A Transformer Flux Balancing Scheme Based on Magnetizing Current Harmonic in Dual-Active-Bridge Converters

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***Abstract*—The Dual-Active-Bridge (DAB) converter transformer flux unbalance, or dc bias, could be a critical issue due to the mismatches of converter circuit parameters and control transients. In this paper, a steady-state flux balancing scheme , based on the second-order harmonic of magnetizing current has been proposed. The relationship between steady-state flux/magnetizing current unbalance and its harmonic contents has been analyzed, with which a new current sensing method and control strategy are introduced. The proposed magnetizing current sensing method can be implemented for both unity and complicated fractional turns ratios, without high sensitivity of dc offset from the analog circuitry. The proposed scheme has been validated with experimental results on 850-V/850-V DAB converters within a system, as well as in an 850-V/6700-V medium voltage DAB unit.**

Keywords—dual-active-bridge converter, flux balancing, DC bias, magnetic saturation

I. INTRODUCTION

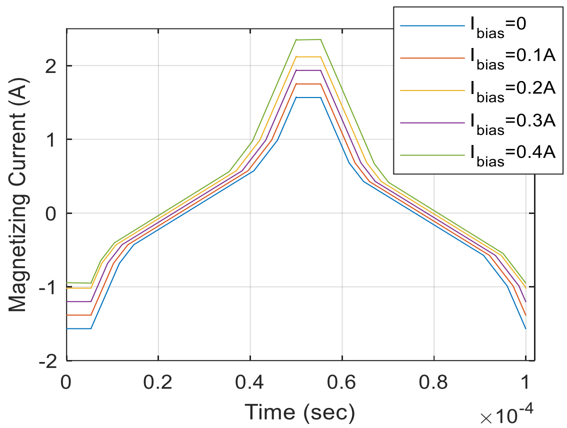
The Dual-Active-Bridge (DAB) converter has been extensively applied in dc microgrids, EV chargers and locomotives to provide galvanic isolation and bi-directional power conversion [1-3]. However, the transformer flux unbalance could become a severe issue, since the device parameter and gate signals delay mismatches might induce volt-second unbalance into the medium frequency transformer (MFT), which has been discussed in [4-6]. The MFT magnetizing impedance usually appears to be small in the low-frequency range, easily accumulating dc bias in transformer magnetizing current and hence saturating MFT or even leading to overcurrent failure of power devices [7].

Many methods have been proposed to balance the transformer flux. A straightforward remedy is to series connect dc-blocking capacitors to the transformer windings, but it will introduce extra weight/volume and loss, especially for high-power DAB. Ref. [8, 9] reported that in zero-voltage switched converters, the volt-second product could be limited by the inherent characteristic of zero-voltage transition (ZVT). It means that the transformer flux can be naturally balanced within the ZVS region thanks to the dead-time effect, but at high switching current and hard switching operation, the effect of dead-time is less or even not effective. In [10-13], the transient flux unbalance due to control transients has been addressed with an intermediate phase-shift or duty-cycle ratio, which, however, cannot affect the steady-state mismatched volt-second product. In [14-16], the steady-state dc-bias of MFT magnetizing current was controlled by directly sensing the winding currents, and [12] proposed a method to measure and control the magnetizing current with one single current sensor. Nevertheless, measuring a small dc component, which is superimposed on a large ac signal, could be challenging due to the dc offset of sensor circuits, and direct measurement of magnetizing current could be hard for an MFT with high-voltage insulation and fractional turns ratio. Ref. [17-19] used additional magnetic and electronic circuits to measure and suppress the unbalance, but the design process with "magnetic ear" could be over-complicated, especially for amorphous and nanocrystalline core MFTs. In [19], a sensor integrated in core was introduced, by measuring a partial core flux the saturation of the transformer core can be detected, and hence controlled. Since the flux unbalance can be also reflected on the magnetostriction, a piezoelectric transducer can be used to detect the flux unbalance and saturation, and hence the flux can be compensated [20].

