Fast Balancing Method for an AC Bridge Based on a Novel Phase Matching Technique

Structured Abstract

Purpose: Development of a method of balancing an AC bridge with minimum computation time. The applications envisioned are in power system monitoring and sensing.

Design/methodology/approach: The method is based on a recursive algorithm, first matching the phase followed by that of amplitude. Each phase step requires three samples per steps.Voltage matching is based on halving the range of measured amplitudes in each step, resulting in an n-step recursive algorithm.

Findings: Computation is minimal - only requires 4 phase matching steps for an error of 1^o. Further steps improve on this error. Matching of amplitude is equally fast. The resolution in amplitude is directly proportional to the number of steps. An example and experimental results demonstrate the efficiency of the method.

Research limitations/implications: Balancing of AC bridges in conjunction with automated measurement systems is a fairly complex process requiring either extensive computation or dedicated hardware (tunable devices, microprocessors, etc.). The current method is recursive and very light on computation. This means the method can be used in sensing systems where neither extensive hardware nor computational resources are readily available.

Practical implications: The method has been developed for power line AC impedance sensing as part of a power line monitoring system. It is however a general method that can be used in any AC bridge application.

Originality/value: The methods used as well as the implementation are entirely original. These have been developed as part of a research in instrumentation of power line monitoring.

Index Terms

AC bridge, Balancing, Phase matching, Magnitude matching, High frequency impedance.

I. Introduction

With the development of high sensitivity sensors in areas such as environmental and biological sensors [De Marcellis and Ferri, 2011, Ghafar-Zadeh et al., 2009] and accurate impedance measurement in a variety of fields including power line health monitoring systems based on impedance monitoring of the line in real time[Pasdar and Sozer, 2013], there is a need of fast and reliable impedance measurement techniques. The balancing of AC bridges as part of automated measurement and sensing systems is an important process that has received considerable attention. Although bridges of various forms may be involved, the usual implementation of an AC bridge involves an unknown impedance and the reference impedance in series between outputs of two voltage generators. The fundamental problem is that of adjusting a null condition at the junction of two impedances [Dutta et al., 2001]. Balancing an AC bridge in order to obtain minimum voltage on the middle point has been done previously based on various methods. In [Mantenuto et al., 2014] and [De Marcellis et al., 2013] purely analog methods to balance the

AC bridge for resistive and capacitive sensors are presented. In order to balance the bridge an active tunable resistor is employed. In another work an accurate analog impedance bridge is presented in [Corney, 2003]. A method for measuring low frequency impedance of capacitive sensors based on lock-In detection circuit with a feedback loop is presented in [Marioli et al., 1990]. Analog methods are subjected to offset, noise and re-tuning. To overcome the analog based bridges limitations, digital bridges based on iterative methods have been developed. Such AC bridges can easily be combined with automatic test systems. They also provide advantages in comparison with conventional AC bridges in high accuracy, reproducibility, reliability, and flexibility. In an iterative method, the minimization is done based on a sequence of steps often resulting in very many steps and slow convergence. [Bachmair and Vollmert, 1980, Helbach et al., 1983, Dutta et al., 1987]. The idea of controlling the AC bridge by means of a microprocessor utilizing a least mean square (LMS) adaptive algorithm to balance the bridge was proposed in [Awad et al., 1994, Tarach and Trenkler, 1993]. In [Chatterjee et al., 2007] the accuracy of the AC bridge balancing is improved by employing an intelligent neuro-fuzzy based LMS module. The method adds a synthetic phase offset to improve estimation accuracy for each impedance under measurement. Iterative methods, however, can be very slow due to the delayed response of the network to each step. In some applications it is preferable to use non-iterative methods in which the balancing condition of the bridge is defined based on a sequence of complex computations on a few, accurately sampled data. A non-iterative method is presented in [Zhang et al., 1998] intended to speed-up the controller based on the Fourier coefficients of an out-of-balance voltage from the bridge. The method is based on complex computations and accurate samplings and requires a complex DSP core. In [Das et al., 2010] a non-iterative method to balance the AC bridge based on trigonometric formulas is proposed. In this method the balance parameters are computed analytically. The technique has four stages of measurement to compute bridge balance without iteration. An automated synchronous sampling based RLC bridge system is given in [Overney and Jeanneret, 2011]. The method is based on samples taken by a high resolution analog to digital converter and computation of a discrete Fourier transformation (DFT) on different subsets of measured signals. In [Surdu et al., 2010] a method to measure an unknown impedance based on AC bridge is presented. The method is based on generating of the signal, having digitally controlled magnitude by the summing of the signals with controllable phases. The phases of the signals are linearly changed. In some other works using relaxation oscillator is suggested to measure capacitive sensors [Nihtianov et al., 2001, Islam et al., 2012]. Based on this method the output frequency is linearly related to the capacitive unbalance of an active bridge. Existing methods were deemed either too complex or too slow and hence the proposed method attempts to circumvent these shortcomings. The presented method is based on a simple step by step algorithm for minimization of voltage, based on phase matching followed by an n-step division algorithm for the minimization of amplitude. In each step in the phase minimization, the algorithm samples the phase at three points and estimates the range in which the minimum phase resides thus narrowing the range in each step. Four steps are sufficient for an accuracy of 1 degree, but of course, higher accuracy is possible with additional estimation steps. Implementation is very simple since the only computation required is the comparison of three amplitudes. Minimization of amplitude is done by simple division of the possible voltage range into two sub-ranges and identification of the half-range in which the minimum resides as input to the next step.

