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Characterization of Current Equalizers for Coaxial Impedance Bridges

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Abstract—In this work, three passive and two active current equalizers designed for use in coaxial impedance bridges are characterized over a wide frequency range. A dedicated measurement circuit is used to determine the current mismatch between the inner and outer currents of the coaxial network. Active equalizers show a reduced current mismatch compared to passive equalizers. However, the resonance behavior measured at low frequency highlights the need for further optimization of active designs.

Index Terms—Bridge circuits, impedance measurement, instrument transformers, measurement techniques.

I. INTRODUCTION

Impedance measurements at the highest level of accuracy are performed by impedance bridges with coaxial networks implementing the four-terminal-pair (4TP) impedance definition [1]. In a coaxial network, the currents in the inner and outer conductors are equal and opposite. This condition may not be fulfilled in an impedance bridge containing multiple meshes, and an imperfect current equalization may cause impedance definition and balance errors, and increased susceptibility to interferences. Therefore, the coaxiality should be ensured by adding a number of coaxial current equalizers (CEs) to the bridge network. These can be passive (PCEs) or active (ACEs) [2], [3]. The basic operation of CEs is analyzed in [4], and the effects of imperfect current equalization are reported in [5], [6] for two specific bridge designs and in [7] for low impedance measurements. However, recent advancements in the development of impedance bridges, aiming at extending operating frequency and impedance ranges, require a more systematic assessment and in-depth analysis of their behavior and non-idealities. To this purpose, we have undertaken a systematic analysis of PCEs and ACEs over a broad frequency range, and the design of a new generation of optimized ACEs. This work reports the first results obtained on PCEs and ACEs employed at METAS (ACEs are also employed at PTB).

II. UNEQUALIZED CURRENTS IN 4TP STANDARDS

Fig. 1(a) shows a simplified representation of a 4TP impedance standard where Z represents the inner impedance element and z_o represents the shield impedance. The 4TP impedance is

$$Z_{4TP} = \frac{V_{HP}}{I_{LC}} \bigg|_{\substack{V_{LP}=0 \\ I_{HP}=I_{LP}=0}} = \frac{V_{HP}}{I_i} = Z + z_o \frac{I_o}{I_i}, \quad (1)$$

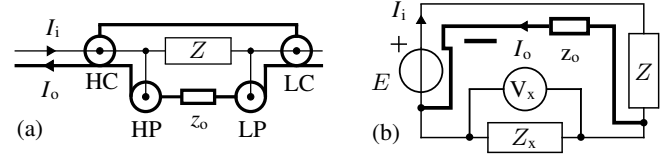


Figure 1: (a) Representation of a 4TP impedance standard. (b) Circuit to measure the current ratio I_o/I_i of current equalizers.

The above shows that Z_{4TP} depends on the current equalization ratio I_o/I_i , and an imperfect current equalization introduces a measurement error. This effect is particularly significant for low-impedance standards, for which z_o can be of the same order of magnitude of Z . Threading a coaxial cable through a high-permeability core makes the inner circuit act as a primary and the outer shield as an almost short-circuited secondary, forcing a current in the outer conductor so that $I_o \approx I_i$. [4].

III. TESTED CURRENT EQUALIZERS

The tested devices are three PCEs and two ACEs. PCE1 and PCE2 have the same core type, with 17 and 16 turns, respectively. PCE3 has 16 turns, but uses a different core type. ACE2 was developed in a European project [8], whereas ACE1 was developed at METAS. Both ACEs follow the topology [4], with an amplifier gain of 3000, a detection winding of 10 turns, and an injection winding of 50 turns. ACE1 employs a different operational amplifier and core type from ACE2. There is also a modified version of ACE1, labeled ACE1b, with a reduced gain of 1000. Each ACE was tested in both active mode (AM) and passive mode (PM). The CEs were modeled by the equivalent circuit of a transformer. The model includes the winding resistance R_{eq} , the equivalent leakage reactance L_{eq} , the core-loss resistance R_c and the magnetizing reactance X_c . These parameters were measured as described in [9] by means of a Keysight E4980AL LCR meter with an excitation voltage of 100 mV from 20 Hz to 500 kHz. The mutual inductance M between the primary (inner) and secondary (outer) windings of the current equalizers was also measured. The parameters measured at 1 kHz are summarized in Table I. The circuit shown in Fig. 1(b) [8] was assembled to measure the current equalization ratio. The voltage E was supplied by a lock-in amplifier, and the voltage E_x was measured using the same lock-in amplifier. The parameters were $E = 100$ mV, $Z = 1$ k Ω , $z_o = 10$ Ω , and $Z_x = 10$ Ω .

Table I: Parameters of CE at 1000 Hz.

