ADVANCED ASSESSMENT OF THE POWER QUALITY EVENTS

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Abstract: This paper introduces a new concept of advanced power quality assessment. The concept is implemented using the software for event detection, classification and characterization. The role of the modeling and simulation in the power quality assessment is also discussed. The use of the field recorded data and simulated data in the equipment performance analysis is outlined. All the mentioned approaches are suggested for power quality assessment use when setting up and verifying the power quality contracts.

Keywords: Power Quality, Event Analysis, Intelligent Systems, Modeling and Simulation.

I. INTRODUCTION

The importance of power quality (PQ) monitoring and compliance assessment is growing [1-3]. As a result, the practice of establishing PQ contracts between the supplier and the users is emerging as a promising approach [4]. This paper introduces a concept of advanced power quality assessment based on a number of software tools that have been developed by the author and his associates [5-9].

The PQ assessment tools are based on the advanced techniques for detection, classification and characterization of various types of PQ events. The events of interest include the voltage sags, swells, interruptions, harmonics, notches, impulses, switching transients, and flickers [1, 5].

Generally speaking, the PQ event detection and classification problem consists of two steps. The first step may include feature extraction, during which the distinct and dominant features (or patterns) of various events are selected and obtained using appropriate techniques. The second step is called decision making: the extracted features are further processed by an inference engine to determine the types of the events. Appropriately chosen features are essential for both simplifying the decision-making system (DMS) and improving the correct identification rate of the system [10-11].

Various approaches for both feature extraction and DMS have been proposed previously for PQ event detection and classification [10-12]. For feature extraction, both Fourier transform and wavelet analysis have been suggested. Fourier transform is suitable for stationary signals while wavelet transform more adapts to dynamic signals [11-12]. For decision making, neural network based approaches have been developed [10-11]. The neural network fundamentally realizes a non-linear functional mapping. However, the correct identification rates resulting from the existing approaches are still low and not quite satisfactory [10-11]. This paper explores new methods for extracting more distinctive and pertinent waveform features and investigates new techniques for decision making. Particularly, not only that the new unique features based on a combination of Fourier and wavelet analysis are identified, but also a novel fuzzy expert system for decision making is introduced [5, 13].

For characterization of PQ events, variety of possible parameters for describing the events have been suggested [1, 14-17]. Nevertheless, much of the work in the past has been directed towards qualitative understanding of the problem. Our work aims at establishing algorithms for characterizing PQ events more precisely.

Another important aspect of power quality studies is the PQ event modeling and simulation. It forms the basis for understanding the power quality phenomena and solving various types of power quality problems [18-20]. Among various types of modeling tools, the Matlab Power Blockset (MPB) and Electromagnetic Transients Program (EMTP) are the two very popular packages [18-19]. Both tools can be used for time-domain simulation of the events and related transients. In comparison, the MPB is more user-friendly and easier to use, while it is much slower than EMTP. Our experience reveals that MPB is handy for simulating small power systems and EMTP more adapts to larger systems [6, 21]. This paper further illustrates the role of the modeling and simulation in the PQ assessment.

For equipment performance evaluation, there has not been a systematic solution to the problem. Most of the recent work was focused on studying the effects of the sag events. The authors in [22] investigate the effects of the sag events on the performance of induction motors. For efficiently studying as well as tuning various waveform parameters, a sag generator is created and used for evaluating the operating characteristics of the equipment. However, the generator only allows the sag magnitude and duration to be adjusted while other parameters such as the phase angle shift, points-on wave, etc. that may also have a significant impact on the equipment behavior are not considered. Similar techniques have also been applied by the authors for testing the AC coil contactors [23].

Reference [24] studied the effects of the capacitor switching transients on the adjustable speed drives (ASD). The simulation package Electromagnetic Transients Program (EMTP) is utilized to evaluate the behavior of the drives. The transient parameters are adjusted by changing the parameters of the system model used in the simulation studies. This is not convenient since a number of experiments may be entailed for obtaining waveforms with certain parameters. Another drawback is inability to efficiently employ the recorded data.

While there are some existing methods for studying the impacts of the sags and switching transients on equipment behavior, effects of other types of events such as the voltage swells, harmonics, flickers, and impulses on equipment operating characteristics have barely been investigated so far. In this paper, a more thorough and effective approach is established for equipment sensitivity study. It is capable of dealing with all types of events and studying all the relevant waveform parameters as well as utilizing both the simulated and recorded data [9].

