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Coupling transformer with a virtual air gap for the protection of dynamic voltage restorers

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Abstract—The dynamic voltage restorers are efficient series compensation devices to improve power quality. Indeed, they are composed of a coupling transformer and power electronics to provide fast voltage sag correction and harmonics compensation. This paper focuses on a new topology of a coupling transformer for the dynamic voltage restorers which improves the protection of the voltage source converter against grid fault including short-circuits, by changing the magnetic state of the transformer core. In this paper, the operating modes in steady state of the proposed coupling transformer equipped with a virtual air gap are studied by both Finite Element simulations and experimental measurements.

Keywords—Power distribution faults, Power Quality, Short-circuit currents, Uninterruptible power systems, Voltage fluctuations.

I. INTRODUCTION

In the overview of the Smart Grid and the decentralized energy, the elimination of the voltage disturbances is a key factor to improve the performances of the electrical grid. Indeed, non-linear load variations, motor starting and short-circuit faults, for instance, can be sources of voltage sags and therefore damage sensitive loads, decrease power quality and cause economic losses [1]. Custom power devices such as on-load tap changers [2,3] or Flexible AC Transmission Systems (FACTS) [4,5] are thus employed in distribution and transmission grids to mitigate the effects of voltage fluctuations and harmonics propagation.

Among them, the series voltage restorers, also known as Dynamic Voltage Restorers (DVR), are an efficient solution to improve power quality [6,7]. These compensation devices act as variable voltage sources inserted in series between the power supply and the critical loads. They mitigate voltage sags by injecting the appropriate voltage through a coupling transformer. Besides, series voltage regulators based on power electronics provide fast voltage sag correction and harmonics compensation.

Nevertheless, the voltage source converter has to be protected from high currents, when a fault occurs in the distribution grid. Nowadays, two solutions exist to protect the power electronic converter of the DVR: oversize the converter or integrate an electromechanic by-pass in parallel with the coupling transformer in order to deflect fault currents from the power electronic converter.

This paper deals with a new topology of the coupling transformer which improves the protection function of the voltage source converter, as an alternative to the current solutions. In the first part, the authors present both the geometry and the principle in steady state of this new topology. They especially explain how a magnetic by-pass obtained by the adding of a leakage return leg with a Virtual Air Gap (VAG) [8] allows modifying the circulation of the magnetic field lines in the coupling transformer. In the second part, the behaviour of this leakage return leg as a magnetic by-pass is detailed thanks to Finite Element (FE) simulations. In the third part, experimental results obtained on a laboratory single-phase reduced scale device are presented. In particular, the authors show that this new topology of the coupling transformer for a DVR is able to protect the power electronics from high fault currents due to a short-circuit on the distribution grid.

II. SERIES VOLTAGE REGULATORS WITH PROTECTED ELECTRONICS

A DVR is mainly composed of a coupling transformer, an energy storage unit and a voltage source converter. The first winding of the coupling transformer is connected to the feeder on the distribution grid. The second winding is connected to a voltage source inverter. The energy storage unit, *i.e.* the DC bus of the voltage source inverter, can be fed directly by the grid - either from the power supply side or the load side - or by an independent energy source [9].

A. Series Voltage Regulators with an Electromechanic By-pass

DVR with an electromechanic by-pass [10,11] include a coupling transformer inserted in the distribution grid between the power supply and the critical loads, an energy storage unit, a voltage source converter and an electromechanic by-pass (Fig. 1). In normal operation, the switches SW1 and SW2 are closed and SW3 is open. Thus, the voltage source converter via the coupling transformer continuously injects the appropriate voltage not to have any voltage disturbances at the loads side and the DVR is able to provide fast voltage sags compensation. When a fault occurs, the electromechanic by-pass connected in parallel to the coupling transformer deflects high fault currents over than a predetermined value. In this case, SW1 and SW2 are open and SW3 is closed, consequently the power electronic converter is protected against overload and short-circuits.