CE	M/mH	R_{eq}/Ω	$L_{\text{eq}}/\mu\text{H}$	R_c/Ω	L_c/mH
PCE1	47.6	0.39	1.29	4321	47.3
PCE2	31.0	0.42	1.44	3338	30.9
PCE3	14.1	0.44	1.42	1715	14.2
ACE1 (PM)	20.2	0.54	0.71	780	16.0
ACE2 (PM)	27.3	0.27	0.37	7372	27.2
ACE1 (AM)	6607	0.54	0.70	164409	6268
ACE2 (AM)	9642	0.27	0.36	81093	9317

IV. MEASUREMENTS

Fig. 2 reports the magnitude and phase of I_o/I_i for the PCEs and for the ACEs operated in PM. In the low frequency range the effect of the CEs is limited. At 100 Hz, $|I_o/I_i| \approx 0.9$ for PCE1, 0.8 for PCE2 and ACE2, and 0.6 for PCE3 and ACE1. Between 100 Hz and 1 kHz the current equalization improves rapidly. At higher frequencies the magnitude increases and approaches the equalization. The phase starts at about 0 rad at low frequency, increases gradually to a maximum of about 0.3 rad from 40 Hz to 120 Hz for all devices, and then decreases again at higher frequency. This behavior is consistent with simulations based on the transformer model and the parameters shown in Table I.

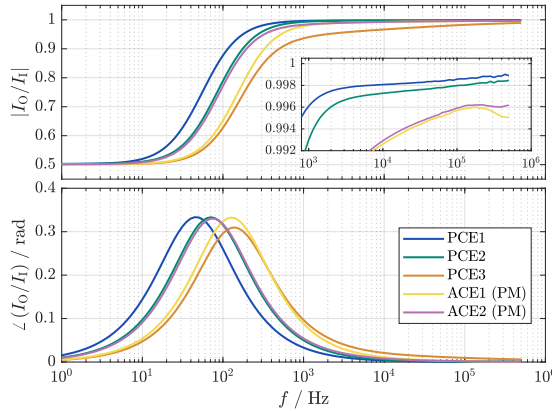


Figure 2: Magnitude and phase of the current mismatch I_o/I_i for PCEs and ACEs operated in PM. The inset shows a zoom of the magnitude around 1 for frequencies above 1 kHz.

Fig. 3 reports I_o/I_i for ACE1, ACE1b, and ACE2. The responses of PCE1 and the non-current equalized case (NCE) are also included as reference. The magnitude of I_o/I_i presents a pronounced peak at 2 Hz for ACE2, reaching a value of approximately 1.9, and at about 18 Hz for ACE1, with a peak of 3. For ACE1b, the peak is reduced to about 2.2 and is shifted to approximately 22 Hz. At 100 Hz the peak of ACE2 essentially disappeared and the magnitude is already close to 1, as shown in the inset. A similar behaviour is observed at 1 kHz for ACE1 and ACE1b. In contrast, PCE1 still shows a magnitude well below 1 in this frequency range, as illustrated previously in Fig. 2. Near the frequencies where the magnitude peaks, the phase approaches $\pi/2$ for ACE2 and about $3\pi/4$ for both ACE1 and ACE1b. Above 100 kHz both ACEs and PCEs shows a similar behavior, with the magnitude

remaining close to 1 (see inset). In this region, even in the NCE case the current mismatch gradually decreases. The increasing inductive impedance of ground loops at high frequency forces the return current to flow progressively on the outer conductor.

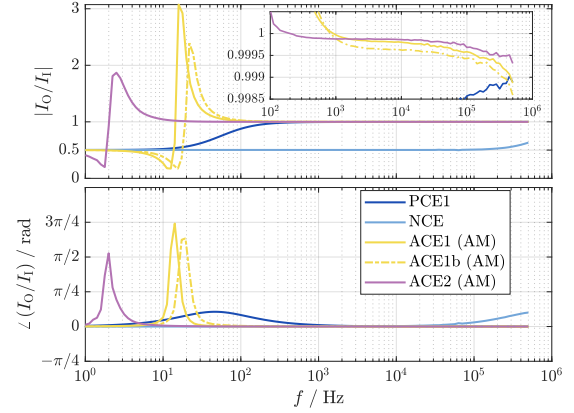


Figure 3: Magnitude and phase of the current mismatch I_o/I_i for NCE, PCE1, ACE1, ACE1b, and ACE2. The inset shows a zoom of the magnitude around 1 for frequencies above 100 Hz.

V. CONCLUSION

Passive and active current equalizers were characterized and tested over a wide frequency range with a dedicated measurement circuit. It has been verified that the frequency response of the passive equalizers can be modeled by a suitable equivalent circuit. At low frequency, PCEs provided only limited current equalization, while ACEs performed substantially better. However, the presence of resonances shows that further work is needed on the design of ACEs. This will be discussed at the time of the conference.

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