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Electrical Circuit Design of a Coupling Transformer with a Virtual Air Gap

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Abstract – The Dynamic Voltage Restorers composed of a coupling transformer and a Voltage Source Converter are efficient series devices to improve the power quality of electrical grids. For the proposed coupling transformer, an embedded magnetic bypass based on the Virtual Air Gap principle aims to protect the Voltage Source Converter against high fault grid currents instead of the usual electro-mechanical bypass. This paper focuses on the design method of the electrical auxiliary circuit of this magnetic bypass.

I. INTRODUCTION

The Dynamic Voltage Restorer (DVR) compensates voltage fluctuations in electrical grids to efficiently improve the power quality [1]. For the existing DVR, the usual protection scheme of the Voltage Source Converter (VSC) is an electro-mechanical bypass [2] which deflects high fault currents from the coupling transformer with a high time response. The proposed alternative aims to reduce this time response by using a magnetic bypass composed of a return leakage leg with a Virtual Air Gap (VAG) added to a standard transformer part to deflect the magnetic flux from the leg connected to the VSC for grid fault conditions.

The operating principle of the VAG as a VSC magnetic protection scheme was validated with both Finite Element Analysis (FEA) and laboratory tests on a single-phase reduced scale device [3]. Then, the operation principle of such a device at industrial rated electrical values has been performed. The design of a single-phase low voltage prototype includes two parts: the magnetic core [4] and the electrical circuit of the magnetic bypass. The aim of this paper is to explain how the second part of design was achieved. From the designed magnetic core, the authors explain how the arrangement, the connection and the supply of the auxiliary windings play a role on the performances of the magnetic bypass of the coupling transformer.

II. DVR WITH POWER ELECTRONICS PROTECTED BY A MAGNETIC BYPASS

The proposed DVR [3] includes a coupling transformer with the primary winding inserted between a supply and critical loads and the secondary winding connected to a VSC and an energy storage unit (Figure 1). The magnetic protection scheme of the VSC is ensured by the adding of a return leakage leg with a VAG which is defined as a monitored local saturation of the magnetic core by a DC current, to the transformer part of the coupling transformer. For the coupling transformer, the VAG can be used to control the circulation of the magnetic flux in the transformer part and then, the magnetic coupling between the windings of the transformer part. According to the state of the VAG, the coupling transformer has two operation modes in steady state: Normal

and Fault operations. In Normal operation, the return leakage leg saturated is magnetically equivalent to an air gap. The coupling transformer behaves as a voltage transformer. In Fault operation, the return leakage desaturated is magnetically equivalent to a high permeability core. The AC magnetic flux is deflected from the secondary leg to the return leakage leg.

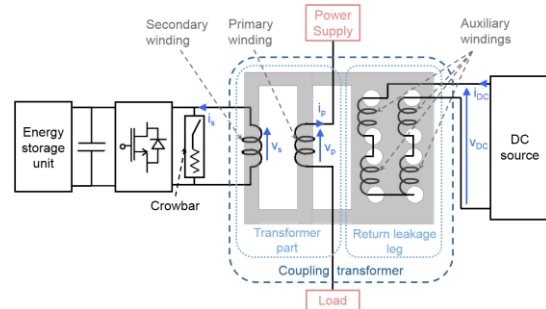


Fig. 1. DVR with a magnetic bypass in a return leakage leg

III. DESIGN OF THE COUPLING TRANSFORMER

A. Design method of the coupling transformer

The electrical specifications for the design of the coupling transformer are those of the electrical grid in which the DVR is inserted: the rated grid current and the regulated voltage range for the Normal operation and the intensity of the fault grid current for the Fault operation. As for standard transformers, the design of the coupling transformer included two steps: the design of the magnetic core and the design of the electrical circuits. The first one was realized in two parts [4]. First the transformer part was designed according to the electrical specifications in Normal operation and with the standard transformer design rules. Then, the magnetic core of the return leakage leg added to the previously designed transformer part was defined with FEA by considering the Fault operation specifications of the coupling transformer.

B. Finite Element model of the coupling transformer

The design of the coupling transformer have been performed with FEA in 2-Dimensions by using the softwares Gmsh and GetDP. This modeling provides a good understanding of the operation of the specific coupling transformer with a VAG which combine both DC and AC magnetic flux. For the magnetic core, the isotropy and the non-linearity of the magnetic materials is taken into account by using first magnetization B(H) curves. For the electrical circuits, the windings are excited by using electrical circuit equations coupled to the Finite Element equations according to the studied case. A sinusoidal current density or a sinusoidal voltage is imposed for the primary winding. A DC current density or a DC voltage is imposed for the auxiliary windings. A sinusoidal voltage is imposed at the terminals of the

secondary winding and especially a zero voltage value in Fault operation.