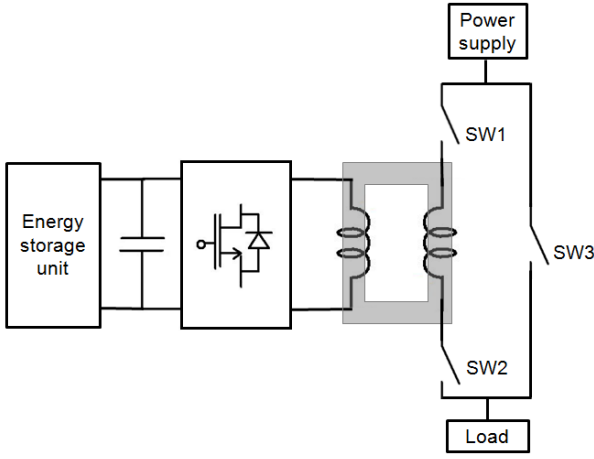


Fig. 1. DVR with the voltage source converter protected by an electromechanic by-pass

B. A Magnetic By-pass Based on the Virtual Air Gap Principle

As regards the current solutions for the voltage source converter protection, the time response of the DVR with an electromechanic by-pass between normal and fault operation can be high since the opening and the closure of the by-pass needs a fault operation detection device. To propose an alternative solution to the electromechanic by-pass of the series voltage regulators described in section II-A, a magnetic by-pass using the VAG principle is proposed. The concept of the VAG [8,12]–[14] is based on the local saturation of a magnetic core (Fig. 2). The effects of this local saturation are similar to those of a mechanical air gap. In order to locally saturate the magnetic core, one or several auxiliary windings inserted in holes or windows inside the magnetic core are fed by a DC current i_{DC} [15]. Consequently, the amplitude of the magnetic field lines which circulate around the holes controls the local saturation of the magnetic core and therefore the thickness of the equivalent mechanical air gap.

For the proposed coupling transformer (Fig. 3), the VAG aims to act as a magnetic by-pass which protects the voltage source converter from high fault currents. The operating modes of the coupling transformer can be obtained by the saturation and the desaturation of the return leakage leg. Actually, for normal line currents, the VAG can be seen as a magnetic open

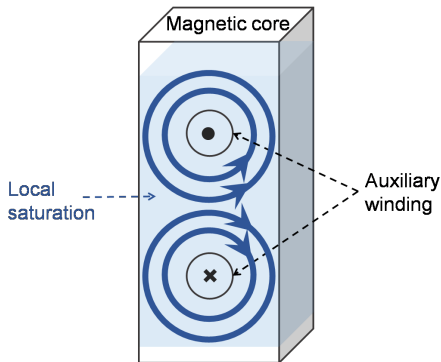


Fig. 2. Local saturation of the magnetic core

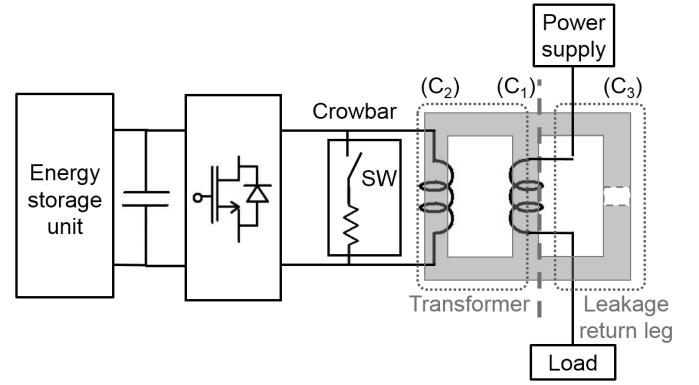


Fig. 3. Single-phase coupling transformer protected by a magnetic by-pass

switch whereas for high line fault currents, it behaves as a magnetic closed switch.

