DETECTION AND SUPPRESSION OF PARASITIC DC VOLTAGES IN 400 V AC GRIDS

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Abstract. *Grid connected static power converters inject parasitic DC currents due to the offset in current sensing, control imperfections, asymmetries in power switches and other secondary effects. Ever growing number of grid connected converters contributes to an increase of DC bias in AC grids, and this brings the cores of distribution transformers closer to saturation and increases their power losses. This paper provides sensitivity analysis of distribution transformers to the DC bias, and considers solutions for detecting and compensating the parasitic DC components in AC grids. Active compensation methods can be advantageously used in suppressing the DC bias at grid connection point of the power converter. The sensing approach proposed in this paper makes use of saturable ferromagnetic cores and a low cost DSP for signal analysis and processing. Proposed algorithm uses distortion of the magnetizing current of a parallel connected saturable core due to the bias. Experimental results demonstrate the capability for detecting and compensating the bias voltages far below 1 mV in 0.4 kV grids. The paper describes the principles of DC bias detection and it provides the guidelines for the proper design of magnetic components. High precision of the proposed DC bias sensing is thoroughly verified on the experimental setup connected to a 0.4 kV grid.*

Key words: *Power quality, distribution transformers, power converters, dc bias.*

1. INTRODUCTION

DC injection into the low-voltage and medium-voltage AC grids comes mostly from grid connected static power converters. Recent developments in power electronics, electrical drives and distributed generation leads to a large number of static power converters connected to the grid, with the potential to inject a parasitic DC bias into the grid. Static power converters with PWM control can produce AC waveforms with a low distortion factor [1], but they can also introduce parasitic spectral components, including the DC bias. Numerical solutions can be used to reduce the parasitic spectral components [2], but the remaining DC offset cannot be eliminated completely. Therefore, all the transformerless

grid-connected power converters have the potential of introducing a small, parasitic DC offset into the AC grid [3]. Widespread use of electronically controlled electrical drives [4], which are often regenerative, makes the problem even more emphasized. Recently introduced multiphase and multimotor drives [5] are also capable of introducing a parasitic DC bias through the front end converter. Hence, whenever the power interface to the grid is performed through a static power converter, there is a potential of DC bias in AC grids has an adverse effect on the operation of power transformers [6,7]. Adverse consequences are also possible in certain electrical loads [8]. Widespread use of distributed power sources attached to the grid through a power electronics interface, as well as an increased use of active rectifiers in modern electrical speed drives [9] and static power converters [10] emphasizes the problem of DC injection. DC bias currents limits specified by the norms [11] and discussed by international working groups are difficult to measure. Consequential DC bias voltages are even lower due to very low equivalent resistance in AC grids. Therefore, the need emerges to measure DC bias voltages and currents in AC grids with high precision.

DC injection of grid connected power converters is caused by the delay mismatch in gating circuits and imperfections of power switches [12], by the offset in current sensing [13], by DC injection based methods for detecting the stator resistance and temperature in grid-connected AC machines [14], while other sources of DC bias include geomagnetic induced currents [15], HVDC transmission, railway signalling equipment and similar. Even a small DC bias may result in saturation of power transformers [16], an increase in their iron losses, increased corrosion and erroneous operation of measurement and protective equipment. Relevant norms [11] prescribe the DC injection limit as 0.5% of the grid-connected power converter rated current. On the other hand, a DC bias of 0.5% of the rated current of $S_n > 500$ kVA distribution transformer [17,18] corresponds to more than 50% of the rated magnetizing current, and this would saturate the core and trip the protections. Considering ever growing number of grid connected static power converters, it is essential do devise and use devices for DC bias detection and compensation [10].

Distribution power transformers with 0.4 kV secondary windings have a very low winding resistance and a very low magnetizing current [17,18]. A DC bias voltage of only 1mV may introduce a 5% offset in the magnetizing current, moving the H field in B-H plane away from the origin. Parasitic DC current in a transformer results in half-cycle saturation and an increase in reactive power, leakage flux, stray losses and temperature of the core, clamping plates, the tank walls and bolts. Therefore, DC bias detection and compensation is required to suppress the parasitic DC voltages in 0.4 kV grid far below 1 mV level. Transformerless grid-connected power converters are the source of the DC injection. Equipped with adequate DC bias sensing and controls [19], they can be also used for suppressing the parasitic DC voltages at the grid connection point.

