A Sensor to Detect the DC Bias of Distribution Power Transformers

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Abstract—**The widespread use of power converters in low-voltage distribution grids has given rise to issues regarding the power quality. In fact, non-linear loads such as AC Drives, switching-mode power supplies and grid-connected converters can cause, besides the generation of several current harmonics, also a DC current component injection into the grid. This DC current component can lead to magnetic saturation of the distribution power transformers; in this condition, the transformers present distorted current waveforms, increased power absorption and overheating, that can damage the transformer insulations. This paper presents a way to diagnose the magnetic saturation by a non-direct measurement of the DC current component flowing in the power transformer. In other words, the proposed solution provides an information about the total DC injection produced by the sum of all the electric devices connected to the distribution power transformer. The DC current component causes a DC voltage drop across the parasitic resistance of the transformer's winding: sensing this DC voltage drop allows to evaluate the DC current component. A magnetic sensor was developed in order to obtain a great sensitivity, and the implemented closed loop control allowed to guarantee a good linearity with a high rejection ratio of the grid voltage variations. Simulation and experimental results confirm the effectiveness of the proposed approach.**

I. INTRODUCTION

The increasing use of power converters in the industry has caused, over time, the emergence of problems relative to power quality. Among them, the non-linear distortion due to the use of power converters is very troublesome. For this reason, regulations have been developed to guarantee that devices connected to the grid do not deteriorate the power quality [1], [2], [3], [4]. Among the different kinds of power quality deteriorations, which can arise from non-linear distortions, there is the issue of the DC current injection. The DC current component can be caused by non-linear loads or by power converters, for example grid-connected systems for renewable energy and DC/AC drives.

At the moment this problem is addressed by international or country-specific regulations that impose a limit to the maximum DC current injection allowed. For this reason, various strategies addressing the DC injection problem from grid-connected inverters for renewable energy applications have been proposed [5], [6], [7], [8]. However, these regulations do not guarantee that the cumulative effect of several power converters connected to the grid remains acceptable, with no harmful effects for electric system sensitive to DC components. The DC current component is detrimental especially for the distribution power transformers. The main effect of a DC current component flowing in a transformer is the asymmetric magnetic core saturation during a sinusoidal semi-period (half-cycle saturation). When operating in half-cycle saturation condition, a transformer presents an increased reactive power absorption, that implies increased power losses and, consequently, overheating [9], [10], [11], [12].

This paper proposes an on-line method to detect indirectly the DC current component that flows into a power transformer, in order to signal a warning in case of excessive amount of DC current.

In literature many on-line and and off-line diagnostic methods are used to detect faults and to monitor the ageing process of the insulating systems [13]. A new method that promises to detect the position of the shorted turns in a very early stage is based on the measure of the transformers leakage flux [14]. Other techniques are based on transfer function methods with injection of a known test signal in order to monitor the status of the transformer winding, in particular in [15] the bushing tap connection results a practical method. The failures of a power transformer can be divided in internal and external causes and several papers show comprehensive discussion of many monitoring methods, [13], [16], [17]. However the detection of the DC current/voltage component in order to state the malfunctioning of grid-connected power converters or the undesired operation of electric loads of a particular user is not found in literature.

The idea behind the solution proposed in this paper is that a DC current component flowing in a power transformer causes a voltage drop across the parasitic resistance of the windings. This DC voltage drop holds the information regarding the extent of the saturation of the transformer. This DC voltage is very small (for high power transformer the winding resistance is in the order of the millihoms), and the traditional sensing mechanism can not detect it from the AC voltage. Furthermore, sensing the DC current flowing in a transformer with a hall-effect current transducer would encounter a similar difficulty, due to the need to separate a small DC current from a very large AC current. This is a very difficult task, considering the well-known DC offset issues of hall-effect transducers.

It is important to note that the proposed solution does not imply a direct measurement of the transformer's current, so it can be adopted independently from the rated power of the transformer.

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In this paper the non-linear behaviour of a magnetic sensor was developed in order to obtain a great sensitivity in the measure of the DC voltage component across one of the windings of a power transformer. The paper shows two different implementations of the proposed DC voltage sensor, in open loop control and in closed loop. The last one operates in order to null the DC flux component inside the magnetic sensor core (the closed loop hall effect sensor operates in the same manner, but for all the flux harmonics). Simulation and experimental results confirm the effectiveness of the proposed approach and in particular they show the good performances of the closed loop control in order to measure/estimate the value of the DC voltage component.

II. Operating Principle

The key element of the proposed sensor is a very precise DC voltage sensing strategy with a high rejection ratio to the offsets usually present in the measure. As a matter of fact, sensing the DC voltage drop across the parasitic resistance of the transformer's winding means extracting a DC voltage component of the order of mV from a sinusoidal signal of peak-to-peak amplitude over 600V. This paper proposes, for the detection of this very small DC voltage component, the use of a toroidal magnetic core with two windings, in the following referred to as Compensated Reactor. The magnetic component is sized mimicking a low power toroidal transformer with a primary voltage equal to the grid one. The secondary winding is used to guarantee closed loop operations by setting to zero the DC Flux component.

