Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Evaluation of Probabilistic-Based Selectivity Technique for Earth Fault Protection in MV Networks

Abdelsalam M. Elhaffar, Nagy I. Elkalashy, Naser G. Tarhuni, Mohamed F. Abdel-Fattah and Matti Lehtonen

***Abstract*—In [1], a Bayesian selectivity technique has been introduced to identify the faulty feeder in compensated medium voltage (MV) networks. The proposed technique has been based on a conditional probabilistic method applied on transient features extracted from the residual currents only using the Discrete Wavelet Transform (DWT). In this paper, the performance of this selectivity technique is evaluated when the current transformers (CTs) impacts are considered. The CTs are modeled considering their frequency characteristics. Furthermore, network noises are added to the simulated signals. Therefore, the algorithm can be tested at different practical conditions, such as nonlinear characteristics of the measuring devices and the impact of noise as well. The fault cases occurring at different locations in a compensated 20 kV network are simulated by ATP/EMTP. Results show a reduction in the algorithm sensitivity with considering CT and noise effectiveness.**

***Index Terms*—Earth fault detection, DWT, probability, initial transients, residual current, CT characteristics, network noise.**

I. Introduction

Initial transients can reliably enhance the faulty feeder identification regardless of the earthing type of MV network [1]-[3]. Extracting transients is carried out using various signal processing methods. One of the best methods used for extracting the transients is the Wavelet Transform which overcomes shortcomings of Fast Fourier Transform (FFT).

The probability functions have been recently used to provide a decisive selectivity function in distribution protection such as addressed in [1], [4]. Combining the benefits of applying a point-probability method and of extracting transient features by the DWT has been gained in [1] to detect the earth faults in fully compensated MV networks. The algorithm procedure is depending on absolute sum of DWT detail coefficients of the residual currents measured at the beginning of each feeder. The absolute sum is used as a detector for the fault event. A novel discriminator is introduced to estimate the faulty feeder. This discriminator is based on conditional probability approach in which the absolute sum of each feeder decides which feeder is the most probable faulty-feeder. This approach is found to be suitable for identifying faulty feeders in unearthed or compensated distribution networks.

In this paper, the proposed selectivity technique introduced in [1] is comprehensively examined concerning the frequency characteristics of the CTs and the impact of the network noises. The CTs are simulated using ATP/EMTP and they are incorporated in a practical 20 kV compensated-network where ATPDraw is used as a graphical interface [5].

II. Selectivity Technique Principles [1]

The proposed technique mainly depends on applying the Bayesian theorem after DWT-based transient feature extraction. A brief introduction on DWT is given in Appendix A. Fig. 1 illustrates the flowchart of the proposed technique implementation. At each measuring node, phase currents of each feeder are measured and the corresponding residual current is computed. Then, the transient features are extracted using DWT. Several wavelet families are tested to extract the fault features using the Wavelet toolbox incorporated into the MATLAB software [6]. Daubechies wavelet 24 (db24) is appropriate for localizing this fault where the sampling frequency is 100 kHz. The absolute sum (S_i) is computed over a power-frequency cycle window of the DWT detail level *d2* of the residual current in a discrete form at each measuring node, as in form:

$$S_i(k) = \sum_{n=k-N+1}^{k} \left| d2(n) \right| \tag{1}$$

where i is denotes the i-th feeder, and N is a number of samples representing a window of 20 *ms*. This absolute sum is used as a detector to detect the fault occurrence.

The selectivity function to estimate the faulty feeder is proposed based on the Bayesian theorem as in [1,4]:

$$\Pr(\text{Feeder } i \text{ is faulty } | S_1,\ldots,S_i) = \frac{\dfrac{f_1(S_i)}{f_0(S_i)}}{\displaystyle\sum_{j=1}^{n} \frac{f_1(S_j)}{f_0(S_j)}} \tag{2}$$

where f_0 and f_1 are the normal distribution density function considering the feeder healthy and considering the feeder faulty, respectively. The distribution density functions are:

$$f_0(S) = \frac{1}{\sigma_0\sqrt{2\pi}} e^{\frac{-(S-\mu_0)^2}{2\sigma_0^2}} \quad \text{and} \quad f_1(S) = \frac{1}{\sigma_1\sqrt{2\pi}} e^{\frac{-(S-\mu_1)^2}{2\sigma_1^2}} \tag{3}$$

where σ_0, σ_1, μ_0 and μ_1 are the standard deviation and the mean for the DWT details level d2 of the healthy and faulty feeder conditions. In [1], it has been found that $\sigma_1 = 3.04$, $\sigma_0 = 0.87$, $\mu_1 = 3.73$ and $\mu_0 = 1.1$ for the simulated MV network.

