Amplitude Frequency Response Measurement: A Simple Technique

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***Abstract*—A simple method is described to combine a modern function generator and a digital oscilloscope to configure a setup that can directly measure the amplitude frequency response of a system. This is achieved by synchronously triggering both instruments, with the function generator operated in the "Linear-Sweep" frequency mode, while the oscilloscope is operated in the "Envelope" acquisition mode. Under these conditions, the acquired envelopes directly correspond to the (input and output signal) spectra, whose ratio yields the amplitude frequency response. The method is easy to configure, automatic, time-efficient, and does not require any external control or interface or programming. This method is ideally suited to impart hands-on experience in sweep frequency response measurements, demonstrate resonance phenomenon in transformer windings, explain the working principle of an impedance analyzer, practically exhibit properties of network functions, and so on. The proposed method is an inexpensive alternative to existing commercial equipment meant for this job and is also an effective teaching aid. Details of its implementation, along with some practical measurements on an actual transformer, are presented.**

***Index Terms*—Frequency response amplitude and phase, impedance analyzer, normal and envelope acquisition mode, sweep frequency measurement, transformer diagnostics.**

I. Introduction

KNOWLEDGE about the amplitude frequency response of a practical system is required for various purposes, such as system identification and characterization, diagnostics, developing functional models, design, and so on. Typically, the measurement takes several hours to complete when done manually by sweeping the frequency of the input sinusoid in discrete steps and recording the system's response. Nowadays, commercial equipment meant for this job requires only a few minutes. However, this equipment is often expensive and not so common in all laboratories. To alleviate this problem, an automatic, fast, and easy-to-implement approach for measuring the amplitude frequency response (i.e., the transfer or driving-point function) of a system is described.

The frequency response is a function that algebraically relates the response of a system and the excitation in the Laplace domain. Characterization of a system by its frequency response (quantified by gain/amplitude and phase) is a preferred choice since it affords certain advantages over time-domain representations, such as in system modeling, analysis and design, and monitoring and diagnostics.

Although the frequency response can be measured either in the time or the frequency domain, from a practical standpoint, it is advantageous to carry out these measurements in the frequency domain. This is because, in the frequency domain, problems arising due to low signal-to-noise ratio (SNR) during impulse waveform acquisition, nonideality of the input impulse (i.e., it not being an ideal Dirac-delta pulse), and aliasing are naturally circumvented. Moreover, features such as averaging and low-pass filtering can be used to an advantage in the frequency-domain approach. It is not, however, as straightforward in the time-domain approach. The only drawback of this approach is that a lot of time is required to complete the measurements when done manually, although this has recently been resolved.

Of the two components of the frequency response, it is general practice to neglect phase data (despite being aware of its importance) and retain only the gain/amplitude response data. This is somewhat analogous to disregarding zeros in comparison to poles. This practice may have arisen because it is generally difficult to interpret phase data, compared to amplitude data. The prevalence of this practice is a spur to devising a rapid means of measuring the amplitude response.

There are several diagnostic tests on a transformer. The frequency response measurement is one such test, which is useful in ascertaining the mechanical integrity of its windings [1], [2]. This is a typical case in which the amplitude frequency response is preferred. Observation of any deviation between two subsequently measured amplitude frequency responses implies a possible mechanical deformation/displacement of the winding. Not only does the measurement have to be repeated for each phase and all windings, but also a fine frequency resolution is desirable to resolve the fine-structure of the frequency characteristic and also enable detection of very small deviations, if any. Naturally, these requirements imply an increased measuring time. Hence, a technique that can be used to perform this measurement in a time-efficient manner becomes necessary. Although the main objective of the paper is to describe the construction of an impedance analyzer using a function generator and digital oscilloscope, it incidentally also qualifies as an effective teaching aid. A few typical examples are listed:

1) Explaining the working principle of a sweep frequency type impedance analyzer;
2) Demonstrating electrical resonance in transformers;
3) Demonstrating some properties of network functions.

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II. Measurement Possibilities and Motivation

The simplest approach is manually to apply a sinusoid of known frequency and amplitude to the system. The oscilloscope records the resulting output signal, and its level relative to the input level is a measure of the gain or amplitude response. Additionally, if phase data is also desirable, then the delay between the input and output signal has to be determined at each frequency over the range of interest. Clearly, this is a very laborious task, and several hours would be needed to gather even a small number of data points.

