AN IMPROVED POWER TRANSFORMER DESIGN FOR DYNAMIC VOLTAGE RESTORATION APPLICATIONS

Pablo ARBOLEYA
University of Oviedo – Spain
arboleyapablo@uniovi.es

Manuel COTO
University of Oviedo – Spain
cotomanuel@uniovi.es

Jose COTO
University of Oviedo – Spain
jcoto@uniovi.es

ABSTRACT

In this paper, the problem of injection transformer saturation in dynamic voltage restoration (DVR) applications is analyzed and an innovative solution is given. The inrush currents caused by the injection transformer saturation are one of the most serious problems that affects to this kind of systems. Most adopted solution is the oversizing of the injection transformer, however this solution drastically increments the cost of the system. What the authors propose is a solution based in a DC reactor type inrush current limiter (ICL). The proposed solution is design a transformer that includes an auxiliary coil that can be used like the dc reactor. To study and validate this design FEA (Finite element analysis) are used.

INTRODUCTION

A voltage sag can be defined as a temporary reduction of the RMS voltage, which has an approximate duration that ranges from 0.5 cycles up to 30 cycles [1]. This phenomenon is virtually impossible to avoid, due to the time it takes to restore the faults that generate this outcome is finite and the propagation of this fault through the lines [2]. An extended explanation of the origin and consequences of this type of voltage sags can be found in [3].

The main function of DVR is to mitigate the voltage sag. One of the problems that must be considered in the design of a DVR is the choosing of the transformer. There are some aspects that must be taken into account, such as voltage drop, power losses, or phase shift angle, but the most serious problem is the power transformer saturation during the energisation transients [4]. The magnetization phenomenon in the injection transformer can generate high values of inrush current. These high current values have two important consequences; the first one is the trip of the converter overcurrent protection during a sag. The second one is a bad restoration of the grid voltage due to the voltage drops caused by the inrush currents. In order to avoid this problem the injection transformer must be oversized but this solution puts up the prize of the DVR [5]. The use of transformerless structures is proposed by some authors; however, the injection transformer provides electrical isolation and voltage boost [6] and [7].

What the authors propose in this paper is the use of a DC reactor type transformer inrush current limiter (ICL) in order to limit the inrush current in the injection transformer. This ICL is similar to the one proposed in [8], however in this case the ICL is connected in an improved power transformer design that includes an auxiliary coil. The use of this current limiter can reduce the injection transformer size and the cost of the whole system [9]. However, this solution maintains the electrical isolation permitting the use of one shared DC-link and allows to boot the voltage level with the transformer turns ratio, so cascaded switches or inverters are no needed.

In order to verify the method, both, simulations using MATLAB/Simulink and experimental tests were carried out in a topology with the auxiliary coil out of the transformer and finally the system with the dc reactor included in the transformer is studied and validated using electromagnetic Finite Element Analysis (Flux 2D).

SYSTEM TOPOLOGY AND CONTROL

In this case of study, the modelled system has he topology of a conventional dynamic voltage restoration system. In Figure 1 a simplified scheme of the proposed system is presented.

In the DC-link an ideal voltage source is used. Some authors use more complex energy source models, see for instance [10], [11].

A three-phase converter is used. Regarding the control, there are basically three methods of mitigating voltage sags [12].The first one is known as presage [5]. Alternative methods are used such as the in-phase voltage injection technique [12]. Finally in [9], the method known as phase advance or minimal energy is described. The common problem that appears in all these methods is the injection transformer saturation. All of these correction methods were tested and implemented in the model. But if the ICL method works with a pre-sag control, it will do with in-phase and minimal-energy control too, due to the fact that it usually generates higher voltage references.