A. Elhaffar, N. Elkalashy, M. Abdel-Fattah and M. Lehtonen are with Department of Electrical Eng., Faculty of Electronics, Communications and Automation, Helsinki University of Technology (TKK), Finland. (Address: PO Box 3000, FI-02015 TKK Finland, fax:+35894515012, email: abdelsalam.elhaffar@tkk.fi)

N. Tarhuni is with ECE department, Sultan Qaboos University, Oman.

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

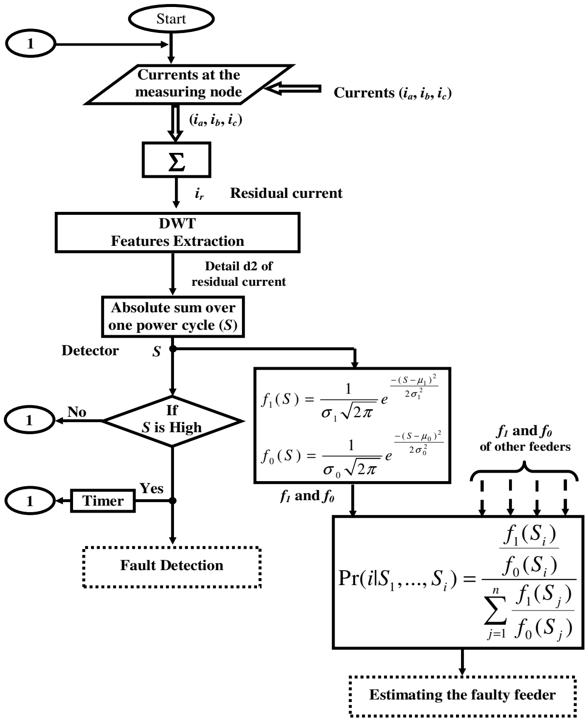


Fig. 1 Implementation of the proposed detection technique.