With the recent availability of powerful and affordable function generators and digital oscilloscopes, the above described manual procedure can be entirely automated with the help of a personal computer (PC). Furthermore, most digital oscilloscopes provide built-in facilities to measure peak-to-peak value of waveforms and also the delay between any two selected waveforms. For each frequency step, these values are measured and transferred to a PC. Thus, compared to the manual approach, some reduction in the overall measuring time can be achieved. It was verified by experiments that measurement using this approach would require about an hour to gather data corresponding to 1000 discrete frequency steps. The reported time includes autoscaling of voltage sensitivity and time-base at each frequency, along with a small time-gap (20 ms) intentionally introduced (from the instant of application of the input to the instant of recording the output response) to permit the response to attain its steady-state value, especially when dealing with highly inductive circuits at low frequencies.

In this context, it is appropriate to mention the salient features of the best solution offered by commercially available equipment—for example, the HP 4195A [3], the Wayne Kerr 6500 series [4], the DOBLE M5000 series [5] instruments, and so on. The latter two series of instruments offer customized solutions for performing frequency response measurements on transformers. Users of M5000 series equipment have indicated that about 5–6 min is required to gather 1250 data points (gain and phase), which is certainly noteworthy. However, in the listed equipment, the underlying principle employed is not made known nor is the mode of frequency application specified. For example, it is not clear whether the frequency is incremented in discrete steps or if continuous sweep is employed. Especially when large settling times are involved (e.g., measurements in the lower frequency regions of a transformer), knowledge of how the input frequency is varied becomes essential. Hence, there is a need to disclose this information. There is perhaps some time-saving achieved by the use of customized hardware (avoiding the use of a separate oscilloscope for data acquisition and its subsequent transfer at each step), by which peak/RMS of input and output and delay between the waveforms are directly measured and stored in local memory. At the end of the measurement, the gain and phase are displayed as a function of frequency. As can naturally be expected, such customized equipment is expensive and hence not easily affordable in all laboratories. Therefore, the main objective of this paper is to illustrate a simple, easily configurable, inexpensive, and time-efficient technique to automatically measure the amplitude frequency response of a physical system. This was the prime motivation. After describing the underlying principle, sample measurements are presented. The proposed technique in its present form can be employed to characterize any physical system operating in the linear region.

III. Principle of Proposed Method

The proposed method employs a function/arbitrary waveform generator and a digital oscilloscope and essentially consists of the following three steps:

1. An arbitrary waveform generator is set to operate in the "Linear-Sweep" mode.
2. This signal is fed to the test system.
3. A digital oscilloscope is set to record both the applied input and the system's response in the "Envelope" acquisition mode.

Under the above conditions, the "envelope" of the input and output will directly correspond to their respective spectra [6], whose ratio will yield the amplitude frequency response.

The function generator, operated in the "Linear-Sweep" mode, outputs a sinusoid of known amplitude and gradually increasing frequency. The rate of increase of frequency has to be kept low compared to the largest settling-time of the physical system. Setting the sweep-duration to the maximum permissible value is one way to ensure this criterion. This requirement would enable the output response to attain a steady-state value before a significant change in frequency occurs. Under these conditions, the envelope of the response will be very nearly the same as that obtainable with a constant frequency input sinusoid. Hence, there is a need to keep the rate of increase of frequency as small as practicable.

The "Linear-Sweep" sinusoid is fed to the test system. The input excitation and response signals are connected to the two channels of a digital oscilloscope, which is operated in the "Envelope" acquisition mode. In this acquisition mode, the oscilloscope operates at the ADC's highest sampling frequency, irrespective of the time-base (or time/div) setting [7] and captures only the envelope of the input and output instead of the complete waveform. Since the measurement of transfer function of a transformer is usually done in the range spanning from 1 kHz up to about 2 MHz, the sampling frequency being used should be high enough (typically > 50 MSamples/s) to capture the fine-structure of the transfer function accurately as well as to avoid aliasing problems. At the end of the sweep, data corresponding to the envelopes of input and output spectra are displayed and stored in the oscilloscope memory.