The Phase shift generated by pre-amplifiers and filters used in the bridge do not have effect on the performance of the matching procedure. The maximum errors in phase and amplitude are indicated and results based on simulation and on measurements are given to show the applicability of the method.

II. FAST AUTO BALANCE BRIDGE

The AC bridge structure treated here is shown in Fig. 1. The device under test (DUT) is denoted as Z and is the subject of the measurement whereas R is a fixed resistance (or, in a more general case, a fixed impedance). The voltages V_1 and V_2 are injected and controlled to obtain a minimum voltage at the mid-point.

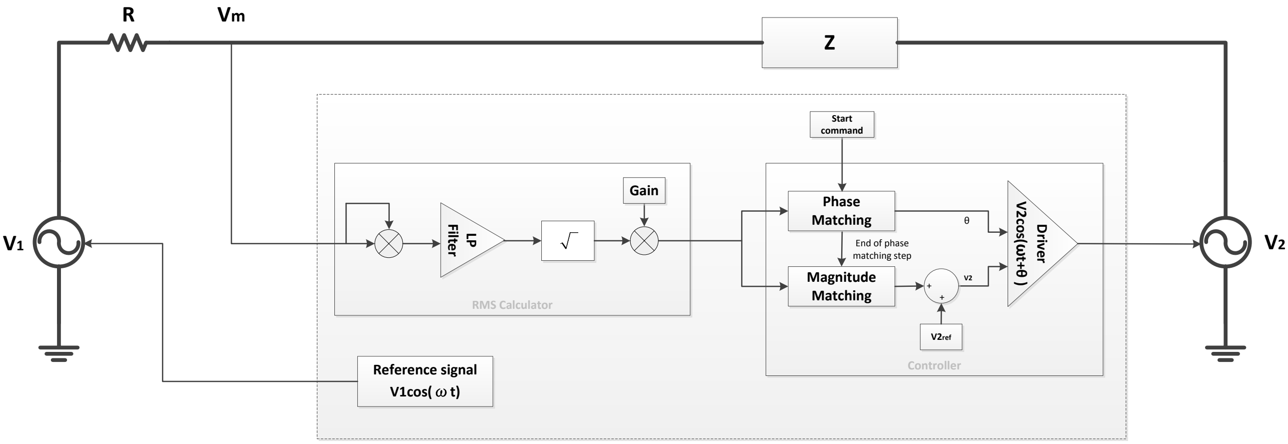

Figure 1: Auto balance bridge block diagram.

Injected voltages are defined as $v_1 = V_1 \cos(\omega t)$ and $v_2 = V_2 \cos(\omega t + \theta)$. The phase difference between the two voltages is θ. V_1 is kept constant while V_2 and θ are adjusted independently, to obtain a minimum in the voltage at the middle point of the bridge (V_m). Based on the phase difference and the combination of the two voltages, the voltage at the middle point in phasor domain is:

$$V_m = \frac{v_2 R}{R+Z} + \frac{v_1 Z}{R+Z} \tag{1}$$

where the unknown impedance is defined as:

$$Z = Z_a + jZ_b \tag{2}$$

By substituting (2) in (1) the middle point voltage is written as:

$$V_m = \frac{V_2 R}{R+Z}(\cos\theta + j\sin\theta) + \frac{V_1}{R+Z}(Z_a + jZ_b)$$

It is possible to express V_m as

$$V_m = f(R, Z)V' \tag{3}$$

where $f(R, Z)$ is a complex function of the DUT's impedance and the fixed resistor and V' is a function of the voltage sources as well as bridge impedances and expressed as

$$V' = \underbrace{V_2 R\cos\theta + V_1 Z_a}_{real} + \underbrace{j(V_2 R\sin\theta + V_1 Z_b)}_{imaginary} \tag{4}$$

The magnitude of V' is:

$$|V'| = \sqrt{V_2^2 R^2 + V_1^2 |Z|^2 + 2V_1 V_2 R(Z_a\cos\theta + Z_b\sin\theta)} \tag{5}$$

Because the other bridge impedances are constant, it is sufficient to minimize V'.

III. CONTROL ALGORITHM

Minimizing the voltage at the middle point of the AC bridge is achieved by setting V_1 to a fixed amplitude and zero phase and adjusting V_2 and θ using the dedicated controlling approach described next to minimize the voltage V_m at the midpoint. The minimization is performed in two sequential stages. The first matches the phase of v_2 to minimize the voltage in (5). The second minimizes the magnitude of V' by setting the magnitude of v_2. We describe first the phase matching algorithm followed by the voltage minimization algorithm.

