A New Approach to the Arcing Faults Detection for Fast Autoreclosure in Transmission Systems

M.B.Djurić, V.V.Terzija
Department of Electrical Engineering
University of Belgrade, Belgrade, Yugoslavia

Abstract: To avoid automatic reclosing on permanent faults, a new numerical algorithm for arcing faults detection has been developed. Some important features of a long arc in air are investigated and used as a base in the algorithm design. The fact that the nonlinear arc behavior influences other voltages and currents distorting them, offered an opportunity to detect the arc by measuring and processing the line terminal voltage and current. A series of simulation studies have shown that the algorithm can be used as an effective tool for arcing faults detection.

Keywords: autoreclosure, power system harmonics, digital signal processing, parameter estimation

1 Introduction

It is known that somewhat about 80 % to as high as 90 % of faults on most overhead lines are transient. For such faults, by deenergizing the line long enough for the fault source to pass and the fault arc to deionize, the service can be restored by automatically reclosing the breaker. This can improve power system transient stability and reliability providing a much higher service continuity to customers. However, reclosure onto a permanent fault may aggravate the potential damage to the system and equipment.

To solve this problem, some interesting concepts were proposed in the past. In [1] three criteria for distinguishing between transient and permanent faults are given. They were based on the analysis of voltages on the opened phase conductor during the reclosing dead time and were devoted to the 220kV - 500kV long lines with shunt reactor compensation. In [2] an adaptive autoreclosure technique was developed using the neural network approach. Features of interest are identified and extracted from faulted voltage waveforms by Fourier transform. A three-layer neural network was developed and trained, providing the technical feasibility of neural network applications in the design of autoreclosure strategy. In designing some modern microprocessor based techniques, it was indicated that no single frequency can be used as a parameter to identify an arcing fault [3].

In this paper the authors report the results of studies on the development of a new numerical digital signal processing algorithm for the arcing faults detection in transmission systems. These results are a part of a project concerning the applications of microprocessors in modern measuring and relaying devices. Starting from a very simple arc model and by processing voltages and currents digitized at the line terminals, by using Fast Fourier Transform (FFT), the arc voltage was in the spectral domain estimated through Least Error Squares Technique. Numerous computer simulations have shown that the numerical algorithm developed can be successfully used as an effective tool for preventing reclosure on permanent faults. The results of laboratory tests are also given, confirming the results obtained through computer simulations.

95 WM 027-3 PWRD A paper recommended and approved by the IEEE Power System Relaying Committee of the IEEE Power Engineering Society for presentation at the 1995 IEEE/PES Winter Meeting, January 29, to February 2, 1995, New York, NY. Manuscript submitted August 11, 1994; made available for printing December 12, 1994.

2 Characteristics of a Long Arc

2.1 Mathematical Models

Studies of long arcs, typical of power system arcing faults, have shown that they are a highly complex nonlinear phenomenon influenced by a number of factors, e.g. the arc path, the arc-column geometry, the rate of cooling etc. In order to simulate such power system transients caused by arcing faults realistically, various approaches and models have been hitherto proposed. One of the earliest experimental studies was that by Strom [4].

In this paper the authors also investigated a long 50Hz power arc in free air between electrodes as Strom did. Typical results of this experimental research [5] are the arc voltage-current characteristic and recorded arc voltage waveforms for a 8kA arc between iron rod electrodes, as shown in Fig. 1. The nonlinear variation of the arc manifests itself into producing high frequency components

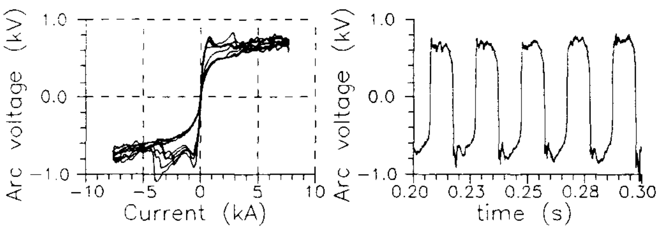

Figure 1: Arc voltage-current characteristics and arc voltage waveforms [5]

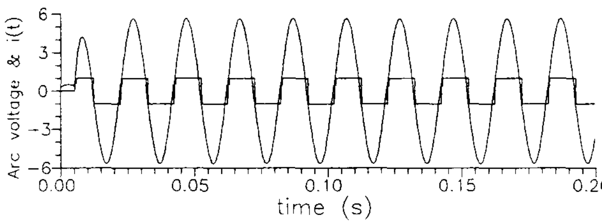

Figure 2: Square-wave arc voltage shape

which in turn distort the arc voltage waveforms into a near square wave. As far as the fault arc current is concerned, the nonlinear arc behavior is of small influence.