An example of this principle is illustrated in Fig. 1(a) and (b). A signal when captured in the "Normal" acquisition mode will store all the sample points to represent the entire signal, whereas the same signal when captured in the "Envelope" acquisition mode stores only the maxima and minima, in each acquisition cycle. Under these conditions, the end-points of the horizontal axis on the oscilloscope will correspond to the initial and final frequencies of the "Linear-Sweep." Using this information together with knowledge of the number of data points acquired, the frequency index/axis can be separately determined. Hence, the synchronous triggering of both of these devices (as explained in the next section) is essential to establish the frequency index correctly. A false or delayed trigger of the

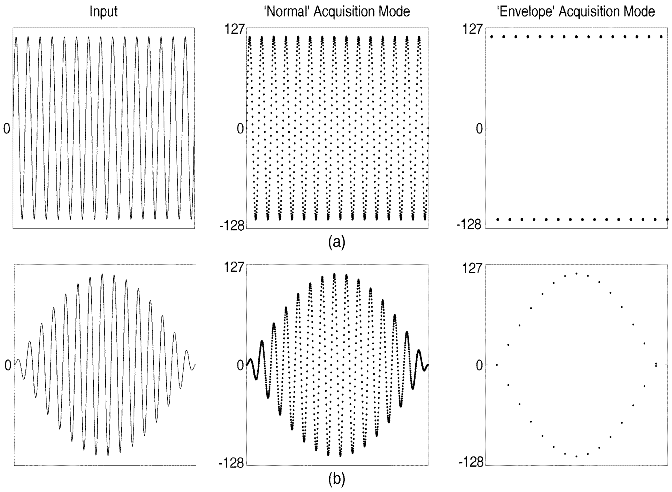

Fig. 1. Comparison of data acquisition in “Normal” and “Envelope” mode for (a) sinusoidal input and (b) amplitude modulated input.

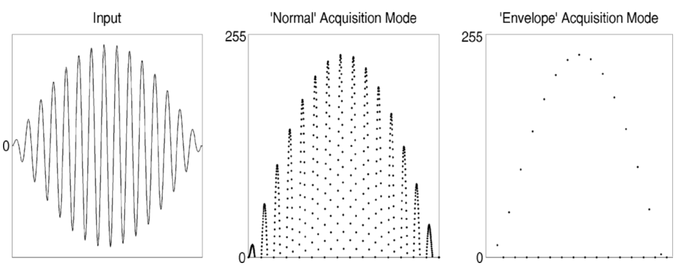

Fig. 2. Signal acquisition with negative half intentionally clipped.

oscilloscope with respect to the function generator will lead to a misaligned frequency index.

In a majority of the cases, the system response is symmetrical with respect to the polarity of the input signal. Therefore, it is sufficient to display only one half of the input and output corresponding to excitation and response. This can be achieved by intentionally clipping the negative part of the waveform, thereby not only enabling better utilization of the vertical resolution of the digital oscilloscope, but also avoiding information redundancy. This aspect is illustrated in Fig. 2, wherein a higher vertical resolution accrues in comparison to that achievable in the corresponding subplot in Fig. 1(b).

IV. Experimental Setup

The function generator, the oscilloscope, and the test system are connected as shown in Fig. 3. Additionally, the “Trigger out” of the function generator is connected to the “Ext Trigger in” option of the oscilloscope. This ensures synchronized operation. It is advisable to set the function generator to output the selected signal with maximum amplitude and zero dc offset (to ensure highest possible SNR). This signal is fed to the test system, as well as to one channel of the oscilloscope, which is taken as reference. From the front panel, the function generator and oscilloscope are set to operate as follows.

