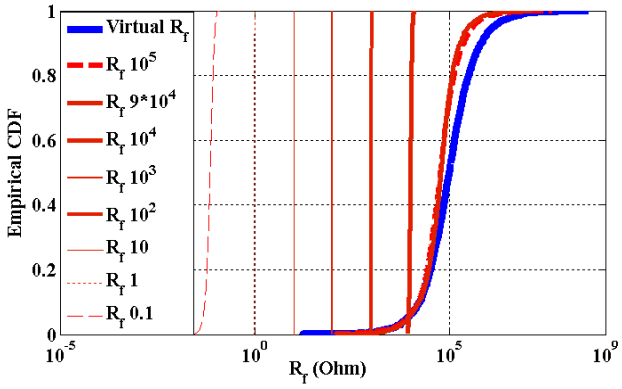

Fig. 6 CDF of R_f at fault and at non-fault

Those two properties are used for detection of faults as illustrated in next section.

THE NEW FUNCTION; SPACE OF μ AND σ^2

According to Fig. 6, it is possible to use μ and σ^2 for detection of the fault condition. Fig. 7 shows the information of Fig. 6 but adapted to the space of μ and σ^2.

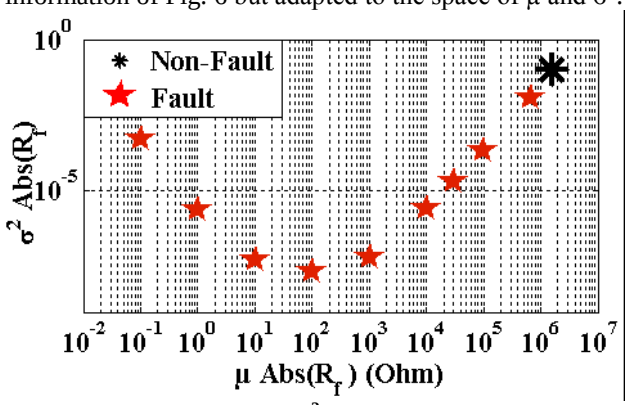

Fig. 7 Space of μ and σ^2 at different conditions

Fig. 7 could be obtained only if measured voltage and current at one time sample are subjected to all possible CT and VT errors. Practically speaking this is not possible because at each time sample only one possible error of CT and VT exists. However, taking into account that the effect of errors on the CDF curve at fault conditions in Fig. 6 is almost negligible, it is possible to resubject the measured voltage and current sample to errros within the accuracy class of CT and VT. The performance of the new CDF curves is then compared to the original ones in Fig. 6.

Retrieval of the CDF curve

Fig. 8 shows the procedure for retrieval of the original CDF curve. Fig. 9 illustrates one sample results for retrieval of the original CDF curves at non-fault and fault conditions. By other formulation, it is required to extract the information if point T (which could represent a fault) really belongs to the CDF curve of fault or not.

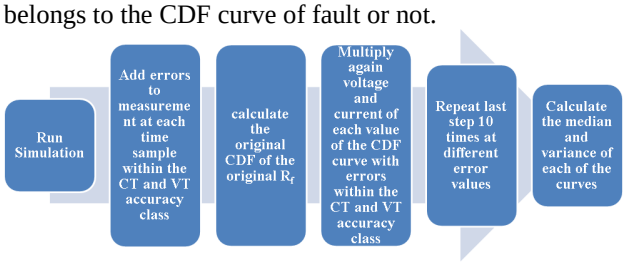

Fig. 8 Procedure for retrieval of the original CDF curves

At fault conditions, the original CDF curve is very good retrieved. At non-fault conditions, the retrieval is possible but might result in some deflections of median and/or variance. Fig. 10 shows the original and retrievd space of μ and σ^2 for the sample T given in Fig. 9. It is clear from the figure that regardless of the deflection at non-fault conditions, the characteristics at fault conditions is quite different than those at non-fault condition.

