A Novel Transient Current-Based Differential Algorithm for Earth Fault Detection in Medium Voltage Distribution Networks

Mohamed F. Abdel-Fattah, Matti Lehtonen

Abstract*-- This paper presents a novel transient current differential algorithm for earth fault detection in unearthed (isolated) and compensated neutral medium voltage (MV) networks. The proposed algorithm uses the transient residual currents, which are very sensitive for earth faults. The transient values of residual currents are calculated at each feeder in the network and used as a fault indicator. The flow of residual current is investigated. It is found that the residual current for the faulted feeder is equal to the summation of all residual currents for all other healthy feeders. Based on this investigation, a differential technique is proposed. A percentage restrain performance is proposed to ensure the selectivity and security of the algorithm. The transient analysis of the algorithm is very sensitive for fault incidence rather than steady state analysis. From practical point of view, the residual currents can be measured easily by one sensor for each feeder and with no need for voltage signals to apply this algorithm. The proposed algorithm is less dependent on the fault resistance and the faulted feeder parameters. The network is simulated by ATP/EMTP program. Different fault conditions are covered in the simulation process; different fault inception angles, fault locations and fault resistances.

***Keywords*: Earth faults, Earth capacitance, Transient current, Transient frequency, Unearthed and compensated medium voltage networks.**

I. INTRODUCTION

DIFFERENTIAL protection is a fast, selective method of protection against short-circuits which is applied in many power system elements; generators, transformers, busbars and transmission lines. As the name implies, it operates when the vector difference, between the two ends of the protected zone, of two or more similar electrical quantities exceeds a predetermined amount. The difference is always zero when no fault exists, otherwise any small difference indicates a trouble in the protected zone leading to a very sensitive protection system. Most differential-relay applications are of the "current-differential" type. The simplest example of such arrangement is shown in Fig. 1. Percentage differential relays create a restraining signal in addition to the differential signal and apply a percent (restrained) characteristic.

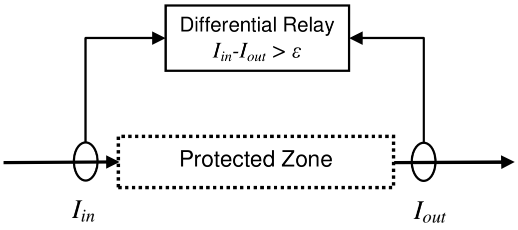

Fig. 1. A simple differential relay arrangement.

The main advantage of unearthed neutral in power systems is small earth fault currents which do not require immediate shut down, but the main problem is the over-voltage that resulted by charging of the system capacitance of the sound phases, which may lead to flashover or breakdown. Also, it may establish a double line to earth fault. In networks with an unearthed (isolated) neutral, the currents of single phase to ground faults depend mostly on the phase to ground capacitances of the lines. When the fault happens, the capacitance of the faulty phase is bypassed, leading to unsymmetrical system. The fault current is composed of the currents flowing through the earth capacitances of the two sound phases as shown in Fig. 2 [1]. Therefore, the faulted phase current will equal to the summation of the healthy phases currents. If these equal currents considered as an input and output currents to the protected zone as presented in Fig. 1 then the differential protection technique can be applied. Only the current signals are required and no need for voltage signals which leading to a practical strong technique.

The fault current in unearthed (isolated) neutral systems is small and in compensated neutral power systems (resonance grounded/earthing systems or Petersen coil systems), the system earth capacitance is compensated by the connected inductance leading to decreasing in the earth fault currents. Therefore, the sensitivity of conventional relays, that normally are based on the fundamental components of the voltage and current at power frequency, to very small values of fault currents will be reduced and it is found that the transient based schemes are more sensitive to fault incidence in these systems. The transient based schemes utilize the transient components in the fault signals to detect the fault. The transient residual current and voltages are proposed to be used for fault detection.

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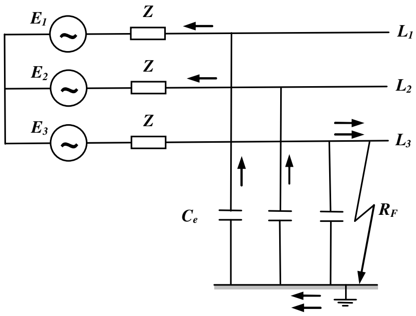

Fig. 2. Earth fault in unearthed neutral network.