C. Series Voltage Regulators with a Magnetic By-pass

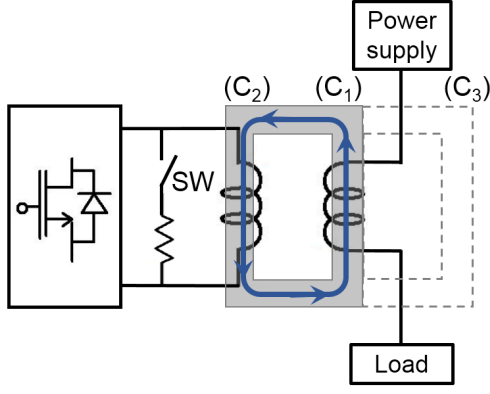
The new topology of the proposed coupling transformer [15] integrates the VAG in a leakage return leg C_3 added to a standard coupling transformer (Fig. 3) to optimize the protection function of the voltage source inverter. As for the series voltage regulators with an electromechanic by-pass described in section II-A, the primary winding of the coupling transformer is connected to a feeder of the distribution grid and the secondary winding remains connected to a voltage source inverter.

In normal operation (Fig. 4a), the leakage return leg is saturated. Thus, as it will be detailed in section III-B, the magnetic flux generated by the primary winding circulates in the secondary leg C_2 only. Hence, the high reluctance of the leakage return leg C_3 improves the magnetic coupling between the primary and the secondary windings during normal operation. In this operating mode, the coupling transformer acts as a voltage transformer. Therefore, the DVR can compensate voltage fluctuations by injecting the appropriate voltage.

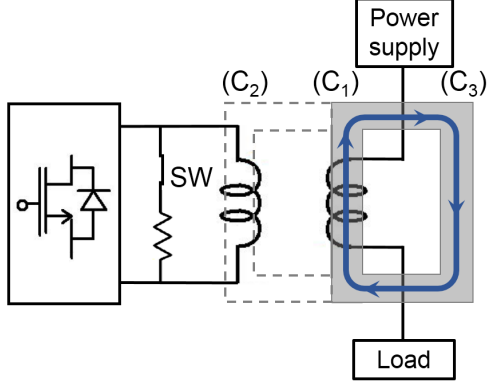
In fault conditions (Fig. 4b), the power electronic converter is protected from high distribution grid fault currents by the closure of a crowbar [16] connected between the secondary winding and the voltage source inverter. Consequently, as it will be shown in section III-C, the magnetic flux generated by the primary winding circulates in the leg C_3 and the magnetic coupling between the primary and the secondary windings is poor.

D. Equivalent Electric Circuit of the Coupling Transformer with a Virtual Air Gap

The equivalent reluctance of the VAG is modified by i_{DC} and influenced by the primary current i_p . Therefore, the coupling transformer (Fig. 5) can be electrically represented by a regular transformer with an extra leakage inductance L_{VAG} which depends on the two previous variables. Fig. 6 shows an electric equivalent representation of the coupling transformer with inductances which are related to the primary (L_p), the secondary (L_s) and the leakage return (L_{VAG}) legs [15]. These



(a) Normal operation



(b) Fault operation

Fig. 4. Magnetic flux path in the coupling transformer for the two different operating modes

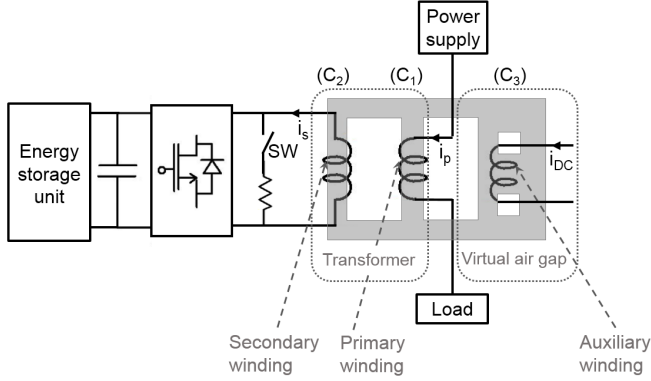


Fig. 5. Coupling transformer with a VAG in the leakage return leg

inductances depend on the reluctance of the magnetic core part considered and the associated number of turns of the winding.