In this paper, a harmonic-based method to measure and control the MFT magnetizing current is introduced. First, a new method for flux unbalance measurement is discussed in Section II. In Section III, a magnetizing current sensor design that can be used for both unity and fractional turns ratios is introduced. Then, the magnetizing current balancing scheme is proposed and tested in Section IV. In Section V, the proposed scheme has been verified in an 850-V/850-V DAB converter system, and an 850-V/6700-V DAB converter unit. Finally, the conclusion is made in Section VI.

II. FLUX UNBALANCE DETECTION

As has been mentioned in the introduction, multiple steady-state flux unbalance detection methods have been proposed. A straightforward way is measuring the winding currents, and the



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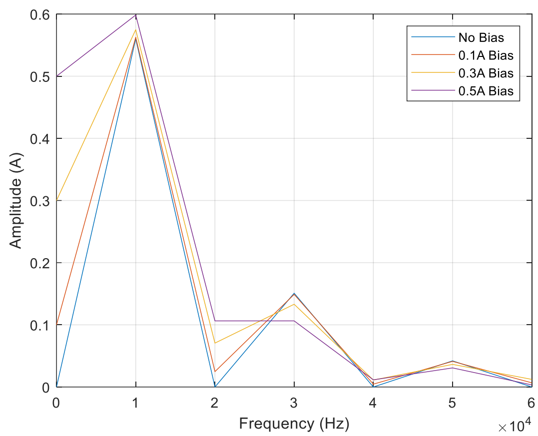

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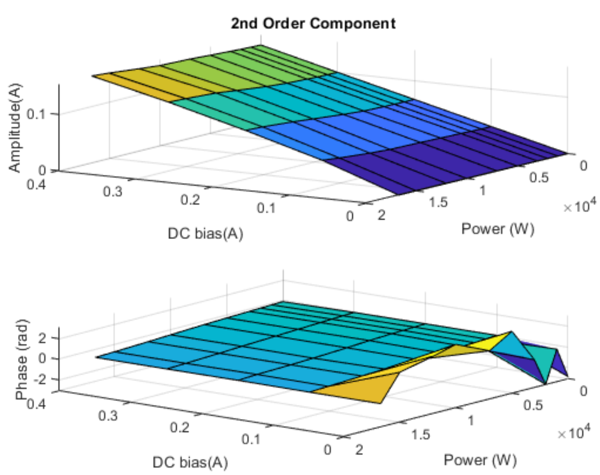

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Fig. 1. Simulation results of MFT magnetizing current with respect to DC unbalance in (a) time domain and (b) frequency domain @ rated condition, and (c) 2nd-order harmonic at different power level.

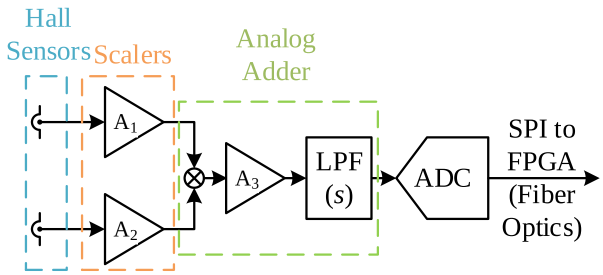
flux unbalance is associated with the dc bias in the weighted sum of the winding currents, or the magnetizing current[14, 15]. Another way is to directly measure the magnetizing current with through-hole Hall sensors [12], as long as the insulation is limited, and the turns ratio is unity or simple fractional. However, due to the inherent offset of Hall sensors and operational amplifier circuits, the dc bias value could be largely impacted by the accuracy of measurement, adding errors in the measurement and control. For instance, the Hall sensors HO 25-P, in the design being discussed, has a maximum offset of 10 mV, generating a dc bias error of ±625 mA in the magnetizing current. That accounts for roughly 30% of the nominal magnetizing current amplitude for the 850-V/850-V transformer discussed in this paper. Moreover, it could not be compensated easily, since the offset may be associated with the previous operational points, and may lead to under- or overcompensated flux and excessive losses.