This kind of sensor, but with a sole winding, was previously used to prevent DC current injection for a photovoltaic transformerless converter [18]. The model of this magnetic component, called simply reactor, is presented in Fig. 1, and it can be considered the series of a resistance and a non-linear inductance (the secondary/compensated winding is not not considered at this stage). The reactor is connected to a source whose voltage is the superposition of a sinusoidal voltage and a DC component. The reactor's current, i_R, is sensed through a current transformer. As it will be explained in the following, the current transformer is employed in order to reject the offset in the measure. To have a cheaper sensor with a lower quality measure, a simple shunt resistor could be employed.

The operating principle resides in the asymmetric saturation of the reactor magnetic core in presence of a DC bias. Fig. 2 shows the waveforms of reactor magnetic flux and magnetizing current in presence of a positive DC voltage component: the magnetic flux saturates deeply at the end of the positive semi-period of the grid voltage, draining more magnetizing current. As a result, the reactor current will present higher values in correspondence of the positive or negative grid voltage semi-period, depending on the sign of the DC voltage component. The asymmetric saturation of the magnetic core holds the information regarding both the DC voltage component sign and amplitude.

To detect this asymmetric distortion every grid voltage period, two indexes, respectively the positive saturation index SI_P (1) and the negative saturation index SI_N (2), are computed by integrating the reactor current in a suitably small window placed around voltage zero crossing.

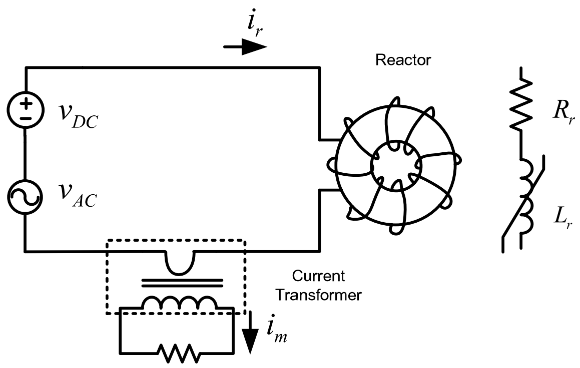

Fig. 1. Schematic of the reactor connected to an AC source with a DC component.

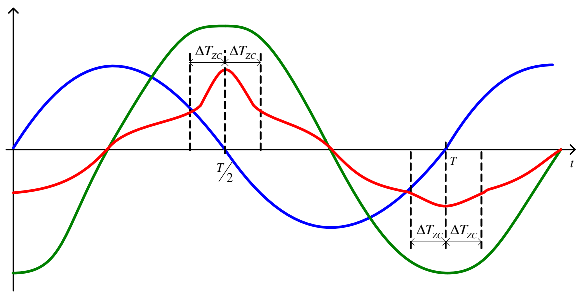

Fig. 2. Reactor voltage (blue line), magnetic flux (green line) and magnetizing current (red line) in presence of a positive DC bias.

$$SI_P = \int_{\frac{T}{2}-\Delta T_{ZC}}^{\frac{T}{2}+\Delta T_{ZC}} i_m(t)\,\mathrm{d}t \tag{1}$$

$$SI_N = \int_{T-\Delta T_{ZC}}^{T+\Delta T_{ZC}} i_m(t)\,\mathrm{d}t \tag{2}$$

In case of a positive voltage bias, the positive semi-period of the flux wave saturates, see Fig. 2, and an asymmetric distortion, due to even harmonics, appears in the reactor current. The $abs(SI_P)$ value will be greater than the $abs(SI_N)$ value and the sign of their difference is the sign of the DC voltage bias, i.e. the sign of the DC current component flowing into the distribution power transformer. The value $H = SI_P + SI_N$ is a rough non-linear indicator of the DC voltage component at transformer's winding and consequently of the DC current component flowing in the power transformer.

The reactor current is measured through a current transformer that renders the system totally immune to offsets in the measurement chain. As a matter of fact, the current transformer removes the DC component, so the DC offset of the output signal is known to be zero. With these premises, a digital dynamic compensation of the offset introduced by the analogue conditioning is feasible and the resulting measurement system is free from offset problems.

Fig. 3 shows the DC component detector. The DC voltage indicator, $H = f(v_{DC})$ holds the information regarding the DC voltage.

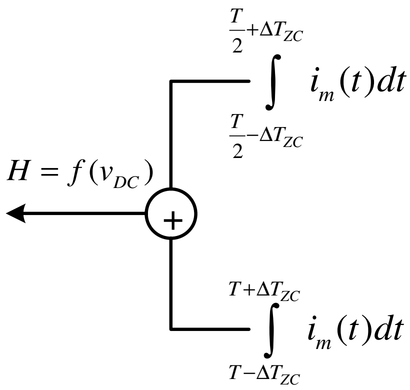

Fig. 3. DC component detector.

