Improved Analog Optical Fiber Link for Signal Measuring in a High Power Testing Facility

José C.Velázquez, Julio C. Montero, Joaquín H. Rodríguez, Raul Garduno

***Abstract*—** This paper introduces a new measuring system for highly aggressive EMI environments based on fiber optic transmission links and microprocessor-based error compensation. The analog fiber-optic transmitter-receiver system as applied in a high-power mid-voltage testing laboratory is presented. The optical fiber links are particularly well suited to this kind of application because of their dielectric nature and electromagnetic interference immunity properties. Additionally, the measuring system relies on a clever error compensation system, feedback and self-check features to monitor all vital functions, including battery charge level, data-link integrity, recovery and, if necessary, synchronization, and sophisticated data analysis. This work demonstrates that the optical fiber approach provides a unique, electrically isolated, lightning-proof analog data transmission system, and that measuring systems based on optical fibers are now feasible and computer microprocessors play an important role in its integration.

***Keywords*—** Electromagnetic interference, Gain variation, High power testing, Measuring systems, Optical fiber link, Voltage offset drift compensation.

I. Introduction

IN Mexico, the CFE (Spanish initials of the National Electrical Utility) owns a large testing facility called LAPEM [1], formed by a group of laboratories intended to validate conformance to standards of all electrical equipments before putting them into public service. Among the most important laboratories is the High-Power Mid-Tension (HPMT) laboratory [2], which is currently being modernized by IIE (Spanish initials of Electrical Research Institute). In the HPMT laboratory, devices such as switches, circuit breakers, transformers, fuses, and others, are tested to verify their response to definite currents and voltages, including destructive short-circuit conditions up to 38 kV and 100 kA.

The electromagnetic environment at the HPMT during the tests is very aggressive due to the interference cussed by high current and high voltage transients. Hence, the major challenge for a measuring system is to achieve the highest immunity to electromagnetic interference (EMI) and electrical isolation at lighting levels, as well as high precision and large bandwidth. These requirements prevent the use of conventional coaxial cables and circuitry, and suggest the use of optical fibers as transmission media and specially designed electronics, for measuring the required electrical signals during the tests.

Optical fibers have been mainly used in digital communications applications, where high speed and large bandwidth are the main requirements, but transmission of a DC component is not required. On the other hand, the accuracy and precision of analog optical fiber transmission links, for a measuring system under very aggressive EMI conditions, is highly dependent on maintaining under control the DC voltage offset drift due to temperature change. Consequently, an error compensation mechanism has to be implemented for the measuring system kind of applications.

This paper introduces a measuring system for electrical signals at very aggressive EMI environments. The system, based on fiber optic transmission links and microprocessor-based error compensation, is able to monitor the data-link integrity and to recover links using feedback and self-recovery features. Section II provides a brief description of the facility and testing requirements. Section III presents a description of the measuring system, including the remote transmitter and the receiver. Section IV describes the signal conditioning mechanism in the transmitter. Sections V and VI describe the DC voltage drift and the bandwidth compensation schemes. Section VII describes the automatic calibration strategy, and Section VIII shows how to find out the transmission error. Finally, conclusions are drawn in Section IX.

II. Test Requirements

Measuring the electrical variables at the HPMT laboratory is a big challenge. Measurement and signal conditioning of large currents and voltages, in the order of tens of kA and kV, have to be considered before transmitting this information to the control room for further analysis. However, the central problem is to preserve the integrity of signals, which have to be transmitted without any distortion. To solve this problem, a measurement system capable of measuring and carrying analog signals with minimum added error and with sufficient amplitude for post processing had to be developed [3]. Also, the signals to be measured depend on the type of test at hand. Every time a test is configured, the amount and type of signals have to be selected.

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J.C. Velázquez is with the Control and Instrumentation Department, Electrical Research Institute, Cuernavaca, Mor 62490 Mexico (Phone: +52-777-362-3811; fax: +52-777-362-3813; e-mail: jconrado@iie.org.mx).

