# Patterns from Transient Signals in Dynamic Series Compensated Lines for Neural Protection

Victor Ortiz, Pavel Zuñiga, Luis Naredo and Alberto Gutierrez

**Abstract -- This paper presents a procedure to obtain patterns from propagating signals in a SSSC FACTS device. The acquired patterns are suitable for neural network relay protection schemes for Fault Detection (FD), Phase Classification (PC) and Fault Zone Estimation (FZE). By considering two fault scenarios, the patterns are obtained through digital simulations which include effects of transducers and noise filters.**

**Keywords: neural network protection, power electronics, fault and switching events.**

## A. Introduction

Transmission lines represent rigid structures that are in direct contact with the environment. As soon as a fault occurs, even in one single phase, the three phases of the line are temporarily disconnected from the rest of the power system through an automatic procedure controlled by protection relays. Line design itself determines the limits of line loading. The level to which protection systems allow a line to be loaded is based on transmission line protection design [1].

Since transmission lines are continuously loaded to higher levels, the concept of Flexible AC Transmission Systems (FACTS) becomes a necessity. Commercially available FACTS technologies can be divided into two main branches: shunt and series compensation. Nowadays it is common in the power system the addition of devices such as SVC, SSSC, UPFC, IPFC [2,3]. This kind of innovative technology has produced a large number of challenges and it is providing great opportunities for further studies with increased potential of practical applications [2-8].

Actual transmission lines make use of high performance protection relays. So far there are several technical difficulties for applying these protection schemes on Series Compensated Lines (SCL) [6]. The performance of relays deteriorates with dynamic series compensation. The reason is that compensation controls modify the system parameters and relays can be confused. In consequence, differential or directional relays are better suited than distance relays for protecting such lines [6]. Independently from their type, relays play a very important role in events primary to power system blackouts. Failures or missoperations of protection schemes are very significant factors in the overall process of reporting wide area disturbances.

Current protection schemes for dynamic series compensation of transmission lines respond as fast as FACTS controls. Typical fault clearing times are between 4 and 6 cycles. At least one cycle of time is consumed by the relay response. Consequently there is a widespread effort for developing new principles to improve clearing times. Relay design is progressing in two directions:

a) One that is concerned with the improvement of conventional relay algorithms based on phasor concepts.

b) Another one that employs transient components, like the traveling wave and the pattern recognition relays.

Approach b) has received more attention over the last few years; nevertheless, the traveling wave principle still finds technological obstacles, some of these are due to transducer limitations. On the other hand, Artificial Neural Networks (ANNs) have demonstrated promissory results; so they are suitable to be applied for fault protection in FACTS devices [9,10]. This brings further motivation to examine interaction between their fast controls and the neural protective relays.

The most widespread application of ANN is pattern classification with multilayer perceptron, since ANN can learn to distinguish among digital inputs [9,10]. These inputs must have a vector representation referred to as pattern. One pattern is extracted as a result of an off-line procedure.

The objective of this paper is to describe the acquisition of patterns and their grouping in clusters to serve as inputs for protection algorithms based on neural relays. A test power system is needed in order to simulate the primary signals and noise effects. This paper gives an insight of a neural relay composed by instantaneous elements for fault detection, phase selection and fault zone estimation.

## B. Problem Statement

Digital relays for transmission lines employ a number of

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filtering and protection algorithms to create a binary output (1,0), before the A/D conversion an analog filtering is applied to the primary signals captured by transducers at line terminals. Afterwards a digital filter extracts features from these inputs.

Standard relay designs make use of a digital filter to obtain phasor measurements. For instance, a Fourier filter is common in distance relays for calculating phasors via a numeric convolution between the Fourier coefficients and the on-line digital signals. It should be noted, however, that a numeric convolution is a low-pass filter which introduces a known delay [1]. This means that voltage and current phasors require one fundamental cycle to be computed in the following form:

$$[M, \theta] \quad (1)$$

where M represents magnitude and θ the phase angle for each variable.

One important task for designers is the coding of a method into a protection algorithm which the relay will follow to achieve the effect of the automatic disconnection of the transmission line. A well-known example of this type of situation is the distance relay which produces a trip by combining the response of three instantaneous elements; namely, the fault detector (FD), the phase classifier (PC) and the fault zone estimator (FZE). The binary output signal is obtained once the phasors are compared with the relay settings.