It is rather difficult to measure very small DC offsets embedded in AC voltages, as the ratio between the two exceeds 10^5-10^6. Required precision of 2-3 ppm has to be maintained over the range of operating conditions. This cannot be achieved even with advanced sensors [13, 20]. Considerable effort has been made in improving precision of DC bias sensing [9, 19, 21, 22] and applying novel sensing techniques within closed loop DC bias suppression systems [10, 12, 23, 24]. In grid connected power converters with intermediate DC link circuit, parasitic DC injection can be determined from line frequency oscillations of the DC link voltage [10] with precision of 0.1%. At the same time, the offset introduced by Hall effect current sensors replaced in the DC link can be removed by auto-calibration [12].

DC injection can be also suppressed [23] by inserting an isolating power transformer, by using the half bridge topologies, or by inserting a series blocking capacitor, but these methods increase the cost, size and power losses. Therefore, the efforts were mainly focused towards improving the accuracy of DC bias methods and devices [13, 18-26]. In most cases, proposed reading of very small DC bias in the presence of a large AC signal is based on nonlinear effects in AC excited, DC biased iron cores. Even a small bias results in detectable amounts of even harmonics [29-32] in distorted magnetizing current of saturable iron cores. Parasitic DC voltage in AC grid can be detected by processing the magnetizing current I_m in parallel connected choke wound on saturable iron core. DC bias sensing proposed in [19, 21, 22, 24-26] compares the positive and negative peaks of the magnetizing current, which gets distorted in the presence of a DC bias. Used in conjunction with an 8A transformerless power converter [24, 25], it suppresses the DC injection to 4mA. The same I_m peak comparing method can be advantageously used [26] in suppressing magnetic saturation in transformers used to connect a static power converter to the grid. With additional compensation winding on parallel connected choke [21, 22], the peak comparing method can be used to measure the DC bias in 0.4kV AC grids, offering precision better than 3mV for phase voltages $U_{ph} = [170V .. 220V]$.

In this paper, the problems of detecting and suppressing the DC bias in AC grids is discussed and analyzed. An overview of sensing methods is followed by the proposal of a new, improved sensing technique based on nonlinearity of parallel connected choke, wound on a saturable iron core [29]. The main objective is achieving precision in DC bias sensing considerably better than 1 mV in 0.4 kV grids. The two main tools in achieving this goal are (i) the algorithm of detecting the bias and (ii) the approach to winding the choke and designing the filters.

Section II provides a brief analysis distribution transformer parameters and studies the effects of parasitic DC voltages in 0.4kV grids, reinstating the required precision of DC bias sensing. In Section III, the state of the art sensing solutions are considered with the aim of identifying the factors that limit their accuracy. Proposed guidelines to designing magnetics are summarized in Section IV. The algorithm proposed to suppress the DC bias is given in Section V, while Section VI summarizes experimental results. Discussion and conclusions are given in Section VII.

2. REQUIRED ACCURACY OF DC BIAS SENSING

DC bias currents may have a detrimental effect on the integrity of the distribution and power transformers or their long term performance, which has a negative effect on the overall system reliability.

Typical winding resistances and magnetizing (no load) currents of distribution transformers up to 2500 kVA are plotted in Fig. 1 from data available in [33]. For transformers rated $S = 1$MVA and above, the rated magnetizing current stays below 1% while the secondary resistance resides below 0.5%. This means that a DC offset voltage of $U_{DC} > U_n /20000$ produces DC bias current equal to the rated magnetizing current. Considering 0.4kV winding, it is of interest to explore the effect of very small DC voltages on DC component of the magnetizing current. In Fig. 2, the ratio between the DC bias current and the rated magnetizing currents is given for $U_{DC} = 1$mV and $U_{DC} = 500\mu$V. For $S = 1$MVA and above, $U_{DC} = 1$mV adds a DC offset of more than 5% to the magnetizing