J.C. Montero is with the Control and Instrumentation Department, IIE, Cuernavaca, Mor 62490 Mexico (e-mail: jcmc@iie.org.mx).

J.H. Rodríguez is with the Control and Instrumentation Department, IIE, Cuernavaca, Mor 62490 Mexico (e-mail: jrr@iie.org.mx).

R. Garduno is with the Control and Instrumentation Department, IIE, Cuernavaca, Mor 62490 Mexico (e-mail: rgarduno@iie.org.mx).

III. DESCRIPTION OF MEASURING SYSTEM

The analog fiber optic link of the measuring system is basically a fiber optic transceiver composed by three main parts, including the remote transmitter, the receiver unit and the fiber optic communication link, as simply shown in Figure 1. The remote transmitter located in the high EMI testing area at the HPMT laboratory, measures, sets up and sends out the analog input signal. The receiver unit, located in the control room at the HPMT laboratory, demodulates and filters the transmitted signal and drives the resultant analog output forward for digitizing and further processing. The communication link consists of two optical fiber channels that provide electrical isolation and immunity to the high voltage and EMI in the HPMT laboratory environment.

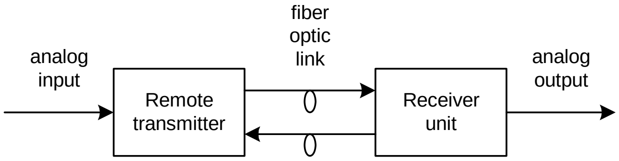

Fig. 1. Analog fiber optic link block diagram.

The analog fiber optic link was designed to accomplish DC to 200 KHz flat zone bandwidth, with maximum DC shifting of 5 mV/°C and no more than 1% gain variation throughout the link.

Due to the wide range of the analog input voltages, the remote transmitter has a conditioning front-end that can manage signals from 200 mV to 200 V in nine selectable attenuation ranges. Once in the remote transmitter, the analog input signal is modulated in frequency, and then converted into an infrared ray to travel along the fiber channel. At the other channel end the receiver is in charge of converting back the signal from light to voltage, amplify, demodulate and conditioning it so it can be used for post processing. The analog output signal is in the range of ±10 volts and can be processed by practically any digitizer device.

Setup features allow selection of input range for operation, diagnostics and automatic self-calibration. Also, the versatile power supply inside the transmitter can detect AC power supply and switch to batteries if AC power is disconnected. An internal digital remote controller senses battery voltage and controls battery charge.

A. Remote Transmitter

The transmitter equipment consists of both digital and analog sections, which are physically separated but interact with one another [8]. The digital section is in charge of receiving and interpreting the serial commands upcoming from the digital section of the receiver equipment at the control room. The analog section performs signal conditioning. Then, the signal is modulated and converted into an infrared light signal in order to be transported through the optical fiber channel.

As depicted in Figure 2, four modules integrate the remote transmitter: digital remote controller, analog conditioning module, analog transmitter and power supply. One fiber optic link is used to receive control commands and the other is multiplexed for control command reply and analog signal transmission.

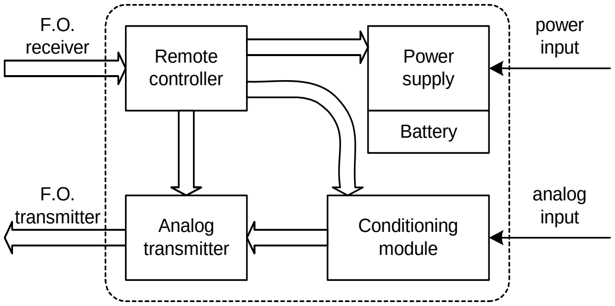

Fig. 2. Transmitter block diagram.

The central element of the analog transmitter is a VCO (voltage controlled oscillator) that oscillates at some initial frequency in accordance with a voltage setpoint V_S to generate the output of the VCO at frequency ω_0, called the central free-running frequency.