The paper focuses in a protection scheme for SCL. In this case there are common pilot schemes with distance relays which can provide simultaneous detection and clearing of phase and ground faults for both, the line and the capacitor [11]. If the FZE does not detect the fault on its protection zone at a high speed, or when the communication channel is affected by the fault, a delay emerges (in the order of milliseconds). More problems and complications are commented next.

With regard to the FD element, the use of an overcurrent logic supervising the operation of the PC and the FZE is widespread. It means that relay reaction arises as soon as an increment in current magnitude appears with respect to certain historical values. Evidently the FD should be set at higher thresholds for digital relay applications; otherwise, whenever there is a switching of the FACTS controls, there might be a false trip as the FD setting is low enough to pick up.

FDs on some digital relays make use of the zero- and negative-sequence currents as inputs to an adaptive slow-acting control loop [7]. Such FDs used to supervise the PC and the FZE may prevent some false operations.

### C. ANN Based Protection Scheme

Figure 1 shows a pattern recognition protection scheme that uses an ANN [9]. This neural network relay is formed, first by a feature extractor (FE), then by three instantaneous elements FD, PC and FZE, and last by a logical element recognizing output combinations of the ANN.

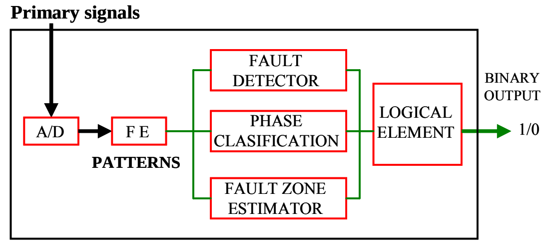


Fig. 1 ANN relay structure.

It is important to notice that fig. 1 relay structure adds a feature extractor (FE). This serves as digital filter designed to improve the classification performance on the ANN. In this paper, a FE based on a delta filter like the one presented in [9] is considered, and our goal is to reveal detailed features from the event to be characterized.

Currently, there is a pressing need .to reduce the time and computer effort at obtaining phasors for implementing conventional protection algorithms. ANN instead require the information from primary signals given as patterns. The pattern must be the knowledge given to the ANN in an off-line training process [9,10]. In other words, this is an a priori information extracted from a data window that is shorter in length than one fundamental cycle. Fig. 2 illustrates the obtaining of a pattern.

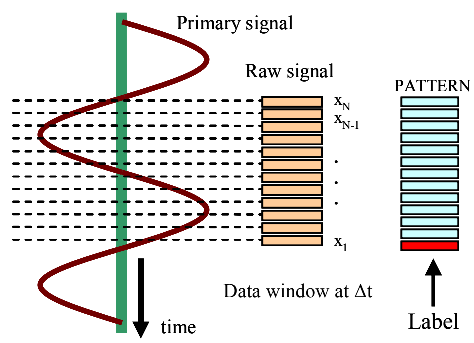


Fig. 2 Procedure for pattern acquisition.

Initially, a primary signal is replicated (simulated or recorded). At each time step Δt and after the A/D conversion, the raw signal must be retained into a data window. As a result, a vector **X** is formed with N samples. Since the procedure is computer-generated, these N values are grouped and assigned to a cluster discernible with a label (see Fig. 2).

At this moment, it is important to mention the following two parameters to be considered for the patterns:

a) Length of data window and,

b) Number of samples on data window.

Our pattern representation contains the information of half of a fundamental cycle at the conventional sampling rate of 32 samples per cycle. The corresponding vectors **X** of voltages and currents, for the same time step Δt, are kept together.

The performance of a neural protection algorithm depends on the ability to train the ANN and on the pattern representation [10]. With reference to the designing stage of ANNs, a training cluster is needed. It is suggested here that a dichotomy for the ANN algorithms should be prepared. This means that the FD, PC and FZE must be solved separately using a different cluster for each case. For instance, the FD needs fault and non-fault patterns, the PC requires patterns for all types of faults, and the FZE only groups the internal and external fault patterns [9]. Figure 3 shows the steps for pattern extraction.

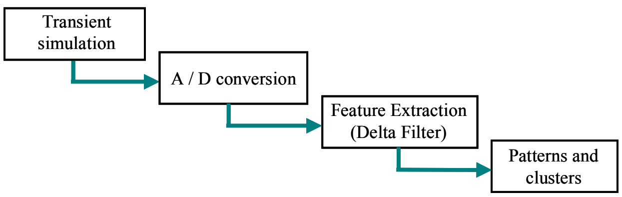


Fig. 3 Pattern generation procedure.