current. The iron loss investigation reported in [37] considers 2-, 3-, and 4-limb cores with single phase AC magnetizing and a superimposed DC bias. Results plotted in Figs. 6 and 7 of [37] suggest that the DC current equal to 5% of the maximum magnetizing current in normal conditions increase the iron losses in 2-, 3-, and 4-limb cores by 9%, 12% and 22%, respectively. Although the core loss in distribution transformers is rather low (0.04% for a 1MVA transformer [33]), its change can be an indicator of the DC injection problem severity.
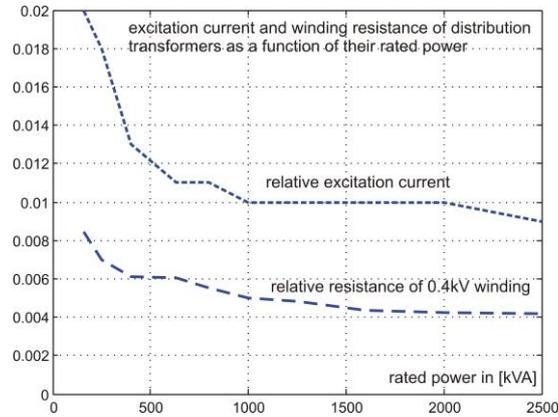
Fig. 1 Relative winding resistance and magnetizing (no load) currents
of three phase line frequency distribution transformers up to 2500 kVA.
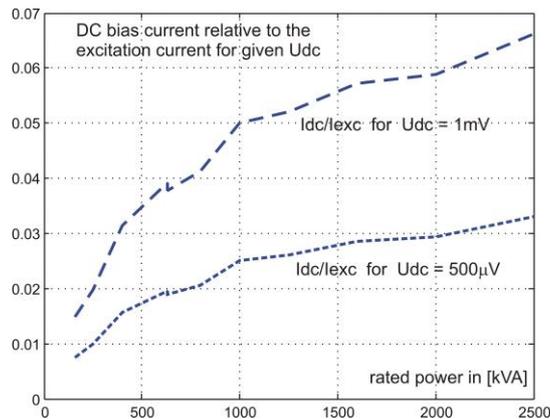
Fig. 2 The ratio between the DC bias current and the rated magnetizing current
for DC offset voltages of 500 μV and 1 mV.

Other effects of DC injection may prove more detrimental to a distribution power transformer. The presence of a DC component contributes to the asymmetric magnetic core saturation during one sinusoidal semi-period, also called half-cycle saturation, causing a number of adverse effects [34-37]. With half-cycle saturation, transformers have an increase in acoustic noise, reactive power, leakage flux and stray losses, harmonics in induced voltages and losses in leads, clamping plates, transformer tank and bolts.

For the standard magnetic material, commonly used in building the magnetic core of the power transformers, the change of H_{max}, H_{rms}, specific power losses P and specific apparent power S are given in Fig. 3. At high values of the flux density B, a DC offset of only 10% of the peak value can double the apparent power and increase the iron losses by 60%. Therefore, it is of interest to suppress the DC bias current far below the level of $I_{mnom}/10$, where I_{mnom} stands for the rated magnetizing current.
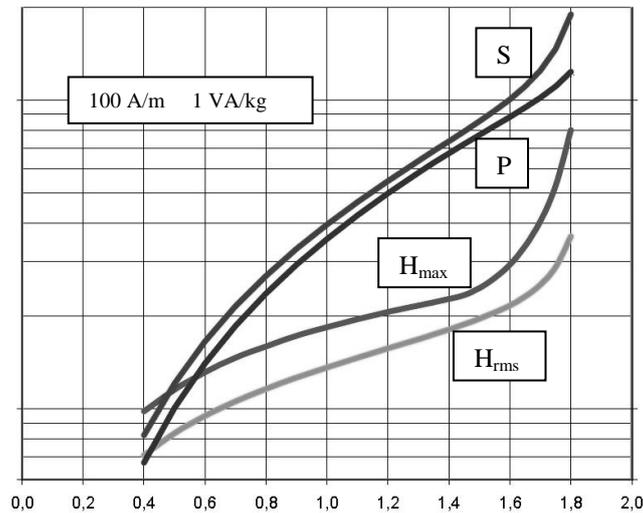
Fig. 3 Peak value of the magnetic field, rms value of the magnetic field, specific power losses and specific apparent power S as a function of the flux density.