The previously described operating principle allows to obtain a great sensitivity to small DC voltage components thanks to the highly non-linear system behavior. It is important to note that the extent of the saturation of the reactor depends on the amplitude of the grid voltage. For this reason, in order to reject the grid voltage amplitude variations and to obtain a good linearity of the measure, a closed loop control that forces the reactor to work with no DC flux was realized. The basic idea is to add another winding to the magnetic core, with a strongly inferior number of turns than the sensing one, and use it to compensate the DC flux in the reactor caused by the DC voltage component at the primary winding. The DC voltage indicator $H = f(v_{DC})$ is the input of a PI regulator which generates the current set-point, i_2^*, for a low power DC-DC converter connected to the compensator winding, see Fig. 4. The DC-DC converter that regulates the current of the compensator winding, i_2, can be replaced with a linear power amplifier as well. In this figure, the primary winding of the Compensated Reactor is connected at the output of a distribution power transformer, whose voltage is a sinusoid with a small DC bias.

In order to correctly evaluate the DC voltage indicator $H = f(v_{DC})$, the information regarding the grid voltage zero crossing is needed. To guarantee a better precision and a lower cost of the solution, the reactor's current was used instead of the grid voltage (which is not measured) as the input of a Phase Locked Loop (PLL), in order to know with precision the integration boundaries (1),(2). Due to the marked distortion of the reactor's magnetizing current, a particular structure of PLL was employed. This feedback system, known as SOGI [19], is a second order filter that allows to obtain from a single distorted signal the filtered signal and its quadrature version. With these two signals, a standard quadrature PLL, usually employed for three-phase systems, can be adopted, allowing to track with high precision

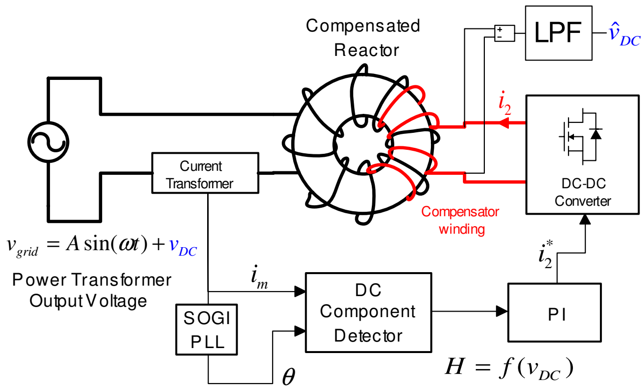

Fig. 4. Schematic of the proposed DC voltage sensor connected to the output of a power transformer. The structure of the control is showed.

and with no steady state error the angle of the reactor's current. The schematic of the SOGI-PLL is presented in Fig 5. The value ω is the grid pulsation, while the parameter k select the bandwidth of the filter. In order to extract only the grid frequency component of the current signal, a value $k = 0.1$ was selected to have a narrow resonance bandwidth.

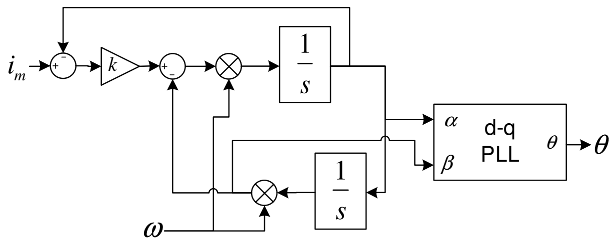

Fig. 5. Schematic of the SOGI-PLL used for the simulation results.

If the reactor is symmetrically saturated, it means that the DC flux due to the DC current at the reactor's primary winding is totally compensated by the DC current injected into the compensator winding, so, in first approximation, it can be written $N_1 I_1^{DC} = N_2 I_2^{DC}$. Expressing the current as the DC voltage over the winding resistance, and assuming that the same wire is employed for the primary and secondary windings (with R the resistance of a single turn), the following equation holds: $N_1 \frac{v_1^{DC}}{N_1 R} = N_2 \frac{v_2^{DC}}{N_2 R}$, that means that $v_1^{DC} = v_2^{DC}$. For this reason, the low-pass filter connected at the secondary winding in Fig. 4 allows to measure the DC voltage at the sensing winding. It must be noted that in this case the sinusoidal voltage at the secondary winding presents a strong attenuation depending on the high turn ratio of the sensor, so a simple filter can be employed. It must be also noted that the power electronics needed to compensate the reactor will not have to withstand neither high voltage (the compensator's winding has a greatly inferior number of turns than the sensing one) nor current (the DC current to compensate is small), so very low power devices can be chosen.

Without additional hardware the DC voltage can also be calculated multiplying the resistance of the compensator winding with the measured DC current component flowing in it. In order to have an acceptable accuracy of the resistance value, the temperature of the magnetic sensor must be detected.