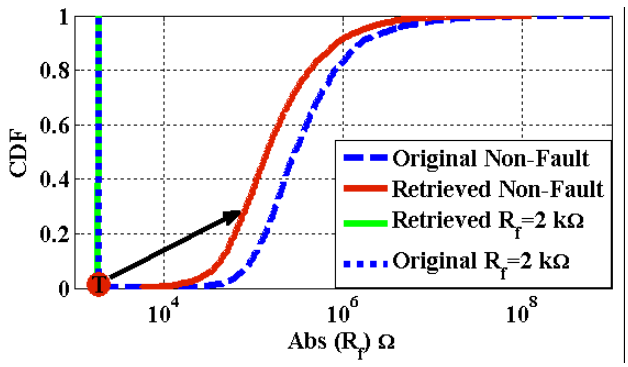

Fig. 9 Retrieval of original CDF

The curves shown in Fig. 9 represent the retrieval due to one of the points on the original CDF curve. By recalling that the original CDF curve represents all possible values of R_f due to all possible errors of CT and VT, it is important to check the back retrieval of the original CDF due to all points of the curve.

Fig. 11 shows the results of this process at non-fault conditions and at a fault of $10^6\Omega$. Although back retrieval at all points of the original CDF curve causes more deflections at non-fault condition, the detection of fault conditions even for high values like $10^6\Omega$ is possible and successful. The

same figure shows the detection of R_f with different calculation methods. The caculation method depends on which variables are used in (1).

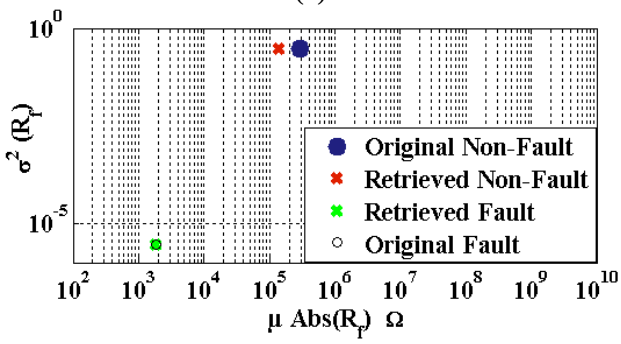

Fig. 10 Retrieval at space of μ and σ^2

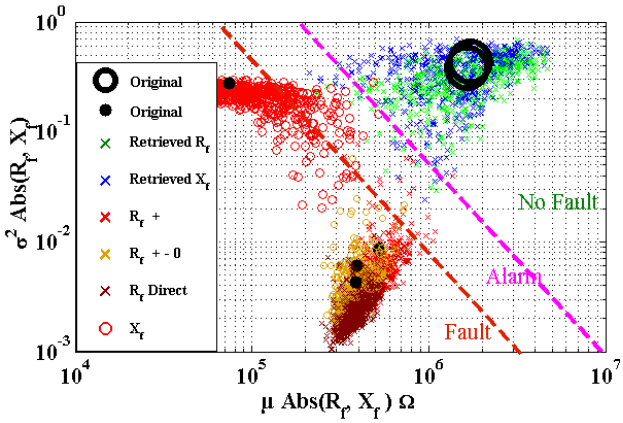

Fig. 11 Retrieval at all points of original CDF

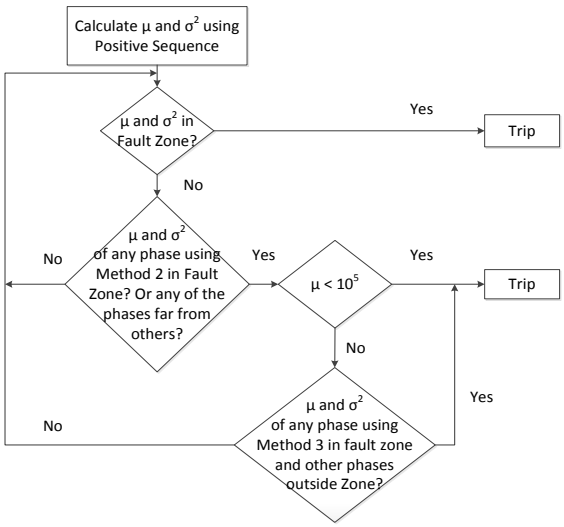

Fig. 12 Flowchart for optimal performance

It is possible to use either only positive sequence components of V's and I's, all sequence components or directly measured phase voltages and currents. Each calculation method has advantages and disadvantages. The basic advantage in using only the positive sequence component is the less required data to be communicated. The other two methods can detect higher values of R_f than by only positive sequence but communication use is higher. Therefore, the flowchart in Fig. 12 is designed such that to achieve the maximum speed and at the same time not to lose detection of very high values of R_f.