High efficiency distribution power transformers that have lower winding resistances and larger DC currents in their windings for the same parasitic DC voltage across the windings. Moreover, their operating point in *B-H* plane comes closer to saturation. Therefore, they are more sensitive to DC bias. With introduction of high efficiency transformers and increasing number of grid connected static power converters, the need to sense and compensate DC bias in 0.4kV AC grids is more evident. Suppressing the DC bias below 1mV level requires detection methods and devices with considerably lower sensing errors.

3. ACCURACY OF PEAK DETECTION METHODS

Previously developed methods for sensing of parasitic DC voltages in AC grids [19, 21, 22, 24-26] make use of changes in magnetizing current of parallel chokes, namely, the iron core reactors which are parallel connected to the grid voltage. In the presence of a DC bias, the magnetizing current changes [29] and provides the grounds for detecting the sign and amplitude of parasitic DC current (Fig. 4). Distorted magnetizing current has the maximum positive value *IMAX* and the peak negative value of *IMIN*. The positive peak of the magnetizing current (*IMAX*) and the negative peak (*IMIN*) are supposed to be equal in the absence of the DC bias. Considering the core which operates next to saturation, an

injection of DC bias would result in considerable change in the magnetizing current. The values *IMIN* and *IMAX* get different, thus providing the means to obtain the sign and estimate of the bias. The peak difference ΔI is used in DC bias detectors presented in [19, 21, 22, 24-26]. All of these solutions compare the positive and negative peaks of the magnetizing current in a parallel connected reactor. The very concept of DC-compensated magnetic core is proved reliable [20] and also used in closed loop current sensing.
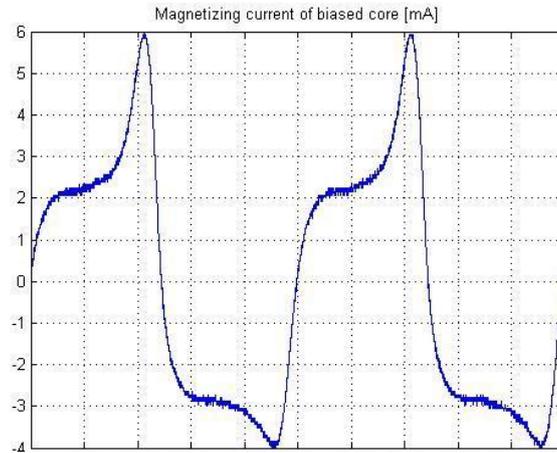
Fig. 4 Suppression of DC injection from transformerless grid connected power converters.

With peak detection method applied to grid-connected power converters (Fig. 5) it is possible to use detected signal and correct the PWM pulses of the converter in order to drive the parasitic DC offset down to zero. Whenever a parasitic DC bias produces an offset in magnetizing current, the difference ΔI arises in a manner illustrated in Fig. 4. The power converter in Fig. 5 acts towards eliminating the bias by means of introducing small changes in PWM pattern. This approach can be used to suppress the DC injection from transformerless grid connected power converters. Any DC injection caused by the converter imperfections results in a DC bias. In turn, the signal ΔI is detected from the saturable core. This signal is used to affect the PWM commands of the grid connected power converter in the way that suppresses the DC injection and brings the difference ΔI towards zero.
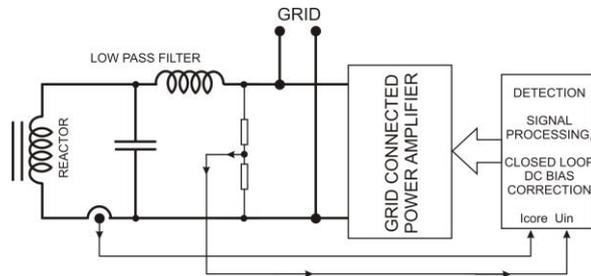
Fig. 5 Suppression of DC injection from transformerless grid connected power converters.
With spectrum-based sensing approach, the LC filter across the choke is not required.