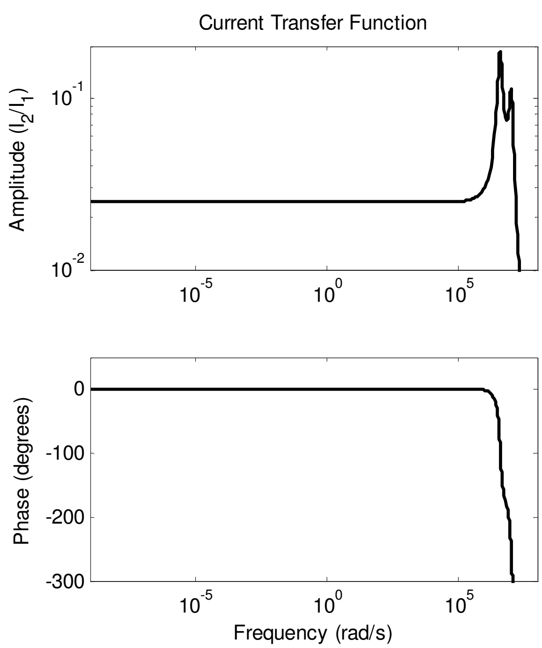


Fig. 2 CT Transfer function versus frequency

III. Instrument Transformers Effects

The current transformer (CT) has been modeled using experimental measurements at the high voltage laboratory, Helsinki University of Technology (TKK), Finland [7]. The current transformer modeling is divided into two parts; the low frequency and high frequency models. The low frequency model parameters of the CT are estimated using open and short circuit tests at power frequency. At low frequency, the stray capacitances have negligible effects. A stable-output power analyzer was used in the measurements. Open circuit tests were only measured from the secondary windings while the short circuits were measured from both the primary and secondary sides. Since the inductance of the secondary windings dominates the impedance at low frequencies, the parameters are calculated using open and short circuit tests at the power frequency. The parameters of the CT model have been identified based upon the use of recorded time response from impulse tests of the CT. For high-frequency modeling, open and short circuit impulse test were carried out. The primary winding was fed with an impulse current signal and the output current on each secondary winding was measured using a calibrated 0.4905Ω resistance. The monitored signals were recorded by an 8-bit, 150 MHz digital oscilloscope controlled by a computer [7]. The digital recorded time signals are Fourier transformed to obtain the frequency spectra from which the desired transfer functions are calculated as shown in Fig. 2. The CT in the considered frequency range has been modeled as in Fig. 3 where CT capacitances are reflected into the secondary winding. Although this capacitance is distributed between turns of the secondary winding, it is modeled by a lumped capacitance which may cause a negligible error in the model. However, capacitance between the primary winding and its associated shield does cause an error which depends on the winding configuration. The corresponding CT parameters are summarized in Table I.

The stray capacitance of the secondary winding can be determined from several different methods [8], [9]. In this paper, the results of [7] are taken into account for representing the CT model attached with ATP/EMTP test case of a practical compensated-distribution network shown in Fig. 4. This compensated MV network is illustrated in Appendix B.

TABLE I. CT Data

CT data	Core 1	core 2	core 3
Primary	200	200	200
Secondary	5	5	5
Class	0.5	0.5	1
VA	60	60	60
Security factor	<3	<3	>10

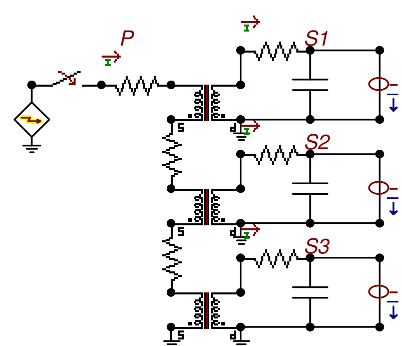


Fig. 3 Simulated CT Model.

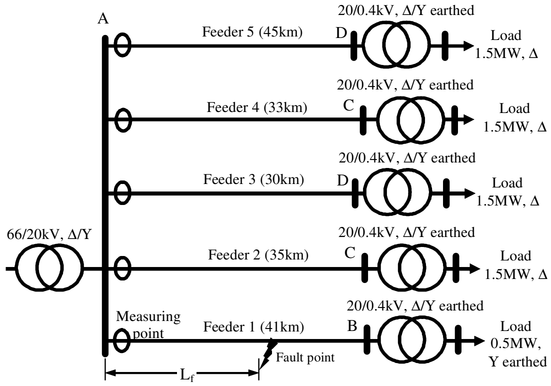


Fig. 4 Simulated system for 251 km distribution network.

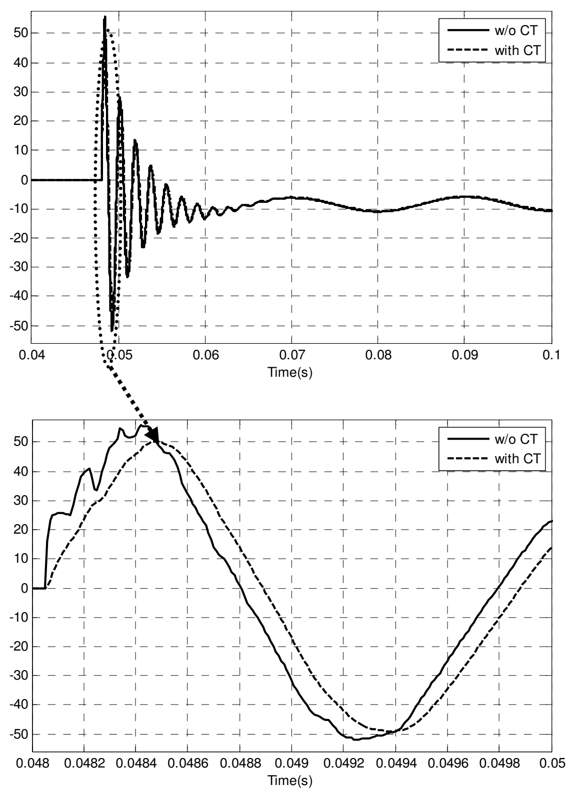


Fig. 5 Enlarged residual current waveforms of the faulty feeder 1 without and with considering the CT (w/o CT and with CT, respectively).

