A New Transient Impedance-Based Algorithm for Earth Fault Detection in Medium Voltage Networks

Mohamed F. Abdel-Fattah, Matti Lehtonen

***Abstract*-- This paper presents a new earth-fault detection algorithm for unearthed (isolated) and compensated neutral medium voltage (MV) networks. The proposed algorithm is based on capacitance calculation from transient impedance and dominant transient frequency. The Discrete Fourier Transform (DFT) method is used to determine the dominant transient frequency. The values of voltage and current earth modes are calculated in the period of the dominant transient frequency, then the transient impedance can be determined, from which we can calculate the earth capacitance. The calculated capacitance gives an indication about if the feeder is faulted or not. The algorithm is less dependent on the fault resistance and the faulted feeder parameters; it mainly depends on the background network. The network is simulated by ATP/EMTP program. Several different fault conditions are covered in the simulation process; different fault inception angles, fault locations and fault resistances.**

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

I. INTRODUCTION

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. 1. Therefore, the capacitance measurement gives an indication if the feeder is faulted or healthy. The main advantage of unearthed neutral in power systems is small fault currents which 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. The small fault currents may reduce the sensitivity of conventional relays that normally are based on the fundamental components of the current and voltage at power frequency. The transient components in the fault signals, which provide very fast information about the possible disturbance in the system, can be utilized to detect the fault, leading to transient based schemes which are very sensitive to fault incidence.

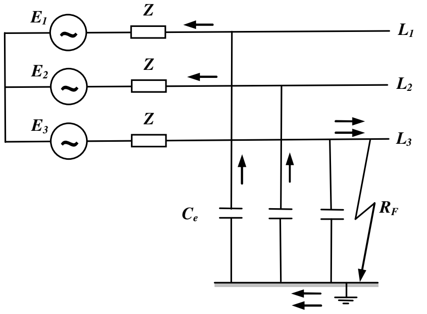

Fig. 1. Earth fault in unearthed neutral network.

In earth faults, the transient components include charge and discharge of the network capacitance and consist of different frequencies. The voltage of the faulty phase falls suddenly, giving rise to the discharge transient while the charge transient is generated by the voltage rise in sound phases during a single-phase to ground fault. This means that a charge transient is always a side effect of the ground fault. Moreover, the charge component dominates the amplitude of the composite transient and therefore it is reasonable to be used for single-phase to ground fault detection. The charge component has to flow through the transformer winding and consequently its frequencies are substantially lower than those of discharge component. According to practical experience, the frequencies of discharge and charge components vary in the range 500-2500 Hz and 100-800 Hz respectively. The amplitude of the discharge component is relatively small, typically only about 5-10 % of the amplitude of the charge component [1, 2].

The three-phase line can be decomposed into three separate and independent modal equivalent circuits. The modal components are the transform of the instantaneous (or time domain) phase quantities, using transformation matrices, into zero, first and second modes. The zero mode is also termed the 'earth mode', while the second and third modes are termed 'aerial modes'. In protection applications, there are three modal transformation matrices that have been widely used. These are Wedepohl, Karrenbauer and Clark transformations [3]. For all of these transformations, the earth mode is the same; it is equal to one-third of the summation of the instantaneous phase values (voltages or currents) as given by (1), (2). The values of the voltage and current earth modes are equal to zero in normal operation and become meaningful in fault condition. They are very sensitive for earth faults; hence they are suggested to be used for fault detection. The voltage and current earth modes are given by:

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$$v(t)_0 = \tfrac{1}{3}[v_a(t) + v_b(t) + v_c(t)] \qquad (1)$$

$$i(t)_0 = \tfrac{1}{3}[i_a(t) + i_b(t) + i_c(t)] \qquad (2)$$

In this paper, a new earth-fault detection algorithm for unearthed and compensated neutral medium voltage networks is presented. The algorithm is proposed to calculate the earth capacitance that can be used as fault indication for the faulted feeder. The capacitance can be calculated using the dominant transient frequency and the transient impedance. Different fault inception angles, fault locations and resistances were simulated to check the validity of the Algorithm.

II. THE PROPOSED TRANSIENT IMPEDANCE-BASED ALGORITHM

A. *The Simulated Network*

Fig. 2, 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 [4]. 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. 10-12).

