Impulse Generator Spectrum Amplitude Measurement Techniques

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Abstract—Various techniques that have been used to calibrate impulse generators and to measure spectrum amplitude are surveyed. A summary of experiments comparing the various techniques is included. The NBS measurement service for calibrating impulse generators is described.

INTRODUCTION

IMPULSE generators (IG's) are widely used as transportable field calibration instruments for the broadband calibration of field-intensity meters (FIM). An FIM is the basic instrument for measuring electromagnetic fields and the spectrum amplitude of broad-band impulsive noise. Until recently these calibrations have not been traceable to NBS.

Spectrum amplitude $S(f)$ is defined by the IEEE [1] as twice the magnitude of the Fourier transform $|V(f)|$ of a time-domain signal function $v(t)$:

$$V(f) = \int_{-\infty}^{\infty} v(t) e^{-j2\pi ft}\, dt \qquad (1)$$

$$S(f) = 2|V(f)|. \qquad (2)$$

Confusion has existed in the literature over whether to use $1/\pi$, 1, $\sqrt{2}$, or 2 as the constant in (1). M. G. Arthur has written an excellent note [2] on the subject which justifies the IEEE choice of 2 as the proportionality constant.

The unit for $S(f)$ is the volt-second or equivalently volts per hertz. The unit in common usage is microvolts per megahertz (μV/MHz). Also in common usage is a decibel expression, decibel-microvolts per megahertz (dBμV/MHz), above 1 μV/MHz.

In the time-domain voltages are measured in terms of absolute Système International (SI), volts. In the frequency domain, however, power is usually a major consideration and as a result voltages are usually expressed in rms voltage. When a peak responding receiver that has been calibrated in terms of the rms value of a sine wave is used to measure $S(f)$, the measurement results will be 3 dB lower than if it were calibrated in terms of the peak value. This has led to the existence of an rms spectrum amplitude. Much of the difficulty in the past in correlating various measurements can be traced to this 3-dB difference.

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This paper discusses the various techniques that have been used to calibrate impulse generators and to measure spectrum amplitude. The techniques included are 1) standard transmission line, 2) harmonic measurement, 3) energy method, 4) sum and difference correlation radiometer, 5) Dicke-type radiometer, 6) video pulse, Military Standard 462, 7) spectrum analyzer, 8) standard pulse comparison, and 9) time-domain measurement with Fourier transformation computation. Advantages and disadvantages of each technique are discussed.

STANDARD TRANSMISSION LINE

Most IG's use a mercury switch to discharge a short coaxial transmission line. For a load matched to the line impedance the generator produces a rectangular pulse of amplitude V_0, which is half the dc supply voltage. The duration t_0 is twice the time delay of the transmission line. The spectrum amplitude is given by

$$S(f) = 2V_0 t_0 |\sin(\pi f t_0)/(\pi f t_0)|. \qquad (3)$$

This equation is used in the standard transmission line method to predict the IG output. V_0 can be determined accurately from a dc voltage measurement of the supply voltage. The line impedance and t_0 are determined by geometrical dimensions and dielectric constants or capacitance measurements. Equation (3) is quite accurate for HF IG's with 10 ns or longer pulses. Its accuracy suffers for $t_0 < 1$ ns, because the waveform is no longer rectangular. The transition (rise and fall) times are comparable to the duration. It also becomes difficult to model or measure accurately the actual time delay of the charge line and the switch.

HARMONIC MEASUREMENT

If one has an extremely narrow-bandwidth receiver, an IG can be calibrated by measuring a single spectral line in the IG's spectrum and comparing it against a known CW voltage standard [3]. The spectrum amplitude is then given by

$$S(f,k) = V_k/f_0, \qquad f = kf_0 \qquad (4)$$

f_0 is the pulse repetition rate of the IG. V_k is the peak voltage amplitude of the kth harmonic of f_0. f_0 can be measured very accurately with a digital frequency counter. V_k can also be measured accurately if the pulse repetition rate is much greater than the receiver bandwidth.

Energy Method

R. B. Andrews [4] has developed a spectrum amplitude measurement technique based upon the measurement of spectrum intensity (watts/hertz). Spectrum intensity is defined [1] as the ratio of the power contained in a given frequency range to the frequency range as the frequency range approaches zero. This technique requires a power meter and a bandpass filter centered at the frequency of interest between the IG and the power meter. It has the advantage that it uses ordinary metrology lab equipment to measure frequency and power. The bandpass filter commonly used is a radio receiver. The major disadvantages are: 1) the necessity of measuring the receiver gain and power bandwidth at each frequency of interest, 2) the power meter must be able to respond accurately to waveforms having a high peak-to-average ratio, and 3) the background noise from the receiver between pulses may drastically corrupt the measurement of the pulse power.