This paper discusses different solutions used for the mentioned PQ assessment steps. The steps are implemented as a part of an automated system. The PQ events can be assessed in a straightforward way through quantification of the parameters and selected indices. This allows for better understanding of the PQ events and related consequences, which in turn may facilitate defining and monitoring the PQ contracts. Once in place, the contracts can be verified by implementing the tools for automated monitoring of the events.

New techniques for automated detection, classification and characterization of PQ events are presented first. Then the role of modeling and simulation for PQ assessment is illustrated. Followed is the proposed procedure for equipment performance evaluation during PQ events. Finally, conclusions, acknowledgements and references are given.

II. AUTOMATED POWER QUALITY MONITORING

This section presents advanced techniques for automated detection, classification and characterization of various types of power quality events [5-6].

A. Power Quality Event Detection and Classification

The flowchart of the proposed solution is shown in Fig. 1. The sub-module "Data Format Conversion" converts the inputs from a specific recording device or simulation package into a common data format comprehensible to other modules of the software. The "Fourier and Wavelet-transform Based Feature Extraction" module obtains unique features pertinent to specific events and "Fuzzy Expert System for Detection and Classification" module reaches a decision regarding detection and classification, as discussed next [5].

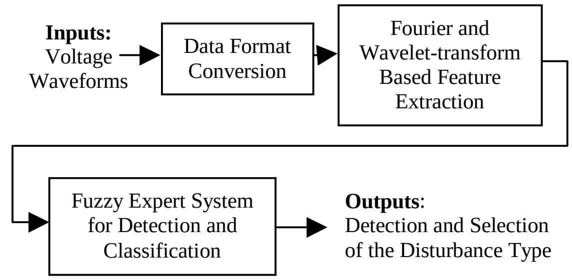

Fig. 1. Detection and Classification flowchart

1) FFT and Wavelet-analysis Based Feature Extraction

A number of power quality events of various types have been simulated and corresponding waveforms obtained. The following eight distinct features inherent to different types of power quality events have been identified: the Fundamental Component (V_n), Phase Angle Shift (α_n), Total Harmonic Distortion (THD_n), Number of Peaks of the Wavelet Coefficients (N_n), Energy of the Wavelet Coefficients (EW_n), Oscillation Number of the Missing Voltage (OS_n), Lower Harmonic Distortion (TS_n), and Oscillation Number of the rms Variations (RN). The formulae for computing these features are given as follows [5].

$$V_n = \sqrt{2}\,\mathrm{abs}(V^n[1])/N \qquad (1)$$

$$\alpha_n = \mathrm{angle}(V^n[1]) - \mathrm{angle}(V^1[1]) \qquad (2)$$

$$THD_n = \sqrt{\sum_{k=2}^{\mathrm{int}(N/2)} \{\mathrm{abs}(V^n[k])\}^2} \Big/ V^1[1] \qquad (3)$$

$$N_n = \mathrm{peak}(\mathrm{abs}(WC^s)) \qquad (4)$$

$$EW_n = \sum_{k=1}^{le} \mathrm{abs}(WC^n[k]) \qquad (5)$$

$$OS_n = \mathrm{root}(v^s{}_{miss}) \qquad (6)$$

$$TS_n = \sqrt{\sum_{k=2}^{10} \{\mathrm{abs}(V^n[k])\}^2} \Big/ V^1[1] \qquad (7)$$

$$RN = \mathrm{root}(V^s{}_{rms} - \mathrm{mean}(V^s{}_{rms})) \qquad (8)$$

In the above equations,

$V^n[k]$ is the Discrete Fourier Transform (DFT) for the samples contained in the nth data window defined as

$$V^n[k] = \sum_{i=0}^{N-1} v[i + (n-1)*N]e^{-j\frac{2\pi ki}{N}} \qquad (9)$$

v[i] represents the sampled input signal
i=0, 1, …, L-1, with L the length of the signal
N is the number of samples in one data window (one cycle)
j is the imaginary unit, and n=1, 2, …10

WC^n are the wavelet coefficients for the samples contained in the nth data window [6, 12], and WC^s is defined as an array composed of $WC^n[k]$ for k=1, 2, …, le, with le being the length of WC^n.

$$v_{miss}[i] = v[i] - 2/N * abs(V^1[1]) * \cos\{angle(V^1[1]) + 2\pi(i-1)/N\} \quad (10)$$

$v^s{}_{miss}$ is defined as an array composed of $v_{miss}[i]$, i=0, 1,…, L-1

$$V^n{}_{rms} = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1} v^2[i+(n-1)N]} \quad (11)$$

$V^s{}_{rms}$ is defined as an array composed of $V^n{}_{rms}$, n=1, 2,…,10

abs(.) gives the absolute value of the argument

int(N/2) equals N/2 if N is even, and (N-1)/2 if N odd.

angle(.) returns the phase angle of the input argument.

root(.) returns the number of roots (or zero-crossings) of the argument.

peak(.) returns the number of peaks of the argument.

mean(.) gives the mean of the argument.