III. Simulation Results

The proposed sensor was simulated in a Matlab/Simulink ® environment. The schematic reported in Fig. 4 was realized. It is to be noted that all signal processing is done with a fixed time step ($100\mu s$), in order to effectively simulate the implementation of the feedback control on a low-cost Digital Signal Processor (DSP). Two sets of simulations were performed: the first evaluated the dependence of $H = f(v_{DC})$ from the grid voltage and DC voltage component without the use of the compensation winding (open loop operations), while in the second set of simulations the compensation was added (closed loop operations). The compensator's regulator was a discrete PI with a sampling time equal to the grid voltage period ($20ms$). SI_P and SI_N values can be updated, in fact, every grid voltage period.

For the reactor the magnetizing characteristic (referred to the primary winding) shown in Fig. 6 was considered. A winding resistance of 30Ω was considered as well. This value is high, and it was chosen to highlight that the system can achieve a very high sensitivity even if a cheap magnetic component is employed as the sensor. The turn ratio between the primary and compensation windings was 1:300.

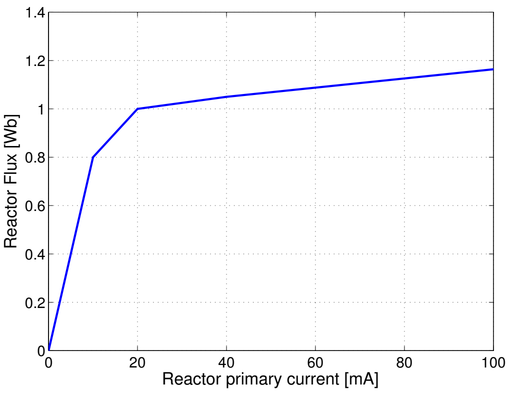

Fig. 6. Reactor's magnetic characteristic referred to the primary winding.

The simulation results are presented in Fig. 7 and Fig. 8.

In the open-loop case the absolute value of H is not meaningful due to the strong non-linearities so it was normalized to the maximum value, while in the closed-loop case the output is the $\hat{v}_{DC}$ (see Fig. 4). It is clear that without compensation there is a heavy dependence from the grid voltage and from the amplitude of the DC bias. The maximum sensitivity is reached around the rated voltage ($230V_{RMS}$); for lower values the reactor is less saturated, while from higher values the effect of the DC bias are damped by the parasitic resistance of the wires.

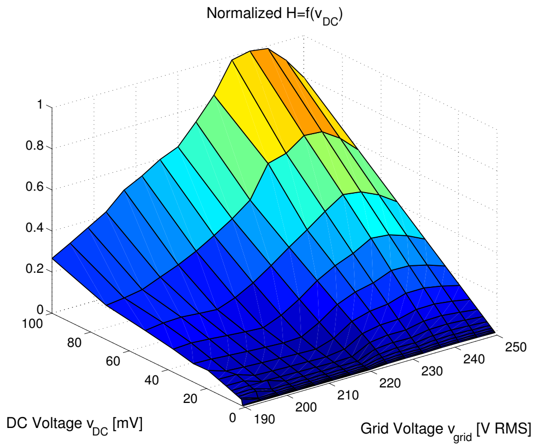

Fig. 7. Normalized DC voltage detected in open-loop operations.

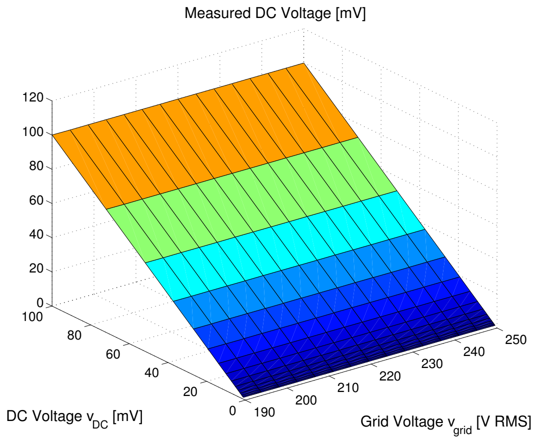

Fig. 8. DC voltage detected in closed-loop operations.

With the compensation enabled, the sensor shows a constant behavior with the grid voltage, while the dependence from the DC bias is linear.

IV. Application of the Sensor to a Distribution Power Transformer

In the previous section it was shown the capability of the proposed sensor to evaluate with high sensitivity a small DC bias in a sinusoidal voltage. In order to give a meaningful information regarding the DC current component flowing in the distribution transformer, it is necessary to sense the DC voltages at the transformer's terminals. For this purpose, three sensors are necessary for a three-phase, four-wires system. Then, in order to calculate the DC current component, the wire resistance is needed. As a matter of fact, the design of MV/LV transformer is almost standard, and the wire resistance can be obtained from a very small set of parameters, such as rated power, short-circuit voltage and copper losses. Fig. 9 shows the variation of the secondary winding resistance with the rated power of a MV/LV ($20kV/400V$) distribution power transformer with a short circuit voltage of 4% and 2% copper losses.