The output frequency of the VCO is:

$$\omega(t) = \omega_0 + G_{VCO} V_E(t) \tag{1}$$

where G_{VCO} is the VCO voltage-to-radian frequency gain in radians per second per volt and V_E is the applied voltage to the control input of the V_{CO} to set the central angular frequency and to modulate $\omega(t)$. The input voltage is:

$$V_E(t) = V_m(t) + V_s + V_N \tag{2}$$

where $V_m(t)$ is the modulaiting signal V_S is the DC setpoint voltage to produce ω_0 and V_N is the noise voltage at the imput of the VCO. Substitution of (2) into (1) yields:

$$\omega(t) = \omega_0 + G_{VCO}\left(V_m(t) + V_s + V_N\right) \tag{3}$$

With sensitivity functions:

$$\frac{d\omega(t)}{d\omega 0} = 1 \tag{4}$$

$$\frac{d\omega(t)}{dG_{VCO}} = V_m(t) + V_s + V_N \tag{5}$$

$$\frac{d\omega(t)}{dV_S} = G_{VCO} \tag{6}$$

$$\frac{d\omega(t)}{dV_N} = G_{VCO} \tag{7}$$

Therefore, the uncertainty for $\omega(t)$ is given by:

$$W_r = \left[\frac{d\omega(t)}{d\omega_0} w_1 + \frac{d\omega(t)}{dG_{VCO}} w_2 + \frac{d\omega(t)}{dV_S} w_3 + \frac{d\omega(t)}{dV_N} w_4 \right] \quad (8)$$

where w_1, w_2, w_3, w_4 are the estimated or measured errors for ω_0, G_{VCO}, V_S, V_N respectively.

On the other hand, the V_{CO} can be expressed as:

$$V_{CO}(t) = V_{AMPL} \sin\left(\omega_0 t + G_{VC} \int V_E(t)\, dt\right) + V_{OFF} \quad (9)$$

which is the heart of the V_{CO} modeling for time-analysis and corresponds to an FM modulator of the form:

$$Y(t) = A \sin\left(\omega_0 t + k \int f(t)\, dt\right) \quad (10)$$

B. Receiver

The receiver equipment is available in a rack-mount configuration. Up to 32 receiver channels can be plugged in one rack enclosure to ease connection to the rack-mounted data acquisition system in the control room. As with the transmitter equipment, the receiver also has both analog and digital sections.

Figure 3 shows a simplified block diagram of one receiver. The analog section is in charge of detecting, amplifying and demodulating the incoming analog signal from the transmitter equipment, as well as amplifying the demodulated signal to a level adequate for digitizing and post-processing. The digital section is the interface between the remote control system and the remote transmitter; it is responsible for sending and receiving commands trough an RS-485 interface.

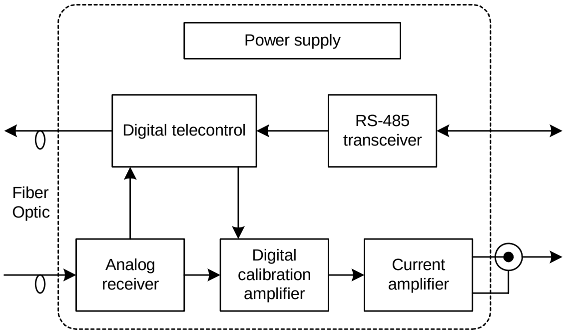

Fig. 3. Receiver block diagram.

IV. INPUT CONDITIONING

Selectable passive voltage dividers condition input voltage signal up to 200 volts. Reducing a voltage is a simple task, but conditioning an analog signal from DC up to 200 KHz with flat bandwidth and no distortion is much more difficult. Figure 4 shows the block diagram for signal conditioning at the remote transmitter input. A passive attenuator is designed using the equation $R_1C_1=R_2C_2$. Resistors R_1 and R_2 are proposed for a 1 M input impedance. Capacitor C_1 is also proposed and C_2 is calculated to get 200 KHz flat bandwidth.