A. Arbitrary Waveform Generator

- Signal – Sine

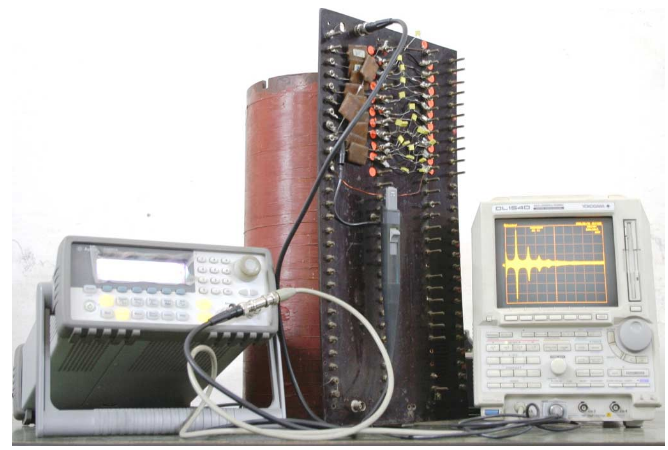

Fig. 3. Test setup for the proposed method (Note: Neutral current spectra displayed on oscilloscope screen).

- Mode – Linear sweep
- Start and end frequency – user-defined (say, 1 kHz to 1.001 MHz)
- Sweep duration – Set to maximum (500 s)
- Amplitude – Set to maximum possible, zero dc-offset
- Trigger – Manual, with Trigger-out option “ON”
- Output impedance – Low or high (i.e., 50 Ω or 1 MΩ)

B. Digital Oscilloscope

- Channel 1 – Reference signal
- Channel 2 – Test system response (either voltage or current)
- Voltage range – Set to $\sim 90\%$ of full scale deflection
- Acquisition – Envelope (in some cases also termed as “peak-detect”)
- Time/div $-$50 s/div (so as to display 500 s)
- Trigger – Normal and External
- Input coupling – ac
- Trigger coupling – ac

Setting the function generator and digital oscilloscope as described above, the oscilloscope remains “armed” and waits for the trigger event to occur (the “*Waiting for trigger*” caption is displayed). Subsequent to the initiation of the “manual” trigger on the function generator, the operation of the two instruments becomes synchronized. At the end of the sweep-duration, both the input and output envelopes are displayed on the screen. (*Note: The oscilloscope display remains blank during the period of the sweep*). It is necessary to choose the times/div setting on the oscilloscope such that it equals the product of number of divisions and times/div so that a direct correlation between the displayed data and frequency axis can be correctly established.

To illustrate the principle of the proposed method, an 8-bit oscilloscope was used. However, when transfer functions have to be compared or used as a base-case (fingerprint) to draw inferences and fault diagnosis, such as in the impulse testing of power transformers, use of a 10-bit or better waveform digitizer is recommended [8], [9].

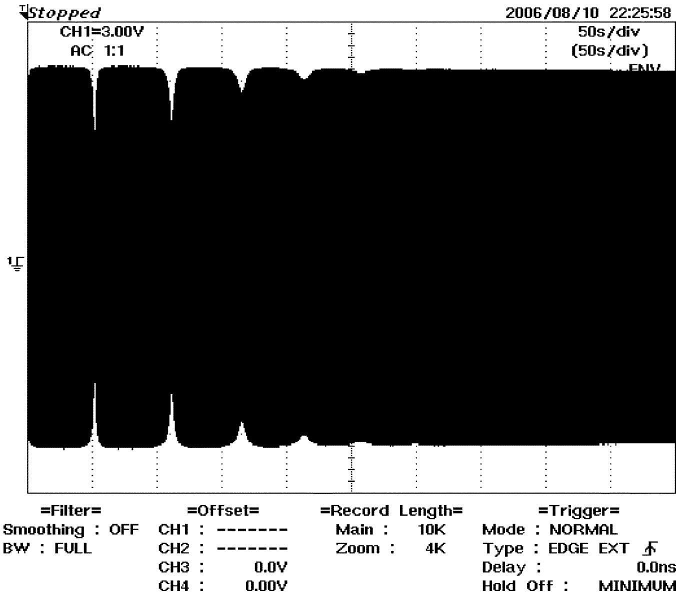

Fig. 4. Linear-sweep voltage spectra displayed on oscilloscope, recorded in envelope acquisition mode (voltage dips illustrate loading effect due to resonance).