The difference ΔI between the peak values of the magnetizing current depends on the instantaneous values of the current at instants of zero crossings of the supply voltage. Therefore, the value of ΔI can be affected by the noise and voltage harmonics coming from the grid. For this reason, the state of the art DC bias detectors include a low pass LC filter, designed to maintain integrity of detected ΔI. This filter is drawn on the left side in Fig. 5.

Reported accuracy of peak detection methods shows the capability to detect the DC bias current component within the choke magnetizing current up to 1/30 of the rated AC magnetizing current ($I_{DC}/I_{mag} = 1/30$). A drop in accuracy is detected with AC voltage off the rated value. In Table 1, the AC voltage is varied from 68% up to 120%. The minimum detectable DC current I_{DC} drops at least 5 times as the voltage shifts away from the rated value. This represents a serious drawback of peak detection methods. Considered drawback can be removed by replacing the peak detection method by other means of extracting the information on the DC bias from the magnetizing current measured in the parallel choke. Sensing precision can be also improved by an improved design of the sensing core, focused on increasing the sensitivity.

Table 1 Reduced sensitivity of the peak detection methods in operation with AC voltages off the rated value

AC voltage	68%	77%	90%	100%	120%
I_{DC}/I_{mag}	1/6	1/10	1/17	1/30	1/4

4. CORE DESIGN

The sensitivity depends on the ratio I_{DC}/I_{mag}. Detectable DC voltage U_{DC} depends in the sum of the active resistances in the reactor circuit, hence, $I_{DC} = U_{DC}/\Sigma R$. Therefore, in order to reduce the minimum detectable $U_{DC} = I_{DC} \cdot \Sigma R = I_{mag} \cdot (I_{DC}/I_{mag}) \cdot \Sigma R$, and given the ratio ($I_{DC}/I_{mag}$), it is of interest to minimize the product $I_{mag} \cdot \Sigma R$. With that in mind, any additional LC filter is counterproductive, as it increases ΣR and reduces sensitivity.

A simple and straightforward way of getting a suitable sensor is adopting a small, ready-made toroidal transformer, with the primary winding already set for the line frequency and the AC grid voltage. In Table 2, a summary is given of the key parameters of standard single phase line frequency transformers wound on toroidal iron core. These toroidal cores are made of most standard iron sheets, and available off the shelf. The Table comprises relative magnetizing current and relative winding resistance for the transformers with the rated power ranging from 20VA up to 500VA. The sensitivity of the core to the DC bias is inversely proportional to the $R3I$ product. Hence, the core of 50VA is five time more sensitive than the core of 20VA. On the other hand, increasing the power from 50VA up to 500VA raises the sensitivity roughly two times. For that reason, it appears suitable to avoid usage of large and heavy 500VA cores, and remaining within 50VA range. The rightmost column in Table 2 provides the factor $R3I3S_{nom}$, which is lower for a larger "sensitivity per VA". Namely, it illustrates how "the investment" into a larger core pays off as an increase in DC bias sensitivity. The most appropriate choices are the cores with 30VA and 50VA.

Table 2 Properties of standard toroidal cores used for single phase line
frequency transformers

S_n [VA]	I_{mag}/I_{nom}	$R_{relative}$	R3I *1000	R3I 3S_{nom}
20	0.0286	0.0483	1.3814	0.0276
30	0.0104	0.0434	0.4514	0.0135
50	0.0088	0.032	0.2816	0.0141
80	0.0096	0.0397	0.3811	0.0305
150	0.0066	0.0341	0.2251	0.0338
200	0.0074	0.0331	0.2449	0.0490
300	0.006	0.0254	0.1524	0.0457
400	0.0055	0.0264	0.1452	0.0581
500	0.0053	0.0238	0.1261	0.0630

The application in Fig. 5 requires the sensing core with only one winding, the winding connected across the AC voltage. Therefore, it is beneficial to use all the winding space of the core and reduce the winding resistance to the minimum. Hence, an off the shelf toroidal transformer of 50VA should be rewound. The secondary winding can be removed, and the available winding space used for the primary winding with an reduced resistance. In this manner, the winding resistance can be halved, and the sensitivity to DC offset doubled.