In normal operation, L_{VAG} is low and so the coupling transformer operates as a voltage transformer. In fault operation, the value of L_{VAG} increases and so the secondary current i_s is reduced and the power electronic converter is protected. Hence, the variation of L_{VAG} with i_{DC} can mitigate i_s during a distribution grid fault.

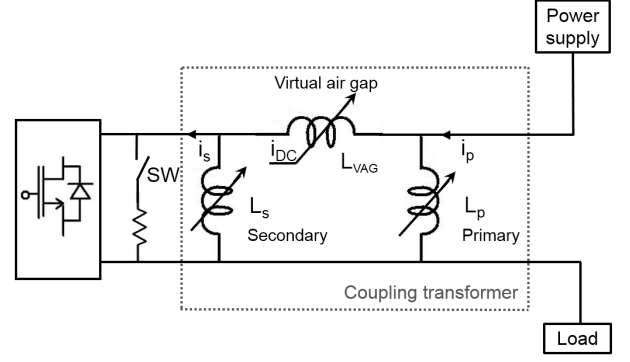


Fig. 6. Electrical equivalent circuit of the coupling transformer

III. NUMERICAL SIMULATIONS

A. Finite Element Model

In order to analyze and to understand the magnetic flux distribution in the coupling transformer, FE simulations of the experimental device presented in section IV have been performed by using the software Gmsh [17] and GetDP [18]. To ensure the validity of the results, every computation have been done by using each of the dual magnetic formulations, *i.e.* both magnetic scalar and vector potential formulations [19]. Moreover, the model is excited by imposing a sinusoidal current density inside the primary winding and a DC current density in the auxiliary winding. The secondary winding, as for itself, is excited by using electrical circuit equations coupled to the FE equations [20]. It allows imposing a voltage value at the secondary winding instead of a current density, and then, taking into account a short-circuit. Hence, this voltage can be set to a non-zero value in the case of normal operation, whereas it is set to zero in the case of fault operation. Lastly, the non-linearity of the magnetic materials is taken into account by using first magnetization $b(h)$ curves.

B. Normal operation

In normal operation, as the amplitude of the AC magnetic field lines which circulate in the leakage return leg is inferior to the amplitude of the DC magnetic field lines, the leakage return leg is highly saturated by the DC field and more than 90 % of the AC field lines generated by the primary winding circulate in the secondary leg (Fig. 7). Hence, the magnetic coupling between the main windings is high and so L_{VAG} is low.

C. Fault operation

When a fault appears in the distribution grid, two approaches are considered to supply the auxiliary winding in fault operation:

- 1) keep i_{DC} constant in fault operation (Fig. 8a),
- 2) cancel i_{DC} at the detection of the fault (Fig. 8b).

The first one is a less efficient but a more economic and an easier option to implement. The other approach is more efficient but needs a detection fault device to modify the intensity of the DC current in the auxiliary winding.

The efficiency of this two approaches will be compared in section IV.

In this operating mode, since the crowbar is closed and according to the Lenz's Law, a magnetomotive force is induced in the secondary short-circuited winding. Hence, it prevents the AC magnetic field lines generated by the primary winding from circulating in the secondary leg. Indeed, less than 10 % of the AC field lines generated by the primary winding circulate in the secondary leg. In the case of a non-zero i_{DC} , the amplitude of the AC magnetic field lines which circulate in the leakage return leg becomes superior to the amplitude of the DC magnetic field lines. Thus, the effect of the local saturation of the leakage return leg is modified (Fig. 8a). On the other hand, in the case where i_{DC} is equal to zero, the VAG is inactive and the AC magnetic lines circulate only in the vertical legs of the leakage return leg (Fig. 8b). Consequently, in both cases, the magnetic coupling between the main windings is low and L_{VAG} is high.