From the modeling point of view, a few authors represented the arc by a nonlinear differential equation [6]. The general form of this differential equation is:

$$\frac{dg}{dt} = f(g, u, i, t) \tag{1}$$

where g, u and i are the arc conductance, voltage and current, respectively. The main problem here is the model parameters selection: the unknown parameters must be estimated from test data. On the other hand, the arc has been represented by the piecewise arc voltage-current characteristics [7]. In this paper, the arc voltage is assumed to be of square wave shape, in phase with the fault arc current, as shown in Fig. 2. Hence, the arc voltage model could be expressed as:

$$v_a(t) = V_a sgn\ i(t) \tag{2}$$

where $v_a(t)$ and $i(t)$ are the arc voltage and current, respectively, V_a is the amplitude of square wave and sgn is signum function, defined as: $sgn\ x = 1$ if $x \geq 0$ and $sgn\ x = -1$ if $x < 0$. The value of V_a is obtained from the product of arc-voltage gradient (over the range of currents, 100A to 20kA, the average arc-voltage gradient lies between 12 and 15 V/cm [8]) and the length of the path, i.e. the flashover length of a suspension insulator string or flashover length between conductors.

2.2 Arc Voltage Amplitude Spectrum

The most distinct characteristics of the arc voltage waveforms are those associated with the variations of the frequency components over time. The spectral analysis of

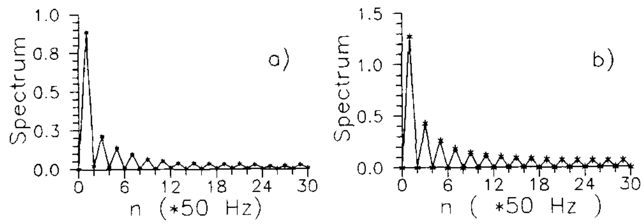

Figure 3: Arc voltage amplitude spectra: a) actual and b) square waveforms

arc voltages from Figures 1 and 2 is provided by means of FFT. The voltage spectra are depicted in Fig. 3.

Since the voltage waveforms are similar in the time domain, their amplitude spectra are similar as well. The arc model adopted in this paper (equation (2)) has an important feature in the spectral domain: the pure square wave can be represented by Fourier series containing odd sine components only, as follows:

$$v_a(t) = \sum_{k=1}^{\infty} \frac{4}{\pi} \frac{1}{2k-1} V_a \sin{(2k-1)\omega t} \tag{3}$$

where k is the harmonics order and ω is the fundamental harmonic angular velocity. That means that the amplitudes of odd harmonics are proportional to $\frac{1}{2k-1}$. The amplitude spectrum retains this feature regardless of the relatively square wave phase shift from the data window (a finite period of time during which the voltage or current samples are digitized and processed). In computer simulated tests data window size and sampling frequency were selected to be 0.02s and 6400Hz, respectively.

If the arc voltage wave spectrum is known, i.e. if a finite number of arc voltage harmonics are obtained, one could estimate from this set of data the value of the square wave amplitude V_a. This is shown in the following section.

3 Arc Voltage Amplitude Estimation

Let us assume the following observation model of the arc voltage k-th harmonic:

$$V_{ak} = \frac{4}{\pi} \frac{1}{2k-1} V_a + \xi_k \tag{4}$$

where ξ_k is a zero mean random noise and V_{ak} is the amplitude of the k-th harmonic of the arc voltage. In equation (4) ξ_k takes into account the measurement errors and the fact that the square wave is only an approximation of the real arc voltage waveform. Value V_a is treated as an unknown parameter to be estimated. If k ($k = 1, \ldots, m$) arc voltage harmonics V_{ak} are known, one can define vector $\mathbf{V_a}$ as a set of m values:

$$\mathbf{V_a} = \begin{bmatrix} V_{a1} & V_{a3} & V_{a5} & \cdots & V_{a(2k-1)} \end{bmatrix}^T \tag{5}$$