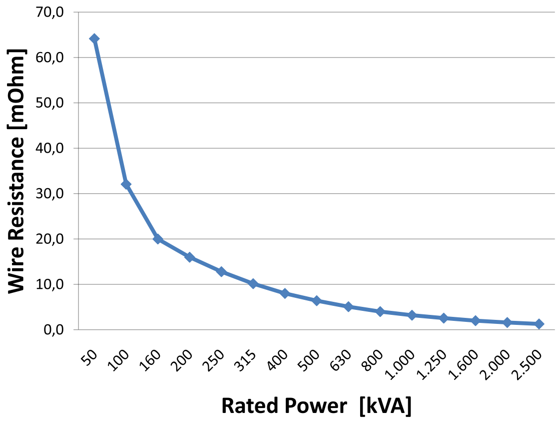

Fig. 9. Variation of the wire resistance with the transformer's rated power.

Once the wire resistance at a certain temperature is known, its variations can be calculated as a function of temperature and the DC current flowing in the transformer can be calculated from the DC voltage detected by the proposed sensor. The diagnostic system is shown in Fig. 10, where T is the transformer's temperature, R_0 is the resistance value for a reference temperature and $i_{DC}^{\%}$ is the percentage of DC current detected in the three phases respect to the nominal current of the transformer. The output $Danger$ is an indicator that the DC current is above a certain threshold decided by the manufacturer of the transformer.

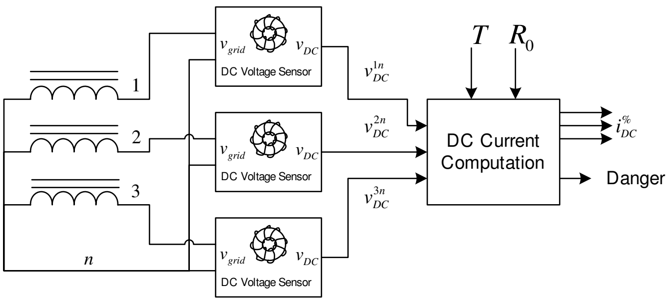

Fig. 10. Diagnostic system that evaluates the DC current component of a distribution power transformer.

The primary winding of the Compensated Reactor can be connected to phase-neutral (Fig. 10) or phase-to-phase connection with the same performances for the proposed solution.

V. Experimental Results

In order to test the feasibility and the effectiveness of the proposed sensing mechanism a test bed was built. A prototype of the system presented in Fig. 4 was realized. The hardware of a general purpose electric drive, in particular a 24V 300W stepper motor drive, was used to acquire all the measures and to implement the control strategy. This board features a DSP MC56F8037 by Freescale and two full-bridges. Obviously, for this application only a full-bridge is utilized as the DC/DC converter that supply the compensator winding. A LC filter was added at the output of the full bridge ($L_f = 1mH$, $C_f = 1\mu F$) and the compensator winding was constituted by two turns. The prototype reactor presents 2950 turns on a Fe-Si toroidal core with area = $2.5cm^2$. The firmware on-board the DSP performs the ADC conversion of the reactor current and the synchronization by means of a SOGI-PLL structure (Fig. 5). The current loop of the full bridge converter is realized with a simple PI controller. In this test bed, the DC voltage component at the compensator winding, $\hat{v}_{DC}$, is sensed with an external voltmeter. This voltage, as explained before, constitutes an esteem of the DC voltage component present at the reactor primary winding i.e., the DC voltage component of the grid. A final engineered sensor would feature a smaller board that would also perform the DC voltage detection and a serial protocol communication in order to return the value of the DC voltage. A picture of the prototype is reported in Fig. 11.

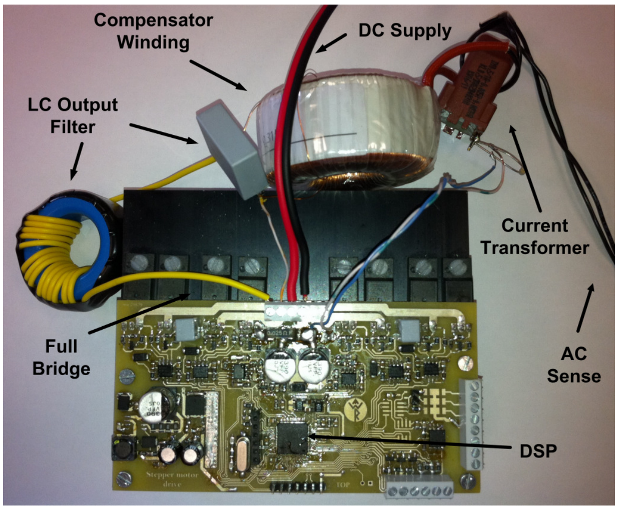

Fig. 11. Picture of the prototype of the Compensated Reactor.