It can be noticed that the operation of the coupling transformer depends on the ratio between the amplitude of the AC magnetic field lines (generated by the primary winding) and the amplitude of the DC magnetic field lines (generated by the auxiliary winding) in the leakage return leg.

IV. EXPERIMENTAL RESULTS

A. Experimental Device

An experimental single-phase device of the coupling transformer (Fig. 9) was made to validate the action of the VAG toward the protection of the voltage source converter connected to the secondary winding of the coupling transformer against high line currents.

The magnetic core of the coupling transformer is composed of two parts:

- a standard transformer part with the main windings for the left side,

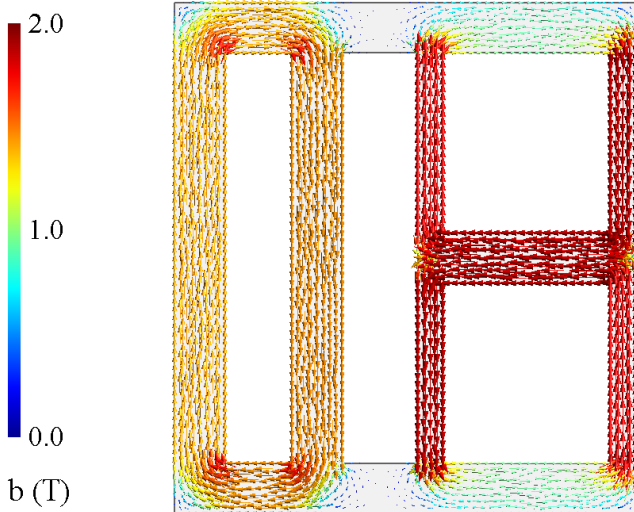
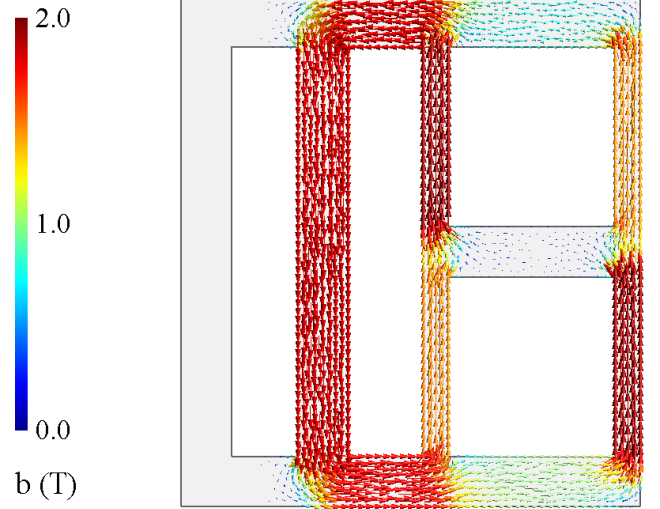
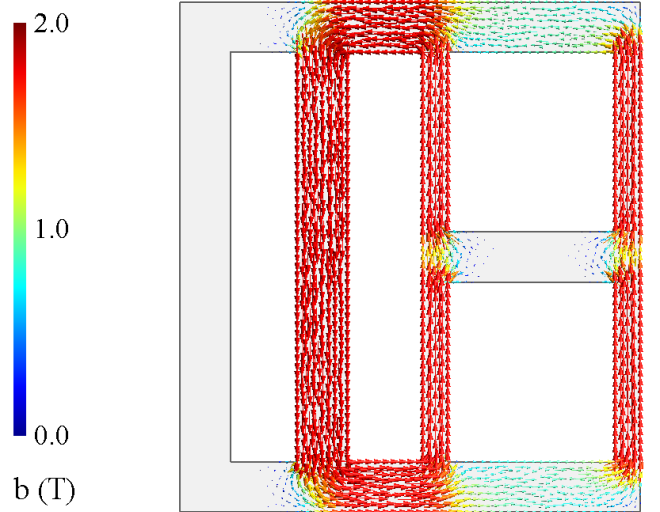


Fig. 7. Flux density distribution in normal operation



(a) With a DC current in the auxiliary winding



(b) Without a DC current in the auxiliary winding

Fig. 8. Flux density distribution in fault operation

- a leakage return leg composed of a pair of rectangular windows and with an auxiliary winding for the right side (Fig. 9).