Advanced magnetic materials with high permeability and low loss can help improve the power density of MFTs, but they can also result in less margin on withstanding volt-second unbalance. The tight margin design leads to higher level of nonlinearity, including saturation and hysteresis features in the flux and magnetizing current, which can introduce more harmonics than the less-compact MFTs. Though most commonly the nonlinearity is undesirable and problematic, the harmonics generated by the nonlinearity can serve as an indication of flux unbalance, since during unbalance the positive cycle and negative cycle are no longer symmetric, leading to more even-order harmonics. Fig. 1 shows a simulation results of a tightly designed transformer with two paralleled amorphous cores of AMCC0125 and rated at 850 V/19 A with unity turns ratio. As shown in Fig. 1(a), the magnetizing current may have harmonics with the change of flux unbalance. From Fig. 1(b), with the FFT calculation, the harmonics could be extracted at the second-order harmonic, even though the signal level is far lower than the dc component, it could be more stable considering the dc offset of the sensing circuit. If the linearity of the circuit is acceptable (e.g. non-linearity smaller than 1%), the harmonic level will be trustworthy. Fig. 1(c) indicates that, regardless of the power transmitted through DAB, the amplitude and phase angle of the second-order harmonic remain unchanged, while a nearly linear relationship between the dc bias and second-order harmonic can be found.

III. MFT MAGNETIZING CURRENT SENSOR

Since for different DAB and MFT designs, the turns ratio is not necessarily unity or a simple fraction number, the direct measurement of magnetizing current with combined winding sensing in [12] is not applicable. Hence, the two winding currents have to be sensed separately, and combined through analog or digital circuits.

The designed sensor board and test results are shown in Fig. 2. In Fig. 2(a), A_1/A_2 denotes the scaler gain for primary and secondary current signals, the ratio of which can be set as close as possible to the transformer turns ratio, with a tolerance at the level of 0.1% by using 0.1% E192 chip resistors. And the output of the amplifiers may have a measuring range of 2.0 p.u. for both sides, to avoid representation and gain selection difficulties in the following step design. Then currents of both sides (for current flowing into the dotted terminal as the positive direction) are summed up by a differential amplifier to extract the



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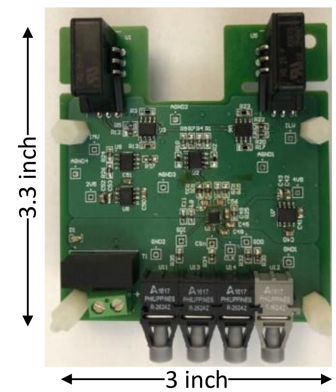

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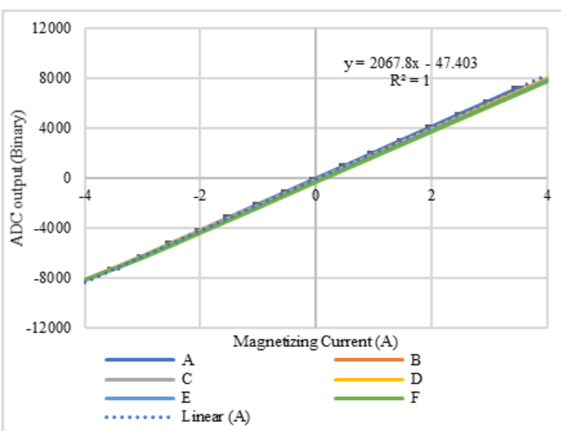

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Fig. 2. (a) Block diagram, (b) photograph, (c) test curve of MFT magnetizing current sensors.