This set determines m linear equations in one unknown and can be written in the following matrix form:

$$\mathbf{V_a} = \frac{4}{\pi}\mathbf{H}V_a + \xi \tag{6}$$

where $\mathbf{H}$ is an $(m \cdot 1)$ coefficient vector given as:

$$\mathbf{H} = [\ 1 \ \ \tfrac{1}{3} \ \ \tfrac{1}{5} \ \ \cdots \ \ \tfrac{1}{2k-1}\ ]^T \tag{7}$$

and ξ is an $(m \cdot 1)$ error vector, to be minimized.

The unknown square wave amplitude V_a can be estimated by means of the ordinary non-recursive Least Error Squares Technique. The objective of this technique is to minimize the sum of squared errors in the model over the given set of observations. The estimate of V_a, $\hat{V}_a$, is determined by the following equation:

$$\hat{V}_a = \frac{\pi}{4}(\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T\mathbf{V_a} = \frac{\pi}{4}\mathbf{H}^{\dagger}\mathbf{V_a} \tag{8}$$

where $\mathbf{H}^{\dagger}$ is the pseudo-inverse of $\mathbf{H}$. Since the matrix $\mathbf{H}^{\dagger}$ is time-invariant, it could be precalculated and later used in V_a estimation. For example, taking into account the first nine harmonics (1st, 3rd, 5th, 7th and 9th) one obtains:

$$\frac{\pi}{4}\mathbf{H}^{\dagger} = [\ 0.6634 \quad 0.2211 \quad 0.1327 \quad 0.0948 \quad 0.0737\ ] \tag{9}$$

By this, the unknown value of $\hat{V}_a$ can be simply estimated using the following equation:

$$\begin{aligned} \hat{V}_a &= 0.6634V_{a1} + 0.2211V_{a3} + 0.1327V_{a5} + \\ &+ 0.0948V_{a7} + 0.0737V_{a9} \end{aligned} \tag{10}$$

The last equation was used as the basis in determining whether the fault is with arc (transient fault), or without arc (permanent fault). Of course, before the implementation of equation (10), one should calculate the arc voltage harmonics. The mathematical structure through which the arc voltage harmonics, i.e. the unknown vector $\mathbf{V_a}$, were calculated is presented in the next section.

4 Arc Voltage Harmonics Calculation

The only available voltages and currents are those measured at the line terminals. They are input signals to distance protection. Computer relaying subsumes analog-to-digital conversion of the phase voltage and current and their further processing in order to detect the fault occurrence, the fault type and the fault location. It is *per se* clear that the nonlinearities caused by the nonlinear variations of the arc manifest themselves into slightly distorting the line terminal voltages and currents. As the arc is a nonlinear element and hence a source of harmonics, these will cause the distortions in all currents and voltages in the network. Hence, the voltages and currents at the line terminals will contain harmonics, as well. The distortion of waves depends on the fault distance and the arc voltage amplitude. It could be concluded through spectral analysis that the line terminal voltage and current contain the harmonics induced by arc voltage, particularly the odd components. These amplitudes are not comparable to the fundamental harmonic amplitude, but in spite of that are recognizable and measurable.

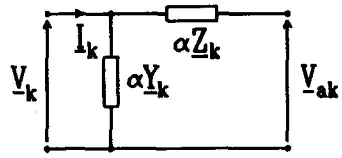

Figure 4: Network equivalent circuit

Thus, one of the obvious ways in which arc voltage harmonics could be calculated is to analyze the equivalent circuit depicted in Fig. 4. In this circuit all variables have angular velocity $k\omega$ and all the line parameters are calculated in terms of $k\omega$. By digitizing voltages and currents at one line terminal, and by processing them by means of FFT, the corresponding harmonic components $\underline{V}_k$ and $\underline{I}_k$ could be calculated. Now, the unknown values of vector $\mathbf{V_a}$ can be calculated from the circuit depicted in Fig. 4. From Fig. 4 the k-th arc voltage harmonic can be simply calculated as follows:

$$\underline{V}_{ak} = (1 + \alpha^2\underline{Y}_k\underline{Z}_k)\underline{V}_k - \alpha\underline{Z}_k\underline{I}_k \tag{11}$$

where $\underline{Z}_k = R(k\omega) + jk\omega L(k\omega)$ and $\underline{Y}_k = jk\omega C(k\omega)$ are frequency dependent line impedance and admittance, respectively, and α is the p.u. relative fault distance of the whole line length. The value of α can be obtained as input data from distance protection, or can be simultaneously calculated from the voltage and current fundamental harmonics phasors. The relation for $\underline{V}_{ak}$ can take any other form, depending on the topology of the network between arc voltage and terminal voltage.