In the work presented here, ten cycles of samples of the three-phase voltage signals (in per unit) are used. The Daubechies-4 wavelet family and the second scale wavelet detail coefficients are utilized. Detailed analysis of the wavelet transform and multiresolution decomposition techniques is outlined in [6, 12].

Next, the statistical properties of the parameters for various power quality events can be obtained. Extensive studies have evinced that the extracted parameters display distinctive patterns under different types of events. Based on these distinctive patterns, appropriate fuzzy rules can be established for distinguishing between different types of events as shown below.

2) A Fuzzy Expert System for Detection and Classification

The core of the rule set of the implemented fuzzy expert system is illustrated as follows [5, 13].

a) Detection: For detection, one rule is used as follows

Rule 1: if THD_n is A_2 or PS_n is B_2 or V_n is C_3 or V_n is C_1 then DETECT=1

b) Classification: fifteen rules are used as follows

Rule 1: V_{n+1} is A_4 and N_n is F_1 and OS_n is G_1 then IMPULSE=1

Rule 2: V_n is A_1 or V_{n+1} is A_1 then OUTAGE=1

Rule 3: V_n is A_6 or V_{n+1} is A_6 then SWELL=1

Rule 4: V_n is A_5 and PS_n is C_1 and PS_{n+1} is C_1 and EW_{n+1} is D_1 and $\{TS_{n+1}$ is H_2 or $[TS_{n+1}$ is H_4 & TS_{n+2} is $H_1]\}$ then SWELL=1

Rule 5: V_{n+1} is A_5 and $\{PS_n$ is C_2 or PS_{n+1} is $C_2\}$ then SWELL=1

Rule 6: V_{n+1} is A_2 then SAG=1

Rule 7: V_{n+1} is A_3 and $\{PS_n$ is C_2 or PS_{n+1} is $C_2\}$ then SAG=1

Rule 8: V_{n+1} is A_3 and $\{PS_n$ is C_1 and PS_{n+1} is $C_1\}$ and $\{THD_{n+1}$ is B_1 or $[THD_{n+1}$ is B_2 and OS_{n+1} is $G_4]\}$ then SAG=1

Rule 9: V_{n+1} is A_3 and PS_n is C_1 and PS_{n+1} is C_1 and OS_n is G_2 and THD_{n+1} is B_2 and THD_{n+2} is B_2 and THD_{n+3} is B_2 then NOTCH=1

Rule 10: V_{n+1} is A_3 and N_n is F_2 and OS_n is G_2 then NOTCH=1

Rule 11: V_{n+1} is A_4 and PS_n is C_1 and PS_{n+1} is C_1 and THD_n is B_3 and THD_{n+3} is B_1 and $\{OS_n$ is G_4 or OS_{n+1} is $G_4\}$ then TRANSIENT=1

Rule 12: V_{n+1} is A_4 and TS_{n+1} is H_3 and TS_{n+2} is H_3 and TS_{n+3} is H_3 and OS_{n+1} is G_4 then HARMONIC=1

Rule 13: THD_{n+1} is B_4 and THD_{n+2} is B_4 and THD_{n+3} is B_4 and OS_{n+2} is G_4 then HARMONIC=1

Rule 14: TS_{n+1} is H_4 and TS_{n+2} is H_4 and TS_{n+3} is H_4 and OS_{n+2} is G_4 then HARMONIC=1

Rule 15: If RN is K_1 then FLICKER=1

In the above rules, $A_i, B_i, C_i, D_i, F_i, G_i, H_i$ and K_i are the membership functions for the input patterns, and the following trapezoidal and triangular functions are used:

$$\mu(x) = trapmf(a,b,c,d) = \begin{cases} (x-a)/(b-a) & a \le x \le b \\ 1 & b \le x \le c \\ (x-d)/(c-d) & c \le x \le d \\ 0 & otherwise \end{cases} \quad (12)$$

$$\mu(x) = trimf(a,b,c) = \begin{cases} (x-a)/(b-a) & a \le x \le b \\ (x-c)/(b-c) & b \le x \le c \\ 0 & otherwise \end{cases} \quad (13)$$

The fuzzy partitions and the corresponding membership functions can be obtained based on both the statistical studies and the expert's knowledge. Opinions from operators can be conveniently incorporated into the system in practical applications.