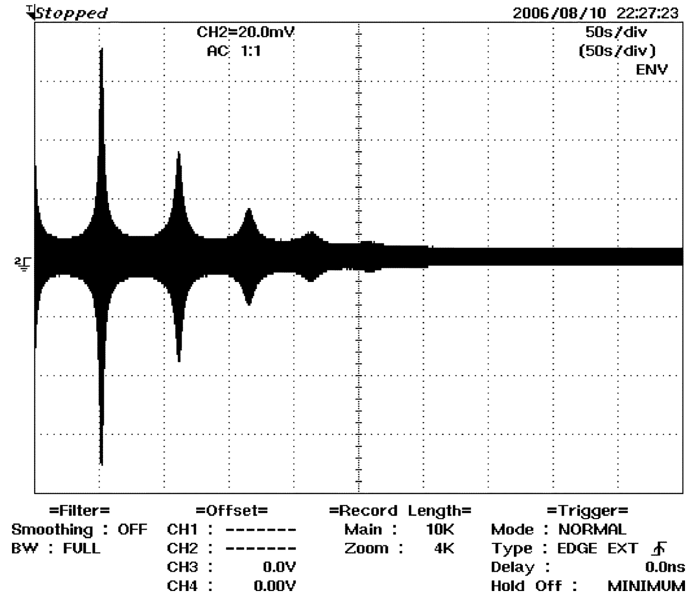

Fig. 5. Neutral current spectra (corresponding to input in Fig. 4) displayed on oscilloscope, recorded in envelope acquisition mode.

V. Experimental Results

To evaluate the performance and time-efficiency achievable by the proposed method, the amplitude frequency response was measured on a transformer model coil (shown as the test system in Fig. 3) and thereafter on an actual transformer. The term transfer function (defined for linear time-invariant systems) is the ratio of the spectrum of the output to spectrum of the input. In what follows, the term transfer function (TF) refers to the ratio of the neutral current spectrum to the input voltage spectrum (i.e., the transfer admittance) of the transformer. Sample measurements of this quantity will be presented. Likewise, any other network function can also be measured. In all experiments, the input sweep-signal amplitude is set to output the maximum amplitude (20 V_{PP}) and the sweep frequency range set to 1 kHz–1.001 MHz. A wideband and sensitive current probe (bandwidth of 120 Hz–60 MHz, and sensitivity 2 mA/1mV) was used to measure the neutral current (i.e., the current flowing from the neutral terminal to ground) on Channel 2. The digital oscilloscope used supported a memory of 10 000 data points per channel. Therefore, each envelope will consist of 10 000 data points (5000 points for each polarity), which in turn implies a frequency resolution of 200 Hz (i.e., 1 MHz/5000).

Sample results from measurements made on a transformer model coil are initially presented. Figs. 4 and 5 show the envelopes corresponding to the excitation (input) and the neutral current (output) as a function of frequency, respectively. In each of these displays (Figs. 4 and 5), the data points corresponding to the two polarities are joined by a line, and hence they appear dark. If interpolation is set to "OFF," then only the positive and negative parts of the envelope will be observable, as in Fig. 1.

Although the function generator produces a constant amplitude sweep signal (on no load), because of the loading effect (which is significant at resonant frequencies), the input voltage dips, and this is seen as cusps in Fig. 4. Corresponding to each of

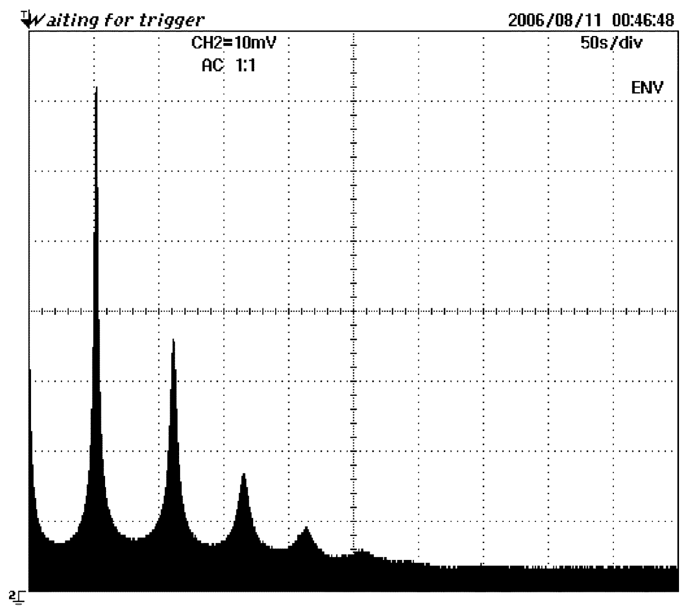

Fig. 6. Positive half of the envelope of neutral current spectra (Note: Ground ref is set to bottom of screen, and the voltage is twice as sensitive).