Effect of retrieval error values

It is found that the retrieval process could be enhanced using ranges of errors other than those defined by the accuracy class of the CT or VT. Fig. 13 shows the results of retrieval due to use of higher error ranges of current (±1%) for combination1.

The results of Fig. 13 indicate that it is possible to retrieve the original CDF curve with relatively higher quality depending on the choice of the range of retrieval error. This point is however out of the scope of the paper.

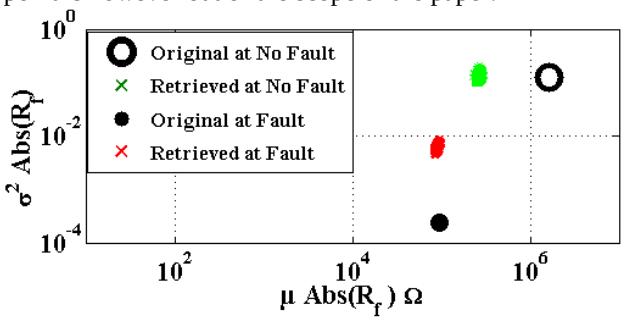

Fig. 13 μ and σ^2 for Fig. 11 at higher retrieval error

COMPARISON TO DIFFERENTIAL RELAYS

Fig. 14 shows the CDF of differential currents (I_d) at different system and fault conditions. The system is loaded at triple its base loading. It is possible to apply the proposed approach on the differential current I_d (i.e. to use μ and σ^2 of I_d). Combination 3 in Table 2 has been used for this test.

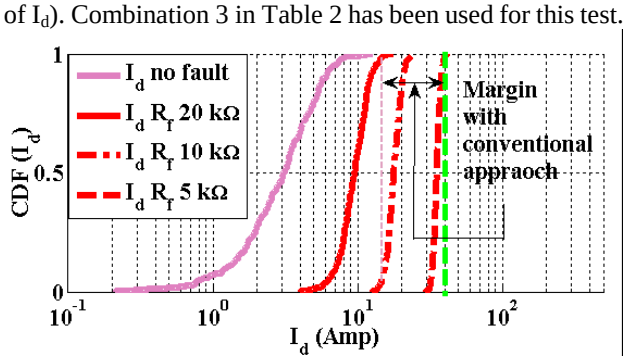

Fig. 14 I_d at triple loading and at different R_f values

As seen in Fig. 15, using the conventional settings (assuming setting of I_d at double the maximum expected value of at non-fault conditions), it is impossible to detect high fault resistances of about 20 kΩ. By applying the proposed approach on I_d, R_f of 20 kΩ is detectable. The maximum detectable R_f using the conventional approach in this case is about 4 kΩ.

In Principle, the proposed approach, at different CT and VT combinations in Table 2, can detect R_f values of about 7 times those detectable by the conventional approach as shown in Fig. 16.