The output for the detection part is the variable "Detect" whose value reflects the credibility that certain disturbance exists. The outputs for the classification parts are fuzzy variables "Flicker", "Impulse", "Interruption", "Swell", "Sag", "Notch", "Transient", and "Harmonic" whose values represent the degree to which the event belongs to each of these categories. The type of the event selected will be the one with the largest membership. In cases where two or more types of disturbances have the same largest membership value, all of them will be outputted for further analysis.

Extensive evaluation studies have demonstrated that the fuzzy DMS results in a correct identification rate of 99%, and that the proposed methods for feature extraction and decision making are efficient and feasible.

The next step for automated power quality monitoring is the event characterization.

B. Power Quality Event Characterization

The characterization of power quality events is aimed at extracting distinctive and pertinent parameters for describing specific event waveforms [6-7, 9]. These parameters may be useful for system planning, troubleshooting and system control. Particularly, these parameters play an essential role in the equipment sensitivity study that aims at improving the immunity or ride-through ability of the loads sensitive to specific types of power quality events, as will be illustrated in the next section. Hence event characterization is an important step for making a successful power quality contract.

Because different types of event waveforms require different parameters for description, the waveforms need to be classified before characterization. The detection and classification system presented above can be used for accomplishing this task. After the type of the event is identified, the corresponding characterization algorithms can be selected for extracting more accurate and pertinent parameters.

The overall structure of the proposed approach for event characterization is depicted in Fig. 2. The inputs are the voltage waveforms that have already been identified as certain types by the detection and classification system described above. The outputs are the waveform parameters pertinent to the input waveforms. The "Fourier and Wavelet Analysis Based Characterization" module is used to process the voltage waveforms utilizing signal processing techniques to obtain the waveform parameters of interest. The wavelet analysis is used for better localizing the time related parameters, while the Fourier transform is utilized for obtaining the magnitude related parameters. As an example, Table 1 gives the characterization results of a voltage sag event [6, 7, 9].

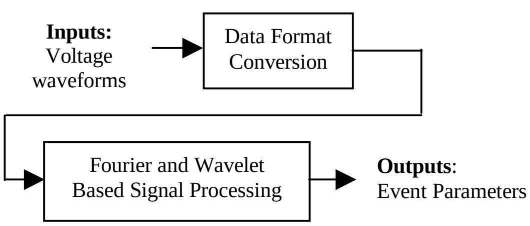

Figure 2. Event characterization flow chart

Table 1. Parameters for a sag event

Sag Parameters	Phase A	Phase B	Phase C
Minimum rms value (p.u.)	0.980	0.940	0.943
Maximum rms value (p.u.)	1.0	1.001	1.001
Average rms value (p.u.)	0.990	0.977	0.978
Final rms magnitude (p.u.)	0.994	0.996	0.997
Peak value (p.u.)	1.411	1.413	1.415
Sag starting time (ms)	0	40.96	47.26
Sag end time (ms)	0	83.33	75.0
Sag duration (ms)	0	42.37	27.74
Sag initial angle(degrees)	0	167.02	5.63
Sag initial phase angle shift (degrees)	0	-1.76	0.263
Sag initial phase angle shift rate (degrees/sec.)	0	-80.05	15.80
Sag end angle(degrees)	0	180.00	61.88
Sag end phase angle shift (degrees)	0	3.09	-1.78
Sag end phase angle shift rate (degrees/sec.)	0	70.48	-71.74
Total harmonic distortion	0.014	0.020	0.026
Rms magnitude unbalance ratio	0.050		
Three-phase phase angle difference deviation (degrees)	3.432		

III. MODELING AND SIMULATION

A. Power System and Equipment Modeling

Power system and equipment modeling is an indispensable part of power quality studies. The accuracy of the modeling is essential for any type of power quality studies, especially for the purpose of stipulating a power quality contract. To this end, model validation is usually carried out. We have developed a genetic algorithm based approach for verifying the system model based on both the recorded and simulated data [8]. The capacitor switching study is taken as an example. By changing the unknown parameters of the system, running simulations, and comparing the simulated and recorded waveforms, the GA approach guides searching for an optimal solution. As an example, Fig. 3 and Fig. 4 show the recorded and simulated waveforms during a capacitor switching event, respectively. The close matching of the simulated and recorded waveforms indicates that the system model is quite accurate.