The residual value is equal to the summation of the instantaneous phase values (voltages or currents) as given by (1), (2), it is equal to three times the earth mode (zero mode of the modal components). The residual voltage and currents are equal to zero in normal operation and become meaningful in fault condition. They are very sensitive for earth faults and from practical point of view, it can be measured easily by one sensor for each feeder; hence it is suggested to use it for fault detection. The residual voltage and current are given by:

$$v(t)_r = v_a(t) + v_b(t) + v_c(t) \tag{1}$$

$$i(t)_r = i_a(t) + i_b(t) + i_c(t) \tag{2}$$

A novel transient differential algorithm for fault detection, using the transient residual currents, will be presented in this paper. The proposed algorithm uses a differential technique for fault indication, with unusual manner. A differential percentage factor is proposed to be used with a suitable setting. The validity of algorithm is confirmed for both of unearthed (isolated) and compensated neutral medium voltage (MV) networks. Different fault conditions; inception angles, fault locations and resistances were simulated to check the validity of the Algorithm.

II. THE PROPOSED TRANSIENT CURRENT-BASED ALGORITHM

A. The Simulated Network

Fig. 3, shows a single line diagram of the simulated medium voltage distribution network. The network consists of a *66 kV* supply which feeds five *20 kV* overhead line feeders through a *66/20 kV* transformer. Each feeder is terminated by a *0.4 kV* load through *20/0.4 kV* transformer. The network is implemented using ATP (Alternative Transients Program), version of EMTP program where the circuit was realized using ATPDraw [2]. The required analysis in ATPDraw are calculated using TACS (Transient Analysis Control System) objects. The transmission line frequency dependent model of EMTP program is intentionally selected to account for the unsymmetrical faults. The feeder lines are represented using the frequency dependent JMarti model. A sampling time of *100 μs* is used. The ATPDraw circuit with required TACS objects and the configuration of the feeders are given in Appendix (Fig. 11-13).

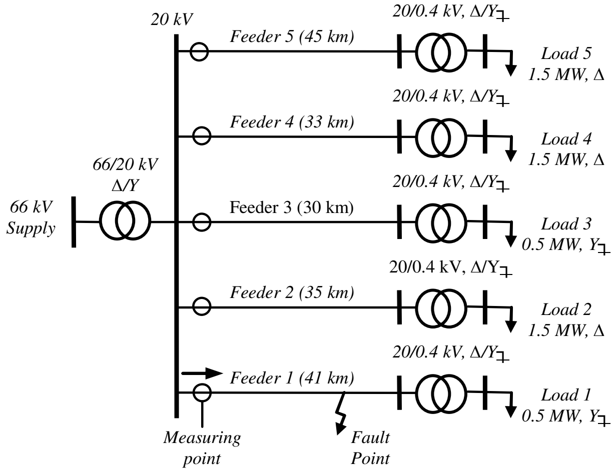

Fig. 3. The simulated medium voltage distribution network.

B. The Proposed Algorithm

For the simulated network shown in Fig. 3, the residual bus voltage and feeder currents are calculated at substation (measuring points). Fig. 4 shows the waveforms of the residual voltage at the bus and the residual feeder currents. The waveforms for all healthy feeders are approximately the same but situation is different for faulted feeder as shown. The transient period is the first few milliseconds directly after fault incidence. From investigations of the simulation results it is found that, a suitable transient window of *2.5 ms* is adequate to cover all different fault conditions; different fault inception angles, fault locations and fault resistances. The enlarged view of the transient period is shown in Fig. 5. In transient period, normally we found a half cycle of the residual voltage and a full cycle of the residual currents. It means that the polarity is not changed for voltage but changed for current.

For the first half cycle of the current, the voltage and current polarities are reversed for faulted feeder and in the same time are equal for healthy feeders as shown in Fig. 5, which agrees with the polarity comparison technique. Therefore the polarity window covers the first half cycle of the current earth mode, it is the most sensitive transient window, in the transient period, to fault incidence. The window starts at beginning of transients, i.e. when the values of the voltage and current earth modes are meaningful. The window terminates at the zero crossing of the current earth mode which normally occurs at the maximum absolute value of voltage. The period of the window is not constant; it varies according to the fault characteristics, mainly depends on the fault resistance and incidence angle [3]. The residual fault current is composed of the residual currents flowing through the earth capacitances of background network as presented in Fig. 6 [4]. The other impedances of the network components are small compared to those of the earth capacitance and can hence be neglected. The earth capacitance of the network depends on the types and lengths of the lines connected in the same part of the galvanic connected network.