One can notice that the algorithm for detecting arcing faults can be used for symmetrical faults only. The authors plan to extend their methodology on the unsymmetrical faults, as well. This problem will be solved in the second stage of this project. Through this paper the authors attempted to give the fundamental concept for detecting arcing faults by combining the knowledge from the classical power engineering, digital signal processing and applied optimal estimation.

Thus, the new numerical algorithm for arc voltage amplitude estimation can be subdivided into the following steps:

1. Acquisition of input signals block (line terminal phase voltage and current).

2. Determination of input signal spectra.

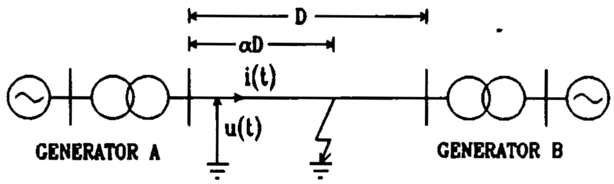

Figure 5: Line and system configuration

3. Fault distance calculation (determination of α by means of distance protection).

4. Arc voltage harmonics calculation (equation (11)).

5. Arc voltage amplitude estimation by applying Least Error Squares approach (equation (10)).

6. Taking a decision whether the fault is with arc (the transient fault), or without arc (permanent fault).

5 Computer Simulated Tests

Digital simulation using the electromagnetic transient program developed at TU KAISERSLAUTERN - Germany [9] is used to generate the sample data required. The schematic diagram of the 400kV symmetrical system on which the tests are based is shown in Fig. 5. Here $u(t)$ and $i(t)$ are the digitized voltage and current, and D is the line length. The line parameters are calculated via line constant program ($D = 100$km, $R = 8\Omega$, $L = 0.21$H and $C = 900$nF). Faults are identified as *close-in* (10km, $\alpha = 0.1$), *midline* (50km, $\alpha = 0.5$) and *remote* (99km, $\alpha = 0.99$) from the left line end, respectively. All tests are made with a fault angle of 90 degrees. Figures 6 and 7 show the left line terminal voltages and currents, sampled with the sampling frequency 6400Hz (128 samples/0.02s) for two *midline* faults: a) without arc (Fig. 6) and b) with arc (Fig. 7). The values of voltages and currents are given in kV and kA, respectively. The corresponding voltage spectra (except the first harmonic which is much greater than the superimposed higher order harmonics) are also given (see Fig. 8) for three data windows after the fault inception. The length of sequential data windows was 0.02s. As expected, in the case of the fault without arc only the superimposed damped travelling-wave components appeared. Contrary, for the fault with arc, a typical spectrum, similar to the spectra depicted in Fig. 3 appeared. The low frequency odd harmonic components (3rd to 15th harmonics) can be clearly identified. By processing voltages and currents from Figures 6 and 7 the arc voltages calculated via the presented algorithm are shown in Fig. 9. The equivalent tests with the smaller arc voltage values gave good results, as well.

It was also concluded that the fault distance did not affect the result (see Fig. 10 for the *close-in* and *remote* fault cases).