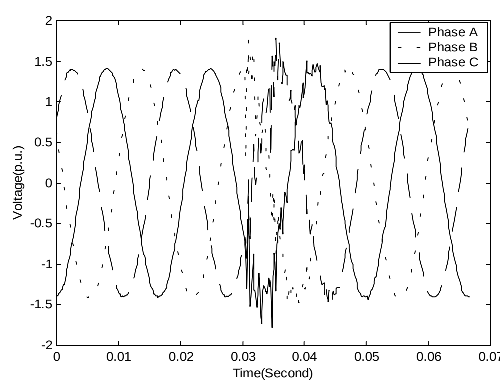

Fig. 3. The recorded switching transient waveforms

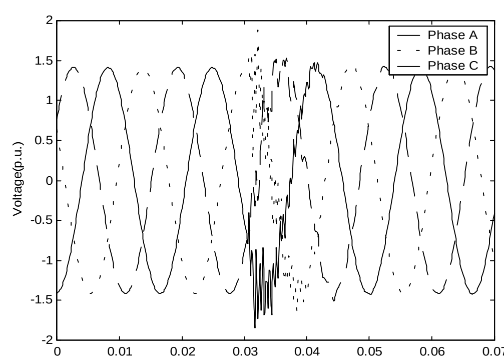

Fig. 4. The simulated switching transient waveforms

B. Simulation Studies

After the system model is verified, different types of studies of interest may be undertaken. Among various possible studies, two types of studies, most relevant to power quality contracts, are illustrated as follows [4].

First, simulation studies can furnish the power supplier a clear and objective picture of the current situation of the system and reduce the uncertainty when signing a contract. For example, the statistical data on the sag depth, magnitude, phase angle shift of the sag events occurring on a certain bus as well as the effects of the sags on certain sensitive equipment may be obtained through simulation studies. These data may constitute the basis for making a contract between the supplier and consumer. Second, simulation studies facilitate troubleshooting of various power quality problems. For example, if the occurrence of sag events with specified characteristics at a certain bus during one year exceeds the contracted number, the supplier may need to investigate the causes of the sags and then mitigate the effects by either adding conditioning equipment or changing the system configuration. The effects of the mitigation measures need to be thoroughly studied before actual implementation. This study may be facilitated by modeling and simulation since a large number of cases can be studied easily by using this approach.

The benefits of simulation studies are further illustrated using the example of equipment performance evaluation.

IV. EQUIPMENT PERFORMANCE EVALUATION

This section presents an approach for equipment sensitivity study [9]. Examination of how sag parameters affect the equipment behavior is emphasized next. As well known, some customer loads may trip or mis-operate due to the voltage sags. With the advent of electronic devices, the trip or mis-operation may no longer be just attributed to the sag magnitude and duration. Instead, other factors like points-on-wave, unbalance ratio, and phase angle shift may also play an essential role in the behavior of the modern loads during voltage sag events. Through equipment sensitivity study, the software can explain why a specific load failed during a sag event, or predict how well a load will perform during an actual sag event.

The overall structure for evaluating the equipment behavior under voltage sag events is depicted in Fig. 5. The inputs are the voltage sag waveforms that can either be recorded in the field or generated by specific simulation packages. The outputs are the operating characteristics of the equipment during the specified sag events. The block "Voltage Sag Characterization" computes various sag parameters. The block "Sag Parameter Tuning" allows the user to tune or edit the sag parameters, obtained from the block "Voltage Sag Characterization", to certain values. The "Recorded Voltage Sag Waveforms" provide us with a set of initial sag parameters based on which further tuning can be made. The recorded waveforms are optional and if they are unavailable, the user can input any desired initial sag parameter and then tune them for testing. In either case, by tuning the sag parameters such as the sag magnitude, sag duration, phase angle shift, etc., the software allows the user to observe and study how specific sag parameters affect the operating characteristics of the equipment under test. This is what we call the equipment sensitivity study. The block "Voltage Sag Generator" reconstructs the voltage sag waveforms based on the selected sag parameters. The constructed voltage waveforms serve as the voltage source for testing the equipment. The voltage sources can either be one phase or three phase depending on the equipment being evaluated. The "Equipment Model" allows development of mathematical models for the equipment [18].