magnetizing current, with a gain A_3 to further magnify the signal. The differential amplifier also serves as an anti-aliasing low-pass filter (LPF) and ADC driver, to filter out the inherent noise of Hall sensor and amplifiers and avoid possible aliasing on the second-order harmonic extraction. The harmonics of the orders higher than Nyquist frequency must be attenuated between the Hall sensors and the ADC, or otherwise, the higher-order harmonics and noise may contaminate the second-order harmonic calculation results. Moreover, thanks to the nature of even-order harmonic distortion canceling for fully differential analog pairs, all the amplification and sampling are implemented with fully differential amplifiers and ADCs, reducing the inherent second order distortion from the analog circuits. To demonstrate the configuration of gains, the parameters of both 850-V/850-V and 850-V/6700-V transformers and sensors are listed in Table. I. Fig. 2(b) shows the magnetizing current sensor for the 850-V/850-V DAB converters, and the calibration test results are shown in Fig. 2(c), indicating that six sensor boards share evident consistency and linearities, without careful effort of calibration, although the dc offset may be different.

TABLE I. PARAMETER COMPARISON FOR UNITY AND FRACTIONAL TURNS RATIOS

	850-V/850-V DAB	850-V/6700-V DAB
Transformer Core	2x AMCC0125	SC2062M1
Core Air Gap	2x 0.13 mm	2x 0.23 mm
Turns Ratio	34:34 (1:1)	34:266 (1:7.824)
Current Rating	19 A/19 A	19 A/2.43 A
Hall Sensors	HO 25-P/HO 25-P	HO 25-P/HO 6-P
Hall Sensors Sensitivities (mV/A)	32/32	32/100
A_1/A_2	3.5/3.5 (2x ADA4941)	3.5/8.765 (2x ADA4941)
A_2/A_1 Ratio with Hall sensitivities	1.0	7.825
A_3	4.975 (THS4531)	4.975 (THS4531)

Then, the magnetizing current can be communicated from ADC to the controller through fiber optics, and the controller FPGA can flexibly determine the sampling and communication rates. Multiple sampling rates have been compared in Fig. 3. From the curve, it can be seen that the window size limits the frequency resolution, and the sampling points determines the Nyquist frequency as well as the amplitude precision. Since only the second order harmonic is used here, the 16-point single cycle window is selected, considering the hardware implementation and accuracy. The currents are sampled at a rate of 16 times of switching frequency, providing 16-point data for downstream fast Fourier transform (FFT).

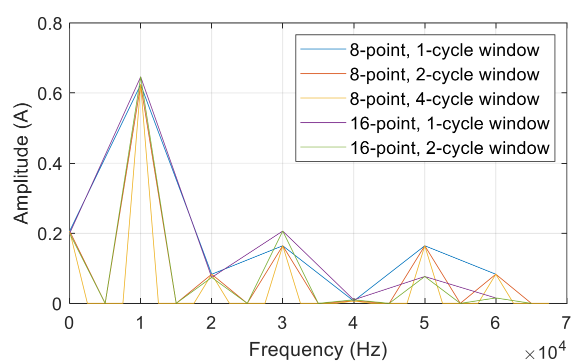


Fig. 3. Comparison of different window size and sampling points for the second order harmonic amplitude.

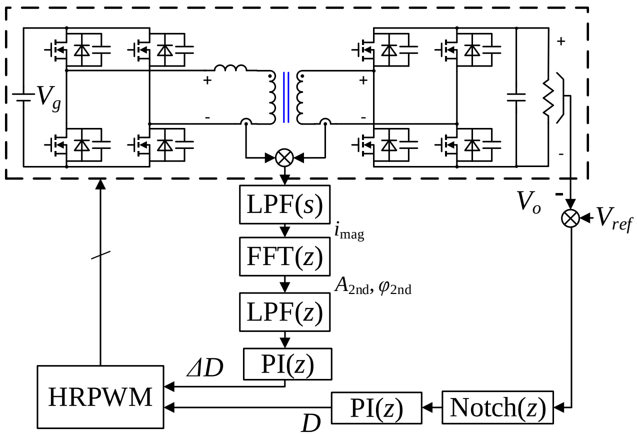


Fig. 4. Control diagram with MFT flux balancing.

