Increased Input Voltage Range for Signal Transmission through Nonlinear Compensation in Analog Optical Fiber Links

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Abstract: - This paper introduces an improved measuring system based on fiber optic transmission links with nonlinear dynamic compensation to increase the input voltage measuring ranges. The transmitter-receiver system as applied in a high-power mid-voltage testing laboratory with highly aggressive EMI is presented. Optical fiber links are used due to their galvanic insulation and EMI immunity properties. The dynamic range compensation system is based on non-linear circuits to accommodate the input dynamic range of a voltage controlled oscillator, which is used to produce a pulsed FM modulation over the optical fiber. This work demonstrates that the optical fiber approach provides a unique, electrically isolated, lightning-proof analog data transmission system, for remote measuring systems in high power test lab applications.

Key-Words: - Nonlinear dynamic range compensation, EMI, High power testing, Optical fiber link.

1 Introduction
Devices such as switches, circuit breakers, transformers and fuses are tested in a High-Power Mid-Voltage (HPMV) testing laboratory 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 HPMV during the tests is very aggressive due to high current and high voltage transients. Hence, the major challenge for a measuring system at HPMV is to achieve the highest immunity to electromagnetic interference (EMI) and electrical isolation at lighting levels, as well as wide signal dynamic range, 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, as well as 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 and transient phenomena, is highly dependent on maintaining under control the DC voltage offset drift due to temperature change and the capability to handle large dynamic voltage changes. Consequently, a compensation mechanism has to be implemented to be able to comply with the measuring system requirements. Non-linear functions are used mainly in voice communications, the non-linear µ-law algorithm is used for companding in the digital telecommunication systems of North America and Japan, and the non-linear A-law algorithm is used in Europe.

The purpose of companding is to reduce the dynamic range of an audio signal. In the analog domain, this can increase the signal-to-noise ratio (SNR) achieved during transmission. Companding is a method of mitigating the detrimental effects of a channel with limited dynamic range. Compression is also used in audio recording and depends on a variable-gain amplifier, and so is a locally linear process.

Measurement systems have not used campaning circuits because in general the objective is not to introduce distortion or additional errors. The purpose of this paper is to present an measurement application that takes advantage of non
linear functions to reduce signal to noise ratio and allows the transmission of analog signals over optical fiber links with great accuracy and precision and wide dynamic range for compressed input signal before transmission and expanded to the original value at the receiver end.

This paper introduces a new measuring system for electrical signals at very aggressive EMI environments. The system, based on analog fiber optic transmission links and digital microprocessor-based error compensation, able to monitor the complete measurement system integrity and to control the status of the remote transmitter hardware. 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 based on non linear network 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.

2 Measuring System

High Power Medium Voltage HPMV laboratories require to measure large currents and voltages, in the order of tens of kA and kW. The measurement of the electrical parameters have to be performed under high electromagnetic interference, and precaution has to be taken to ensure complete electrical insulation before transmitting voltage signals and 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 an the introduction of nonlinear circuits to provide a safety margin in the voltage handling capabilities of the transmitter.

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, performs the measurements, 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.](image)

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 and non linear network is used to ensure that the optimum input voltage to the modulator is not exceeded. 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 subjected to a non linear network that has the inversed mathematical function to the network used in the transmitter. The final output voltage is in the...
range of ±10 volts and can be acquired and processed by a digitizer.

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.

2.1 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 Pulsed Frequency Modulation PFM and converted into an infrared light signal in order to be transported through the optical fiber channel.

As depicted in Figure 2, five modules integrate the remote transmitter: digital remote controller, analog conditioning module, non-linear networks, 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.

![Transmitter block diagram](image)

Fig. 2. a) Transmitter block diagram. b) Actual implementation for the Transmitter Non-linear network.

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 $\omega_0$, called the central free-running frequency. The output frequency of the VCO is:

$$\omega(t) = \omega_0 + G_{VCO} V(t) \quad (1)$$

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

$$V(t) = V_m(t) + V_s + V_N \quad (2)$$

where $V_m(t)$ is the modulating signal $V_S$ is the DC setpoint voltage to produce $\omega_0$ and $V_N$ is the noise voltage at the input of the VCO. Substitution of (2) into (1) yields:

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

On the other hand, the VCO can be expressed as:

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

The non linear function is based on the I–V characteristic of two diodes in parallel configuration to have symmetric current for positive and negative input signal voltage. The equation of an ideal diode is:

$$I = I_s \left( e^{V_D/(nVT)} - 1 \right),$$

Where

$I$ is the diode current, $I_s$ is a scale factor called the saturation current, $V_D$ is the voltage across the diode, $VT$ is the thermal voltage,
and \( n \) is the emission coefficient, also known as the ideality factor. The emission coefficient \( n \) varies from about 1 to 2 depending on the fabrication process and semiconductor material and in many cases is assumed to be approximately equal to 1 (thus the notation \( n \) is omitted).