5. Control of the DC Bias Suppression System

In Fig. 5, the sensing choke is connected across the AC voltage. The DC bias within the AC voltage may be injected from the grid side power converter in the right of the Figure, but also from other grid side converters connected to the same grid. To begin with, it is necessary to detect the bias. As discussed before, conventional peak detection methods have a series of drawbacks, and there is a need to deploy a more robust, more reliable and more sensitive algorithm for extracting the bias information from the magnetizing current of the choke.

Robustness against the grid noise, PWM noise and other noise sources intrinsic in AC grids is a vital feature in sensing the DC bias. Instead of relying on time-domain properties of relevant signals, it is possible to mode to frequency domain and consider the second harmonic of the magnetizing current, renown for being proportional to the DC bias. In Table 3, a core of a small toroidal single phase transformer is tested for the second harmonic in the presence of the DC bias. The bias voltages are changed from 0mV up to 1.4mV. The test is performed with AC voltages ranging from 70% up to 116%. For a wide range of AC voltages, the amplitude of the second harmonic is proportional to the bias. Therefore, it can be advantageously used in detecting the bias. Notice in Table 3 that the residual second harmonic, obtained with U_{DC}=0, does not exceed 0.42% of the rated magnetizing current. Considering a sensing core with the weight of $m < 0.7$ kg, this corresponds to 9 μA, and it contributes to the measurement error of 140 μV (0.14 mV).

Table 3 Second harmonic of the magnetizing current, expressed relative to the rated value of the magnetizing current. The values are given for the range of AC voltages and DC bias values.

U_{DC}[mV]	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
U_{AC}=70%	0.001	0.02	0.026	0.071	0.097	0.12	0.144	0.157
U_{AC}=88%	0.002	0.036	0.067	0.093	0.123	0.156	0.184	0.200
U_{AC}=100%	0.0026	0.0338	0.07	0.096	0.132	0.158	0.185	0.209
U_{AC}=116%	0.0042	0.031	0.078	0.097	0.143	0.157	0.191	0.198

The bias amplitude is obtained from the amplitude of the second harmonic, while the sign is obtained from the phase shift of the second harmonic with respect to the fundamental. In Fig. 5, the signals are fed back to the grid connected power converter. Within the PWM algorithm of the converter, it is necessary to introduce small changes of the width of the voltage pulses, thus introducing a small DC correction of the output voltages. This change is calculated so as to suppress the DC bias from the grid. Namely, as a consequence, the grid connected converter and the DC offset within its output voltage would introduce the DC injection required to drive detected DC bias down to zero. Precision in keeping the bias at zero is defined by the sensor, and it is estimated to 140 μV.

From the results given in Table 3, the amplitude of demodulated 2nd harmonic can be expressed as

$$H_2(U_{DC}) \approx K_2 U_{DC},$$ (1)

where $K_2 \approx 0.15$ for the sensing core under consideration, and U_{DC} is the DC bias across the primary winding. This bias produces the primary side DC bias current I_{DC}. If R_p is the primary resistance,

$$H_2 \approx K_2 R_p I_{DC} \approx K_3 I_{DC}.$$ (2)

In Fig. 6, controller produces the modulation index m for the auxiliary PWM H-bridge which feeds the voltage U_2 across the compensating winding. As a consequence, the current I_2 provides correction and zeroes out the DC bias within the core. Assuming that the primary winding has N_1 turns while the secondary (compensating) winding has $N_2 = q N_1$ turns, the second harmonic in the presence of both primary and secondary magnetomotive forces is

$$H_2 \approx K_3 (I_{DC} - qI_2).$$ (3)

Assuming that the controller has an integral action with the gain K_i,

$$U_2 = \frac{K_i}{s} H_2 = \frac{K_i}{s} K_3 (I_{DC} - qI_2).$$ (4)