A. Phase Matching

In the phase matching stage V_m is minimized with a minimum number of samples and steps. The purpose is to find the phase angle θ that will minimize V'. During this part of the algorithm, the amplitude of v_2 is kept constant. V' may be written in a much simpler form as

$$|V'(\theta)| = \sqrt{a + b\cos\theta + c\sin\theta} \tag{6}$$

where a, b and c are constants defined based on V_1, V_2, R and Z. The three voltage samples are taken at three equally spaced phase angles for each step, which are defined as

$$\begin{cases} V'(1,i) = V'(\theta_i) \\ V'(2,i) = V'(\theta_i + \frac{band_i}{2}) \\ V'(3,i) = V'(\theta_i + band_i) \end{cases} \tag{7}$$

where θ_i is the base phase for the i^{th} step and $band_i$ is the phase searching band for the i^{th} step.

In the first step, the range between 0° and 360° needs to be considered for the search. The voltage measurement is sampled at 0°, 120° and 240°. The three voltage samples are compared and depending on the relations between them a mode is defined. There are six possible modes defined based on three voltage measurements, as shown in Table I. The condition associated with each mode narrows the searching band to 60°.

Table II lists the 6 modes and their corresponding phase shift $(shift_i)$ required in step i. This phase shift defines the lower limit of the phase angle that will minimize the middle point voltage. The upper limit is $shift_i$ plus

Table I: Definition of modes in the first step.

Mode	Samples relation
1	$V'(3,1) > V'(2,1) > V'(1,1)$
2	$V'(3,1) > V'(1,1) > V'(2,1)$
3	$V'(2,1) > V'(3,1) > V'(1,1)$
4	$V'(2,1) > V'(1,1) > V'(3,1)$
5	$V'(1,1) > V'(3,1) > V'(2,1)$
6	$V'(1,1) > V'(2,1) > V'(3,1)$

the span of a mode. The net effect of the first step is to narrow the search to a 60° range between $shift_i$ and $shift_i + 60°$.

Table II: Definition of phase shift for each step.

Mode	6	5	2	1	3	4
$shift_i$	$3seg_i$	$2seg_i$	seg_i	0	$-seg_i$	$-2seg_i$

The base phase for step 2 is defined based on the first step base phase and the corresponding phase shift due to the first three samples mode. The i^{th} step base phase for $i > 1$ is defined as:

$$\theta_i = \theta_{i-1} + shift_{i-1} \tag{8}$$

For $steps > 1$, $band_i$ and seg_i are defined based on the following recursive formulas:

$$band_i = seg_{i-1} \tag{9}$$

$$seg_i = \frac{band_i}{4} \tag{10}$$

where seg_i is the phase range, defined with respect to the related modes in the i^{th} step; in the first step $seg_i = 60°$.

In the first step, $\theta_1 = 0$ and $band_1 = 240°$. In each subsequent step, $i > 1$, three samples are taken within the range, specifically; one at the starting base phase θ_i, the second in the middle of the range $(\theta_i + band_i/2)$, and the third at the end point of the range $(\theta_i + band_i)$. The three sampled voltages $V'(1,i)$, $V'(2,i)$ and $V'(3,i)$ are compared with each other. There are four possible relations between the three voltage measurements as shown in Table III.

Based on the method shown, the phase matching error after n_θ phase matching steps is:

$$phase\ error = \frac{60°}{4^{n_\theta - 1}} \tag{11}$$

The required number of samples to perform the n_θ steps is $2n_\theta + 1$.

Table III: Definition of modes in the $step > 1$.

Mode	Samples relation
1	$V'(3,1) > V'(2,1) > V'(1,1)$
2	$V'(3,1) > V'(1,1) > V'(2,1)$
5	$V'(1,1) > V'(3,1) > V'(2,1)$
6	$V'(1,1) > V'(2,1) > V'(3,1)$

B. Magnitude Matching

At the end of the phase matching stage, the amplitude of the middle node voltage is the minimum possible value that can be obtained by adjusting the phase. The phase of the v_2 signal at this stage is θ_{min} which satisfies the minimum value of (5). θ_{min} is found as:

$$\theta_{\min} = \tan^{-1}(\frac{Z_b}{Z_a}) \tag{12}$$

by substituting (12) in (4), $|V'|$ at the end of the phase matching procedure is:

$$|V'(\theta_{\min})| = \sqrt{V_2^2 R^2 + V_1^2 |Z|^2 + 2V_1 V_2 R(Z_a \cos(\theta_{\min}) + Z_b \sin(\theta_{\min}))} \tag{13}$$

The above relation can now be simplified as

$$|V'| = |V_2 R + V_1 |Z|| \tag{14}$$

There will be two samples for each step, which are defined as follows

$$\begin{cases} V'(1,i) = V'(V_{\min}(i)) \\ V'(2,i) = V'(V_{\max}(i)) \end{cases} \tag{15}$$

where $V_{\min}(i)$ and $V_{\max}(i)$ are the minimum and maximum values of V_2 for the i^{th} step. For the first step the minimum and maximum voltage are defined as:

$$\begin{cases} V_{\min}(1) = Vd_{\min} \\ V_{\max}(2) = Vd_{\max} \end{cases} \tag{16}$$

where $Vd_{\min}$ and $Vd_{\max}$ are the minimum and maximum achievable voltage the hardware can produce for V_2.