IV. Magnetizing Current Balancing Control Scheme

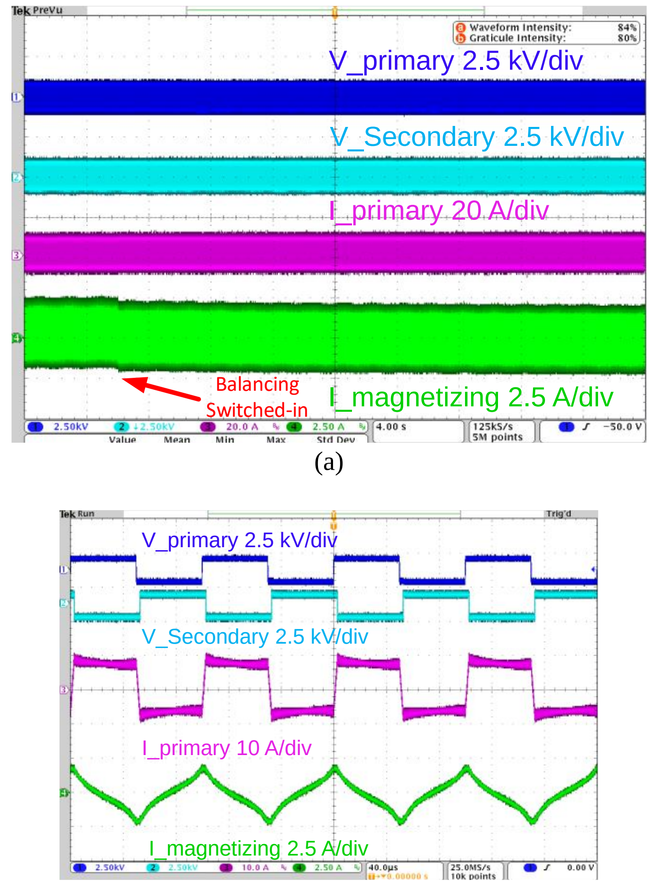
With the MFT magnetizing current sensor design, a second-order-harmonic-based controller has been designed to control the dc bias of the magnetizing current and hence balance the MFT core flux, which is illustrated in Fig. 4. The single phase-shift (SPS) modulation is used, with a switching frequency of 10 kHz, and a resolution of 2.5 ns for PWM modulation. The magnetizing current signal is sampled at 160 ksps, transmitted to the FPGA, and then transformed with a 16-point FFT algorithm in DSP. The amplitude of the second-order harmonic is used to indicate the amplitude of flux unbalance, while the phase angle indicates the polarity of the unbalance. The phase angle should be positively biased when phase angle is positive, while negatively biased for a negative value. Due to high voltage gain of amplifiers and high inherent noise of Hall sensors, the transformed amplitude and phase angle are further filtered with relatively low bandwidth digital low pass filters. Because the objective is to balance the steady-state flux, the low pass filter may not impact the overall control performance.

Similar to [12, 14] with a PI controller, the second-order harmonic of magnetizing current is controlled through a primary or secondary side duty-cycle (or known as inner phase-shift) offset ΔD, generating a dc voltage bias in primary or secondary winding to counterpart the steady-state unbalance in magnetizing current. The transient flux balancing control is also used in modulation scheme as in [12] to avoid the unbalance induced by control dynamics, which can be too high and fast to be restrained by the steady-state balancing.

V. Experimental Verification

With the proposed sensor and control strategy, the hardware test was conducted for verification in both 850-V/850-V DAB converter system and 850-V/6700-V DAB converter unit. By validating the method in 850-V/850-V converters, the basic operation of the proposed method can be verified, especially for the unity ratio case. The 850-V/6700-V DAB converter provides a case for a complicated fractional transformer turns ratio.