The thermal voltage \( V_T \) is approximately 25.85 mV at 300 K, a temperature close to “room temperature” commonly used in device simulation software. At any temperature it is a known constant defined by:

\[
V_T = \frac{kT}{q},
\]

Where
\( q \) is the magnitude of charge on an electron (the elementary charge),

\( k \) is Boltzmann’s constant,

\( T \) is the absolute temperature of the p-n junction in kelvins

Under reverse bias voltages the exponential in the diode equation is negligible, and the current is a constant (negative) reverse current value of \(-I_S\).

For even rather small forward bias voltages the exponential is very large because the thermal voltage is very small, so the subtracted ‘1’ in the diode equation is negligible and the forward diode current is often approximated as

\[
I = I_S e^{V_D/(nV_T)}
\]

The current for a diode network of two diodes in parallel one forward and one backwards is:

\[
I = \text{sgn}(V_D) I_S e^{(V_D)/(nV_T)}
\]

This diode equation is used to limit the voltage range of a bipolar signal at the input to the modulator, and the inverse function to reconstruct the original shape of the input voltage at the receiver.

The output voltage for the transmitter is:

\[
v_{\text{out}} = -\text{sgn}(V_{\text{in}}) V_T \ln \left( \frac{|V_{\text{in}}|}{I_S \cdot R} \right)
\]

The output voltage (Inverse Function) for the receiver is:

\[
v_{\text{out}} = \text{sgn}(V_D) R I_S \left( e^{V_D/(nV_T)} \right)
\]

### 2.2 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 PFM signal from the transmitter module, the demodulated signal is introduced to the inverse nonlinear function network to recover the original signal from the transmitter. And the output level is adjusted for digitization 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 through an RS-485 interface.

Fig. 3. a). Receiver block diagram b). Actual implementation for the Receiver Nonlinear network inverse function.
2.3 **Signal Conditioning**

At the transmitter the input voltage is adjusted by means of selectable passive voltage dividers to control the input voltage signal in the range of 1V to 200V to a voltage in the range of 0V to 2V (Voltage range accepted by the VCO) and with a frequency response from DC up to 200 KHz with flat bandwidth and minimum distortion.

The introduction of a non-linear network helps to accommodate the transient signals generated by the short circuit tests, and the optimum setting of the input near the maximum voltage (2 volts) accepted by the VCO.

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.](image)

Table 1 show that the introduction of a non-linear network allows the handling of input voltages tree times the voltage of a linear circuit without compensation.

3 **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. Input vs. output Time response for non-linear compensated measurement system.](image)

3 **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 %.

In Fig. 5 The triangular continues wave is the input voltage, the squared wave is the non-linear output and the doted triangular wave is the reconstructed signal at the receiver.

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

\[ G(s) = \frac{1.984 \times 10^{13}}{s^2 + 4.084 \times 10^6 s + 9.87 \times 10^9} \]  \hspace{1cm} (11)

which 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 \( \zeta = 0.65 \), and time constant \( \tau = 0.489 \mu s \).

5 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 5 shows the Transmitter-Receiver signals with channel selector at the input, and offset and gain calibration is required for optimum performance of the non-linear compensation. 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.

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. DC offset calibration is necessary before gain calibration.

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 \( V_o/V_i \) Gain error. The calibration data array is generated with specific values for each channel link.

Fig. 7). represents the plot of a simulated current in a short circuit test for non-linear compensated measurement system.
In Fig. 7 Non-linear compensated case. The continues sinusoidal wave centered at 0V DC is the input voltage, the strait line with negative slope represents a transient to be added to the input, the sinusoidal wave following the strait line slope is the reconstructed wave (A gain of 2 was used to differentiate the input from the output).

In Fig. 8 The continues sinusoidal wave centered at zero V dc is the input voltage, the strait line with negative slope represents a transient to be added to the input, the doted distorted sinusoidal wave is the truncated output due to the fact that the VCO is not able to handle voltages above 2V.

The results of obtained by the use of non-linear networks improves the dynamic range of the input voltage at the transmitter and is able to reconstruct the original signal maintaining original bandwidth, low distortion, improving signal to noise ratio.

![Graph](image)

Fig. 8) represents the plot of a simulated current in a short circuit test for linear measurement system.

6 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 °C. The precision of the transmitter is:

7 Conclusions

This paper introduced an improved non-linear analog optical fiber link with wide dynamic range 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 combining the attenuation steps with a non-linear network ) and bandwidth (DC to 200 kHz). Hence, the link can be used in a wide variety of measuring applications where galvanic isolation, high EMI immunity, and handling of transient signals (with more then 300%) 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.

Finally, The results show that use of non-linear networks improves the dynamic range of the input voltage at the transmitter and is able to reconstruct the original signal maintaining original bandwidth, low distortion, improving signal to noise ratio.

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