To obtain the patterns a test system was implemented. The power system model to be adopted is in accordance with the fault study and the tools used for simulation are described in references 11 and 12. The aim here is to characterize transient phenomena from diverse network configurations. Nevertheless, primary signals to be observed require the detail of propagated traveling waves, along with the fast response features from the FACTS controls [7,8].

### D. Analysis of Series Dynamic Compensated Lines

Figure 4 shows a fault on a transmission line. The fault becomes a new source, which produces traveling waves (TWs). These, once generated, travel in both directions at about the light speed (3e8 m/s) and are subject to attenuation and distortion in their propagation along the transmission line [13]. These two effects combined degrade the quality of the wavefronts at large distances from the fault inception point.

The frequency-dependence features of the line parameters are inherent phenomena that cause changes in the velocity of the various components of TWs. Nowadays, the most used method for considering these effects is summarized by expressions (2), (3) and (4) [13]:

$$\mathbf{v}_L - Z_C * \mathbf{i}_L = \mathbf{h} * \left(\mathbf{v}_0 + Z_C * \mathbf{i}_0\right) \qquad (2)$$

$$\mathbf{v}_0 - Z_C * \mathbf{i}_0 = \mathbf{h} * \left(\mathbf{v}_L + Z_C * \mathbf{i}_L\right) \qquad (3)$$

$$\mathbf{h} = F^{-1}\left\{ e^{\sqrt{\mathbf{YZ}l}} \right\} \qquad (4)$$

where $Z_C$ is the characteristic impedance of an uniform line, **v** and **i** are vectors for voltages and currents, respectively; **h** is a propagation matrix, **Y** is the line admittance parameter matrix, **Z** is the line impedance parameter matrix, $l$ is the length of the line and $F^{-1}$ represents the Fourier inverse transform.

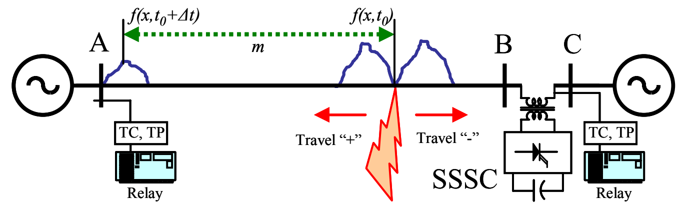


Fig 4.- Traveling waves in SCL.

For the series compensation case, a lumped capacitor model has been proposed in [12]. However, this paper is focuses in the study of SCL with a Static Synchronous Series Compensator (SSSC), including the effect of its control. All models to be adopted in the test system are in accordance with the fault study. Then, it is considered a FACTS model of dynamic and fully integrated elements [4].

The wave reflection phenomenon is well documented in Power Transmission and Distribution, as well as in Digital Communications. More recently, it is gaining relevance in the field of control applications [6]. As soon as a TW arrives to a series-compensated line terminal, it is not immediately reflected back because the series compensation is present. The TW experiences a particular distortion (the effect of reversing currents [6]). Fig. 5 shows a representative line terminal and the three cases of reflections, based on series impedance value, are listed as follows:

1. *Z1 = ZE, which corresponds to the case when there is perfect electromagnetic coupling. In this case there are not reflections.*
2. *Z1 > ZE, in this case there is a positive voltage wave reflection.*
3. *Z1 < Z2, in this case there is an effect of negative voltage wave reflection).*

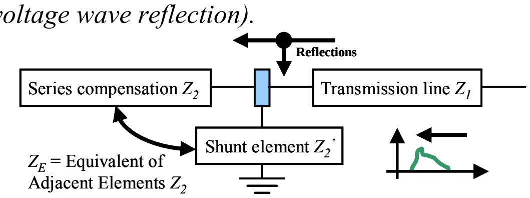


Fig. 5. Reflections produced for a change in the transversal impedance.

The aim of a series compensation unit is to manipulate the inductive reactance of a transmission line for increasing power transfer capability, improving power system stability, lowering system losses, enhancing voltage control, improving power regulation, etc [4]. Series compensation usually is in the order of 15-30% of the line capability; this is to avoid undesirable sub-synchronous oscillations.

Series compensators normally are equipped with both, automatic and manually operated bypass switches; to protect the former ones from over-voltages during faults and to enable operation of lines while compensators are out of service.