In the 850-V/850-V converters, the magnetizing current can be measured with a current probe clamping both the primary and secondary side current. The test results are shown in Fig. 5. From



(a)

(b)

Fig. 5. Test of a single 850-V/850-V DAB unit.

Fig. 5 (a), after the flux balancing control switched into the control loop, the dc bias of magnetizing current changes from 0.35 A to around -0.05 A. And as Fig. 4 (b), the magnetizing current is almost balanced for positive and negative half-cycle, which verifies the control strategy proposed. From the Code Composer Studio user interface for debugging, the measured second-order harmonic value was approx. 0.5 A, and after suppression, the amplitude was approx. 0.35 A, both including the noise from the sensor circuitry, which was estimated as around 0.3 A.

After verifying a single DAB unit. Six DAB converters using harmonic-based flux balancing strategy were installed in a converter system to interface 5-level cascaded H-bridge converter and 850-V dc-link (marked as LV side). The test result is shown in Fig. 6, in which the magnetizing current of DAB unit A2 and B2 were measured, and the CHB side (marked as MV side) transformer current of unit B1 was measured, too. At first, all DAB units were controlled with the flux balancing, and at one time point the flux balancing control were disabled for all the units. It can be seen that from the overall current waveforms that after the flux control being by-passed, the magnetizing currents diverted mainly due to the inconsistency of switch timing and channel resistances of the devices. The difference of symmetry of magnetizing and winding currents can be spotted from the zoomed-in waveforms, too.

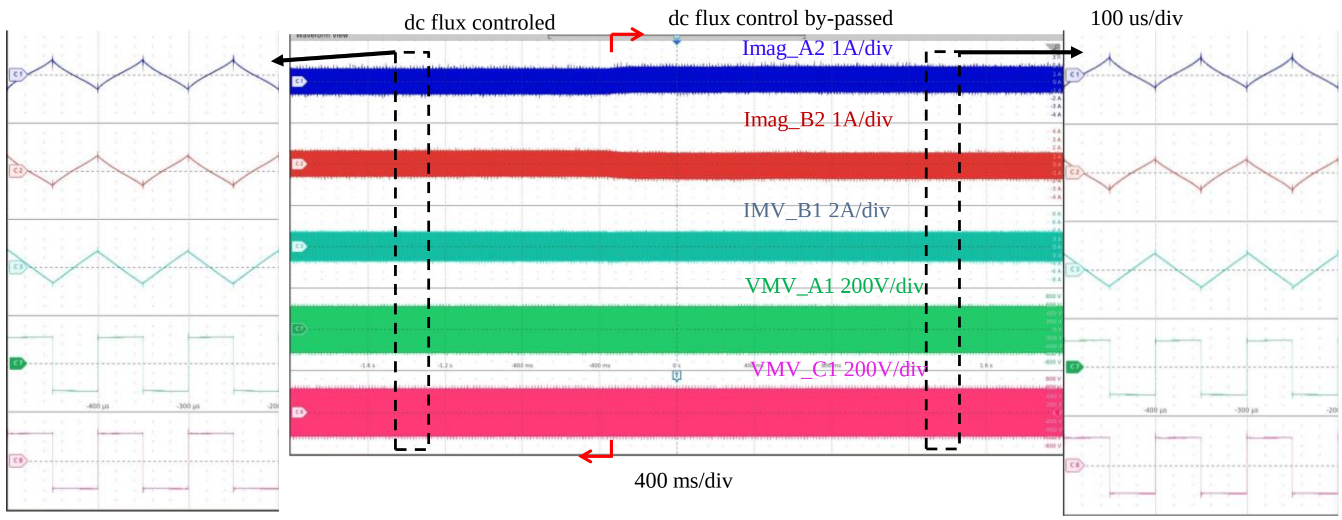
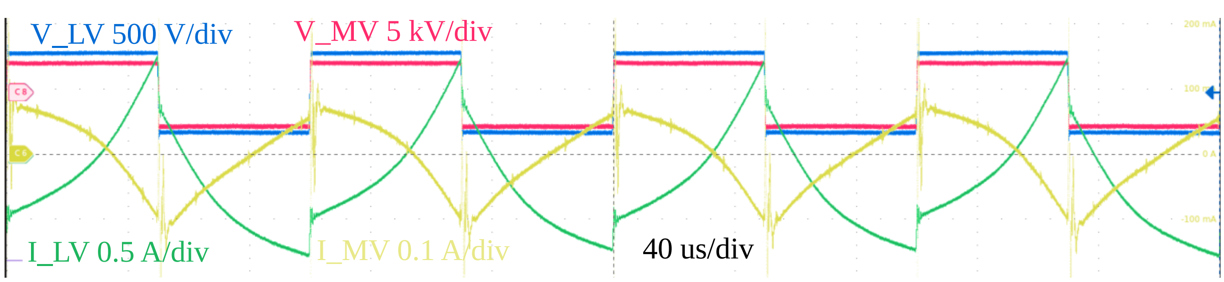