Sum and Difference Correlation Radiometer

In the late 1960's, NBS developed a sum and difference correlation radiometer (SDCR) to calibrate impulse generators [5], [6]. The SDCR is similar to the previously described energy method in that $S(f)$ is obtained by measuring the spectrum intensity. The unknown impulse is measured by comparing it against a known thermal white-noise source. The SDCR is designed so that a null voltage is obtained when the power from the external IG is balanced against the SDCR internal sources. These are the correlated part of the SDCR's internal noise and a stable CW generator, the output of which is adjusted by a precision attenuator. NBS has built two SDCR's, one at 30 MHz and the other at 1 GHz. The SDCR radiometer technique has the potential of great accuracy. In addition it does not require a precise measurement of the SDCR impulse bandwidth and bandpass characteristics as this parameter does not appear directly in the relevant equations. There are, however, several major disadvantages. First, it provides data at a single fixed frequency. Second, the SDCR is a quite sophisticated and expensive instrument. Its primary usefulness is as an independent measurement technique in a national standards laboratory. Third, it required that the IG source impedance be measured. This is not always an easy task as the source impedance of some generators is a time varying quantity. The simple mercury switch is the worst case with R_g jumping from the transmission-line impedance to an open-circuit.

Dicke Radiometer

In 1974, Oranc [7] proposed using a Dicke radiometer to calibrate impulse generators. The Dicke radiometer measures the noise temperature of an input broad-band signal. It is a linear radio receiver in which the input is switched alternately between the unknown signal source and a known thermal noise source. A synchronous detector locked to the input switching frequency is used to detect the difference between the two input noise temperatures.

Video Pulse—Military Standard 462

The video pulse method is probably the most widely used IG calibration technique due to the fact that it is specified by Military Standard 462 and because it uses common laboratory instruments such as calibrated CW signal generator, a tunable receiver, and an oscilloscope. It consists essentially of connecting the IG to a narrow-band filter (such as radio receiver) and observing with an oscilloscope the envelope response (i.e., video pulse) of the filter output. The impulse bandwidth (IBW) of the filter is defined in Military Standard 462 as the peak value of the video pulse divided by its area. The IG is then replaced by the CW generator and its output $V_{CW}(f)$, is adjusted to give the same peak value as obtained from the IG. $S(f)$ is then given by

$$S(f) = V_{CW}(f)/\mathrm{IBW} \tag{5}$$

The major difficulty in this method is accurately determining IBW. Measurements can vary wildly depending upon the actual shape of the filter passband in both amplitude and phase.

Spectrum Analyzer

A spectrum analyzer is perhaps the easiest to use instrument for making broad-band spectrum amplitude measurements. It gives an immediate visual display of relative spectrum amplitude versus frequency. Some spectrum analyzers of recent design are also capable of making quite accurate $S(f)$ measurements [6]. Of major importance is that the input impedance, gain, and bandwidth of the instrument be constant and not a function of frequency. It must also be free of spurious and image responses. Reeve [6] has found that some FIM and EMI receivers currently in use are not suitable because of impedance, gain, and bandwidth variations with frequency. The spectrum analyzer is used as a tuned calibrated voltmeter to measure the effective input voltage $V_{CW}(f)$, from the IG. $S(f)$ is computed from (5). It is also necessary to know the IBW, which can be determined from the video pulse area or preferably by using a standard IG. The major problem in using a spectrum analyzer is its susceptibility to overload due to the fact that the input signal is applied directly to the input mixer diodes. The solution is to use a preselector bandpass filter (bandwidth > 10 IBW) between the IG and the input mixer.

Standard Pulse Comparison

Potentially the most accurate IG calibration technique is to compare its output to that of a known standard pulse generator. The IG under test is connected to a narrow-band filter, such as a radio receiver, and the video pulse output peak is noted. Then the IG is replaced by the standard pulse generator and a precision attenuator. The attenuator is then adjusted to give the same video pulse peak as before. The unknown spectrum amplitude is simply the standard S_{std} in dBμV/MHz less the attenuator setting in decibel.