There are three different trends for the voltage samples based on the relationship between them. The following three different scenarios can occur in each step:

$$\begin{cases} V_{\min}(i) < V_2 < \frac{V_{\max}(i)}{2} : if\ V'(V_{\min}(i)) < V'(V_{\max}(i)) \\ \\ V_2 = \frac{V_{\min}(i) + V_{\max}(i)}{2} \quad : if\ V'(V_{\min}(i)) = V'(V_{\max}(i)) \\ \\ \frac{V_{\max}(i)}{2} < V_2 < V_{\max}(i) : if\ V'(V_{\min}(i)) > V'(V_{\max}(i)) \end{cases} \tag{17}$$

The magnitude matching steps start by obtaining two samples indicated as $V'(V_{\min}(1))$ and $V'(V_{\max}(1))$. The whole range of possible voltages is divided into two regions. Comparison of the magnitudes of the two samples indicates the region where the minimum amplitude occurs. In the next step the specified region will be divided again into two regions. In each step, the size of the region that contains the minimum point becomes smaller. The sampling range for $steps > 1$ is defined as follows:

$$\begin{cases} \left\{ \begin{array}{l} V_{\min}(i) = V_{\min}(i-1) \\ V_{\max}(i) = \frac{V_{\min}(i-1)+V_{\max}(i-1)}{2} \end{array} \right\} : & if\ V'(V_{\min}(i)) < V'(V_{\max}(i)) \\ \left\{ \begin{array}{l} V_{\min}(i) = V_{\min}(i-1) \\ V_{\max}(i) = V_{\max}(i-1) \end{array} \right\} : & if\ V'(V_{\min}(i)) = V'(V_{\max}(i)) \\ \left\{ \begin{array}{l} V_{\min}(i) = \frac{V_{\min}(i-1)+V_{\max}(i-1)}{2} \\ V_{\max}(i) = V_{\max}(i-1) \end{array} \right\} : & if\ V'(V_{\min}(i)) > V'(V_{\max}(i)) \end{cases} \tag{18}$$

The magnitude matching error after n_v steps in the magnitude matching procedure is defined as

$$Magnitude \quad error = \frac{Vd_{\max}}{2^{n_v}} \tag{19}$$

At the end of the magnitude matching process, the magnitude of V' will be the minimum achievable voltage magnitude based on the number of matching steps. The required number of samples to perform the n_v steps is $n_v + 1$. The search algorithm is summarized in Fig. 2.

The technique presented above can be implemented as simple as an analog RMS calculator along with controllable voltage generators controlled by a microcontroller, or digitally calculating the RMS value based on one complete period of the signal. Calculating the RMS value limits the speed of the matching process which is a function of the permissible balancing error and the frequency of measurement. The minimum time needed to balance the AC bridge is expressed as

$$t_{req} = \frac{2\left\lceil 1.66 \log \frac{60^\circ}{\Delta\theta_{per}} \right\rceil + \left\lceil 3.32 \log \frac{Vd_{\max}}{\Delta V_{per}} \right\rceil + 3}{f_{bal}} \tag{20}$$

where $\Delta\theta_{per}$ is the permissible phase error in degrees, ΔV_{per} is the permissible magnitude error, and f_{bal} is the AC bridge frequency.

C. Signal Matching Error

By substituting the relative magnitude and phase errors in (5) the maximum error at the middle point can be expressed as

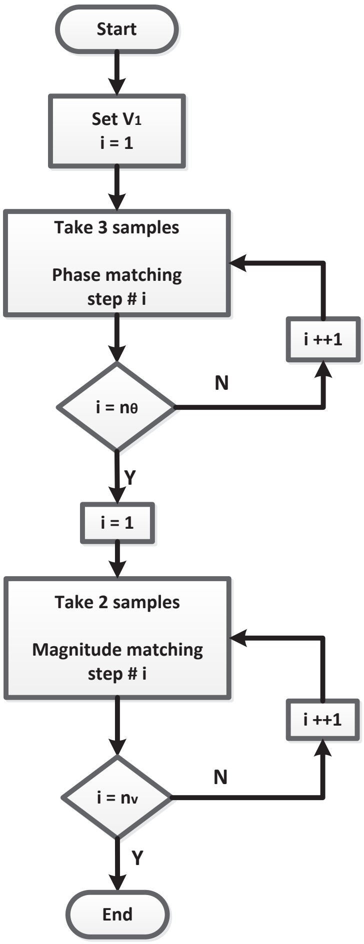

Figure 2: Magnitude and phase matching procedure flow chart.