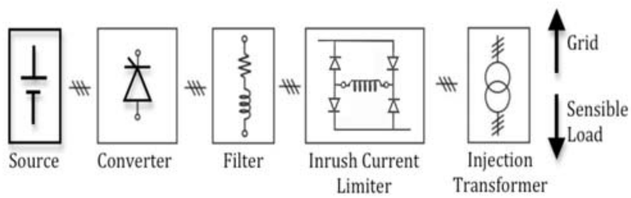

Fig. 1. Single-phase representation of the proposed system

SYSTEM TRANSFORMER MODEL AND FILTER VALUES

The authors modeled a 250/250V, 30kVA injection transformer with 400W copper losses and approximately 150W iron losses. The short circuit voltage is 5% and the rated frequency is 50Hz. The sags will be generated in a 400V 50Hz network so voltage boost function of the injection transformer is not needed. The p.u. obtained values with a Sbase=30kVA and V1base=V2base=250V are the next:

R1 = R2 = 0.067 p.u.
L1 = L2 = 7.6696e-5 p.u.
Rm=416.67 p.u.

Where:

- R1 and R2 are respectively the primary and secondary power transformer winding resistances in p.u. value.
- L1 and L2 are respectively the primary and secondary power transformer leakage inductances in p.u. value.
- Rm is the core loss resistance in p.u. value.

The saturation characteristic is given in terms of pairs current and magnetization flux values. Table 1 contents the mentioned saturation characteristic without hysteresis.

TABLE I
SATURATION CHARACTERISTIC

Current (p.u.)	**FLux (p.u.)**
0	0
0.001	0.60
0.0015	0.830
0.00216	1.080
0.003	1.140
0.004	1.1675
0.005	1.187
0.008	1.195
0.011	1.2025
1	1.47

PROBLEM STATEMENT

The DVR injection transformer performance during a voltage sag is analyzed. The voltage sag generated in the three-phase 400V, 50Hz feeder has a depth of 140V (RMS) with a connected load of 32kW. Analyzing the simulation results, it can be observed that the severity of this sag is serious enough to produce the injection transformer saturation.

In Figures 2 and 3 the obtained results without and with ICL device can be observed and compared. In both figures, DVR upstream and downstream voltages are depicted as well as converter currents and power supply by the grid, by the DVR and absorbed by the load.

As it can be observed in Figure 2, the saturation of the injection transformer during the sag, causes a bad voltage restoration and extremely high currents through the converter.

EXPERIMENTAL RESULTS

In order to validate ICLs in DVR applications to limit the inrush current, a set of laboratory tests were carried out. The case of study and the laboratory bench were chosen to be able to study the worst scenario. This scenario consists on a voltage sag with a depth equals to the nominal voltage value. This implies during the sag the voltage drops to 0V if the voltage restorer is not used. Moreover the DVR provides to the load an active power equals to the injection transformer nominal power. In this case, the used scheme to test the system in laboratory can be observed in Figure 4.

In Figure 4a) and b), control and power scheme are represented.

In Figure 5 a case of study without ICL is presented using a 5kVA, 400/400V, 50Hz one-phase power transformer is used.

The load rated power is 5kW. Both V1 and V2 are 410V (RMS) voltage sources. During the voltage sag the power

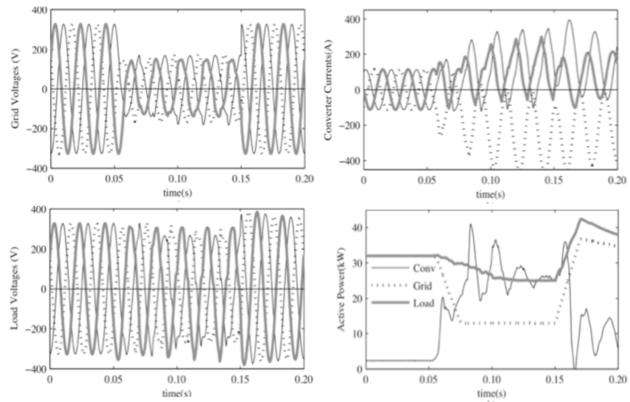

Fig. 2. DVR behavior under injection transformer saturation scenario during a sag condition