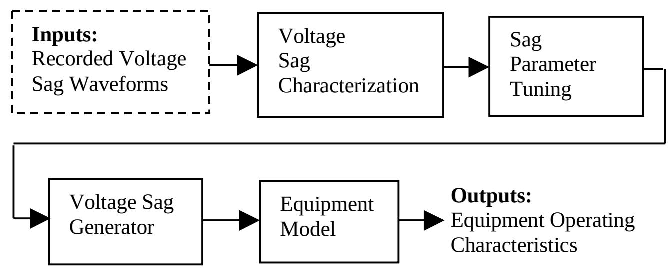

Fig. 5. The overall structure for equipment behavior evaluation

Through the sensitivity studies, the operating characteristics of the equipment during various sag events can be evaluated and responses tabulated. For example, by changing only the sag magnitude while fixing all the other sag parameters at specified values, we can obtain a representation of the equipment operating characteristic versus sag magnitude. Table 2 shows the maximum speed drop (MSD) of a motor under test versus the sag magnitude during the type A sags while the sag duration and phase angle shift are fixed at 50 ms and 20 degrees respectively. Characteristics such as the electromagnetic torque, currents, etc. can be analyzed similarly. The operating characteristics of the equipment versus other sag parameters can be obtained and archived in the same way. By comparing the parameters of a specific sag event with the saved equipment operating characteristics, automatic equipment behavior diagnosis can be realized. Table 3 shows such an example. It is seen from the table that the sag magnitude is the main factor that has caused the mis-operation of the equipment.

Table 2. MSD in percent versus the sag magnitude during type A sags

Sag magnitude (p.u.)	0.1	0.3	0.5	0.7	0.9	1.0
MSDM (%)	40.1	35.5	23.6	20.1	8.2	0.0

Table 3. Equipment behavior analysis results

Parameters	Critical Values	Actual sag parameters	Differ-ence	Affect
Sag Type	A	A	\	\
Phase Angle Shift (Degree)	10.0	10.0	0	No
Sag Magnitude (p.u.)	0.59	0.32	-0.27	Yes
Sag Duration (ms)	100.0	100.0	0	No

Note that the above procedure also applies to the equipment sensitivity study under other types of events except that the waveforms of the concerned type are used instead of the sag events.

The equipment sensitivity study presented here is quite helpful for implementing a power contract. For example, if a customer reports frequent failure of variable speed drives (VSD) to the power supplier, the supplier can timely pinpoint the cause of the failure using the methodology presented here and further investigate possible mitigation solutions. Prompt solution certainly will reduce any costs incurred.

V. CONCLUSION

Increased demand on the quality of power has resulted in a quite new form of power delivery contracts, namely power quality contracts, which may be beneficial to both the electricity suppliers and consumers. Practical implementation of any power quality contracts entails explicit definition and quantification of various indices. This paper proposes advanced techniques for automated power quality monitoring, system and equipment modeling, and equipment performance evaluation. Specifically, new techniques for automated detection, classification and characterization of various types of power quality events have been illustrated. Feasibility of Fourier and wavelet transform as well as fuzzy expert system for power quality monitoring applications is explored. Additionally, significance of integrating the system and equipment modeling into power quality analysis is demonstrated. A practical method for equipment performance evaluation is also discussed.

VI. ACKNOWLEDGEMENTS

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VIII. BIOGRAPHIES

Mladen Kezunovic (S'77, M'80, SM'85, F'99) received his Dipl. Ing. Degree from the University of Sarajevo, the M.S. and Ph.D. degrees from the University of Kansas, all in electrical engineering, in 1974, 1977 and 1980, respectively. Dr. Kezunovic's industrial experience is with Westinghouse Electric Corporation in the USA, and the Energoinvest Company in Sarajevo. He also worked at the University of Sarajevo. He was a Visiting Associate Professor at Washington State University in 1986-1987. He has been with Texas A&M University since 1987 where he is the Eugene E. Webb Professor and Director of Electric Power and Power Electronics Institute. His main research interests are digital simulators and simulation methods for equipment evaluation and testing as well as application of intelligent methods to control, protection and power quality monitoring. Dr. Kezunovic is a registered professional engineer in Texas, and a Fellow of IEEE.