$$|V_m|_{err} = \frac{\sqrt{(\Delta V_2)^2 R^2 + V_1^2 |Z|^2 + 2V_1 R \Delta V_2 f(n_\theta)}}{|R+Z|} \tag{21}$$

where n_v is the number of magnitude matching steps and n_θ is the number of phase matching steps. The error of the V_2 due to the magnitude matching procedure and $f(n_\theta)$ are written as

$$\Delta V_2 = (\frac{V_1 |Z|}{R} \pm \frac{V d_{\max}}{2^{n_v}}) \tag{22}$$

$$f(n_\theta) = Z_a \cos(\theta_{\min} + \frac{60^\circ}{4^{n_\theta - 1}}) + Z_b \sin(\theta_{\min} + \frac{60^\circ}{4^{n_\theta - 1}}) \tag{23}$$

The resultant magnitude of the voltage at the end of the phase and magnitude matching procedure is dependent on the number of steps of the matching process, network impedances, as well as the upper band of the voltage that the hardware can produce at v_2.

IV. CASE STUDY

The performance of the bridge balancing method for a device under test is investigated next. In the tested network $V_1 = 1\ V$, $R = 100\ \Omega$, $DUT = 100\Omega + 10nF$ and the frequency of operation is $100kHz$. The performance of the phase and magnitude matching method are first simulated. The matching speed and accuracy is then compared with the LMS method. In the second step the bridge is set up in the laboratory and the phase and magnitude of the voltage sources are controlled with a programmed algorithm in Labview. The Labview uses 15 steps to search for the phase and magnitude of v_2 in order to decrease the amplitude of the middle node voltage's. The impedance of the device under test at the frequency of operation is:

$$Z = 100 - j159.15 \tag{24}$$

The magnitude of V' vs. the magnitude and phase of v_2 is shown in Fig. 3.

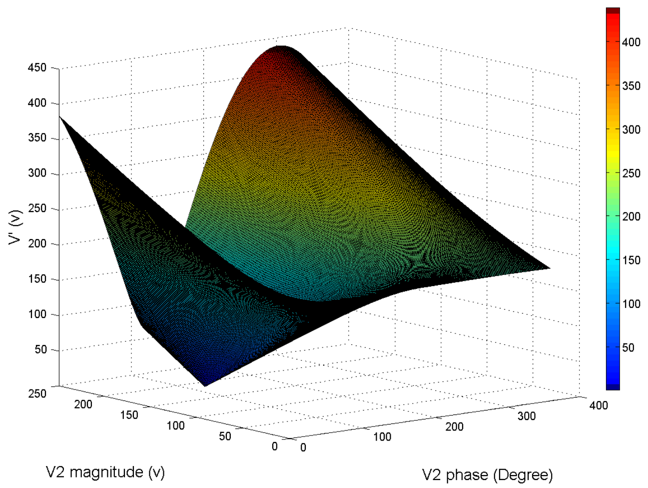

Figure 3: The magnitude of V' vs. the magnitude and phase of v_2.

Based on the pattern of the magnitude of V' shown in Fig. 3 there is a unique solution for the minimum magnitude of V'.

A. Simulation

In order to find the proper phase of v_2, 8 steps (n_θ) are performed in the phase matching procedure; similarly 8 steps (n_v) in the magnitude matching procedure are used to find the proper magnitude of v_2. The phase upper and lower searching bands vs. number of phase matching steps is shown in Fig. 4. At the end of each step the difference between the upper and lower phase searching bands is decreased significantly. As shown, after 5 steps the accuracy of the phase matching procedure is better than $1°$.

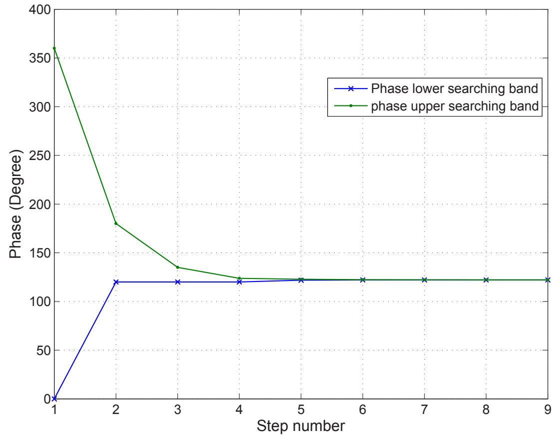

Figure 4: Phase matching procedure vs. number of steps.