The magnetic core is built with Epstein sheets stacked with double-lapped joints each other like on the Epstein frame. The vertical legs of the leakage return leg are composed of twice as less sheets as the others legs of the magnetic core. This arrangement of the sheets makes it possible to saturate easily the leakage return leg with a low DC current intensity, in normal operation. As regards the windings, the turn ratio between the main windings is equal to 1 and the number of turns of the auxiliary winding was determined to saturate the leakage return leg during normal operation. Table I describes the characteristics of the experimental device of the coupling transformer. Besides, some flux sensors coils are wound around the magnetic core to observe the magnetic

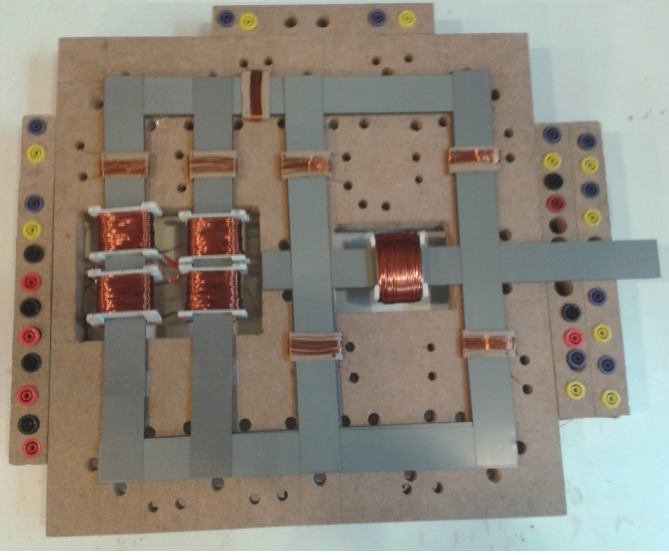


Fig. 9. Experimental single-phase device of the coupling transformer

TABLE I. CHARACTERISTICS OF THE EXPERIMENTAL DEVICE

Size of the Epstein sheets (Length×Width×Thickness)	30.5 cm×3 cm×0.035 cm
Size of the magnetic circuit (Length×Width×Thickness)	30.5 cm×3 cm×0.35 cm
Number of turns of the main windings	120
Number of turns of the auxiliary winding	750
Maximum primary voltage V_p	15 V
Maximum primary current I_p	10 A
Maximum DC current I_{DC}	0.5 A

flux distribution (Fig. 9).

The experimental analysis concerns the action of the VAG on the voltage source converter protection in steady state. Consequently, the experiments have been made with the secondary winding short-circuited, which means that the crowbar is assumed to be in closed position and the voltage injected by the voltage source inverter is equal to zero. The primary winding is fed by a laboratory voltage source with a resistance which represent the power supply and the loads of the distribution grid. The auxiliary winding is connected to a voltage DC laboratory power supply in series with a resistance to impose a current in this winding. Fig. 10 shows the electrical equivalent circuit for this experimental case.

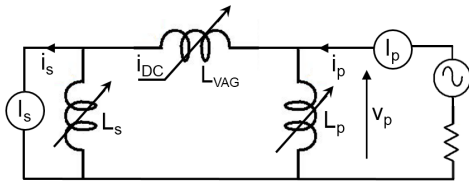


Fig. 10. Electrical equivalent circuit of the coupling transformer when the crowbar is closed