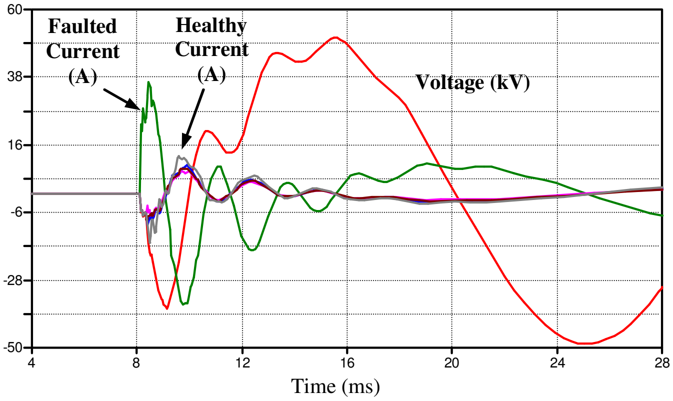

Fig. 4. The waveforms of the residual voltage and the residual currents for faulted and healthy feeders, for one period (*20 ms* for *50 Hz*) after the fault incidence, (*8 ms* incidence time, *10 Ω* fault resistance and *80%* fault distance).

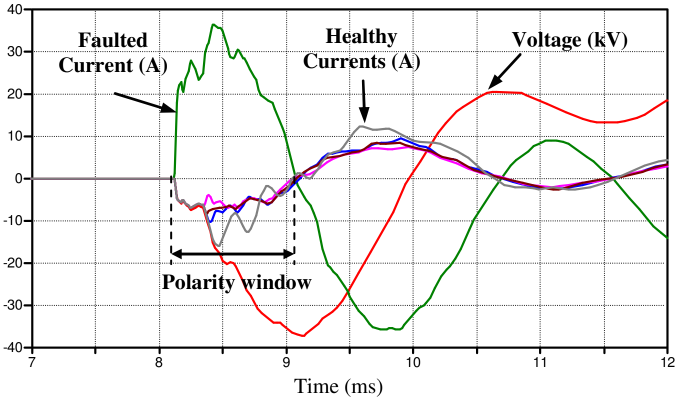

Fig. 5. The transient period for the waveforms shown in Fig. 4.

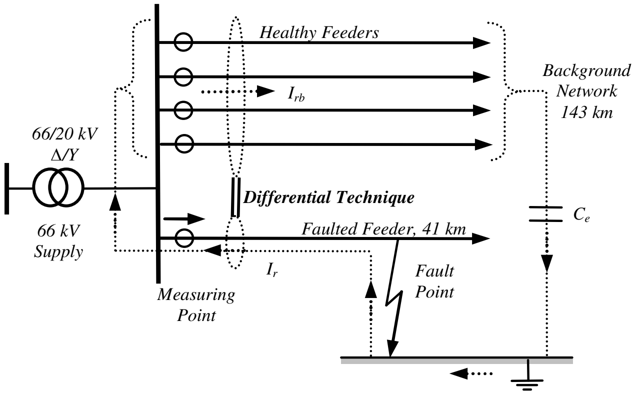

Fig. 6. The flow of the earth fault residual currents, during a single-phase to ground fault, through the earth capacitance of the background network.

From Fig. 6, it can be shown that the residual current for the faulted feeder (I_r) is equal to the residual current of the background network (I_{rb}); summation of residual currents of other healthy feeders, but in case of a healthy feeder, the summation of other feeders gives an unequal result. Hence, the differential technique can be used here for fault detection. The input and output currents are the feeder residual current and background network residual current. The proposed application of the differential technique is here different from usual; if the input and output currents are equal then the feeder is faulted otherwise it is healthy. The algorithm proposes to analyze the data in the polarity window presented. In [3], the technique is based on the transient impedance which requires voltage and current signal analysis. The proposed algorithm here is only based on current signal analysis which leading to a practical strong algorithm. The average values of the residual currents will be calculated in polarity window, and can be calculated from the discrete samples as follows:

$$I_r = \frac{\sum_{k=1}^{N} i_{r,k}}{N} \qquad (for\ each\ feeder) \qquad (3)$$

where:

$i_{r,k}$ is the instantaneous residual current at sample k calculated from (2).

N is the number of samples in the polarity window.