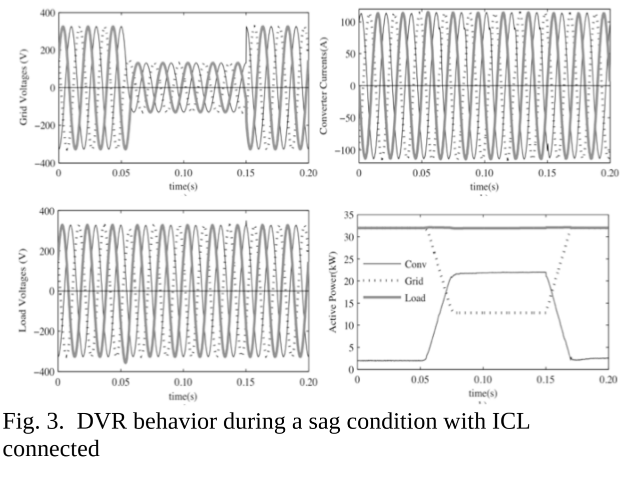

Fig. 3. DVR behavior during a sag condition with ICL connected

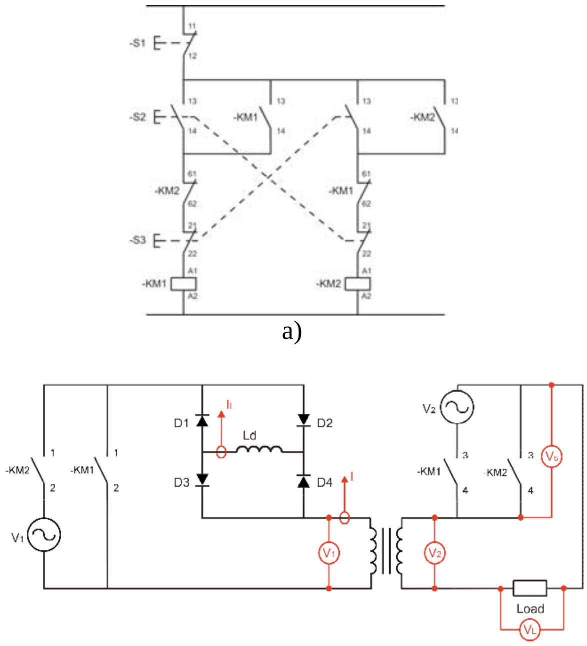

Fig. 4. Laboratory setup

transformer is fed using a voltage value higher than the rated voltage of the injection transformer, and the power supplied by the DVR is the power transformer rated power. In such case a severe saturation scenario is reached in the power transformer as it can be observed in Figure 5a). At t=0.916s the voltage sag is generated. In the first cycle the current rises up to 70A (The rated current is 12.5A (RMS.)). It must be remarked that during this first cycle the saturation in current sensor is produced. Analyzing the evolution of the transient decaying of this inrush, we can assert that the current exceed 100A. In this case, the internal injection transformer resistance is not high enough to produce an appreciable voltage drop and the system produces acceptable fault compensation. In Figure 5b), the measured V1 and Vs voltages are shown. In Figure 5c) the measured load voltage (VL) is represented.

In the test presented in Figure 6 the effect of the ICL are depicted. In this case equivalent sag is produced but this time the ICL limits the inrush to values lower than 25A.

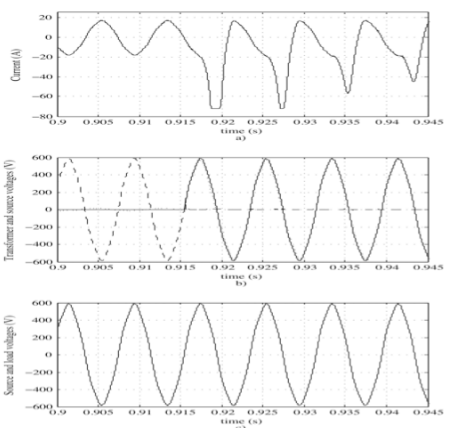

Fig. 5. Tests without ICL.