The most accurate method of generating a standard pulse with a known spectrum amplitude at a particular frequency is the rectangular RF pulse technique [6]. A CW signal generator provides a stable sine wave of known frequency and constant level. An RF switch is driven by a baseband pulse generator and is used to gate on and off the CW sine wave thus producing a rectangular RF pulse. The spectrum of the modulation waveform is translated from a distribution about zero frequency to a distribution about the carrier frequency f_c. As seen earlier, a rectangular pulse produces a $\sin(x)/x$ spectrum. Thus a rectangular pulse modulated RF burst produces a $\sin(x)/x$ spectrum centered at f_c. This technique has an advantage over baseband impulses in that it can concentrate uniformly most of the signal energy in the frequency region where a measurement is to be made. For a rectangular RF pulse the exact expression for $S(f)$ contains two terms

$$S(f) = V_0 t_0 \left| \frac{\sin(\pi \Delta f t_0)}{(\pi \Delta f t_0)} - \frac{\sin[\pi(2f_c + \Delta f)t_0]}{[\pi(2f_c + \Delta f)t_0]} \right| \quad (6)$$

where $\Delta f = f - f_c$. $S(f)$ can be completely characterized by knowing the peak amplitude V_0, and the duration t_0. These values can be obtained by direct measurement. The amplitude can be obtained by measuring the CW output power with the RF switch in the ON state. t_0 can be measured using a calibrated oscilloscope. An alternate technique is to use a spectrum analyzer or receiver to determine the frequency at which the nulls occur in the RF pulse spectrum. The most critical component in the standard RF pulse generator is the RF switch. It is required to have extremely high switch isolation (>120 dB typical) and fast switching times (<5 ns).

Time Domain Measurement/Fourier Transformation Computation

With the exception of the standard transmission line method the previous techniques for determining spectrum amplitude have all been some variation of a frequency domain measurement using a narrow-bandpass filter. An alternate technique is to measure the time domain waveform $v(t)$ of the signal to be measured. From $v(t)$ the spectrum amplitude $S(f)$ can then be computed using the basic definition of spectrum amplitude, equations (1) and (2). This technique has been known for a long time, but it has not been widely used because it has been very time consuming. It has required photographing an oscilloscope CRT display of the signal which is not very accurate to be analyzed. Many data points must then be read by eye from the photograph, typed onto paper tape or computer cards, and then processed on a time share or large central computer. The process easily consumes an entire working day or more.

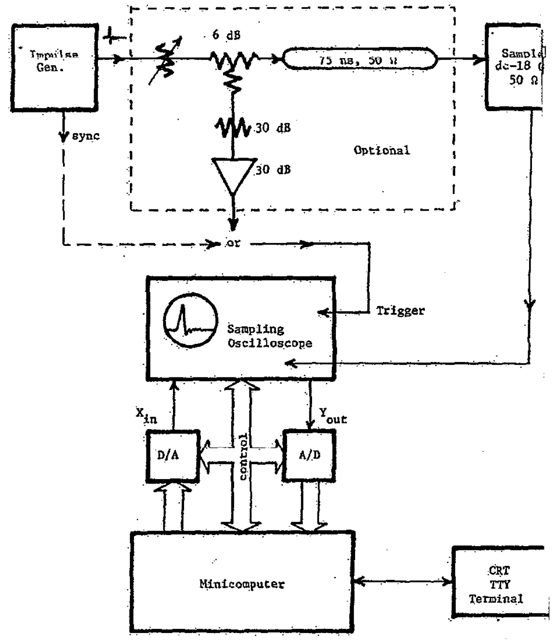

Fig. 1. NBS automatic pulse measurement system for calibrating pulse generators.

With the advent of inexpensive (<10 k$) minicom ters, this has all changed. The cost of computing capabi is now comparable to that of a high performance oscil scope, and it is now cost-effective to dedicate a minico puter to be hard-wired to an oscilloscope. In additi sampling oscilloscopes are commercially available w bandwidths as great as dc-18 GHz which permit $v(t)$ a hence $S(f)$ to be measured over a very broad range wit single instrument. In 1974, NBS built an Automatic Pu Measurement System (APMS) as shown in the block agram of Fig. 1. The APMS is described in detail in N Technical Note 672 [8] and in W. L. Gans' 1976 CP paper [9]. This system is used by NBS to calibrate impu generators.