IV. Performance of the Proposed Algorithm

In this section, the algorithm described in section II is investigated considering the power network shown in Fig. 4 and the CT model are combined in one arrangement during the occurrence of a resistive earth-fault where the earth-fault current is fully compensated. The algorithm performance is compared to the case reported in [1].

A. *Effect of the CT Model*

For comparison purposes, an earth fault of resistance equal to 1mΩ is considered at 20 km in Feeder1 and occurred at 48 ms. The filtering effect of the CT is clearly obvious in the corresponding residual-current waveforms of the faulty feeder shown in Fig. 5 considering the dynamics of CT model [10]. From Fig. 5, the dynamic effect of the CT can be summarized in three points that the initial transients generated due to fault occurrence are smoothed, damped, and delayed. The first two issues have a great affect on the DWT output value as observed in Fig. 6 where the detail level d2 used to localize the initial transients generated at the fault instant are extremely reduced. Correspondingly, the detector has lower magnitude with the CT as shown in Fig. 7. However, the detector corresponding to the faulty Feeder1 is still the highest one compared to the healthy feeders as confirmed in Fig. 8. Therefore, applying the proposed selectivity function is still valid. The corresponding performance of the discriminator $P_{r(\text{Feeder j})}$ for Feeder j is shown in Fig. 9. The discriminator P_{Feeder1} performance has unity value during the period of initial transients as extracted by DWT; however the other discriminators are zero. Such performance provides evidence of applying the proposed selectivity function although CT impact is not compensated.

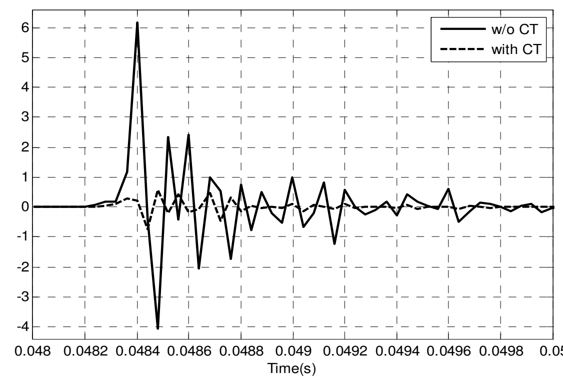


Fig. 6 The CT impact on DWT detail level d2 of the faulty feeder 1.

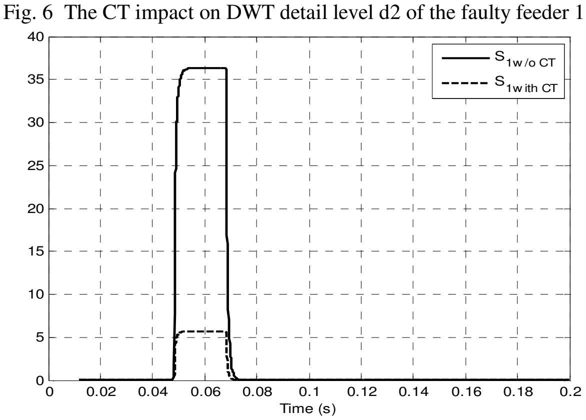


Fig. 7 The CT impact on the detector of the faulty feeder 1.

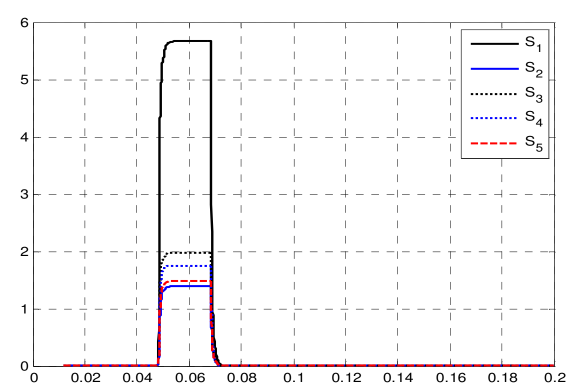


Fig. 8 The feeder detectors with considering the CT.