these cusps, a peak in amplitude is observed in Fig. 5, denoting natural frequencies (or poles) of the transformer model coil. In both these figures, the symmetry of the envelope about the horizontal axis can also be clearly noticed. Invoking this property, ground or reference levels of both the channels are positioned at the bottom of the display, which artificially increases the vertical resolution. Imposing this condition, Fig. 5 would look like Fig. 6, from which it can be observed that the finer details of the spectrum are now better resolved.

Transferring data corresponding to the two envelopes into a PC can be easily achieved, and subsequently, a ratio of the two quantities can be computed to obtain the transfer function. The transfer function is shown in Fig. 7(a), and it contains 5000

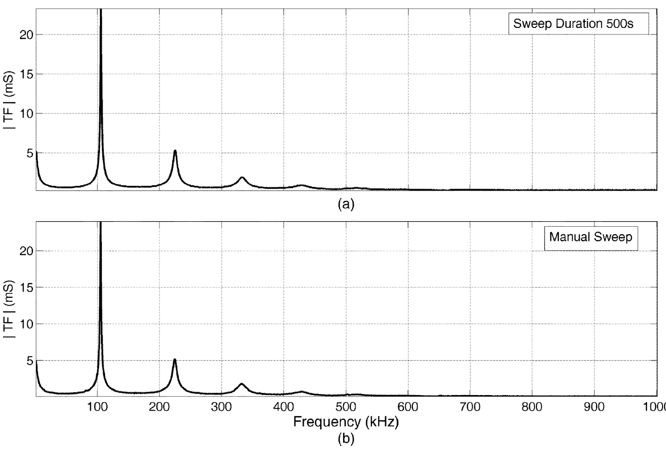

Fig. 7. Transfer function of a transformer model coil. (a) Proposed method, sweep duration of 500 s. (b) Manual sweep.

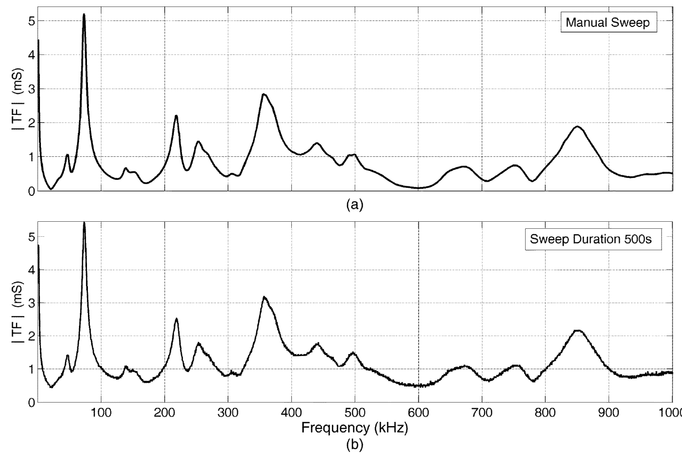

Fig. 8. Amplitude frequency response of actual transformer. (a) Manual sweep. (b) Proposed method sweep duration of 500 s.

data points (or 200-Hz resolution). This frequency resolution achieved is good enough, even for fault detection purposes on actual transformers. The natural frequencies (or poles) of the system are clearly evident from this plot. To establish the correctness of the proposed approach, the transfer function amplitude response was also gathered by the manual method (1000 points), and the resulting transfer function is shown in Fig. 7(b). The close degree of the match validates the proposed method.