The operating signal of the proposed differential algorithm is equal to the absolute value of the difference between the feeder residual current and the background residual current; summation of other feeder residual currents (the summation is equal to zero in fault condition). To improve the performance of the proposed differential algorithm, a percentage restraint technique will be applied. The absolute of the difference will be divided by the total absolute value of all feeder residual currents (i.e. summation of the absolute values of all feeder residual currents) as follows:

$$K = \frac{\left|I_r - I_{r,back}\right|}{I_{r,total}} \times 100 \qquad (4)$$

where

$$I_{r,back} = \sum I_r \qquad (for\ other\ feeders) \qquad (5)$$

$$I_{r,total} = \sum \left|I_r\right| \qquad (for\ all\ feeders) \qquad (6)$$

In faulty condition, the values of the differential factor K are different for healthy and faulty feeder. For faulty feeder the average value of K is always equal to *100%*. The polarities, in the polarity window, are taken into account leading to strong algorithm; which achieved by the minus sign in (4). For faulty feeder, the polarity of the background residual current will be opposite to the polarity of the feeder residual current, and hence the result of the difference gives value equal to two times the feeder residual current value. Also, the total sum of the absolute values of the residual current for all feeders gives value equal to two times the feeder residual current value, and then the value of K should equal to *100%*. For healthy feeders, the average value of K mainly depends on the number of background network feeders and its lengths with respect to the faulted feeder.

For the simulated system shown in Fig. 3, with comparable feeder lengths, the average value of *K* is equal to *25%* but this value may change with different network configurations. For example, for nine feeders network, the average value of *K* will equal to *12.5%*, this is better for selectivity but on the other hand for three feeders network the average value of *K* will equal to *50%*. The proposed algorithm is not working with two feeders network which is not common in distribution networks, in which the two average value of *K* will equal to *100%* (for both of the faulty and healthy feeders). The suitable setting value of the differential factor is the average value between the healthy and faulty conditions, which lies at the middle of the gap between them.

Therefore the proposed setting value of the differential factor *(K)* is 62.5%. For compensated networks (Peterson coil/resonance grounded/earthing networks), the impedance of the compensation coil is relatively high at transient frequencies. Consequently, the transients are about similar in both of unearthed and compensated neutral networks. This is clearly investigated from the simulation data that will be presented in the following section.

C. *Results and Setting*

For the case shown in Fig. 4, the calculated values are:

The faulted feeder residual current: $I_{rf} = 6.80\ A$

The healthy feeder residual current: $I_{rh} \approx -1.69\ A$

The faulted feeder differential factor: $K_f = 99.71\ \%$

The healthy feeder differential factor: $K_h \approx 25.15\ \%$

Fig. 7 shows the variation of the differential factor, for healthy and faulty conditions with the fault incidence time, over the power frequency period (*0-20 ms*), Fig. 8 shows its variation with the fault resistance and Fig. 9 shows its variation with the fault distance. The values of the ratios for healthy and faulty conditions for unearthed network are presented by solid lines and for compensated network are presented by dash lines.

From the simulated results presented in Fig. 7-9, it can be investigated that there is an adequate gap between the healthy and faulty condition, and no overlapping between the two conditions. This gap can covers many of sources of error in the measurements, that may give incorrect higher or lower differential factors, and the proposed algorithm will operate effectively.The proposed technique is valid at higher values of fault resistance (up to *1 MΩ*) and from Fig. 8, we can investigate a higher error in the samples of small amplitude at higher resistances after *30 kΩ*. In these cases the limitation of application will mainly depend on the sensitivity of the measuring devices due to very low values of voltage and current samples.

The simulations were performed at sampling frequency of *100 kHz*. It is found that lower sampling frequency around *10 kHz* can be used for data analysis without affecting much in the sensitivity of operation, hence it is suitable for practical implementation.

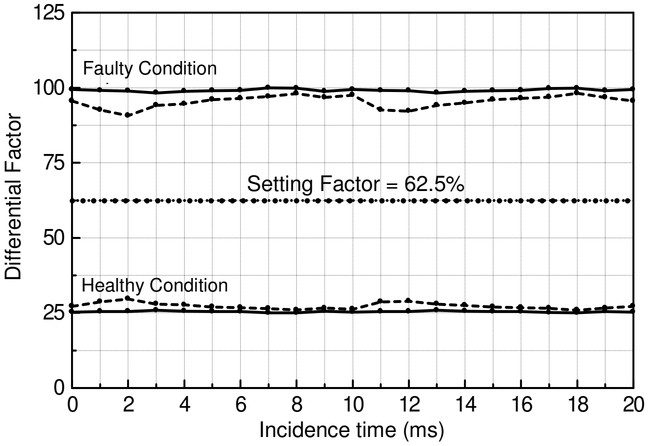

Fig. 7. The variation of the differential factor for healthy and faulty conditions with the fault incidence time, over the power frequency period (*0-20 ms*) at *80 Ω* fault resistance and *80%* fault distance for unearthed and compensated networks.