B. *The Proposed Algorithm*

For the simulated network shown in Fig. 2, the earth modes of the bus voltage and feeder currents are calculated at substation (measuring points). Fig. 3 shows the waveforms of the voltage earth mode at the bus and the current earth modes for each feeder. 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 extract the transient frequencies in all different fault conditions; different fault inception angles, fault locations and fault resistances, hence it will be used with DFT (Discrete Fourier Transform) method. The enlarged view of the transient period is shown in Fig. 4.

The DFT method will be used to extract the dominant transient frequency (of higher amplitude) from the charge transient component, from *0* to *1200 Hz*. In MATLAB, the discrete Fourier transform (DFT), is computed with a fast Fourier transform (FFT) algorithm. At the beginning of the research; a sampling frequency of *100 kHz* (*10 μs*) is used for investigation.

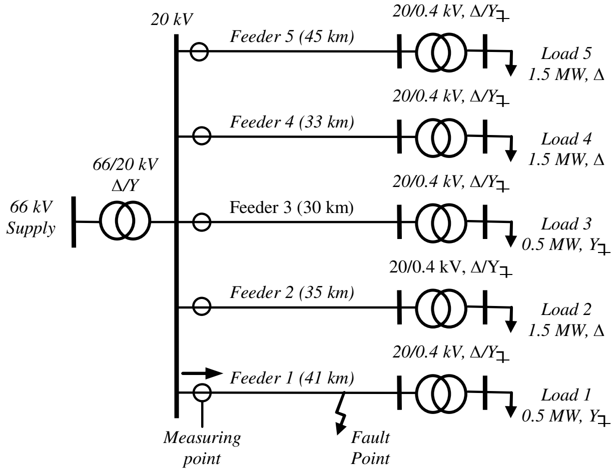

Fig. 2. The simulated medium voltage distribution network.

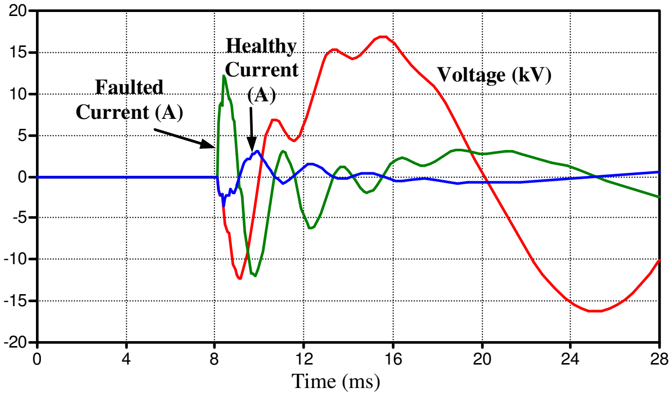

Fig. 3. The waveforms of the voltage earth mode at the bus and the current earth modes of faulted and healthy feeders, for one period (*20 ms* for *50 Hz*) after the fault incidence, (*8 ms incidence time, 10 Ω* fault resistance and *80%* fault distance).

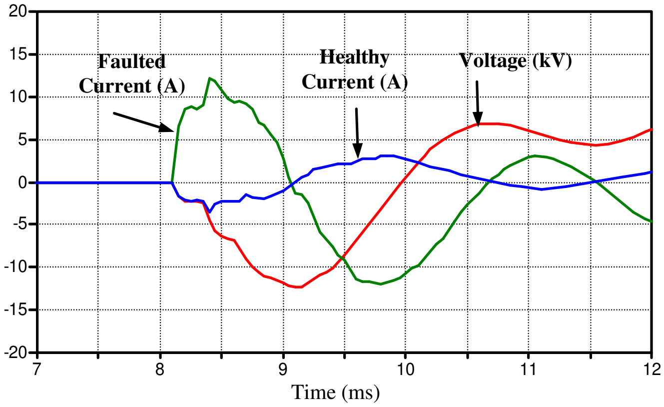

Fig. 4. The transient period for the waveforms shown in Fig. 3.