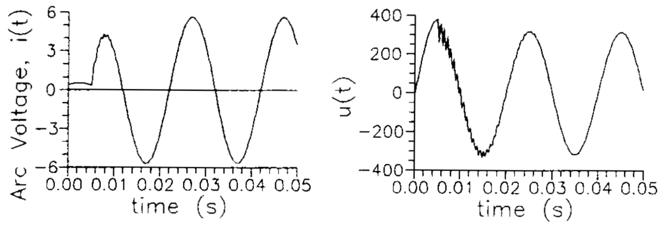

Figure 6: Midline fault without arc

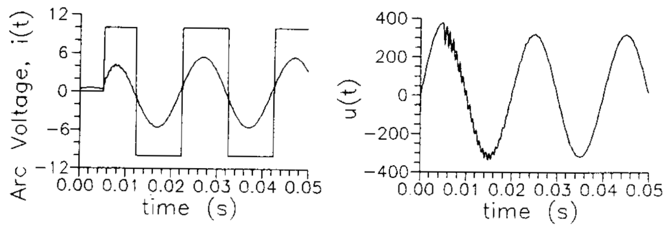

Figure 7: Midline fault with arc

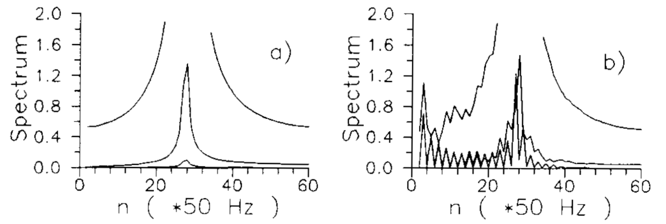

Figure 8: Voltage spectra: a) without arc and b) with arc

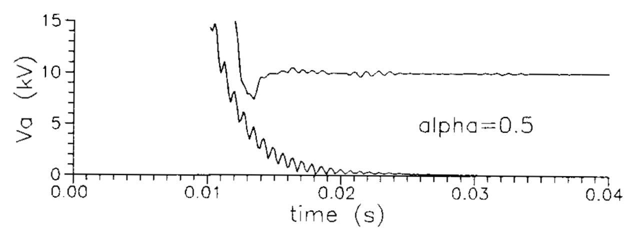

Figure 9: Estimates of the arc voltage V_a (midline fault cases)

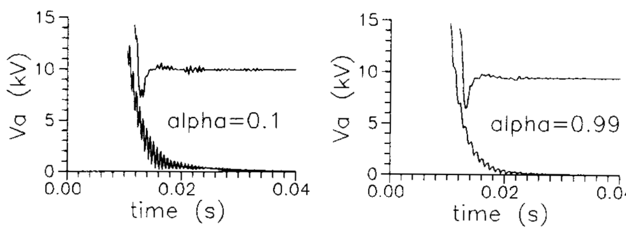

Figure 10: Close-in and remote fault cases

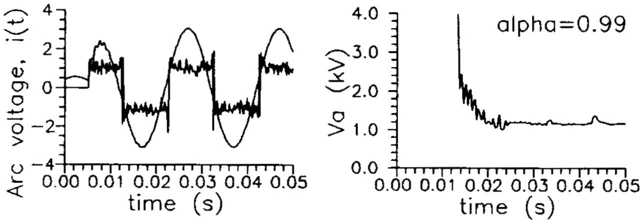

Figure 11: Test with a more realistic arc

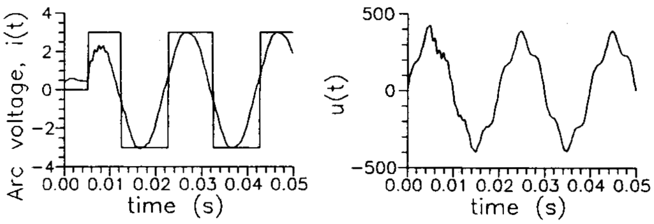

Figure 12: Test in the presence of power system harmonics

The authors varied the fault angle, in order to investigate the influence of the decaying DC offset current on the arcing fault detection. It is well known that FFT is not capable of providing correct results in these cases. Thus, one has to filter out the decaying DC offset, or to apply some other estimation techniques, such as the Newton Type Algorithm presented in [10] and [11].

Since the square wave shape is only an approximation of the real arc voltage waveform, in the following test an example is shown where arc voltage took a more realistic shape [9] (see Fig. 11). The satisfactorily accurate estimates of V_a are shown in Fig. 11.

In the end, the algorithm sensitivity to harmonics generated from some other power system nonlinear sources is investigated. The 5th harmonic was artificially injected from the generator A end in an unrealistic amount of 0.3 p.u. All relevant variables are depicted in Fig. 12. The estimates of arc voltage V_a are shown in Fig. 13. They do not deviate from the exact $V_a = 3$ and could be accepted as a correct input data for distinguishing between faults with and without arc.