The patterns needed for ANN based relays must consider the complex variation of line impedance, as well as the compensators own protection equipment which enters into operation under fault conditions [11]. These conditions may have a substantial impact on the training of an ANN relay. In practice, these features are well known for relays based on phase measurements. Nevertheless, a neural relay requires details from the traveling waveform since the fault inception.

### E. Application Examples

In order to obtain ANN patterns, digital simulations are carried out using the test power system shown in Fig. 6. It consists of two parallel lines connected between sending and receiving end nodes, along with their source impedances. A SSSC FACTS device is connected in line $L_2$ to achieve active power regulation.

The test system has the following parameters: $R_s$=$R_r$=0.1Ω, $L_s$=$L_r$=0.007H, C=2200μF and the three phase line-to-ground voltages $v_s=V_{sm}\sin30°$kV peak and $v_r=V_{rm}\sin0°$kV peak, $V_{sm}=V_{rm}=230\sqrt{2}/\sqrt{3}$ , for a frequency of 60Hz. Lines $L_1$ and $L_2$ are 100km long. The SSSC connected in $L_2$ is achieving capacitive compensation, and it consists of a 48-pulse full model constructed using individual elements such as GTO switches and transformers, as detailed in [4]. The simulations suppose that the transient response has already passed and that the system is in steady state. The device is inserted to adjust active power, and is set to regulate approximately 1.5 times the active power that flows with no compensation. At the beginning of both experiments switches $S_1$ and $S_2$ are closed, while $S_3$ is opened. Switch $S_3$ closes to simulate the fault.

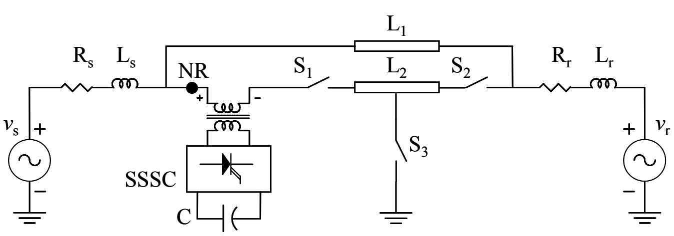


Fig. 6. Test power system.

For the test system shown in Figure 6, it is assumed that the load flow is from left to right. Two experiments are carried out in order to obtain different responses. All waveform measurements are taken at the Neural Relay (NR) point. The test system was implemented in Matlab environment and compared with an EMTDC model. Both models produce similar waveforms, but FACTS controls are better detailed in the Matlab model.

### *A. Example 1: Three phase internal fault*

A three phase fault occurs in $L_2$ at 10 km from the SSSC connection point. Six cycles after fault inception switches $S_1$ and $S_2$ disconnect the faulted line and the FACTS device. The corresponding waveforms for three phase currents and voltages at the NR point are depicted in Fig. 7 and 8. For an internal fault is considered that the SSSC remains active until the fault is cleared within the time programmed for instantaneous elements.

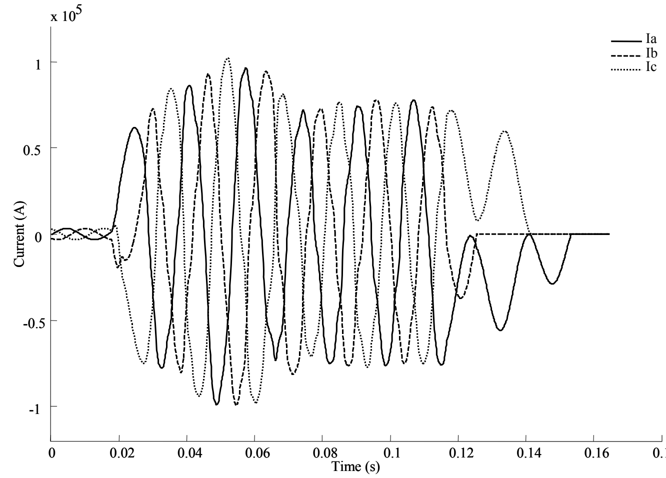


Fig. 7. Three phase currents for a three phase fault.