IV. DESIGN OF THE ELECTRICAL CIRCUIT PART

A. Parameters studied

The second step of the design of the coupling transformer consists in adding the auxiliary windings to ensure the performances of coupling transformer, *i.e* the magnetic coupling between the primary and the secondary windings in Normal operation and the limitation of the secondary current i_s in Fault operation. In this case, FEA focuses on the study of three parameters of the electrical circuit of the auxiliary windings: the orientation of the auxiliary windings in the return leakage leg, their connection and the behavior of the DC power supply. For these configurations, the magnetic coupling in Normal operation, the intensity of i_s in Fault operation, the variation of the voltage at the DC source terminals v_{DC} and the variation of intensity of the DC source i_{DC} is compared to determine the best way to realize the magnetic bypass of the coupling transformer.

B. Influence of the behavior of the DC source toward the performance of the coupling transformer

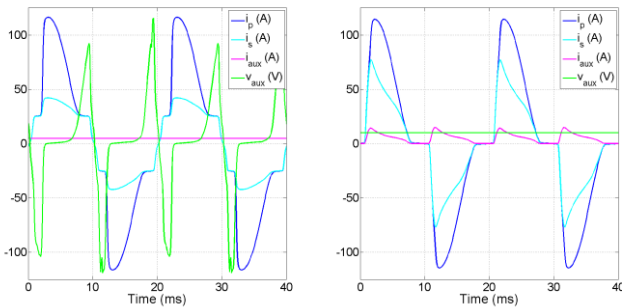


Fig.2. FEA results: $I_{DC} = 5$ A (left) or $V_{DC} = 10$ V and $R_{DC} = 2 \Omega$ (right)

FEA consider a current source or a voltage DC source with a resistance for a magnetic density equal to 2 T in the saturated return leakage leg (Figure 2) to supply each auxiliary winding. The limitation of i_s is better with a current source. The variation of i_{aux} is more important with a voltage one whereas the induced overvoltage v_{aux} with an ideal current source has to be controlled. Hence, a compromise has to be made to avoid the DC source electrical values variations.

V. LOW VOLTAGE SINGLE-PHASE COUPLING TRANSFORMER

A. Experimental device

TABLE I

LOW VOLTAGE SINGLE-PHASE COUPLING TRANSFORMER CHARACTERISTICS	
Rated current	41 A rms
Regulated voltage	$\pm 10 \%$
DC Current (Normal operation)	5 A
Size (Length*Width*Thickness)	30 cm * 30 cm * 4.8 cm
Electrical steel	PowerCore C135-35

Based on the previous design, a single-phase low voltage coupling transformer (Figure 3 and Table 1) has been realized and tested to confirm FEA. It is composed of a UI-shape transformer part, a return leakage leg with four pairs of circular holes and vertical auxiliary windings.

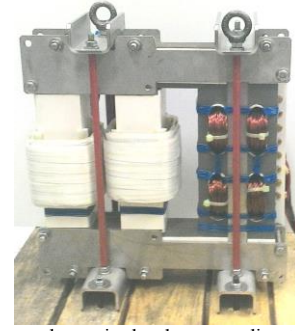


Fig.3. Low voltage single-phase coupling transformer

B. Influence of the number of auxiliary windings supplied toward the performance of the coupling transformer

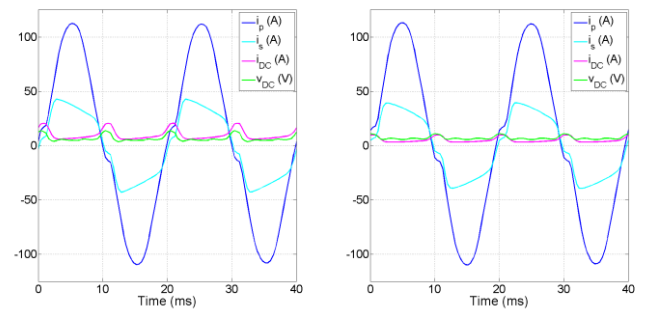


Fig.4. Tests results: one pair (left) or two pairs (right) of auxiliary windings

The laboratory tests of the coupling transformer consist in generating of a high primary current in safety conditions during the starting of a 22 kW induction machine. One pair or two pairs (Figure 4) of auxiliary windings are connected in series to a DC voltage source with the number of Ampere-Turns constant, $N_{DC}I_{DC} = 1600$ A.tr. The magnetic coupling in Normal operation and the limitation of i_s are slightly better with two pairs supplied. Moreover, the variation of i_{DC} and v_{DC} is reduced by 50% with two pairs of auxiliary windings supplied. Consequently, the coupling transformer operates more efficiently when the saturation is spread across the all return leakage leg with a possible lower local saturation level.

CONCLUSION

The realization of the electrical circuit with the auxiliary windings of the DC source impacts the performances of the coupling transformer. The extended paper will study the influence of the parameters previously cited, by FEA and experiments to find the appropriate auxiliary electrical circuit.

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