The current I_2 comes as a consequence of the voltage U_2. With the resistance R_2 and the inductance L_2 of the compensating winding,

$$I_2 = \frac{U_2}{R_2 + sL_2}.$$ (5)

Eventually, the current I_2 response to the bias I_{DC} is defined by

$$I_2(s) = \frac{K_i K_3}{s^2 L_2 + s R_2 + K_i K_3 q} I_{DC}(s). \tag{6}$$

Dynamic response of the closed loop can be tuned by the gain K_i. Since the DC bias fluctuations are rather slow, there is no need to select excessively fast response and too large gain. In the experimental setup, response time is characterized by the time constants of 200ms. In steady state conditions, the current I_2 is proportional to the bias I_{DC}, and it reflects the bias voltage U_{DC} of the grid at the point of the common connecctions (PCC).

$$I_2(\infty) = \frac{1}{q} I_{DC}(\infty). \tag{7}$$
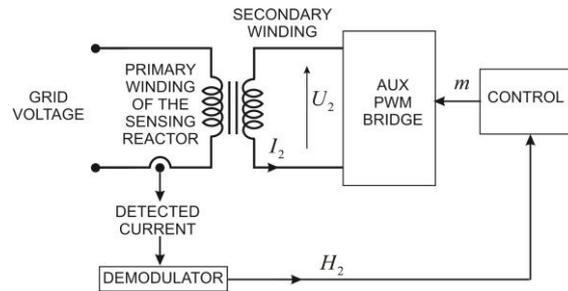
Fig. 6 Using the sensing reactor with the compensating winding. Control circuit sets the voltage U_2 in order to obtain the current I_2 of the compensating winding which zeroes out the offset from the sensing core.

While the circuit in Fig. 6 detects the DC bias within the AC grid, the setup in Fig. 7 can be used to perform an active action and compensate the bias. The controller senses the second harmonic and introduces the correction Δm of the modulation index which is used within the grid connected power converter. In this way, a DC current I_2 is injected into the grid. When the controller reaches the balance, the current I_2 zeroes out the original DC bias of the grid and brings the voltage U_{DC} to the zero.
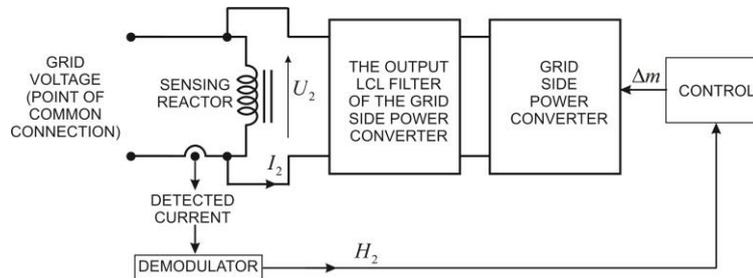
Fig. 7 Using the grid connected power converter as an actuator in closed loop DC bias suppression system. Control circuit detects the second harmonic, concludes on the DC bias, and produces the DC voltage correction U_2. This voltage injects the DC current I_2 which zeroes out the DC bias detected across the grid connection.

6. EXPERIMENTAL RESULTS

The setup in Figs. 5 and 7 comprises the sensing choke, the signal processing block and the grid connected power converter capable of injecting a controllable DC bias. The closed loop gains of the bias-removal control loop are set to obtain the closed loop response characterized by the time constant of 150 ms. Experimental results are given in Fig. 8, where the trace of detected DC bias illustrates the operation of the DC bias suppression controller. The scaling is 500ms per division on the x-axis and 0.5mV per division on vertical axis. An artificial bias of 2.5mV is introduced into the systems, and it is removed in, roughly, 200ms.
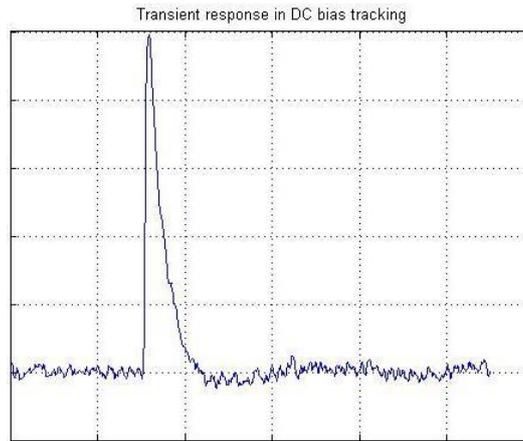
Fig. 8 Transient response of the DC bias suppression controller. The scaling of x-axis is 500ms per division. The vertical axis shows detected DC bias with the scaling of 0.5mV per division. An artificial bias of 2.5mV is introduced into the systems, and it is removed in, roughly, 200ms.