When considering the speed of the arc voltage calculation (the algorithm convergence), one could conclude from the former that it is fast enough from the autoreclosure point of view. The reliable information of the fault type can be obtained practically in 30ms after the fault inception.

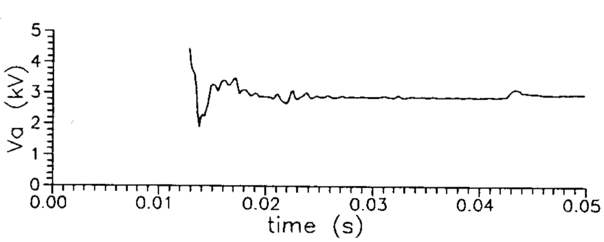

Figure 13: Estimates of the arc voltage V_a in the presence of power system harmonics

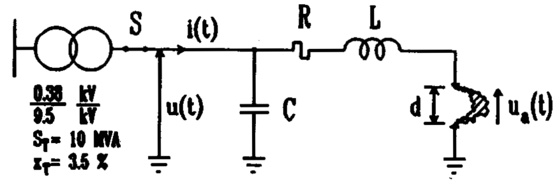

Figure 14: Laboratory test circuit

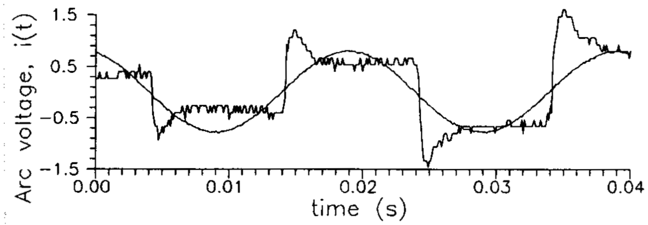

Figure 15: Arc voltage and arc current (p.u.)

6 Laboratory Testing

In order to investigate the relevant phenomena concerning the arcing faults detection and to check the validity of the new algorithm presented in this paper, the laboratory test circuit shown in Fig. 14 has been prepared. The arc between iron rod electrodes is initiated by means of a fuse wire, when switch S in Fig. 14 is closed. On arc initiation, i.e. immediately after melting and evaporation of the fuse wire, the arc voltage started with the values determined by the distance d between the electrodes. Distance d was selected to be 4cm. Voltage $u(t)$, current $i(t)$ and arc voltage $u_a(t)$ were digitized using a digital oscilloscope with the sampling frequency of 25.6kHz. A typical arc voltage and current waveforms are depicted in Fig. 15. The nonlinear arc nature caused the slight distortion of measured voltage $u(t)$, as shown in Fig. 16. All variables are given in per unit values, with the following bases: I_B = 10A, U_B = 10kV and U_{aB} = 100V.

By processing the digitized current $i(t)$ and voltage $u(t)$, the arc voltage amplitude was estimated during 0.08s after

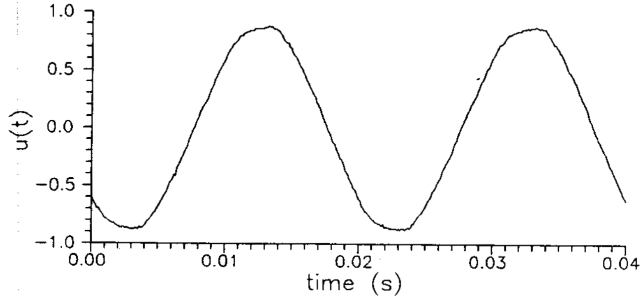

Figure 16: Distorted voltage (p.u.)

the fault inception. The authors performed 7 tests: 5 faults with arc and 2 faults without arc. In all 7 cases the presented numerical algorithm yielded correct results. The values of the estimated arc voltage V_a were round 80V. From these results, one concludes that the arcs were slightly elongated, or somewhat longer than the minimum arc path ($d = 4$cm). Tests with the larger values of R and L were also performed. In all cases the algorithm detected the fault type correctly.