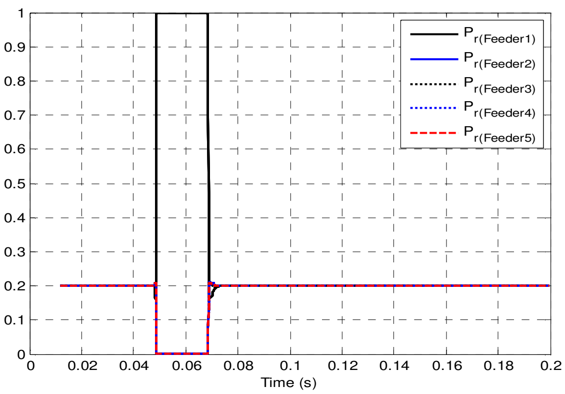


Fig. 9 The discriminator performance.

B. *Effect of Network Noise*

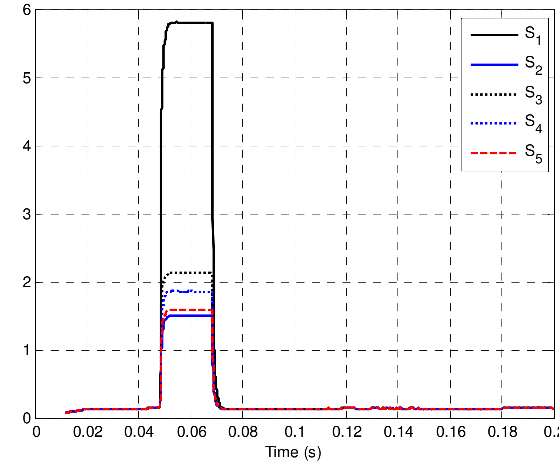
In electrical networks noise is always present in many forms. Specifically, Gaussian noise contaminating measurements is considered as the main disturbing noise effect in this work. The Gaussian noise signal is generated using the form:

$$S_n = \sigma_n \sqrt{-2\log(A)} \times \cos(2\pi B) \qquad (4)$$

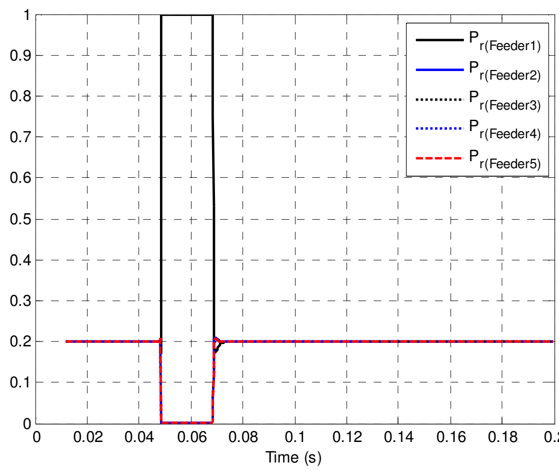
where A and B are random numbers, which are independent and uniformly from 0 to 1. These random numbers are implemented in ATPDraw environment using the TACS expression (RAN) with two different seeds. σ_n is the noise standard deviation and it is value in MV networks is empirically estimated using measurements. A measurement case of staged earth fault with fault resistance 236 kΩ was processed for testing the transient directionality [11]. From this field data, the noise is extracted and the signal to noise ratio (SNR) is estimated to be 21 and 35 for each feeder where there are two feeders. This range of SNR is because the earth fault current is small in unearthed/compensated networks and it is even much smaller at very high resistances like 236 kΩ.

The noise standard deviation is computed from the worst case of SNR = 21 at the fault resistance of 236 kΩ. Accordingly, the noise signals are added to the primary phase currents before the CTs and therefore before the computation of residual currents. The effect on performance for this case is shown in Fig. 10. Although the noise is obvious on the detector performance as shown in Fig. 10.a, the discriminator can identify the faulty feeder as depicted in Fig. 10.b. DWT-based denoising of the measured signals is expected to provide a better performance for the proposed algorithm in a similar concept reported in [11].