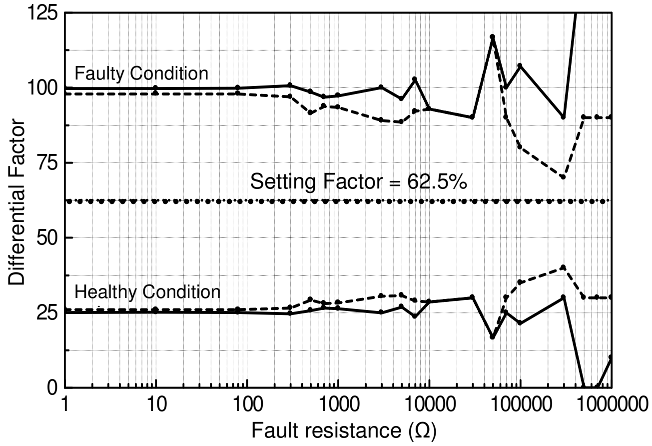

Fig. 8. The variation of the differential factor for healthy and faulty conditions with the fault resistance at *8 ms* incidence time and *80%* fault distance for unearthed and compensated networks.

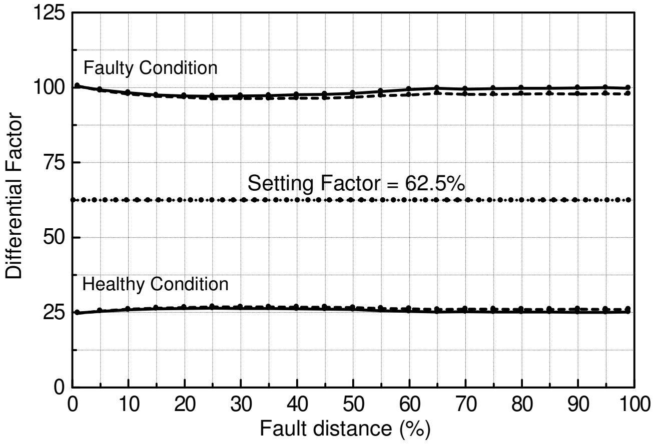

Fig. 9. The variation of the differential factor for healthy and faulty conditions with the fault distance at *8 ms* incidence time and *80 Ω* fault resistance for unearthed and compensated networks.

The proposed algorithm is very simple and requires few calculations and does not need complicated calculations or special signal processing. The proposed algorithm uses the residual currents only and no need for voltage signals. The residual currents can be measured easily by one sensor for each feeder. At normal operation, the residual currents are zero or very small values. The algorithm is proposed to work after transient detection that is confirmed by all feeder currents. The feeder is confirmed to be faulted if the magnitude of differential factor (normally around *100%*) is greater than the setting value. The security of the algorithm can be increased by using the polarity check to confirm the fault incidence. This can be done by confirming that the polarity of the faulted feeder current is opposite to the polarity of all other healthy feeder currents. This technique is very immune to any higher values of residual currents due to unbalance operation, which is limited to specific level.

The proposed differential technique here supervises all the network feeders, to discriminate between the healthy and faulted feeders after transient detection, which is not usual in normal differential algorithm that protects only a specified zone such as one section of the transmission line. Fig 10 presents the flowchart that summarizes the main steps in the programming process for the proposed transient current-based differential algorithm.

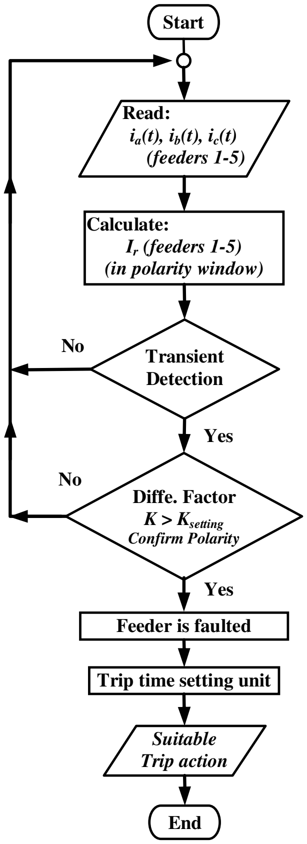

Fig. 10. The main steps in the programming process for the proposed transient current differential algorithm.