From the results, a practical low sampling frequency can be used without affecting the accuracy. This can be investigated from the frequency range of the transient period which is very effective from *200 Hz* to *1000 Hz*. Hence lower practical sampling frequencies around *10 kHz (100 μs)* will be adequate hence the proposed algorithm will be suitable for microprocessor based relaying.

The frequency domains for the currents are quite similar but the magnitudes are different; the higher magnitude is of course for the faulted feeder current. The frequency domain output from DFT of the faulted current waveform, presented in Fig. 3, is shown in Fig. 5. For this case, the dominant frequency is *318 Hz* which is equivalent to about *3.15 ms* period. In this transient period the values of the voltage and current earth modes will be calculated, after that the impedance can be calculated as a ratio of the voltage to the current. All these values are at the same transient frequency; which in this case is equal to *318 Hz*. As expected, the dominant transient frequency is different from case to another, depending up on the fault conditions, including the fault resistance, incidence angle and the fault distance. The average value of a sinusoidal waveform over the period is equal to zero; hence it is suggested to use the average value of the waveforms to eliminate the values of higher frequencies contained as possible. For the fundamental transient frequency, the average values will be calculated in the first half of the period to ensure the same polarity [5], and can be calculated from the discrete samples as follows:

$$\textit{The average voltage is} \quad V_0 = \frac{\sum_{k=1}^{N} v_{0,k}}{N} \tag{3}$$

$$\textit{The average current is} \quad I_0 = \frac{\sum_{k=1}^{N} i_{0,k}}{N} \tag{4}$$

$$\textit{The average impedance is} \quad Z_0 = \frac{V_0}{I_0} \tag{5}$$

where:

$v_{0,k}$ is the instantaneous voltage earth mode at sample *k,* calculated from (1).

$i_{0,k}$ is the instantaneous current earth mode at sample *k,* calculated from (2).

N is the number of samples in the window.

The rms and average values are related to peak value by constant factors; *0.707* and *0.636* respectively, and then the rms value is related to the average value by a constant factor of *1.111*. The impedance is calculated as a ratio of the voltage to the current, hence, no need for other factors to be considered. The fault current is composed of the currents flowing through the earth capacitances of the sound lines (background network) as presented in Fig. 6, and hence the calculated impedance will depend mostly on the earth capacitance of background network [6]. 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. In practice, for radial medium voltage distribution networks, it is the area supplied by one HV/MV substation transformer.

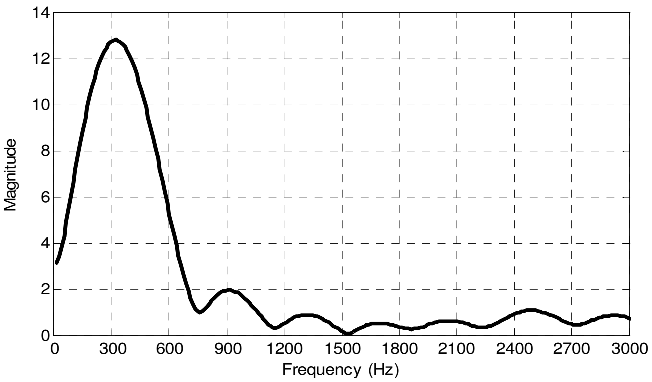

Fig. 5. The frequency domain output from DFT of the faulted current.

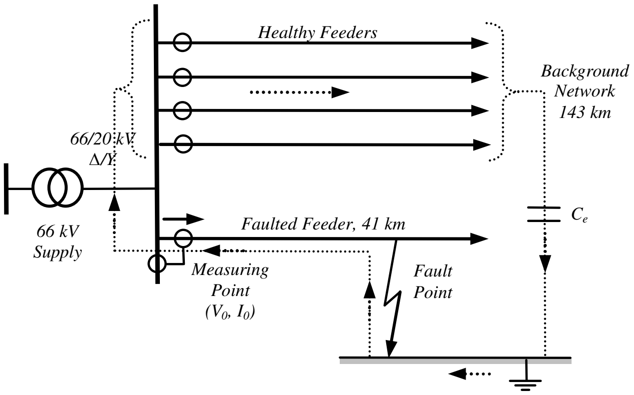

Fig. 6. The flow of the earth fault currents, during a single-phase to ground fault, through the earth capacitance of the background network.