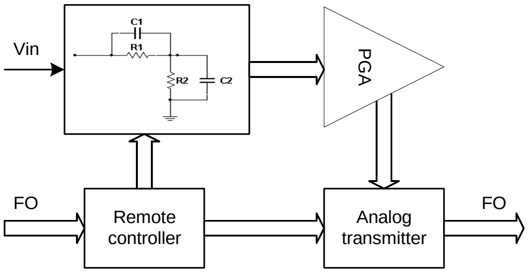

Fig. 4. Signal conditioning in transmitter.

There are seven steps of attenuation and two steps of magnification signal. Table I shows the combination of passive attenuator and Programmable Gain Amplifier (PGA) for conditioning analog signals from 200 mV up to 200 volts. Additional ranges of attenuation can be obtained with an appropriate combination of passive attenuator and PGA.

TABLE I
ATTENUATION COMBINATION.

Vin (Vpp)	Pasive Attenuator	PGA	Atten.
200	50	0.5	100
100	50	1	50
40	50	2.5	20
20	5	0.5	10
10	5	1	5
4	1	0.5	2
2	1	1	1
1	1	2	0.5
0.400	1	5	0.25

V. DC DRIFT COMPENSATION

Since high power testing implies not only AC signal but DC signals too, it is very important to have minimum DC shifting in order to have a very small overall transmission error. The transmitter equipment is the one exposed the most to the two main sources for DC shifting: internal heating and ambient temperature. Internal heating is produced by the normal behavior of electronic devices and external influence is due to the size of the high power testing zone, where it is impossible to have a controlled environment. Changes in temperature origin a DC drift of 20 mV per Celsius degree.

In order to correct the effects of internal heating and ambient variations against the transmitter, first the temperature natural response curve was obtained. What it means is that the equipment was tested inside a thermal chamber with no compensation circuitry, and after turning the circuits on and stabilized them for 30 minutes at a 25°C temperature, the calibration process is performed. Calibration consisted of grounding the input signal and adjusted some points in the transmitter and receiver circuits to obtain this very same signal at the receiver output. After this the chamber temperature was dropped to a 0°C level and sustained there for a 30 minutes period, and then reading and registering the dc offset level. The next step was to program the temperature chamber with a ramp from 0°C to 50°C along a 6 hour period (Fig. 5).

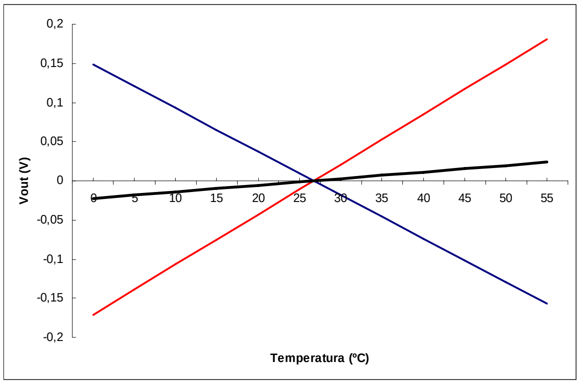

Fig. 5. Transmitter DC drift compensation.

VI. BANDWIDTH COMPENSATION

Communication systems usually consider a 3 dB bandwidth, which implies a gain reduction at 0.707 of the signal originally being transmitted. Hence, the error is about 30% of the signal usually originated by a low pass filter. Figure 6 shows the frequency response of the measurement system transmission media. The shape corresponds to a Butterworth low-pass filter. The frequency response of the original design is shown as the simulated plot, with a -3 dB cut-off frequency at 1 MHz. The actual response shows a cut-off frequency a bit below the desired 1 MHz bandwidth. Finally, the optimized response shows a large flat zone within 0.05 dB deviation up to 200 KHz, after that the cut-off frequency is at 800 KHz. For measurement purposes the 200 Khz flat zone is the most important requirement to be satisfied to keep measurement errors within ±0.5 %.