III. CONCLUSIONS

A novel transient current differential algorithm is proposed for both of unearthed and compensated medium voltage networks. The algorithm uses only the residual current signals for each feeder of the network. A new application of differential protection is proposed based on investigation of a phenomenon in the unearthed and compensated networks. It is found that the residual current for the faulted feeder is equal to the summation of residual currents of all other healthy feeders, hence it is used for fault detection which is different from the usual application of differential protection. A percentage differential factor is proposed, with polarity confirmation, to increase the selectivity and the security of the algorithm. The proposed differential algorithm supervises all network feeders, not only one feeder. Different simulations, using ATP/EMTP program, at different fault angles, fault resistances and fault distances, have been done to confirm the algorithm validity. Lower sampling rates around *10 kHz* can be used. From the simulation results it is found that the performance of algorithm is accepted and suitable for practical implementation.

IV. APPENDIX

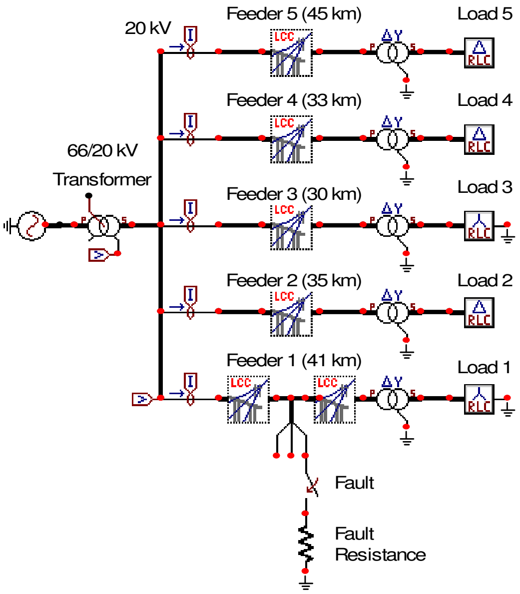

Fig. 11. The ATPDraw circuit of the simulated unearthed medium voltage system:

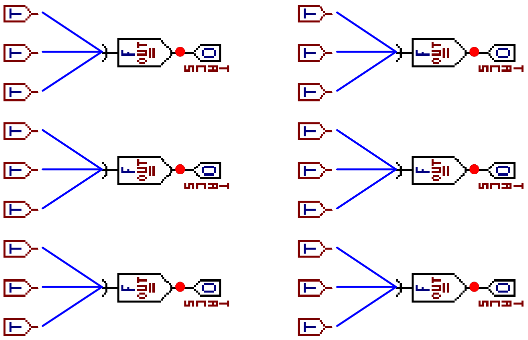

Fig. 12. The used TACS objects in ATPDraw.

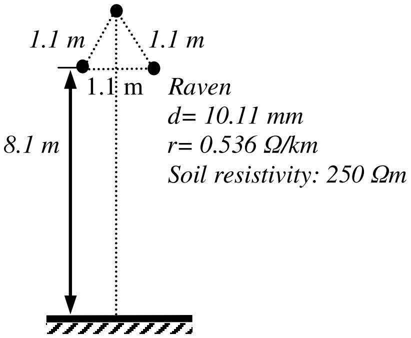

Fig. 13. The configuration of the feeders.

V. REFERENCES

[1] M. Lehtonen and T. Hakola, *Neutral Earthing and Power System Protection - Earthing Solutions and Protective Relaying in Medium Voltage Distribution Networks*, Vassa, Finland: ABB Transmit Oy, FIN-65101, 1996.

[2] L. Prikler and H. Høidalen, "ATPDraw User's Manual", SINTEF Energy Research, TR A4790, Nov. 1998.

[3] M. F. Abdel-Fattah and M. Lehtonen, "A Transient Fault Detection Technique with Varying Fault Detection Window of Earth Modes in Unearthed MV Systems", *Power Quality and Supply Reliability, 6th international conference (PQ2008),* Pärnu, Estonia, August 2008.

[4] R. Kaczmarek, W-Y. Huang and P. Bastard, "Equivalent Circuit Application to a Phase to Ground Fault Detection in Distribution Networks Without Voltage Measurements", *SUPELEC*, France, 2004.

[5] S. Hänninen, M. Lehtonen, T. Hakola, E. Antila, J. Ström and S. Ingman, "Characteristics of Earth Faults in Power Systems with a Compensated or an Unearthed Neutral", *CIRED 97*, June 1997.

VI. BIOGRAPHIES

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