Therefore, for faulted feeder, the calculated impedance will be the capacitive impedance of the background network while for healthy feeder; it is the capacitive impedance of the feeder itself; both defined at the dominating transient frequencies. Also, from Fig. 6, the calculated capacitance for the faulted feeder will be negative because its direction is opposite to the measurement direction which verifies the directionality technique.

In [5], the technique is based on the transient impedance which highly dependent on the transient frequency band, in the transient period. The proposed algorithm here is based on earth capacitance estimation which improves the performance. The earth capacitance of the feeder depends on the type and length. From the dominant transient frequency and calculated transient impedance, the earth capacitance can be calculated as follows:

$$C_e = \frac{1}{2\pi \, f_{tr} \, Z_0} \tag{6}$$

Where:

f_{tr} is the dominant transient frequency that determined from the frequency domain output from DFT.

Z_0 is the average impedance calculated from (5).

For the case shown in Fig. 3, the calculated values are:

The dominant transient frequency	$f_{tr} = 318.004\ Hz$
The voltage	$V_o = -6.5251\ kV$
The faulted feeder current	$I_{0f} = 7.9679\ A$
The healthy feeder current	$I_{0h} = -1.9271\ A$
The faulted feeder impedance	$Z_{0f} = -0.8184\ k\Omega$
The healthy feeder impedance	$Z_{0h} = 3.3840\ k\Omega$
The faulted feeder capacitance	$C_{ef} = -0.6113\ \mu F$
The healthy feeder capacitance	$C_{eh} = 0.1478\ \mu F$

It is found that, the calculated capacitance is not accurate due to the sources of error in this technique; that are the error from the FFT method which highly effected by the sampling frequency, the error due to neglecting the network impedances which effect increases with higher frequencies and the error due to the effect of frequencies of higher magnitudes around the dominant frequency, including the discharge transient frequency. To overcome these errors, it is proposed to use the ratio (K_c) of the calculated capacitances ($C_{e,calc.}$) to the total network capacitance ($C_{e,total}$) as a fault indicator as given by (7).

$$K_c = \frac{C_{e,calc.}}{C_{e,total}} \tag{7}$$

The capacitance is directly proportional to the lengths of the feeders; which are *41, 35, 30, 33* and *45 km*, total length of *184 km*, hence we can determine the values of these ratios in healthy and faulty conditions for all feeders as follows:

For healthy condition:

For feeder (1), $K_{c1} = 0.22$
For feeder (2), $K_{c2} = 0.19$
For feeder (3), $K_{c3} = 0.16$
For feeder (4), $K_{c4} = 0.18$
For feeder (5), $K_{c5} = 0.25$

For faulty condition:

For feeder (1), $K_{c1} = -0.78$
For feeder (2), $K_{c2} = -0.81$
For feeder (3), $K_{c3} = -0.84$
For feeder (4), $K_{c4} = -0.82$
For feeder (5), $K_{c5} = -0.75$

For the same feeder, the summation of the ratio magnitudes, or the magnitude of the difference, in healthy and in faulty conditions, is equal to one. It must be noted that the total earth capacitance must be scaled to include the error in the calculated values. From the calculated values, the average scaled value of the total earth capacitance of the network is equal to *0.7818 µF*. By this technique, for the case shown in Fig. 3, the ratio of the healthy feeder is equal to *0.1891* and the ratio of the faulted feeder is equal to *-0.78187*, which comparable to the calculated values. From the calculated values of the ratios, the average value of the healthy condition is *0.2*0 and the average value of the faulty condition is *-0.80*. 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, also the setting of the algorithm will be proposed.

C. Results and Setting

Fig. 7 shows the variation of the ratios 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. The setting value of the ratio will be chosen at the middle between the average ratio values of healthy and faulty conditions to achieve maximum performance of the algorithm operation. These values are *0.2* and *-0.8*, and then the setting value will be *-0.3*. The limits of the setting value will be from *0.0* (for network with two feeders) to *-0.5* (for network with very high number of feeders), hence its value always negative.