In operation, the impulse to be measured is applied rectly to the input of the sampler. If the impulse amplitu is greater than ±400 mV then broad-band coaxial atte uators must be used between the impulse generator a the sampler. The IG must also supply a suitable sta trigger pulse to the sampling oscilloscope approximate 75 to 100 ns prior to the impulse. Some electronic IG normally supply such a trigger pulse. However, the va majority of IG's use mercury switches and are not capab of being triggered reliably. The synchronized pulse fro these generators cannot be used. A trigger pick off a coaxial delay line must be used to provide the necessa trigger for the sampling oscilloscope. When a delay line necessary the overall system bandwidth is degraded bel the sampler 18-GHz bandwidth. The major contribut is due to skin effect in the coaxial delay line. With an dinary 75 ns, 1.5 cm O.D. coaxial cable the 3-dB bandwid is 3 GHz. For higher frequencies and impulse durations less than 250 ps a superconducting coaxial delay line is used.

The APMS time domain method of calibrating impulse generators has the advantages of: 1) very broad frequency coverage (dc-18 GHz), 2) rapid measurement time of typically 2 min for repetition rates in excess of 10 kHz, and 3) providing a large amount of data (typically several hundred data points). It does have some disadvantages, however. The major one is that it cannot measure $v(t)$ over the complete interval $-\infty < t < +\infty$. It can only acquire a limited finite amount of data points. A time window of finite extent is used to observe the impulse. Any signals emanating from the IG other than the main impulse and positioned in time outside of the time window are ignored. Their contribution to the composite spectrum amplitude is not accounted for in the Fourier transform computation. Another problem which arises when either external attenuators and/or a trigger pick off delay line arrangement are used is the necessity to also calibrate the attenuation versus frequency of these additional components to provide correction factors for the measured $S(f)$. This is not a major problem however because the APMS can also be used as a network analyzer to determine the "S" parameters of these components [8]. The major effect is a reduction in the overall accuracy.

Experimental Results

This section presents some of the results of a set of experiments to compare the various $S(f)$ measurement techniques. The energy method and the Dicke radiometer techniques were not used. The other techniques were investigated and were found to all give consistent results.

A standard 10-ns impulse generator was built using a small mercury switch; 3-mm 50-Ω semi-rigid coaxial cable; a stable dc voltage supply and a digital voltmeter. Measurements were made on the NBS APMS using the time domain measurement/fast Fourier transform computation (hereafter abbreviated as TD/FFT) technique. There was agreement within ±0.6 dB over the low-frequency portion of the spectrum up to 85 MHz which covers a 15-dB range. The spectrum nulls near the frequencies $f_n = n \cdot 1/t_0$ were extremely sharp and as expected the agreement between theory and experiment was very poor. However, good agreement was obtained for the peaks on the higher order lobes of the spectrum.

Experiments were performed in 1972 by Reeve [6] to measure spectrum amplitude using the NBS SDCR. He used a step recovery diode IG with a 300-mV 200-ps impulse as the broad-band impulsive noise source to be tested. The same generator was measured in 1976 using the TD/FFT technique on the NBS APMS. At 30 MHz the SDCR gave a result of 37.15 dBμV/MHz while the TD/FFT gave 37.5 dBμV/MHz for a difference of only 0.35 dB.

Measurements were also made on several commercial mercury switch IG's, including 10 ns and ½ ns models, to compare the manufacturer's calibration and the TD/FFT, standard pulse, Military Standard 462, and spectrum analyzer techniques. For a 10 ns IG over the frequency range of 5 to 60 MHz the worst case disagreement was 1 dB between the Military Standard 462 and the spectrum analyzer. Between the TD/FFT and the standard pulse comparison the largest difference was 0.4 dB.

TABLE I
Comparison of $S(f)$ Measurements on an NBS SRD Impulse Generator (S/N 3-75-1)

Frequency in GHz	S(f) in dBμV/MHz				
	TD/FFT	Std. Pulse	Mil. Std. 462	Spectrum Analyzer	Harmonic
0.05	72.9	72.1	72.4	71.8	71.2
0.10	72.2	72.4	73.2	71.6	71.8
0.20	71.6	72.5	73.1	72.9	72.3
0.50	70.7	68.9	68.6	70.4	70.7
1.0	68.7	68.7	69.2	69.6	68.3
2.0	68.4	68.1	68.8	68.9	68.4
5.0	58.6	58.0	58.6	59.0	57.8