Considering the impact of the current transformer and the noise, it was found that they can effectively reduce the discriminator sensitivity, which is limited by a fault resistance up to 170 Ω for a setting of a 90% probability fault condition. However the algorithm sensitivity was 1500 Ω without considering the CT and network noises as reported in [1]. Such shortcoming can be overcome by normalizing the input of the conditional probability function.



(a) Detector



(b) Discriminator

Fig. 10 The proposed Algorithm performance considering network noise.

V. Conclusions

A conditional probabilistic selectivity technique has been evaluated considering practical conditions such as measuring devices (CTs) and network noises. The CT model has been represented in ATP/EMTP program and incorporated with a 20-kV distribution network in one arrangement and the noise has been added as well. As the proposed technique is depending on extracting initial transients generated due to fault occurrence, frequency characteristics of the CTs have a considerable effect on the proposed technique performance. Furthermore, the noise impact has a noticeable effect on the detector performance. However, the measured signals can be de-noised to overcome the network noise. Generally, the algorithm sensitivity is highly reduced up to fault resistance of a 170Ω. Towards achieving an improvement in the conditional probability performance, its input quantities can be normalized, in which such proposal will be presented in a work to follow.

VI. APPENDICES

A. Discrete Wavelet Transform (DWT)

Wavelets are families of functions generated from one single function, called the mother wavelet, by means of scaling and translating operations. The scaling operation is used to dilate and compress the mother wavelet to obtain the respective high and low frequency information of the function to be analyzed. Then the translation is used to obtain the time information. In this way a family of scaled and translated wavelets is created and it serves as the base for representing the function to be analyzed [8]. The DWT is in the form:

$$DWT_{\psi}(m,k) = \frac{1}{\sqrt{a_o^m}} \sum_n x(n) \psi\left(\frac{k - nb_o a_o^m}{a_o^m}\right) \quad (5)$$

where $\psi(.)$ is the mother wavelet that is discretely dilated and translated by a_o^m and $nb_o a_o^m$, respectively. a_o and b_o are fixed values with $a_o>1$ and $b_o>0$. m and n are integers. In the case of the dyadic transform, which can be viewed as a special kind of DWT spectral analyzer, $a_o=2$ and $b_o=1$. DWT can be implemented using a multi-stage filter with down sampling of the output of the low-pass filter.

B. Simulated System

Fig. 4 illustrates the single line diagram of a 20-kV compensated, a five-feeders distribution network simulated using ATP/EMTP, in which the processing is created by ATPDraw [5]. The feeder lines are represented using the frequency dependent JMarti model.

The considered faults are resistive type with fully compensation of earth fault currents. The aforementioned CT model in section III and the MV network are combined in a single arrangement and the corresponding ATPDraw network is shown in Fig. 11. The best waveforms that can be analyzed for detecting earth faults are residual waveforms where the residual current is:

$$i_r = i_a + i_b + i_c \quad (6)$$

where i_r is the residual current and i_a , i_b and i_c are the phase currents.

VII. ACKNOWLEDGEMENT

The authors gratefully acknowledge the valuable discussions with Prof. Mohamed Elmusrati, Telecommunication group, University of Vaasa, Finland.

VIII. APPENDICES

[1] N. Elkalashy, M. Lehtonen, and N. Tarhuni "DWT and Bayesian Technique for Enhancing Earth Fault Protection in MV Networks" IEEE/PES, Power Systems Conference and Exposition, PSCE2009, 15-18 March 2009, Seattle, Washington, USA.

[2] N. Elkalashy, N. Tarhuni and M. Lehtonen "A Simplified Probabilistic Selectivity Technique for Earth Fault Detection in Unearthed MV Networks" the Institution of Engineering and Technology (IET), Generation, Transmission & Distribution, Vol 3, no. 2, pp. 129-144, Feb. 2009.

[3] N. Elkalashy, M. Lehtonen, H. Darwish, A-M. Taalab and M. Izzularab "DWT-Based Detection and Transient Power Direction-Based Location of High Impedance Faults Due to Leaning Trees in Unearthed MV Networks" IEEE Transactions on Power Delivery, vol. 23, no. 1 , pp. 94-101, Jan. 2008.