In this part some discussion about the Figures 7, 8 & 9. It is found that there is an adequate gap between the healthy and faulty condition, and no overlapping between the two conditions. This gap can covers any sources of error in the measurements, that may give incorrect higher or lower ratios, and the proposed algorithm will operate effectively. For the simulated system, the magnitude of the average ratio of the faulty condition is equal two four times the average value of the healthy condition; this related two the number of the feeders and its lengths. At faulted condition we have four healthy feeders and one faulted feeder, hence, we can find the factor four. This is for comparable length feeders, as an example if we have a ten feeders network, then we will find a factor nine. In this case, the average value of the healthy condition will be *0.10*, the average value of the faulty condition will be *-0.90*. By choosing a suitable value of the setting, the performance of the proposed algorithm will not be affected by number of feeders in the network. From the practical point of view the required sampling rate is an important factor. From the results of different analysis at different frequencies, it investigated that the minimum sampling frequency that can be used for analysis is around 6 kHz without affecting much in the selectivity and security of the proposed algorithm, definitely the sensitivity is increased with higher sampling rate. Therefore, the simulations were performed at sampling frequency of 100 kHz and the data were analyzed at sampling frequency of 6.25 kHz after using a sub-sampling factor of 16. This lower sampling frequency of the proposed algorithm indicates the applicability and the suitability for microprocessor based relaying.

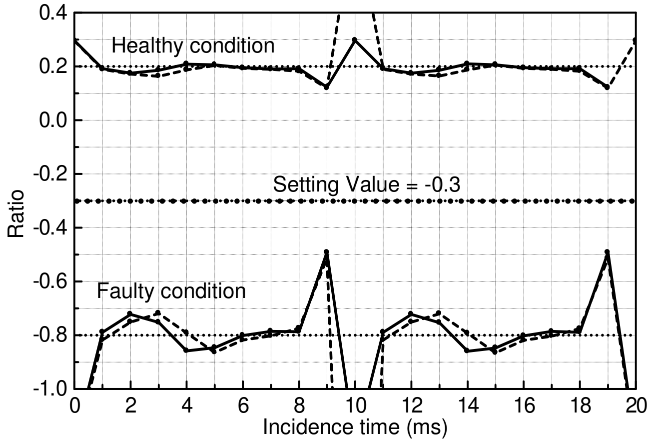

Fig. 7. The variation of the ratios for healthy and faulty conditions with the fault incidence time, over the power frequency period (*0-20 ms*) at *80 Ω* fault resistance and *80%* fault distance for unearthed and compensated networks.

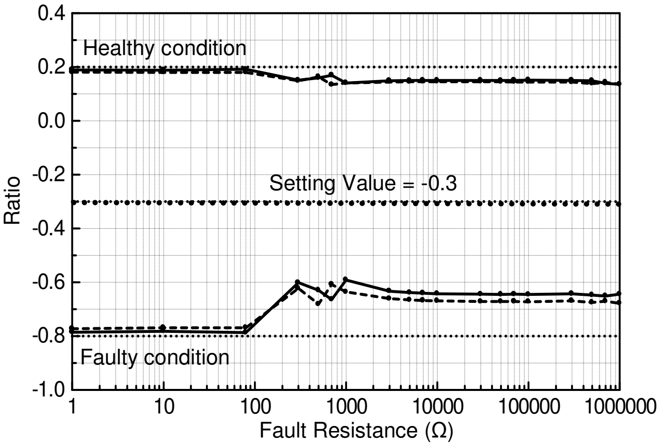

Fig. 8. The variation of the ratios for healthy and faulty conditions with the fault resistance at *8 ms* incidence time and *80%* fault distance for unearthed and compensated networks.

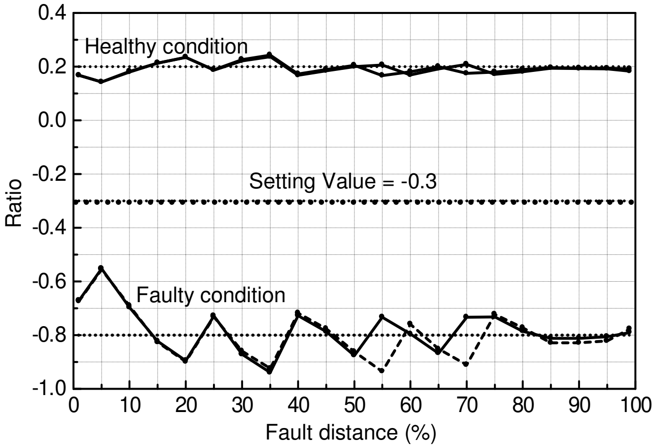

Fig. 9. The variation of the ratios for healthy and faulty conditions with the fault distance at 8 ms incidence time and 80 Ω fault resistance for unearthed and compensated networks.