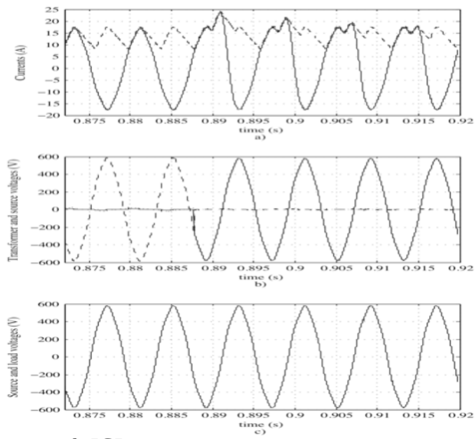

Fig. 6. Tests with ICL.

In Figure 6a) we can also represent the measured current through the DC reactor inductance (IL).

IMPROVED POWER TRANSFORMER

The main problem of the solution exposed above is the size and the requirements of magnetic material for the reactor, and the cost increase of whole system, so the next step is the design of a transformer that includes an auxiliary coil that can be used like the dc reactor, Figures 7 and 8.

To study and validate this design FEA (Finite element analysis) are used. The obtained results show that the using of the new design of the injection transformer with the embedded DC reactor coil can reduce the amount of magnetic material used to construct the dynamic voltage restorer.

In Figure 9, it can be observed the effect of the auxiliary coil in the inrush currents. In Figure 9a) no auxiliary

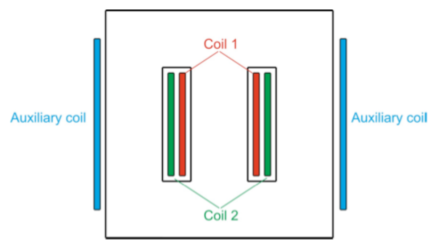

Fig. 7. Transformer proposed.

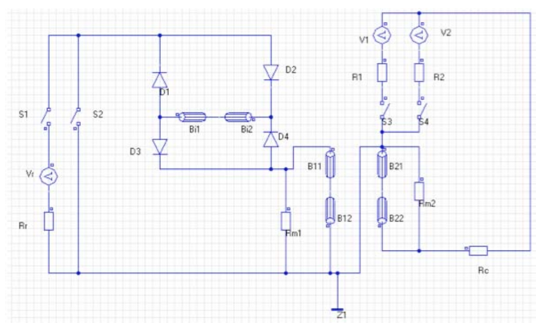

Fig. 8. Electrical scheme of transformer proposed.

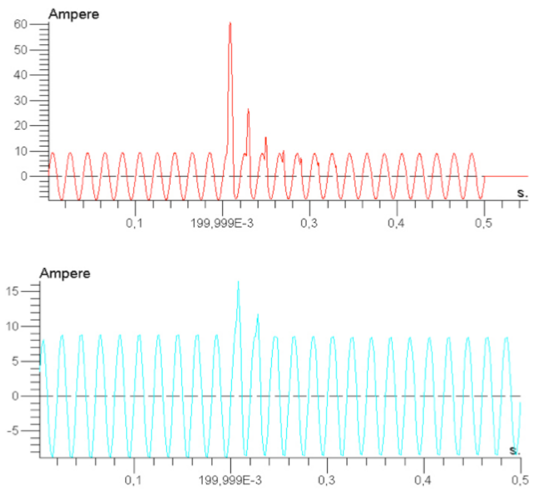

Fig. 9. Primary currents in the injection transformer. With and without auxiliary coil.

current is connected, when the sag occurs and the dynamic restorer begins its operation the power transformer reaches the saturation and the inrush peak value reaches 60A. In the other hand, if the auxiliary coil and the diodes are connected in the same scenario (Figure 9b)) the inrush peak value is limited to 16A. Varying the number of turns of the auxiliary coil this inrush current can also be avoided. Further works should discuss the optimum value of the coil in order to obtain the cheapest machine with undistorted injected voltages due to the inrush.