Next, measurement of transfer function was performed on a single-phase, 6.9 kV/11 kV (used for the surge arrestor operating-duty test) transformer by both the manual and the proposed method. The linear-sweep was applied to the 11 kV winding, and the remaining windings were shorted and connected to ground. Measurement was carried out with coaxial cables connected in the three terminal configuration [10]. The sheath of each coaxial cable is connected to the guard terminal. The TF obtained from the manual method consisted of only 458 points, whereas the TF resulting from the proposed method contains 5000 points; as a result, some finer aspects appear more pronounced in the TF plot. The results are presented in Fig. 8, and the degree of match (correlation index 0.98, manual sweep data interpolated) is observed to be reasonably good.

The experiments were repeated with sweep durations of 200 and 100 s in order to ascertain the influence of sweep duration on the measured transfer function, if any. The results are shown in Fig. 9. A comparison of these plots to that in Fig. 8(b) shows that they are very similar (the correlation index is 0.99 and 0.99, respectively), implying that even a 100-s sweep duration is more than sufficient for the system under consideration.

It should be noted that when measurements are done manually, the vertical sensitivity of the oscilloscope is adjusted each time to the required range, and hence the noise superimposed on the amplitude response is very low. However, the same cannot be achieved in the proposed approach since the voltage sensitivity cannot be dynamically changed to match the signal level being recorded. Because of this, natural frequencies with higher damping (or lower amplitude) in the TF will tend to have increased noise levels. This can be observed by an inspection of the two subplots in the frequency region between 500 to 800 kHz, in Fig. 9, compared to that in Fig. 8(a). However, this can

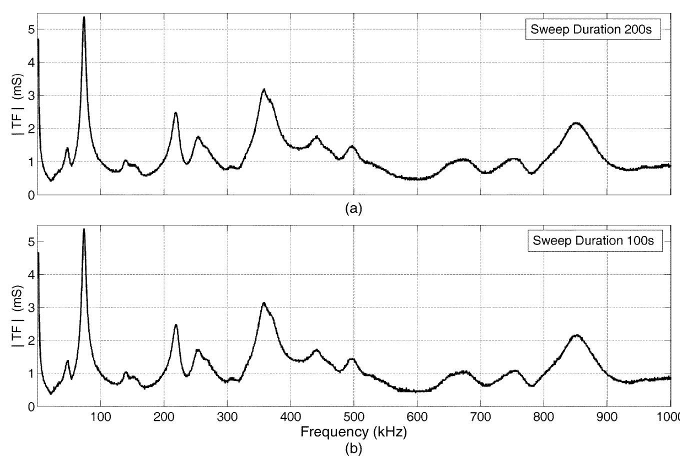

Fig. 9. Transfer function measured on an actual transformer by the proposed method with different sweep durations.

be resolved to a certain extent by repeating the measurement in the frequency region of interest with increased voltage sensitivity. An initial coarse-run can provide an idea of the expected amplitude in a given frequency range, which can later be used to set a suitable voltage scale for the channel. Fig. 10 shows parts of the same transfer function acquired in four different frequency regions, as four separate measurements (each measurement was done with a 500-s sweep duration). The transfer function thus measured (shown in Fig. 10) can be compared with that in Fig. 8(a). It emerges that the transfer function measured in this manner is obviously superior (in terms of SNR, amplitude, and frequency resolution) to those in Figs. 8(b) and 9.

Although several measurements have been made employing the proposed method, for brevity, only a few sample results have been presented here. In fact, this approach has now become a default procedure for recording transfer or driving-point functions within the authors' research group.

VI. Implementation and Learning Experience Assessment

The proposed method to measure the driving-point or transfer function of a circuit/system was discussed and demonstrated

TABLE I
STUDENTS' ASSESSMENT ON THE USE OF PROPOSED TECHNIQUE

Sr. No.	The proposed technique …	Agree %	Neutral %	Disagree %
1.	… is easy to configure and understand.	73	10	17
2.	… can be used to measure driving-point function, transfer function and so on.	66	14	20
3.	… can be useful to observe resonance, settling time phenomena.	60	30	10
4.	… can be used to measure the phase vs. frequency response.	07	13	80

TABLE II
ON COMPARISON OF MANUAL SWEEP METHOD AND PROPOSED TECHNIQUE

Sr. No.	Parameter	Manual Sweep			Proposed Technique		
		Low (%)	High (%)	Neutral (%)	Low (%)	High (%)	Neutral (%)
1.	Complexity	20	70	10	74	23	03
2.	Accuracy	27	53	20	33	54	13
3.	Time involved	16	71	13	67	23	10
4.	Signal-to-noise ratio	23	54	23	54	23	23