III. CONCLUSIONS

A new transient-based algorithm for earth fault detection for unearthed (isolated) and compensated neutral medium voltage networks is proposed. It is based on determining the dominant transient frequency by using FFT method and calculating the transient impedance in the transient period, from which the earth capacitance can be calculated. The earth capacitance gives a good indication about the earth fault, as it equals to all the background network earth capacitance in faulty condition but equal to line earth capacitance in healthy condition. To overcome the sources of errors in the calculation, it is proposed to use the ratio of the calculated capacitances to the total network capacitance as a fault indicator. Extensive simulations by ATP/EMTP program and analysis by MATLAB (FFT method) has been done to investigate and validate the performance of the proposed algorithm for different fault conditions including different values of incidence time, fault resistance and fault location. There is an adequate gap between the healthy and faulty condition, and no overlapping between the two conditions. This gap can cover any source of errors in the measurements that may give incorrect higher or lower ratios. An average setting value of -0.25 can be used as the default setting value that can be used for different network configuration. The performance of the proposed algorithm is promising and it can be more enhanced by choosing the ratio setting value from *0.0* to *-0.5*, at the middle between the average ratio values of healthy and faulty conditions, depending on the network configuration. The proposed algorithm is applicable with a lower sampling frequency of 6.25 kHz and hence suitable for microprocessor based relaying.

IV. APPENDIX

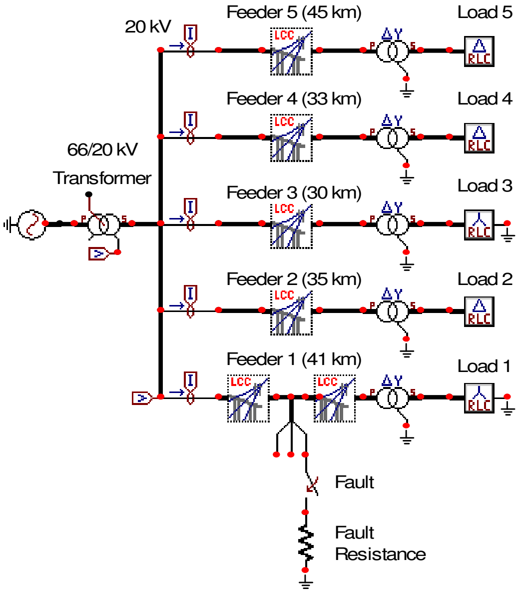

Fig. 10. The ATPDraw circuit of the simulated unearthed medium voltage system:

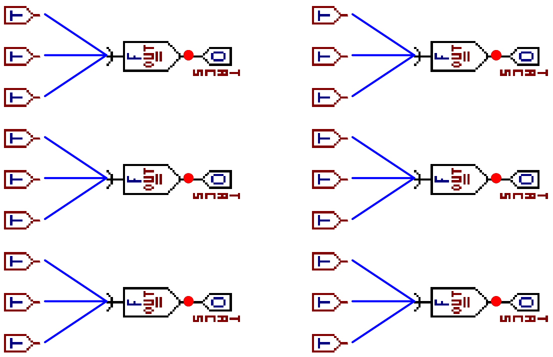

Fig. 11. The used TACS objects in ATPDraw.

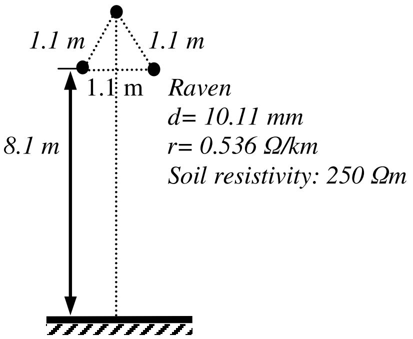

Fig. 12. The configuration of the feeders.

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VI. BIOGRAPHIES

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