The voltage of the upper and lower searching band vs. number of steps is shown in Fig. 5. At the end of each step the difference between the upper and lower magnitude searching band is decreased again. As shown, after 8 steps the accuracy of the magnitude matching procedure is better than $10\ mV$. The magnitude and phase of v_2 at

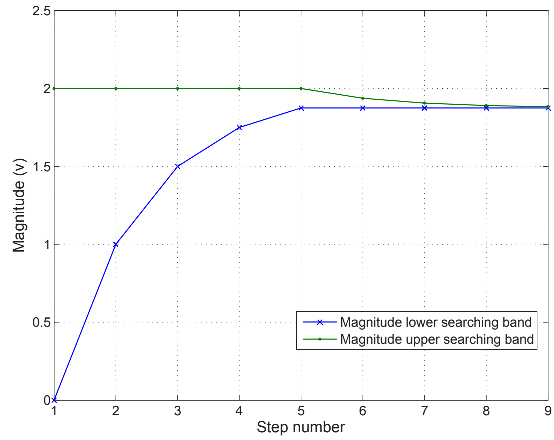

Figure 5: Voltage matching procedure vs. number of steps.

the end of the phase and magnitude matching procedure are found to be $1.878\ V$ and $122.142°$.

The ratio of the time needed to balance the bridge to the period of the bridge signal vs. permissible phase and voltage errors is shown in Fig. 6

In order to show the performance of the method compared to other matching methods, the magnitude of V' vs. number of matching steps for the method as well as the general LMS matching method are shown in Fig. 7. For the proposed method the total number of phase matching and magnitude matching steps is 16. For the general LMS matching method the total number of matching procedure is selected to be 16 as well. Based on the results shown the proposed method has less perturbation compared to the general LMS matching method; moreover the magnitude

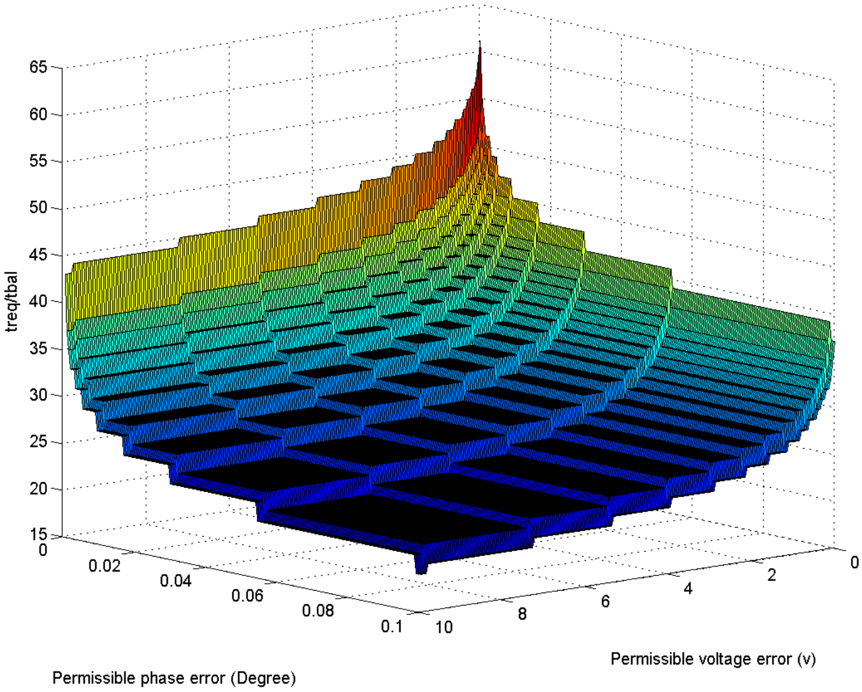

Figure 6: Ratio of the time needed to balance the AC bridge to the bridge signal period vs. permissible phase and voltage errors.

of V' at the end of the matching process is $0.068\ V$ while this magnitude for the general LMS matching method is $0.959\ V$, which shows better matching accuracy for the current method with the same number of matching steps.

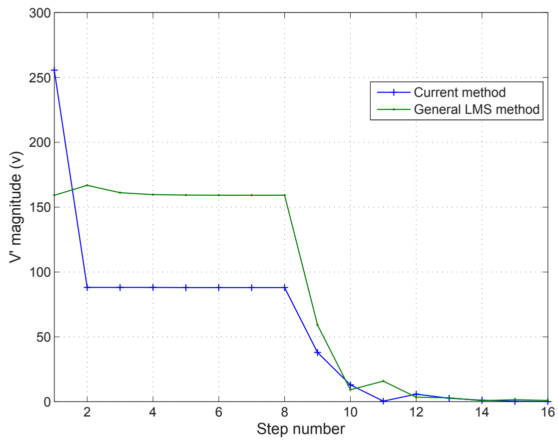

Figure 7: Magnitude of V' vs. number of steps for the current method and the LMS matching method.