Fig. 6. Test of an 850-V/850-V DABs in a converter system.

Another test has been performed in the 850-V/6700-V DAB converter, with the nanocrystalline core-based 850-V/6700-V rated medium voltage transformer. The sensor parameters have already been shown in Table I, and the compensation duty cycle ΔD was imposed on the medium voltage side. From Fig. 7(a), when the transformer flux balancing control was not enabled, unipolar distortion can be found in both LV and MV winding currents, especially for LV winding current, generating evident second-order harmonic components. After the harmonic-based control being implemented, the dc flux could be gradually adjusted, and from Fig. 7(b), both the LV and MV winding current can be regulated to be more symmetric. Even though the currents were not linear, due to the permeability variation, and the dc bias components from the MV side cannot be measured due to the limited current probe accuracy, the distortion was symmetric for both positive and negative halves, indicating that the core had no significant dc flux bias. Therefore, the proposed method is still valid for fractional turns ratio and DAB transformers.

VI. Conclusion

In this paper, a magnetizing current harmonic-based MFT



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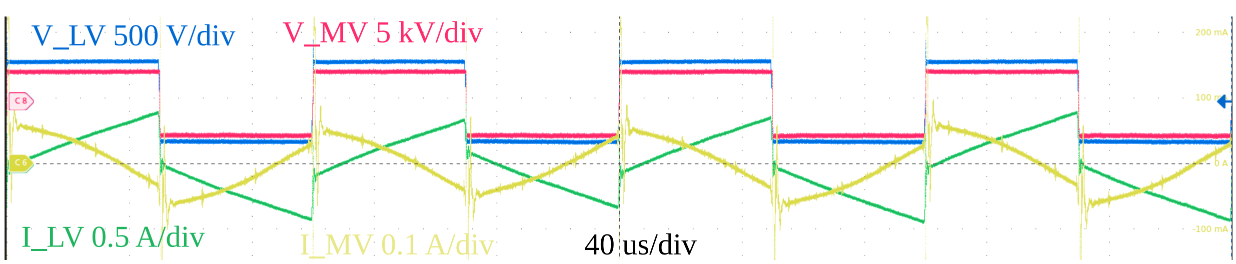

(b)

Fig. 7. Test of an 850-V/6700-V DAB converter (a) without, and (b) with the proposed method.

flux balancing scheme, including both the sensing and control methods, has been proposed. The estimation of the relation of second-order harmonic and dc unbalance has been made, and the sensing circuits, sampling and control strategy have been introduced and implemented. The proposed measurement and control scheme have been utilized in an 850-V/850-V DAB-based converter system, as well as an 850-V/6700-V DAB converter unit. Through the discussion and experimental validation, the proposed harmonic-based flux detection and balancing method is valid for both unity and fractional turns ratio and from low to medium voltage DAB converters, without demanding specific effort for dc offset calibration.

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