7 Conclusion

A new numerical digital signal processing algorithm for arcing faults detection in transmission systems is presented. It could be used for blocking automatic reclosing of lines with permanent faults. The algorithm was derived by processing line terminal voltage and current. A very simple arc model has been adopted. Through spectral analysis the arc voltage has been estimated by means of the Least Error Squares Technique. The detection algorithm was successfully tested with data obtained through computer simulation and data recorded in the laboratory tests. The overall approach can be applied in solving some similar problems in power engineering, e.g. distance protection, harmonics propagation and estimation, etc. The authors are currently designing the equivalent algorithm aimed for unsymmetrical arc faults analysis and detection.

8 Acknowledgement

The authors wish to thank prof. M.S.Savić and prof. N.Rajaković for their helpful advice and discussions. Prof. D.DJ.Tošić is grateful acknowledged for his suggestions during early phasis of this work.

References

[1] Y. Ge, F. Sui, Y. Xiao, "Prediction methods for preventing single-phase reclosing on permanent fault", IEEE Trans. on Power Delivery, Vol.4, No.1, Jan. 1989, pp.114-121.

[2] R.K. Aggarval, at. al., "Neural-Network Based Adaptive Single-Pole Autoreclosure Technique for EHV Transmission Systems" IEE Proc.-Gener. Transm. Distrib., Vol.141, No.2, March 1994, pp.155-160.

[3] B.D. Russell, at. al., "An Arcing Fault Detection Technique Using Low Frequency Current Components - Performance Evaluation Using Recorded Field Data", IEEE Trans. on Power Delivery, Vol.4, No.1, Jan. 1989, pp.1493-1500.

[4] A.P. Strom, "Long 60-cycle Arc in Air", Trans. Am. Inst. Elec. Eng., 65, 1946, pp.113-117.

[5] V. Terzija, D. Nelles, "Parametrische Modelle des Lichtbogens und Parameterschätzung auf Grund der simulierten und echten Daten", TB-183/93, Univ. Kaiserslautern, July 1993.

[6] M. Kizilcay, K.-H. Koch, "Numerical Fault Arc Simulation Based on Power Arc Tests", ETEP, Vol. 4, No.3, May./June. 1994, pp.177-185.

[7] A.T. Johns, at. al., "Improved Technique for Modeling Fault Arcs on Faulted EHV Transmission Systems", IEE Proc.-Gener. Transm. Distrib., Vol.141, No.2, March 1994, pp.148-154.

[8] A.S. Maikapar, "Extinction of an Open Electric Arc", Elektrichestvo, Vol. 4, 1960, pp.64-69.

[9] D. Lönard, R. Simon, V. Terzija, "Simulation von Netzmodellen mit zweiseitiger Einspeisung zum Test von Netzschutzeinrichtungen", TB-157/92, Univ. Kaiserslautern, 1992.

[10] M. Djurić, V. Terzija, I. Škokljev, "Power System Frequency Estimation Utilizing the Newton-Raphson Method", Archiv für Elektrotechnik, Vol.77, No.3, March 1994, pp.221-226.

[11] V. Terzija, M. Djurić, B. Kovačević, "Voltage Phasor and Local System Frequency Estimation Using Newton Type Algorithm", IEEE Trans. on Power Delivery, Vol.9, No.3, July 1994, pp.1368-1374.

9 Authors

Milenko Djurić was born in Sarajevo in 1948. He received his Dipl.Eng., M.Sc. and PhD degrees in Electric Power Engineering from the School of Electrical Engineering, University of Belgrade, in 1972, 1977 and 1984, respectively. In 1984 he joined the School of Electrical Engineering, Belgrade, where he is a Professor, teaching courses in Power System Protection and Elements of Power Systems. His areas of scientific interest are power system protection, power system control and digital signal processing applications in power systems.

Vladimir Terzija was born in Donji Baraći in 1962. He received his Dipl.Eng. and M.Sc. degrees in Electric Power Engineering from the School of Electrical Engineering, University of Belgrade, in 1988 and 1993, respectively. In 1988 he joined the School of Electrical Engineering, Belgrade, where he is a Research Assistant at the Power System Department, working towards his PhD degree. Since April 1992 he has been with TU Kaiserslautern (Germany), where he spent an academic year working as a Research Assistant. His area of scientific interest are power system transient processes, power system protection and digital signal processing applications in power systems.