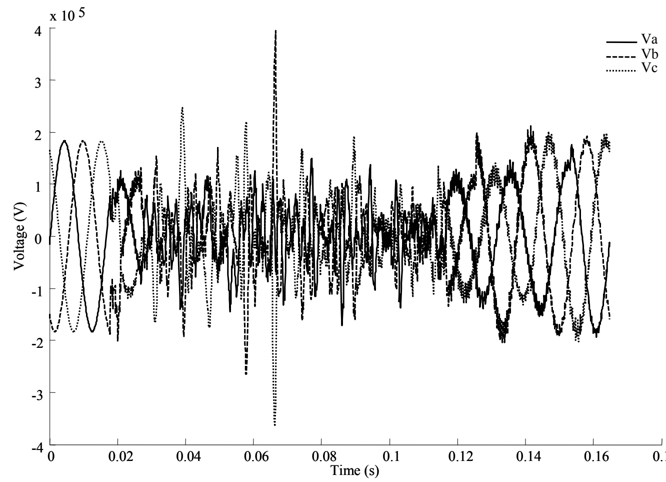


Fig. 8. Three phase voltages for a three phase fault.

An internal fault usually results in more energy absorption than a single-phase fault. This energy absorption is highest if the compensating element is located at the end of the line and the substation has low short circuit impedance. Fig. 9 and 10 shows the delta signals as a result of applying the FE. The latter signals were processed from waveforms in Figs. 7 and 8.

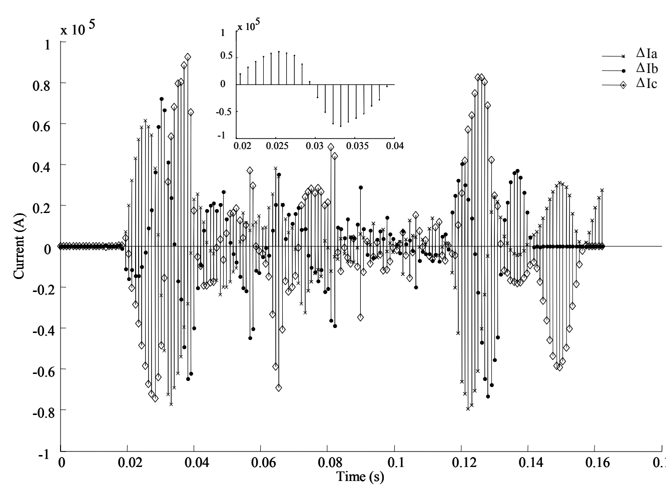


Fig. 9. Three phase delta currents for a three phase fault.

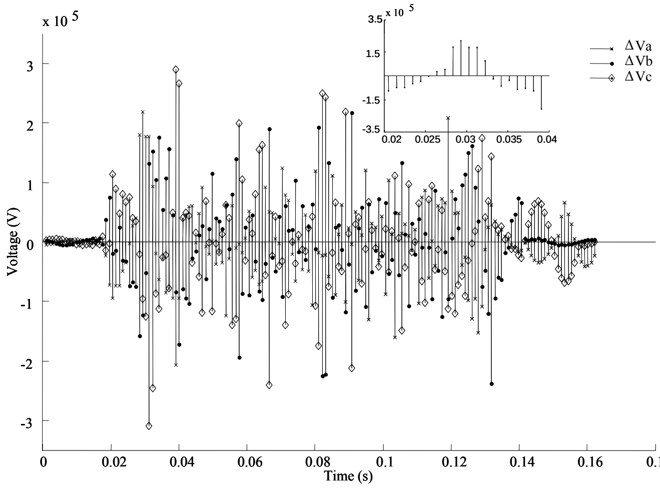


Fig. 10. Three phase delta voltages for a three phase fault.

Delta signals include noise effects from the transducers, the A/D conversion and the sampling effect. It can be noticed that the delta filter also produces a noise phenomenon due the fulfilling of the data window. Once the samples of the first cycle are finished a transition occurs between the post-fault and the fault conditions. The pattern is the information captured after fault insertion. The results of this procedure are the patterns presented as inserts in the corresponding figures. Notice the detail required by ANN relays.

### *B. Example 2: Phase a to ground fault*

A single fault to ground occurs in phase *a* of $L_2$, at 90 km from the SSSC connection point. Fault clearing time takes place after six cycles when switches $S_1$ and $S_2$ disconnect the compensated line. The corresponding waveforms for three phase currents and voltages at the NR point are depicted in Fig. 11 and 12. For an internal fault it is considered that the SSSC remains active until the fault is cleared within the time programmed for instantaneous elements.