CONCLUSIONS

In this paper, a novel power transformer design for DVR applications has been proposed.

This new topology includes an ICL in the injection transformer primary side. Several simulations were conducted using matlab/SIMULINK. Obtained results were compared and validated through experimental laboratory setup. Conclusions extracted both from simulations and laboratory tests were similar.

The authors have demonstrated that an auxiliary coil in power transformer can be used as dc reactor to reduce the saturation, limiting the inrush current peak value.

As a consequence, the DVR can be designed using only injection transformers and reducing the cost of extra core material for reactors. Furthermore, the inrush current limitation avoids overcurrent protection trips in the power converter, increasing whole system reliability.

It must be noticed that ICL is based in diode type semiconductors so no control is needed and system robustness is higher than IGBT or GTO based systems.

In addition there is no need of protection, extra measurements and gate driver circuits.

REFERENCES

[1] V. Ramachandaramurthy, C. Fitzer, A. Arulampalam, C. Zhan, M. Barnes, and N. Jenkins, “Control of a battery supported dynamic voltage restorer,” *Generation, Transmission and Distribution, IEE Proceedings*, vol. 149, no. 5, pp. 533–542, 2002.

[2] J. Nielsen and F. Blaabjerg, “A detailed comparison of system topologies for dynamic voltage restorers,” *Industry Applications, IEEE Transactions on*, vol. 41, no. 5, pp. 1272–1280, 2005.

[3] M. Bollen, “Voltage sags: effects, mitigation and prediction,” *Power Engineering Journal*, vol. 10, no. 3, pp. 129–135, 1996.

[4] N. Woodley, L. Morgan, and A. Sundaram, “Experience with an inverterbased dynamic voltage restorer,” *Power Delivery, IEEE Transactions on*, vol. 14, no. 3, pp. 1181–1186, 1999.

[5] P.-T. Cheng, W.-T. Chen, Y.-H. Chen, C.-L. Ni, and J. Lin, “A transformer inrush mitigation method for series voltage sag compensators,” *Power Electronics, IEEE Transactions on*, vol. 22, no. 5, pp. 1890–1899, 2007.

[6] B. Li, S. Choi, and D. Vilathgamuwa, “Transformerless dynamic voltage restorer,” *Generation, Transmission and Distribution, IEE Proceedings-*, vol. 149, no. 3, pp. 263–273, 2002.

[7] C.S. Lam, M.C. Wong, and Y.-D. Han, “Per-unit design of a transformerless, h-bridge dynamic voltage restorer with closed-loop load voltage and current-mode control,” in *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005*, vol. 4, 2005, pp. 2420–2427 Vol. 4.

[8] M. Hagh and M. Abapour, “Dc reactor type transformer inrush current limiter,” *Electric Power Applications, IET*, vol. 1, no. 5, pp. 808–814, 2007.

[9] J. Nielsen, M. Newman, H. Nielsen, and F. Blaabjerg, “Control and testing of a dynamic voltage restorer (dvr) at medium voltage level,” *Power Electronics, IEEE Transactions on*, vol. 19, no. 3, pp. 806–813, 2004.

[10] A. Prasai and D. Divan, “Zero-energy sag correctors optimizing dynamic voltage restorers for industrial applications,” *Industry Applications, IEEE Transactions*, vol. 44, no. 6, pp. 1777–1784, 2008.

[11] S. Casoria, G. Sybille, and P. Brunelle, “Hysteresis modeling in the matlab/power system blockset,” *Math. Comput. Simul.*, vol. 63, no. 3-5, pp. 237–248, 2003.

[12] J. Frame, N. Mohan, and T. huei Liu, “Hysteresis modeling in an electro-magnetic transients program,” *Power Apparatus and Systems, IEEE Transactions on*, vol. PAS-101, no. 9, pp. 3403–3412, 1982.