Steady state accuracy is tested in regimes where the sensing is more difficult, namely, with AV voltage reduced to 70%, where the DC bias has a lesser effect on distortion of the magnetizing current.

For the close-loop DC bias suppression, given in Fig. 7, the results are given in Table 4 for a range. These results present the residual error for a range of DC bias voltages. These results demonstrate that, for a range of operating conditions, precision in sensing and removing the DC bias can be maintained with residual errors inferior to 140 µV. Considering the amplitude of superimposed AC voltages, this results brings the measurement precision better than 1 ppm.

Table 4 Steady state accuracy of the proposed solution

U_{DC} [mV]	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
Residual error in [µV]	80	101	33	129	117	57	73	17
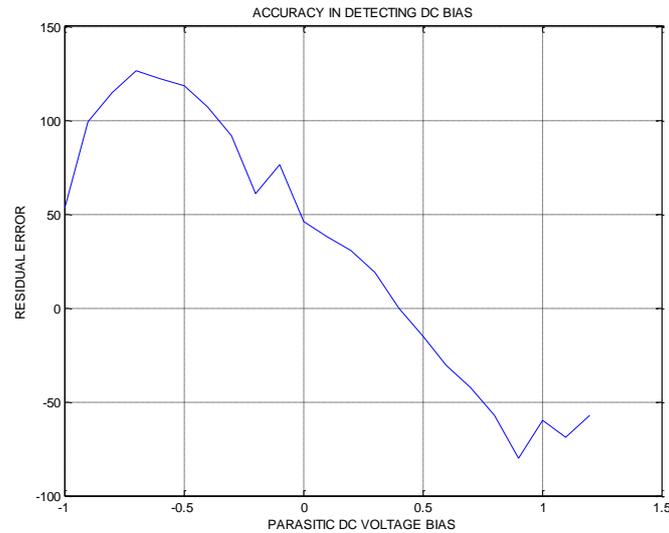
Fig. 9 Residual error obtained in the steady state, with the circuit given in Fig. 6.
On x-axis, parasitic DC bias in 0.4kV AC grid is given, expressed in [mV].
Residual error is given on y-axis in [μV].

When using the proposed detection method in a manner illustrated in Fig. 6, that is, as a sensor, the results are given in Fig. 9. These results present the residual error for a range of DC bias voltages, and demonstrate that precision in sensing the DC bias can be maintained with residual errors inferior to 125 μV. Compared to U_{AC}, the measurement precision is better than 1 ppm.

7. CONCLUSIONS

Growing number of grid connected converters contributes to an increase of DC bias in AC grids, and this brings the cores of distribution transformers closer to saturation and increases their power losses. The paper provides the analysis of contemporary distribution transformers and probes their sensitivity to the DC bias. It also presents a detailed analysis of the available solutions for detecting and compensating the parasitic DC bias in AC grids, and explored their limits. An active compensation method is proposed, where the grid connected power converter monitors the parasitic DC voltages at the point of common connection, and it provides the DC voltages which correct and suppress the bias. The sensing approach proposed in this paper makes use of saturable ferromagnetic cores and a low cost DSP for signal analysis and processing. Proposed algorithm uses distortion of the magnetizing current of a parallel connected saturable core due to the bias. Experimental results demonstrate the capability for detecting and compensating the bias voltages far below 1 mV in 0.4 kV grids. For a range of operating conditions, precision in sensing and removing the DC bias can be maintained with residual errors inferior to 140 μV. Considering the amplitude of superimposed AC voltages, this results brings the measurement precision better than 1 ppm.

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