As mentioned before, an internal fault usually results in more energy absorption than a single-phase fault. Fig. 13 and 14 shows the delta signals after the FE application. These were obtained from the waveforms of Figs. 11 and 12.

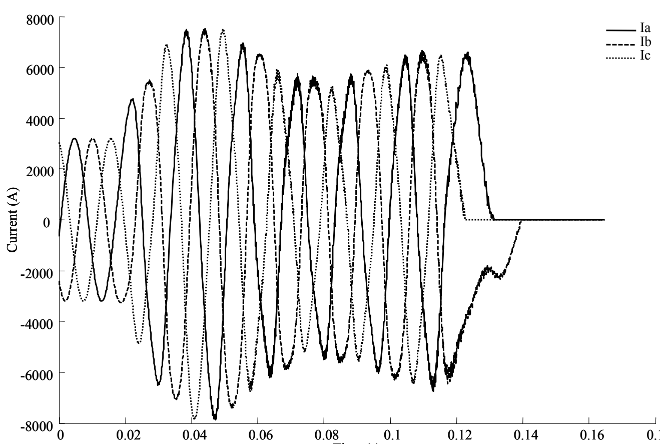


Fig. 11. Three phase currents for a-g fault.

The figures were analyzed using a similar procedure as the one for the three phase fault. It can be noticed that the patterns for internal faults have similar features in both cases.

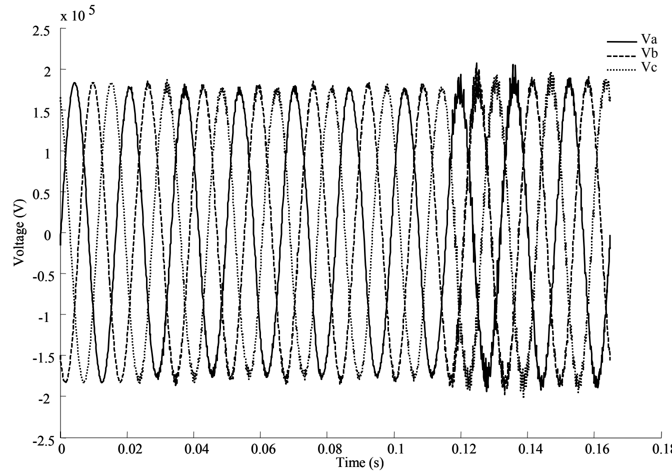


Fig. 12. Three phase voltages for a-g fault.

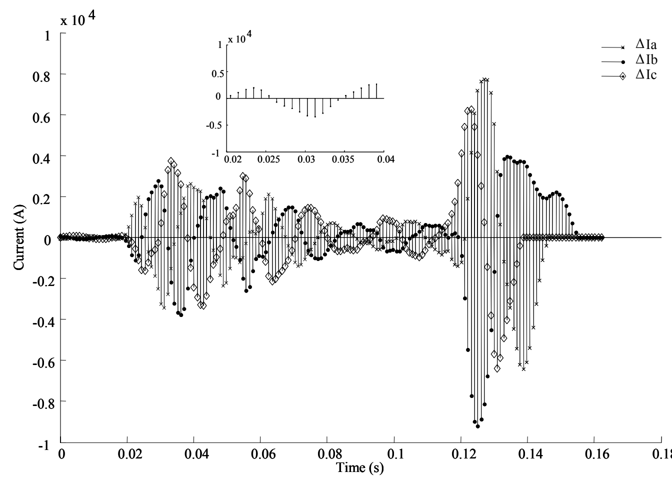


Fig. 13. Three phase delta currents for a-g fault.

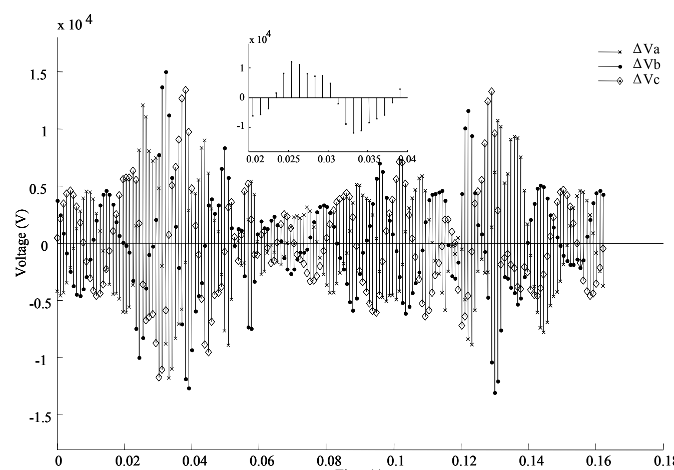


Fig. 14. Three phase delta voltages for a-g fault.