[4] S. Hanninen, M Lehtonen and U. Pulkkinen "A Probabilistic Method for Detection and Location of Very High Resistive Earth Faults" *Electric Power System Research*, vol. 54, no. 3, pp. 199-206, June 2000.

[5] L. Prikler and H. Hoildalen, *ATPDraw users' manual*, SINTEF TR A4790, Nov. 1998.

[6] *Wavelet Toolbox for MATLAB*, Math Works 2005.

[7] A. Elhaffar and M. Lehtonen. "High Frequency Current Transformer Modeling for Traveling Waves Detection" Power Engineering Society General Meeting 24-28 June 2007, Tampa, USA.

[8] H.Y. Lu; J.G. Zhu; S.Y.R. Hui, "Experimental determination of stray capacitances in high frequency transformers" IEEE Trans. On Power Electronics, vol. 18, Issue 5, pp. 1105- 1112, Sept. 2003

[9] D. A. Douglass, "Current transformer accuracy with asymmetric and high frequency fault current", IEEE Trans-PAS, Vol. 100, No. 3, March 1981.

[10] Spoor, D.J. Zhu, J. Nichols, P., "Filtering effects of substation secondary circuits on power system traveling wave transients", Proceedings of the Eighth International Conference on Electrical Machines and Systems, 2005. ICEMS 2005, 27-29 Sept. 2005, Volume: 3, pp. 2360-2365, Vol. 3.

[11] N. Elkalashy, M. Lehtonen, H. Darwish, A-M. Taalab and M. Izzularab "Verification of DWT-Based Detection of High Impedance Faults in MV Networks" The 9th International Conf. on Developments in Power System Protection, DPSP2008, 17-20 March 2008, Glasgow, UK.

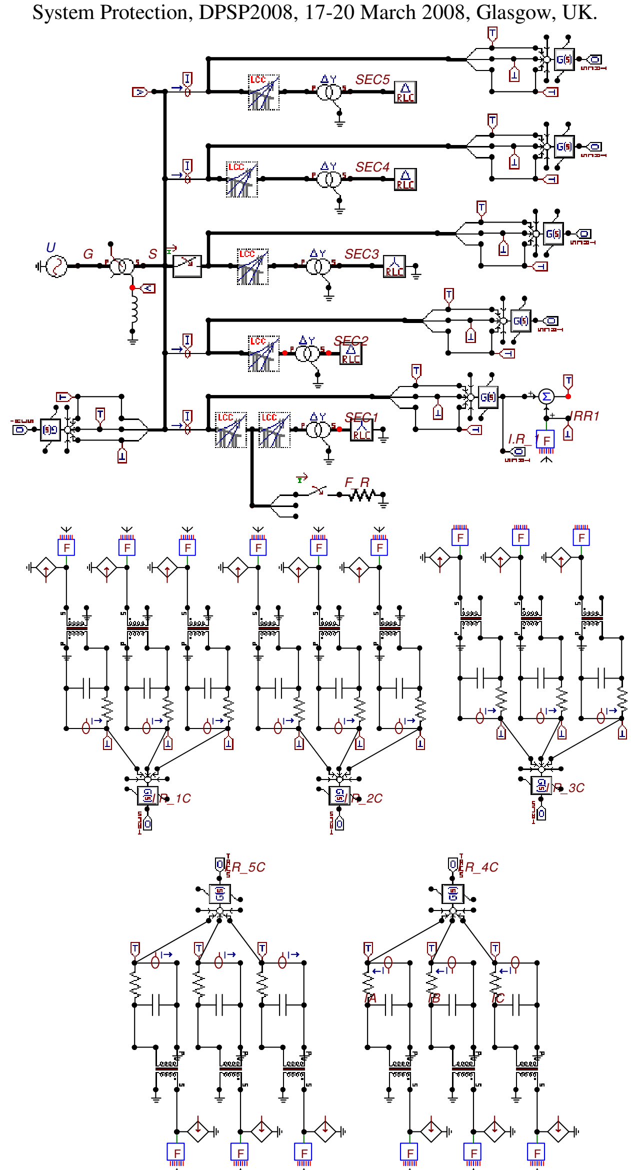


Fig. 11 ATPDraw network.