The whole fiber optic analog link can be simply modeled with the second order transfer function:

$$G(s) = \frac{1.984 \times 10^{13}}{s^2 + 4.084 \times 10^6 s + 9.87 \times 10^{12}} \qquad (11)$$

That has the following main properties: DC gain G_{dc}=2.01, Peak gain G_p=2.02, natural oscillation frequency f_n= 500 kHz, damping coefficient □=0.65, and time constant τ=0.489 □s.

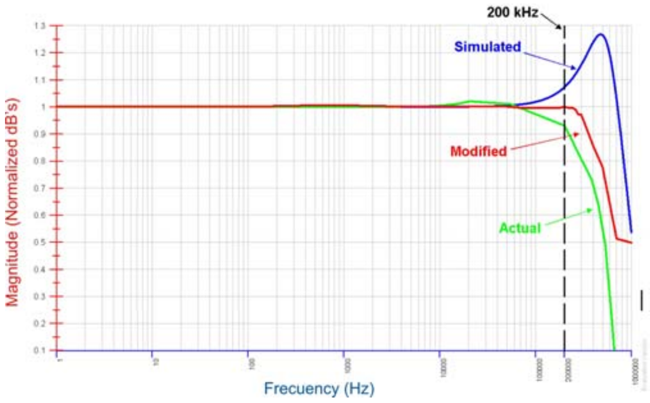

Fig. 6. Measurement system bandwidth.

VII. AUTOMATIC CALIBRATION PROCEDURE

The calibration process reduces errors in DC offset and V_o/V_i Gain. The calibration program allows input selection at the remote transmitter and digitizes the output voltage at the analog receiver. Figure 7 shows the Transmitter-Receiver system with channel selector at the input, and offset and gain calibration at the output. Telecontrol commands from receiver controller to remote controller are used to select the ground GND reference input for offset calibration and high precision voltage reference input for gain calibration. The PGA is selected for unit gain in both cases.

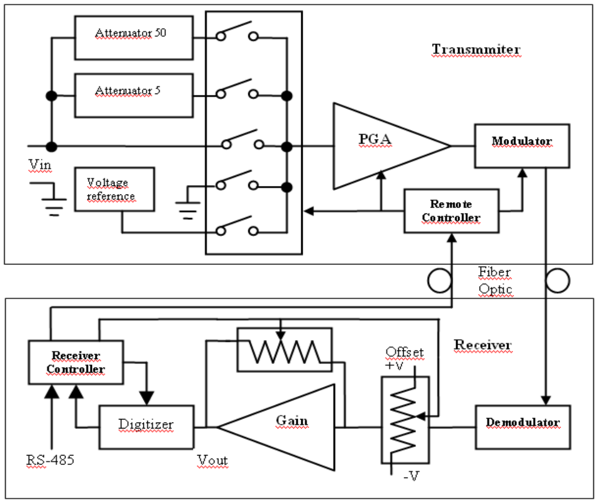

Fig. 7. Calibration circuit.

An RS 485 link enables communication between the Data Acquisition System and receiver controller. The calibration command can be selected in configuration software in Data Acquisition System. The calibration program loads a specific file with a calibration array for first calibration. After that, every new calibration array is overwritten in the file. Figure 8 shows the calibration process. DC offset calibration is necessary before gain calibration.

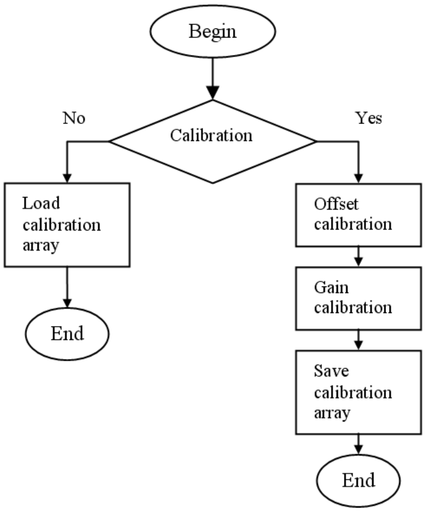

Fig. 8. Block diagram for calibration program.