The purpose of the proposed sensor is to detect the DC current flowing into a transformer winding, for this reason a specific test bed was built. The schematic of the proposed test bed is reported in Fig. 12. The compensated reactor was connected to the secondary output of a 3000 VA transformer, in order to test the robustness of the compensator to the variations of the grid voltage, an autotransformer was also added.

The source of the DC current was a properly programmed 4 kW grid-connected converter, that was instructed to inject 1 kW of active power with a selectable DC current injection. Therefore, the output current of the grid-connected converter, i_{GC}, comprehends a fixed value of the AC component, i_{GC-AC}, and a variable DC component, i_{GC-DC}, that will cause a DC voltage component at the transformer output. The DC current was measured with a precise digital power meter, while the DC voltage at the reactor compensation winding was measured with a voltmeter. In this case the measure of the DC voltage does not present problems since the AC voltage component is strongly reduced by the turn ratio of the reactor.

A picture of the experimental test bed is reported in Fig. 13.

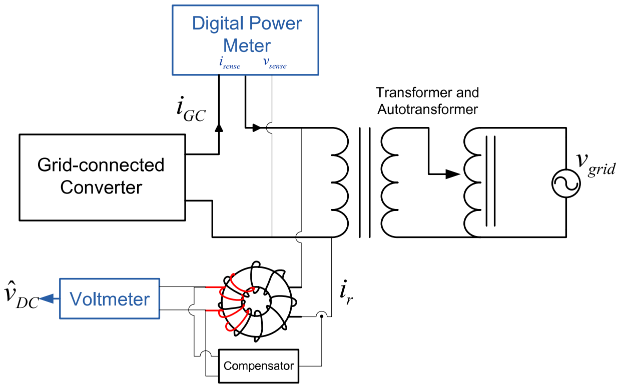

Fig. 12. Schematic of the test bed.

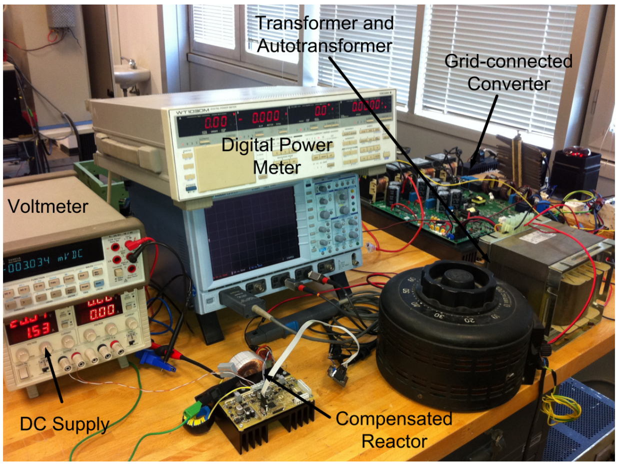

Fig. 13. Picture of the test bed utilized for the experiments.

In order to evaluate the effectiveness of the proposed strategy a series of measures of the DC voltage at the compensator winding versus the DC current component injected into the transformer was realized. During the experiments the temperature of the transformer was kept quite constant, in order to limit the variations of its parasitic resistance. The results of these measures are reported in Fig. 14, and it is evident that the compensation system succeeds in keeping the reactor in a symmetrical saturation condition, ensuring a good linearity of the measure. In this set of measures, the grid voltage was $v_{grid} = 220V_{RMS}$.

The slope of the curve reported in Fig. 14, $K = \frac{\hat{v}_{DC}}{i_{GC-DC}}$, which also represents an esteem of the resistance of the transformer winding, is equal to 0.5Ω while the measured resistance of the transformer winding was 0.33Ω. This difference can be explained because, as explained in section II, the relationship

$$N_1 \frac{v_1^{DC}}{N_1 R} = N_2 \frac{v_2^{DC}}{N_2 R} \tag{3}$$

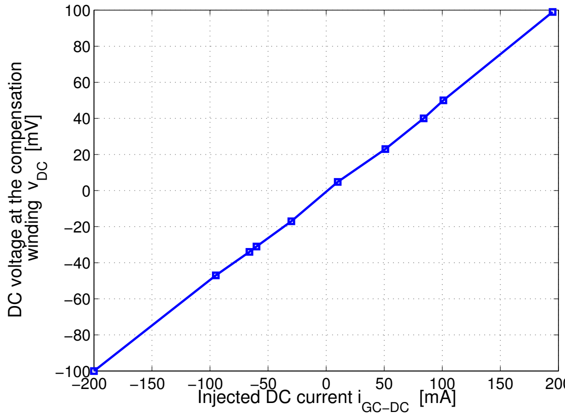

Fig. 14. DC voltage detected at the reactor compensation winding versus the DC current injected by the grid-connected converter into the transformer with a $v_{grid} = 220V_{RMS}$