## F. Future Developments

Recent work has examined the possibility of simulating all types of transient scenarios on FACTS in order to acquire a priori information. Then the customization process of the pattern representation begins. Future developments will include the combination of existing devices to extend the volume of patterns contained in the cluster. In addition, more sophisticated control systems will improve the operation of FACTS devices.

## G. Conclusions

Initial results applying the described procedure to obtain patterns for neural relays are reported here. This task involves the extraction of information from the primary signals, the analog and digital filtering and the noise control.

In this paper an insight regarding the design of ANN relays is provided. The neural relay can be applied for protection of dynamic series compensated lines. A test system is used to obtain a digital representation as patterns, which is oriented to improve fault clearing times. Two contingencies are considered; namely, fault 1 which is a three-phase to ground short circuit on Line $L_2$ near the NR point, and fault 2 which is a single-phase to ground short circuit on Line $L_2$ far from the NR point. The pattern representation is based on the analysis of these two contingencies.

The problem of analyzing electromagnetic transients on transmission systems equipped with FACTS devices is addressed in this paper. Comments about traveling waves propagated through lines have been given. A power system testing model has been implemented both, in MatLab and in EMTDC; this is to create relaying signals. The authors are currently pursuing research work on all these aspects of FACTS control and design, with particular emphasis on determining the effects of these devices on the protection systems.

## H. References


[1] IEEE Power System Relaying Committee, *Guide for Protective Relaying Applications to Transmission Lines (IEEE P1345)*, The Institute of Electrical and Electronic Engineers, Inc. NY, 1998.

[2] N. Hingorani and L. Guyyi, *Understanding FACTS, concepts and technoloy of flexible AC trasmission systems*, IEEE Press Editorial, NY 2000. ISBN 0-7803-3455-8.

[3] Yong Hua Song, Allan T. Johns, *Flexible ac transmission systems (FACTS)*, first edition, IEE Power and energy series, 1999.

[4] Zuñiga Pavel, *Analysis and control of a series compensator*, Ph D Thesis, CINVESTAV-Guadalajara, Mexico, June 2006

[5] A.Y. Abdelaziz A.M. Ibrahim, M.M. Mansour and H.E. Talaat, "Modern approaches for protection of series compensated transmission lines", Department of Electrical Power and Machines, Ain Shams University, Cairo, Egypt, accepted 24 October 2004. Available online 10 May 2005.

[6] Scott G. Helbing, G. G. Karady, "Investigations of an advanced form of series compensation", IEEE *Trans. Power Delivery*, vol. 9, no. 2, pp. 939-945, Abril 1994.

[7] E. V. Larsen, K. Clark, S. A. Miske, Jr., J. Urbanek, "Characteristics and rating considerations of thyristor controlled series compensation", IEEE *Transactions on Power Delivery*, vol. 9, no. 2, pp. 992-1000, Abril 1994.

[8] Sasan G. Jalali, Ron A. Hedin, Marcos Pereira, Kadry Sadek, "A stability model for the advanced series compensator (ASC)", IEEE *Transactions on Power Delivery*, vol. 11, no. 2, pp. 1128-1137, Abril 1996.

[9] Ortiz V., *Artificial Neural Networks Relay for transmission lines*, Ph D Thesis, Autonomous of Nuevo Leon University, Mexico, February 2004.

[10] T. Dalstein, *Using Artificial Neural Networks in Protective Relaying*, Ph D Thesis, Technical University of Berlin, Germany, November 1994.

[11] R. Marttila, "Performance of distance relay MHO elements on MOV protected series-compensated transmission lines," IEEE Trans. Power Del., vol. 7, pp. 1167–1178, July 1992.

[12] IEEE PSRC Working Group Report D-10, *EMTP Reference Models for Transmission Line Relay Testing*, 2004

[13] H. W. Dommel, *Electromagnetic Transients Program Reference Manual* (EMTP Theory Book), Prepared for Bonneville Power Administration, P.O. Box 3621, Portland, Ore., 97208, USA, 1986.


## I. Biographies


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