For DC offset calibration the input selected at the Tx is GND, then 1,000 samples are acquired and digitized, the average value is compared with GND reference in Data Acquisition System. A 256 step digital potentiometer in the analog receiver is adjusted to minimize the DC offset error.

The high precision and low noise internal DC reference in the Transmitter is selected as an input, then 1,000 samples are acquired and digitized, the average value is compared with voltage reference value in Data Acquisition System. A Programmable Gain Amplifier in the analog receiver is adjusted to minimize the Vo/Vi Gain error. The calibration data array is generated with specific values for each channel link. Figure 9 shows the plot of actual current measurement.

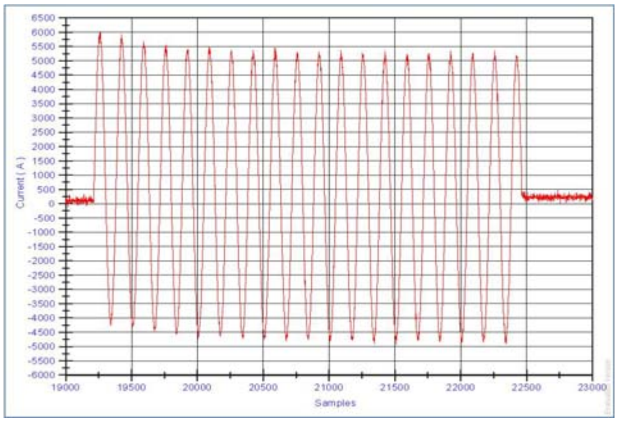

Fig. 9. Plot of current in a short circuit test

VIII. Error Estimation

The accuracy and precision are measured and estimated for the transmitter, the receiver and for the complete optical fiber link measuring system. The accuracy is determined by the systematic errors and limited by the precision. The precision is determined by the random errors. The sources of systematic error are: Linearity Deviation, Frequency response, Voltage offset, Signal Gain, and Optical power regulation for the optical link. The sources of Random error are: Thermal Voltage offset drift; Modulator-demodulator Thermal Voltage offset drift, Modulator-Demodulator Thermal Voltage gain drift, Thermal noise, Power supply noise. Thermal Voltage offset and Thermal Voltage gain drift of the modulator is compensated locally to limit the error. Thermal Voltage offset and Thermal Voltage gain drift of the demodulator is compensated by maintaining constant the temperature at the control room at 20 ºC. The precision of the transmitter is:

$$E_t = \sqrt{T_o^2 + M_o^2 + M_g^2 + T_n^2 + S_n^2} \tag{12}$$

Where E_t is the transmitter error estimation, T_o is the thermal voltage offset drift, M_o is the modulator voltage offset drift, M_g is the modulator voltage gain drift, T_n is the transmitter thermal noise and S_n is the transmitter power supply noise. The random error for the receiver is:

$$E_r = \sqrt{R_o^2 + D_o^2 + D_g^2 + R_n^2 + RS_n^2} \tag{13}$$

Where E_r is the receiver error estimation, R_o is the receiver thermal voltage offset drift, D_o is the demodulator voltage offset drift, D_g is the demodulator voltage gain drift, R_n is the receiver thermal noise and RS_n is the receiver power supply noise.

For the complete measurement system considering the transmitter, receiver and optical fiber link the random error estimation is:

$$P_m = \sqrt{E_r^2 + E_t^2} \tag{14}$$

where P_m is the precision of the measuring system, E_r is the receiver error estimation and E_t is the transmitter error estimation.

IX. Conclusions

This paper introduced an improved analog optical fiber link for signal measuring in a high power testing laboratory. The proposed link includes both novel transmitter and receiver. This link is very versatile due to its very wide range of input signal magnitudes (200 mV to 200 V) and bandwidth (DC to 200 kHz). Hence, the link can be used in a wide variety of measuring applications where both galvanic isolation and high EMI immunity are required.

The remote transmitter circuitry incorporates a clever hardware and software thermal compensation method that cancels undesired errors due to temperature variation. This approach permitted accomplishment of strict international requirements regarding maximum measurement errors for measurement of electrical signals (< 1%) in high power testing facilities.