A set of experiments were also performed to measure the $S(f)$ output of an NBS step recovery diode IG which produced a 12-V impulse of 100-ps duration [10]. The frequency-domain measurements were all made using a commercial spectrum analyzer along with various combinations of attenuators and preselector filters. Two NBS standard RF pulse generators were used covering the bands 5 to 500 MHz and 1 to 12 GHz. A 300-kHz bandwidth and 20-kHz pulse repetition rate was used for all measurements except the harmonic technique in which case a 300-Hz bandwidth and 100-kHz repetition rate was used. The results of this experiment, Table I, show good agreement. The worst case difference is 2.1 dB at 500 MHz. The frequency domain measurements at 500 MHz had the poorest accuracy due to the preselector bandwidth used which resulted in a poor signal-to-noise ratio. The spectrum analyzer detected a small 1-dB 3-MHz ripple in the spectrum at frequencies up to 200 MHz. This was due to a small 60-mV secondary pulse 330 ns after the main impulse. This secondary pulse was not included in the TD/FFT measurement time window which helps explain part of the differences noted at low frequencies. Particularly encouraging were the microwave results between 2 and 5 GHz.

NBS IG Calibration Service

NBS now offers a calibration service for the spectrum amplitude output of impulse generators using the TD/FFT technique. The capabilities of this service are listed in Table II. The calibration range avoids deep spectrum nulls and higher order lobes. The uncertainty limits were arrived at after an error analysis including the effects of: 1) vertical voltage calibration; 2) horizontal time base calibration; 3) sampler bandwidth; 4) VSWR; 5) vertical noise; 6) time base jitter; 7) A/D and D/A quantization; and 8) FFT aliasing.

Due to journal length limitations, this paper has only briefly touched on the various aspects of spectrum am-

TABLE II
NBS Impulse Generator Spectrum Amplitude Calibration Capabilities

Parameter	Limits
Max. Impulse Amplitude	± 400 mV
Max. Impulse Amplitude with Ext. Attenuators	± 1.2 kV
Load Impedance	50 ohms
Frequency Range	5 MHz to 6 GHz
Frequency Spacing	5, 10, 20, 50, or 100 MHz
Frequency Uncertainty	± 1%
Spectrum Amplitude Range	-15 dB $< [S(f)-S_o] < +5$ dB $S_o \sim 2\, V_{pk}\, t_o$
Spectrum Amplitude Uncertainty	$f \leq 1$ GHz, ± 0.6 dB 1 GHz $< f \leq 4$ GHz, ± 1.2 dB 4 GHz $< f \leq 6$ GHz, ± 2.0 dB

plitude measurement problems. Readers desiring additional information are referred to a forthcoming NBS Technical Note entitled "Spectrum amplitude—Definition, generation and measurement" by J. R. Andrews and M. G. Arthur.

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Present Capabilities of the NBS Automatic Pulse Measurement System

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***Abstract*—In 1972, NBS began development of an Automatic Pulse Measurement System (APMS) consisting essentially of a minicomputer-controlled wide-band sampling oscilloscope. The objective of the work was to produce a fast general purpose pulse waveform acquisition and processing instrument with spectral capability in the frequency range dc-18 GHz. The purpose of this paper is to report the highlights of work done on the APMS from early 1975 to present.**

The measurement applications of the APMS now consist of both publicly offered calibration services and in-house experimental measurements. In the first category, calibration services are available for the following physical parameters: a) Impulse generator spectrum amplitude; b) Wide-band coaxial attenuation/gain; c) Pulse generator transition time.

Still in the experimental stage are measurements involving reflection coefficient and impedance, group delay, pulse distortion, and wide-band antenna characteristics.

I. INTRODUCTION

IN 1972, NBS began development of an Automatic Pulse Measurement System (APMS) consisting essentially of a minicomputer-controlled wide-band sampling oscilloscope. The objective of the work was to produce a fast, general purpose pulse waveform acquisitio and processing instrument with spectral capability in t frequency range dc-18 GHz. A number of papers have bee written about the APMS [1]–[3]. The purpose of this pap is to report the highlights of work done to date, to descri the present capabilities of the APMS, and to suggest t areas where future efforts should be directed.

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II. APMS DESCRIPTION

Fig. 1 is a simplified block diagram of the APMS. T sampling oscilloscope is a commercially available unit th has been modified to allow either stand-alone or con puter-controlled operation. It should be noted that th type of oscilloscope is not a real time instrument. Rathe it acquires one voltage versus time point of the measure waveform per waveform occurrence. Thus only repetiti waveforms may be observed. The advantage of this sam pling scheme over conventional real time oscilloscopes the large amount of available bandwidth. Whereas con ventional oscilloscopes are presently limited in bandwidt to below 1 GHz, the effective bandwidth of the samplin oscilloscope used in the APMS is about 18 GHz.

When the sampling oscilloscope is switched to com puter-controlled operation the oscilloscope is connecte