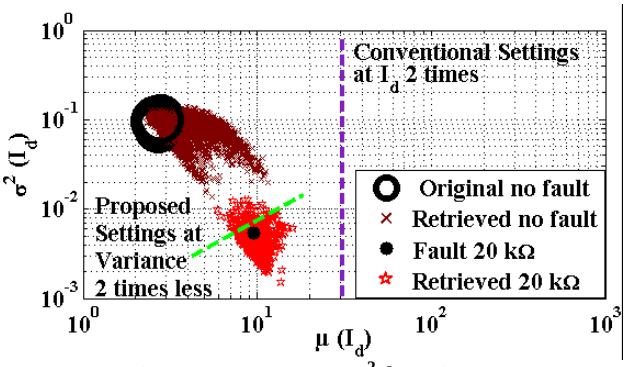

Fig. 15 Space μ and σ^2 for Fig. 14

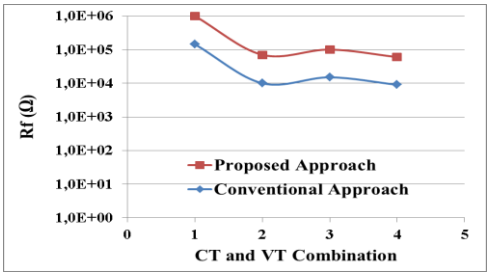

Fig. 16 Detectable R_f 7 times conventional approach

Deflections due to retrieval could decrease the detection capability of the proposed approach to be about 5 times more than the conventional approach. Further inspection is still required to get behind how to best retrieve back the original CDF curves. Fig. 16 also indicates one interesting point; using CT and VT of low accuracy classes with the proposed approach can result in detection of R_f as high as those detectable using CT and VT of very high accuracy class with the conventional approach. This means that materials used for manufacturing of CT and VT could be made with materials of less quality which is economically cheaper. Also, utilities don't have to change existing CT and VT with new, more accurate ones.

CONCLUSIONS & FUTURE WORK

This paper proposes a new protection function that incorporates measurements errors in a way that enables detection of very high values of fault resistances. Results show that the function could detect till about 10^6 Ω. Based on that, tree faults could be detected at very early stages of occurrence of the fault. In high voltage level, the function can detect very high values of fault resistances and at the same time keeps secure against other non-fault phenomena like power swing, voltage instability and load encroachment. This helps in two points: 1- saving of the stability of the system because the fault is detected very early before it could affect the system. 2- Sometimes and under highly stressed system operation, disconnection of the faulty line could lead to further cascade of the system components. Some preventive control actions could be required to alleviate this cascade and to reduce the impact of disconnection of the faulty line on the system. By early detection of the fault any preventive control actions which require communication delays and other calculations could be done early enough before disconnection of the faulty line. This helps to get behind the impact of the line disconnection on the system before the line is disconnected. And therefore may help to take better control or protection actions. Applicability of the function, using a laboratory model of a transmission line and through actual field measurements, has been tested and is successful.

Beside the previous points, comparing the function to conventional percentage differential relays, two important gains can be achieved:

1- Theoretically speaking, the function can detect fault resistances up to 7 times those detectable by conventional percentage differential
2- using CT and VT of low accuracy classes with the proposed approach can result in detection of R_f as high as those detectable using CT and VT of very high accuracy class with the conventional approach.

Several future works are still required to enhance the retrieval process.

REFERENCES

[1] A. El-Hadidy, C. Rehtanz, 2011, "mitigation of blackouts due to mal-operation of distance relays by using the fault resistance information", *21th International Conference and Exhibition on Electricity Distribution* (CIRED), Frankfurt, Germany.

[2] S. H. Horowitz, A. G. Phadke, 2008, *"power system relaying"*, 3rd Edition, John Wiley and Sons Ltd., West Sussex, England, 272.

[3] A. Otto, R.Schäfer, S. Reinhard, F. Frey, 1990, "Detecting High- Resistance Earth Faults," ABB Review, no. 1, 19-26.

[4] CIGRE Study Committee B5, 2008, "High Impedance Faults", Report Nr. SC, B5/WG94 DFR-r2.0.

[5] N.I. Elkalashy, M. Lehtonen, H.A. Darwish, M.A. Izzularab, A. Taalab, 2007, "Modeling and experimental verification of high impedance arcing fault in medium voltage networks", *IEEE Transactions on Dielectrics and Electrical Insulation*, vol.14, no.2, 375-383.

[6] S. Hanninen and M. Lehtonen, 1999, "Method for Detection and Location of Very High Resistive Earth Faults", *Europ. Trans. Electr. Power (ETEP)*, Vol. 9, 285-291.

[7] M. Sarlak, S.M.Shahrtash, 2013, "High-Impedance Faulted Branch Identification Using Magnetic-Field Signature Analysis", *IEEE Transactions on* Power DElivery, vol.28, no.1, pp.67-74.

Acknowledgments

The authors would like to deeply thank Dipl.-Ing. Marco Tusche, Ruhr-Universtität Bochum, Germany and Dipl.-Ing. Christian Langesberg, TU-Dortmund, Germany for their invaluable support in mathematical and statistical issues encountered during the development of the proposed approach.