In contrast with the non-iterative methods presented in [Zhang et al., 1998, Das et al., 2010] that rely on complex computation, the presented method is based on simple comparisons between measured samples. Computation-less

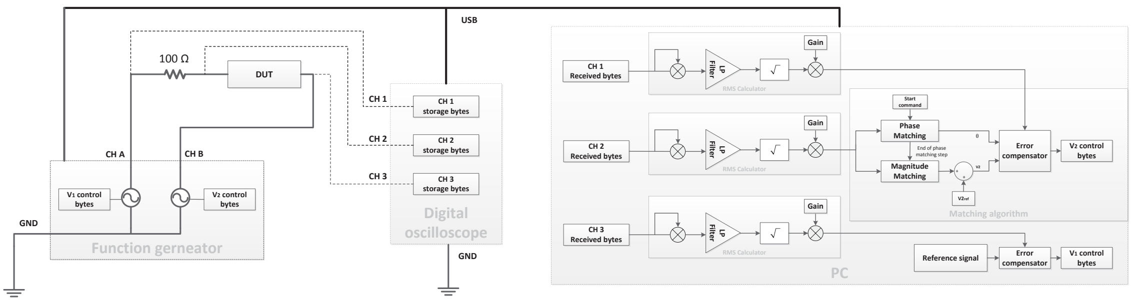

Figure 8: Test setup block diagram.

phase machining technique decreases the effect of quantization error of the processor. Compared with the iterative methods, the present method is able to match the phase with accuracy of $1°$ in just 4 steps, which is faster than the method presented in [Overney and Jeanneret, 2011]. Since the method introduced in this work eliminates the need of linearly sweeping the phase to find the balancing point of the bridge, it can be used in [Surdu et al., 2010] to balance the bridge in fewer steps.

B. *Laboratory test*

The performance of the matching method was also tested based on the balancing bridge set up in the laboratory. The block diagram of the test set up is shown in Fig. 8. v_1 and v_2 are generated by a programmable function generator. The amplitude and phase of the generated signals are controlled by an algorithm in Labview. The amplitude of the two generated signal and the middle node are measured with a digital oscilloscope. The amplitude of the middle node is sampled in several steps and the phase and magnitude of the v_2 are set based on the proposed method.

Fig. 9 shows the phase of the upper and lower searching bands vs. number of phase matching steps is shown. At the end of the 4^{th} step of the phase searching procedure the phase of v_2 is found to be $123°$ which is close to the estimated phase based on the simulation.

In Fig. 10 the magnitude of the upper and lower searching bands vs. number of magnitude matching steps is shown. At the end of the 7^{th} step of the magnitude searching procedure the magnitude of v_2 is found to be $1.938V$ which is close to the estimated magnitude based on the simulation.

The magnitude of V_m vs. number of matching steps for the method is shown in Fig. 11. For the proposed method the total number of phase matching and magnitude matching steps is 11. The magnitude of v_m at the end of the matching procedure is $0.0184V$.

V. Conclusion

A novel method for automatic AC bridge balancing was presented, and shown to be fast and efficient. In order to control the AC bridge, novel phase and voltage matching techniques were introduced with very low computational load. In fact, the computation required is trivial. The AC bridge was simulated and implemented. Simulation and

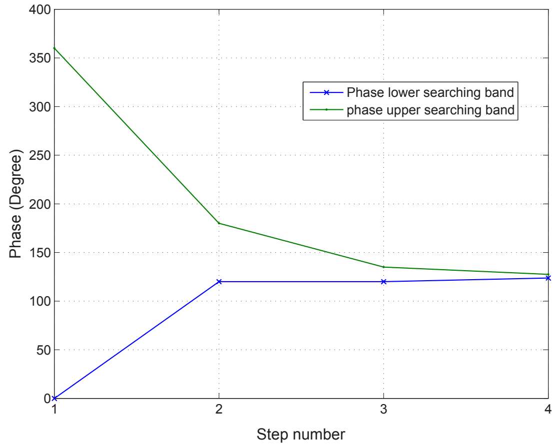

Figure 9: Phase searching bands vs. number of steps.

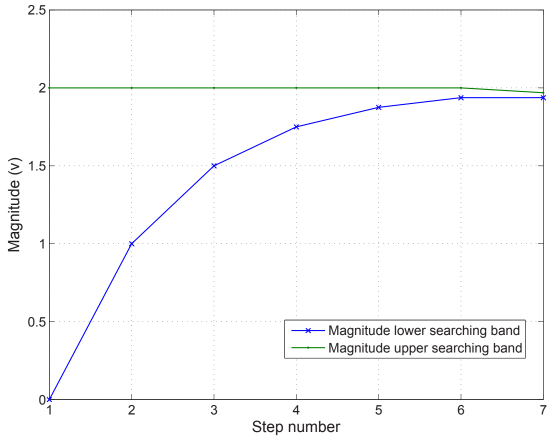

Figure 10: Magnitude searching bands vs. number of steps.

experimental test results compared to the LMS balancing method show the accuracy of the proposed bridge balancing technique. The method is applicable to all AC bridge measurements.

References

S. Awad, N. Narasimhamurthi, and W. Ward. Analysis, design, and implementation of an ac bridge for impedance measurements. *Instrumentation and Measurement, IEEE Transactions on*, 43(6):894–899, Dec 1994.

H. Bachmair and R. Vollmert. Comparison of admittances by means of a digital double-sinewave generator. *Instrumentation and Measurement, IEEE Transactions on*, 29(4):370–372, Dec 1980.