Also, the automated calibration procedure dramatically reduces the amount of time needed to set the test initial conditions, as well as the duration of maintenance periods for the communication links.

The transfer function was obtained from experimental data. With this model it is possible to analyze the system dynamic behavior in both time and frequency domains. Although the step response is not shown in the paper, the time constant of the whole optical link is around 0.5 microseconds, which means the measuring system can perfectly deal with the signals in the required 200 KHz flat zone of the frequency response.

Finally, the operation of the measuring system relies on clever error compensation scheme, feedback and self-check features to monitor all vital functions.

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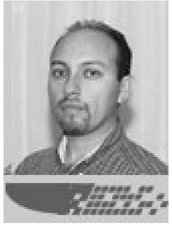
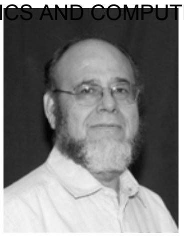
Jose C. Velazquez. Obtained a BSc degree in Electronics Engineering from the Orizaba Institute of Technology, Mexico, and a MSc degree in Digital Systems from the National Polytechnic Institute, Mexico. He has been a researcher and project manager in the Control and Instrumentation Department at the Electrical Research Institute since 1992. His research interests are digital communications and interoperability of digital communication systems. He has been responsible for many research projects with the electrical industry of Mexico. He is currently working in the modernization project of the high power tests laboratory of the Mexican National Electric Company.



Julio C. Montero Cervantes. Obtained the Electronics Engineer degree from the Instituto Tecnológico de Piedras Negras in Coahuila, México, in 1988 and the Master of Science degree in Electronics from the Centro Nacional de Investigación y Desarrollo Tecnológico (CENIDET), in Cuernavaca, Mexico, in 1994.

Since 1992, he has been a research engineer in the Control and Instrumentation Department at the Electrical Research Institute. He has participated in several R&D projects related to digital and analog communication systems, especially in strong EMI environments, and has published several papers in this area.



Joaquin H. Rodriguez-Rodriguez. Graduated as a Mechanical and Electrical Engineer from University of Nuevo Leon at Monterrey, Mexico in 1974, and obtained a Masters of Science degree in Electrical Engineering from the University of Toronto, Canada in 1980. He also got a Diploma in Technology Marketing from Instituto Tecnologico de Estudios Superiores de Monterrey (ITESM) in 2001, and a Diploma in Micro Electro-Mechanical Systems (MEMS) coordinated by the Mexico-US Foundation for Science in 2003. As part of his professional experience, he worked as a research engineer for Trench Electric Ltd. of Toronto, Canada from 1979 to 1981. He joined the Electrical Research Institute in Mexico as a researcher and head of the telecommunications laboratory, where he developed projects related to electronics, optical fibers and telecommunications systems for the electrical utilities in Mexico from 1982 to 1988. In the last four years, he has been working on MEMS Applications and optical fiber sensors for on-line monitoring of Power electric apparatus. He was professor at ITESM, the University of Morelos and the Center for Research and Technological Development, all in Mexico. Has published many technical papers and participated in national and international technical meetings. From 1985 to 2007 was recognized as National Researcher in Mexico by the National Research System (SNI).

Raul Garduno-Ramirez. Is an Electrical Engineer by ESIME-IPN (1985), Mexico, a Master of Science by CINVESTAV-IPN (1987), Mexico, and got a Doctor of Philosophy degree from the Pennsylvania State University (2000), USA, as a Fulbrigth Scholar. In 1986 worked at the National Laboratory of Mechanical Engineering, Japan, developing industrial robot controls. Since 1987 works at the Electrical Research Institute, Mexico, on power plant automation and control systems development. His areas of interest include intelligent control systems, turbogenerator control and multiobjective optimization of power plant operation. Has published more than seventy technical papers in international conferences and journals, and four book chapters. Dr. Garduno is member of the Mexican National Research System since 1989 and Senior Member of IEEE (2003).