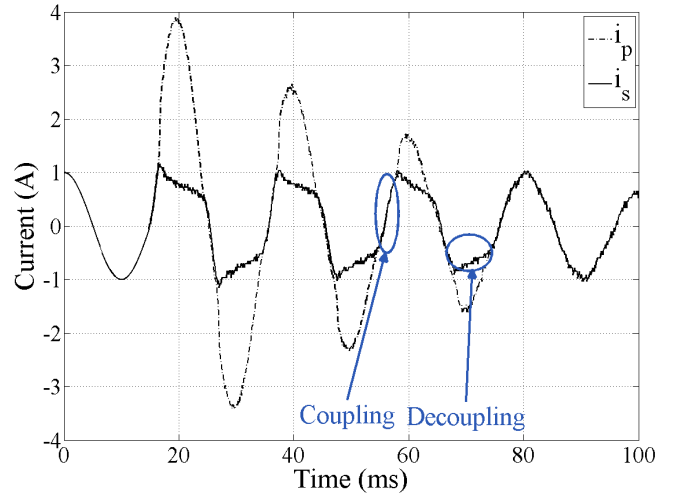


Fig. 11. Magnetic coupling and decoupling of the main windings with the intensity of the DC current i_{DC} equal to 0.1 A

B. Results

1) *Magnetic coupling and decoupling:* As it was explained previously, when i_p is inferior to a predetermined value that is fixed by i_{DC} , the coupling transformer operates as a current transformer. The VAG is active, and consequently, the AC magnetic field lines go through the primary and the secondary legs. In this case, the primary and the secondary windings are highly magnetically coupled. Besides, it could be noted that the ratio between i_s and i_p is equal to 0.97 for the experimental device considered, due to the design of the magnetic core by double overlapping with Epstein sheets. In fault conditions, when i_p is higher than the predetermined value, the magnetic coupling between the primary and the secondary windings is low since the AC magnetic field lines generated by the primary winding circulate in the leakage return leg. Hence, i_s is limited and it can be considered that the voltage source inverter is protected against high fault currents. Thus, the magnetic coupling and decoupling between the main windings depends on i_p for a fixed i_{DC} (Fig. 11).

The decoupling between the main windings is automatic when i_p suddenly increases. Indeed, as soon as the fault in the distribution grid is eliminated, the coupling transformer can operate in normal operation without any exterior action and vice versa. Consequently, the VAG allows a fast and spontaneous magnetic commutation and acts as a by-pass which permits or not the circulation of the AC field lines in the leakage return leg.

2) *Control of the secondary current limitation:* The limitation of i_s is fixed by i_{DC} . Actually, i_{DC} partly controls the saturation of the leakage return leg, and so the magnetic coupling between the primary and secondary windings. The higher the amplitude of the DC field lines in the leakage return leg, the more the leakage return leg is saturated and the less i_s is limited (Fig. 12). For instance, Fig. 11 shows that i_s is limited to 1.2 A when i_{DC} is equal to 0.1 A.

It can be noticed that the best performances of the coupling transformer as concerns the limitation of i_s are obtained

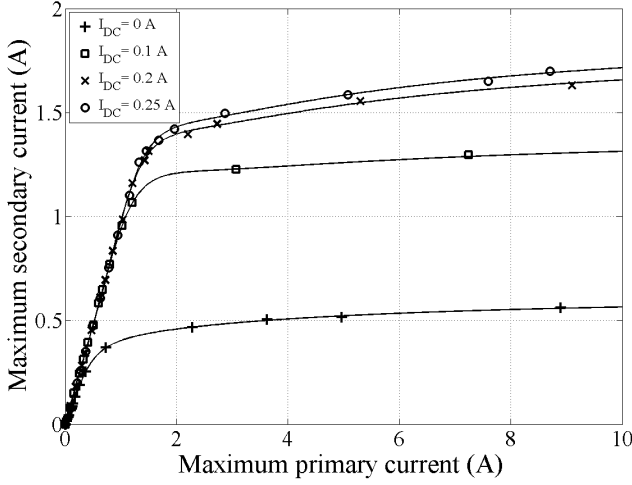


Fig. 12. Variation of the secondary current i_s according to the primary current i_p and the DC current i_{DC}

when i_{DC} is equal to zero. That is why, this supply strategy of the auxiliary winding is considered, even if in this case an additional fault detection device is needed to modify i_{DC} injected in the auxiliary winding.