A. Chatterjee, M. Dutta, and A. Rakshit. An intelligent method of impedance measurement employing pso-aided neuro-fuzzy system with lms algorithm. In *Fuzzy Systems Conference, 2007. FUZZ-IEEE 2007. IEEE International*, pages 1–6, July 2007.

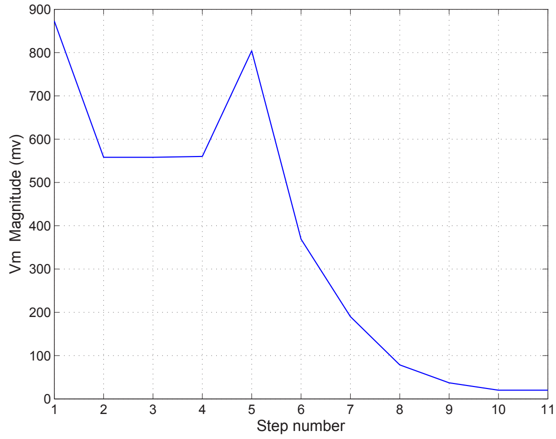

Figure 11: Magnitude of output vs. number of steps for the experimental setup.

A. C. Corney. Digital generator assisted impedance bridge. *Instrumentation and Measurement, IEEE Transactions on*, 52(2):388–391, April 2003.

N. Das, T. Jayakumar, and B. Raj. Noniterative digital ac bridge balance. *Instrumentation and Measurement, IEEE Transactions on*, 59(11):3058–3060, Nov 2010.

A. De Marcellis and G. Ferri. *Analog circuits and systems for voltage-mode and current mode sensor interfacing applications*. Springer-Verlag, New York, USA, 2011.

A. De Marcellis, G. Ferri, and P. Mantenuto. A novel 6-decades fully-analog uncalibrated wheatstone bridge-based resistive sensor interfaces. *Journal of Sens. Actuators B, Chem.*, 189:130–140, 2013.

M. Dutta, A. Rakshit, S. Bhattacharyya, and J. Choudhury. An application of an lms adaptive algorithm for a digital ac bridge. *Instrumentation and Measurement, IEEE Transactions on*, IM-36(4):894–897, Dec 1987.

M. Dutta, A. Rakshit, and S. Bhattacharyya. Development and study of an automatic ac bridge for impedance measurement. *Instrumentation and Measurement, IEEE Transactions on*, 50(5):1048–1052, Oct 2001.

E. Ghafar-Zadeh, M. Sawan, and D. Therriault. Cmos based capacitive sensor laboratory-on-chip: A multidisciplinary approach. *Analog Integr. Circuits Signal Process.*, 59:1–12, 2009.

W. Helbach, P. Marczinowski, and G. Trenkler. High-precision automatic digital ac bridge. *Instrumentation and Measurement, IEEE Transactions on*, 32(1):159–162, March 1983.

T. Islam, A. Gangopadhyay, and Z. Zaheeruddin. An oscillator based active bridge circuit for converting capacitance change into frequency for capacitive humidity sensor. In *Communications, Devices and Intelligent Systems (CODIS), 2012 International Conference on*, pages 480–483, Dec 2012.

P. Mantenuto, A. De Marcellis, and G. Ferri. Novel modified de-sauty autobalancing bridge-based analog interfaces for wide-range capacitive sensor applications. *Sensors Journal, IEEE*, 14(5):1664–1672, May 2014.

D. Marioli, E. Sardini, and A. Taroni. Measurement of small capacitance variations. In *Precision Electromagnetic Measurements, 1990. CPEM '90 Digest., Conference on*, pages 22–23, June 1990.

S. Nihtianov, G. Shterev, B. Iliev, and G. Meijer. An interface circuit for r-c impedance sensors with a relaxation oscillator. *Instrumentation and Measurement, IEEE Transactions on*, 50(6):1563–1567, Dec 2001.

F. Overney and B. Jeanneret. Rlc bridge based on an automated synchronous sampling system. *Instrumentation and Measurement, IEEE Transactions on*, 60(7):2393–2398, July 2011.

A. Pasdar and Y. Sozer. Smart high voltage circuit breaker in overhead power lines for smart grid applications. In *Energy Conversion Congress and Exposition (ECCE), 2013 IEEE*, pages 1118–1123, Sept 2013.

M. Surdu, D. Surdu, and A. Koffman. Precision universal ac bridges with phase controlled dividers. In *Precision Electromagnetic Measurements (CPEM), 2010 Conference on*, pages 347–348, June 2010.

D. Tarach and G. Trenkler. High-accuracy n-port impedance measurement by means of modular digital ac compensators. *Instrumentation and Measurement, IEEE Transactions on*, 42(2):622–626, Apr 1993.

J. Q. Zhang, S. Ovaska, and Z. Xinmin. A novel fast balance technique for the digital ac bridge. *Instrumentation and Measurement, IEEE Transactions on*, 47(2):371–377, Apr 1998.