holds as long as the length of the connecting wires of the windings can be neglected. This is generally true if the number of turns is high, but because the compensator winding is constituted only by two turns, the length of the connecting wires must be considered. In fact, the total length of the connecting wires was equal to 1 turn (in order to clamp the wire with the hall-effect probe of the oscilloscope), it means that the previous relationship can be rewritten

$$N_1 \frac{v_1^{DC}}{N_1 R} = N_2 \frac{v_2^{DC}}{(N_2+1) R} \tag{4}$$

considering $N_2 = 2$, it means that $\frac{3}{2} v_1^{DC} = v_2^{DC} = \hat{v}_{DC}$, thus

$$\frac{\hat{v}_1}{i_{GC_{DC}}} = \frac{3}{2} \frac{\hat{v}_{DC}}{i_{GC_{DC}}} \simeq \frac{2}{3} 0.5\Omega \simeq 0.33\Omega \tag{5}$$

This fact can also be used as an advantage, because a compensator winding with an higher resistance than the primary one could be used as an effective mean to amplify the DC voltage present in the grid, making the measure easier.

Fig. 14 shows that, considering the additional length of the compensation winding, the correct DC voltage could be sensed. Instead, in most voltmeter, being the accuracy tied to a certain percentage of full-scale reading, the DC voltage component can not be sensed.

The performances of the proposed sensor were evaluated with a variable grid voltage. The measures reported in Fig. 14 in case of a $v_{grid} = 220V_{RMS}$ were repeated for grid voltages from $190V_{RMS}$ to $240V_{RMS}$. Since, in this range, the V_{DC}/i_{GC-DC} characteristics are the straight lines, Fig. 15 summarizes all the measures with the slopes of these lines i.e., the coefficient $K = \frac{\hat{v}_{DC}}{i_{GC-DC}}$. Varying the grid voltage the experiments showed a slight variation of K, this is because the reactor current shows very large variations with the grid voltage, altering the behaviour of the compensation system. A compensation/calibration of the sensor is needed if it is important to increase the accuracy of the measure.

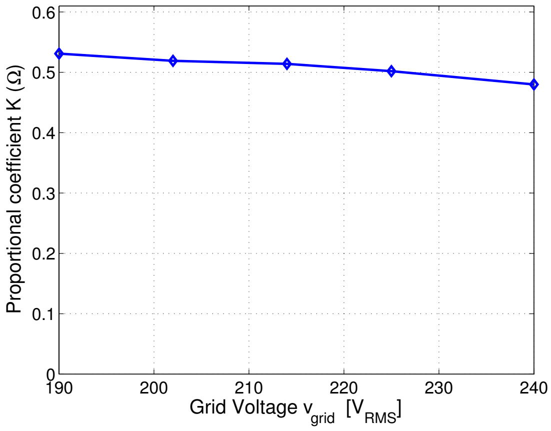

Fig. 15. Proportional coefficient $K = \frac{\hat{v}_{DC}}{i_{GC-DC}}$ for different values of the grid voltage.

In the following some oscilloscope captures are reported, in order to highlight some aspects of the proposed sensor and to show its robustness to AC grid voltage variations.

Fig. 16 shows the correct behavior of the SOGI-PLL structure adopted for the synchronization with the grid, whose schematic was reported in Fig. 5. The proposed solution, in fact, does not require the measure of grid voltage and therefore the angle of this one must be extracted from the reactor primary current. The first harmonic of the heavily distorted reactor current (due to saturation and hysteresis) is correctly extracted, along with its quadrature component. Then, the PLL reconstructs the angle. It is important to note that the internal variables of the DSP are displayed by a DAC (Digital-to-Analog Conversion) with an output range of $0-2V$, that comprises the whole range of the signed fixed point 1.15 arithmetic of the DSP i.e., the zero value is equal to $1V$ at the DAC output, the most negative value is equal to $0V$ and the most positive value is equal to $2V$.

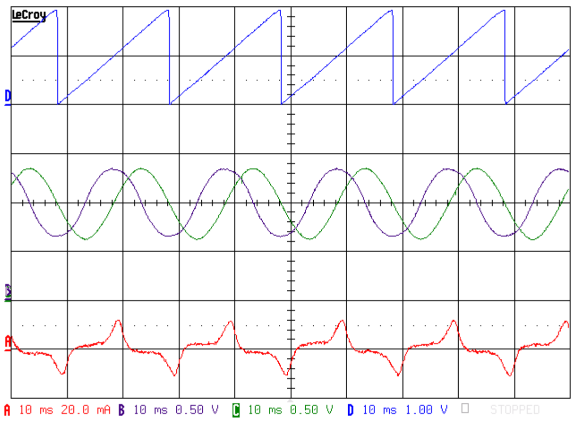

Fig. 16. Experimental waveforms of the SOGI-PLL structure used for grid synchronization. Reactor current angle (top waveform), reactor current first harmonic with quadrature signal (middle waveforms) and reactor primary current (bottom waveform).