3) *Inductance behaviour of the virtual air gap*: As it was mentioned in section II-D, the coupling transformer with a VAG can be seen as an equivalent variable inductance L_{eq} connected in series in the electrical grid. When the secondary winding is short-circuited, L_{eq} corresponds to L_{VAG} in parallel with L_p (Fig. 10).

In normal operation, since L_{VAG} is low (Fig. 13), the coupling transformer behaves as a voltage transformer to compensate distribution grid voltage fluctuations. When a fault appears in the distribution grid, for a fixed i_{DC} , L_{VAG} increases since the AC magnetic field lines cancel the saturation of the leakage return leg by circulating in the latest. Moreover, the highest variation of the inductivity between normal and fault operations is obtained by cancelling i_{DC} in the auxiliary winding at the apparition of a fault in the primary winding. For very high i_p , the measured equivalent inductance of the coupling transformer seen by the primary winding keeps low due to the design of the experimental device. Actually, in this case the primary leg is saturated by the amplitude of the AC magnetic field lines, so L_{eq} corresponds to the inductance L_p of the primary leg saturated.

V. CONCLUSION

A new topology of the coupling transformer with a VAG inserted in a leakage return leg was presented. As regards both the FE simulations and the experimental results, the local saturation and desaturation of the magnetic core is able to improve the protection of the voltage source converter of a DVR against high line currents. Indeed, the flux density distribution during normal and fault operations, explained with the FE model, showed that the VAG behaves as a magnetic by-pass by modifying the circulation of the AC magnetic field lines in the magnetic core. Moreover, the operation principle of the coupling transformer, *i.e.* the behaviour of the leakage return

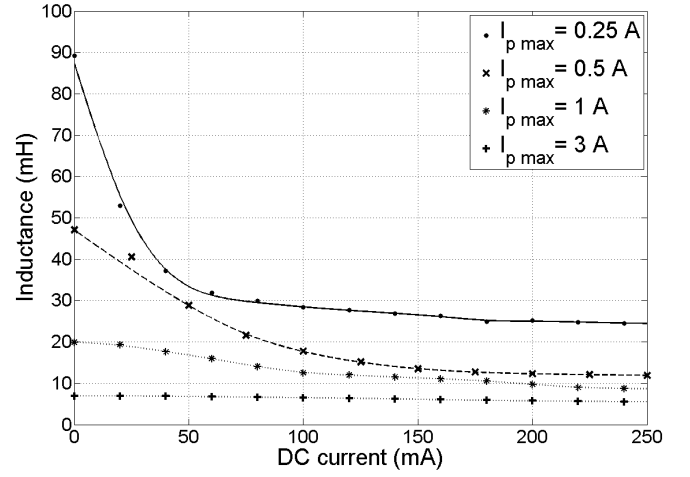


Fig. 13. Variation of the equivalent inductance L_{eq} according to the DC current i_{DC} and the primary current i_p

leg as a magnetic by-pass which limits the secondary current described has been validated with a laboratory single-phase reduced scale device.

A low voltage prototype of the coupling transformer with a VAG in a leakage return leg is currently designing. Then, experiments will be realised to validate the operating principle of the VAG with a 23 V and 41 A coupling transformer. Experiments will consist in observing the behaviour of the coupling transformer during a motor starting which characterizes a transient fault and induces voltage disturbances. Moreover, the influence of the steel grades on the magnetic coupling and decoupling phenomenon will also be studied.

At long term perspective, a medium voltage prototype of the DVR composed of three single-phase coupling transformers with a VAG will be inserted in series in the distribution grid. It will be designed to regulate 10% of the rated single voltage and to protect the voltage source converter against grid fault currents.

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