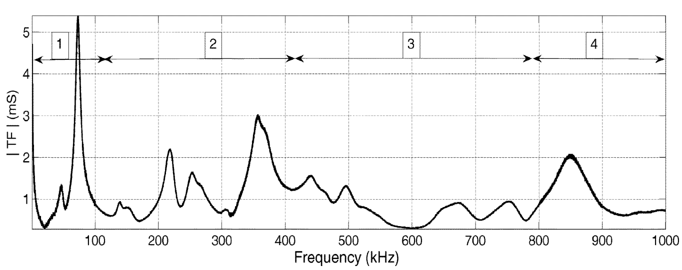

Fig. 10. Segmented frequency sweep.

in a laboratory session of a fourth-semester, graduate-level circuit analysis course. A class of 30 students was initially taught about network functions, characterization techniques (time and frequency domain) and analysis. The features of the digital oscilloscope and signal source were highlighted, and their advantages and disadvantages with respect to their analog counterparts were discussed. Thereafter, experiments were performed in groups of five by a manual sweep and by the proposed technique on a model transformer winding. The students' experience was elicited on various learning aspects, and their responses are summarized in Tables I and II. The students were then informed about the wide range of possible uses of this technique in analog electronics (e.g., filter design), instrumentation and measurement courses (e.g., the impedance analyzer), and so on. Additionally, this method has been introduced at the Master's level in two courses, viz. High Voltage Power Apparatus (3:0 credits) and High Voltage Testing Techniques (2:1 credits). Students have found the method to be very beneficial in understanding the subtle aspects of sweep frequency response measurements, resonance and settling time phenomena in transformers, and also in learning about the intricacies of operation and use of a modern network analyzer (employed by power utilities in their regular monitoring and diagnostic work). Since the proposed method is easily configurable by the student, s/he gets hands-on experience and also is better placed to estimate the influence of various parameters on the measured quantities.

VII. DISCUSSION

The suitability of the proposed method was clearly demonstrated for a transformer model coil as well as on an actual transformer. Some salient features of the proposed method are enumerated.

- The experimental results show a reasonably good match between the transfer function measured using the manual method and the proposed "Linear-Sweep" method, thus demonstrating the suitability of the proposed method. Furthermore, it is a simple, easy-to-configure, and automatic procedure that can be easily set up by any individual using available equipment.
- The proposed method yielded 5000 (equally spaced) data points within 500 s, which can be compared to the 1250 data points acquired in about 300 s, using commercial equipment [5]. Thus, the proposed method compares reasonably well with the best commercially available solution.
- The proposed method can yield only amplitude frequency response data since phase measurement is not possible when using the "Envelope" acquisition mode.
- The measurements were repeated several times on the same test system, and the resulting transfer functions were found to be indistinguishable, proving that the suggested approach inherently does not introduce any significant variation in the measured data and, hence, can be considered robust. This feature becomes important when two subsequent transfer functions of a transformer are to be compared to identify and/or detect faults during diagnostic testing.

- No difficulties are foreseen in extending the proposed method for field measurements. Of course, issues such as electromagnetic interference, shielding, suitable cables, and terminations will have to be addressed in the usual manner.
- Although the applicability of the method is demonstrated for a transformer, it can be extended to any linear physical system with suitable checks and considerations.
- The proposed method could be utilized as an educational tool in laboratory classes.

VIII. Conclusion

A procedure to combine a signal generator and a digital oscilloscope to function as an impedance analyzer has been described. The setup is very simple to configure, automatic, cost-effective, time-efficient, and does not require any external programming or control. Employing the proposed method, amplitude frequency response measurements were made on a transformer, and the results demonstrate its practical applicability. Furthermore, the method can serve as a very valuable teaching aid in the laboratory to demonstrate practically to students some aspects of resonance, settling time phenomena in electrical networks (for example, in transformers), properties of network functions, fundamentals of sweep frequency response measurements, and so on. Features afforded by the proposed method compare to those afforded by commercial equipment. Thus, the proposed method can be considered as novel and effective.

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