Fig. 17 and Fig. 18 show the behavior of the compensation system reported in Fig. 4. The top waveform represents the output of the block DC Component Detector, $H = f(v_{DC})$, and in closed loop operations (Fig. 17) is correctly at $1V$ (equal to zero). The compensation winding current is also present (bottom waveform, i_2 in Fig. 4), and the reactor primary current is symmetric. In Fig. 18 the compensation system was turned off, the DC current injected into the transformer causes a DC voltage at the reactor primary winding, that renders asymmetric its current. This effect is correctly detected by the algorithm, in fact $H = f(v_{DC})$ is below the $1V$ voltage level, indicating that a negative DC component was detected.

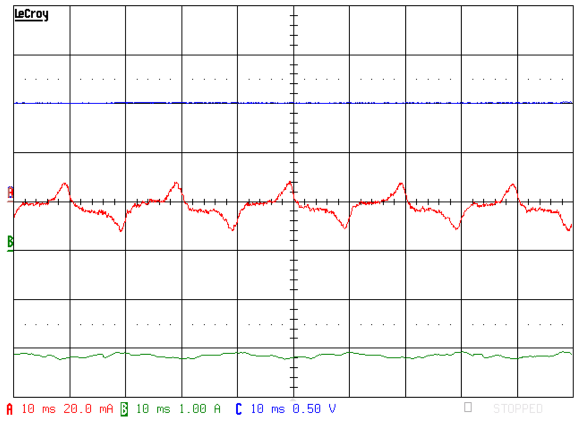

Fig. 17. Experimental results in case of $v_{grid} = 222V$ with $185mA$ of DC current component in the transformer. $H = f(v_{DC})$ (top waveform), reactor primary current (middle waveforms) and compensation winding current (bottom waveform).

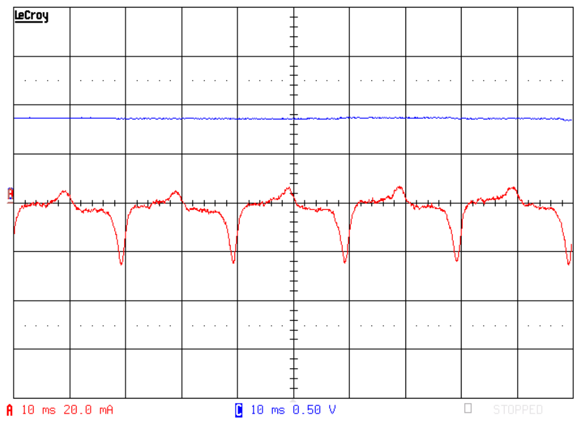

Fig. 18. Experimental results in case of $v_{grid} = 222V$ with $185mA$ DC current in the transformer without the reactor compensation system. $H = f(v_{DC})$ (top waveform), reactor primary current (middle waveforms).

Fig. 19 shows the dynamic behavior of the proposed sensor when a step variation of the DC current injected into the transformer is applied. The parameter of the regulator were chosen to ensure the stability in a wide range of variations of the reactor current, so the response is deliberately rather slow. It is to be noted that with a different choice of the parameters or a different regulator topology, the bandwidth of the system could be enhanced.

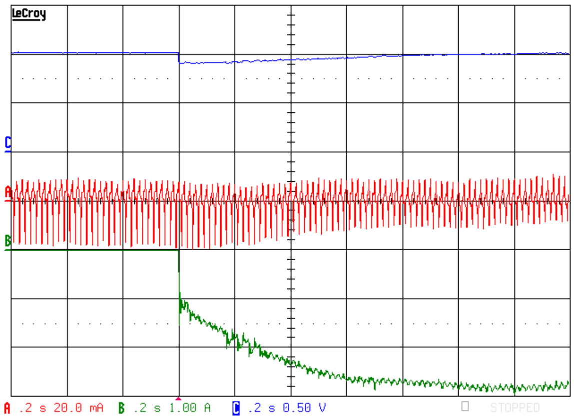

Fig. 19. Transient response when a DC current step of $180mA$ is applied to the transformer. $H = f(v_{DC})$ (top waveform), reactor primary current (middle waveforms) and compensation winding current (bottom waveform).

VI. Conclusion

This paper proposes a novel sensor to diagnose the extent of the asymmetric saturation of a distribution power transformer due to DC bias. The main cause of the DC bias is the widespread use of electronic converters (power supply, AC drives, grid-connected converters for renewable energy sources) which cause non-linear distortion in the grid current. The DC current flowing in the power transformer causes a small voltage drop on the transformer's winding resistance. The proposed DC voltage sensor is able to measure/estimate the DC voltage component with a high sensitivity and free from offset problems. Simulation results showed a very good behaviour of the proposed solution in closed loop operations in presence of significant variations of the amplitude of the grid voltage. A suitable test bed was built in order to validate experimentally the effectiveness of the compensated reactor sensor to estimate the DC voltage component across a transformer winding.

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