LOW-COST ACTIVE SHIELD FOR MV/LV SUBSTATIONS

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ABSTRACT

This paper deals with the design and simulation of a low-cost active shielding system for the mitigation of the magnetic field generated by electrical installations, like power lines or substations. A previously developed prototype is now improved by extending the hardware features and adding a Perturb and Observe algorithm that makes the shielding system more flexible and adaptable to any magnetic field source and to its loading conditions. The new algorithm is fully described; moreover, its behavior is tested by several simulations referred to a complex MV/LV substation.

INTRODUCTION

The magnetic field (MF) generated by power-frequency electrical installations has provoked concern in recent decades. One solution for a strong mitigation of the MF is the use of an active shielding system [1]. This technique consists in a coil (or a set of coils) where an alternating current (with a certain magnitude and phase) is injected by external equipment, in such a way that the MF generated by the loop counteracts the original field, resulting in a mitigated MF. This technique has shown to be attractive not only for the reduction of the MF in wide areas close to overhead lines [2]–[4], but also in MV/LV substations [5], [6] and other industrial applications [7]. However, the need of an external power supply increases the complexity of the shielding system in comparison with other mitigation techniques, so its properties must be selected carefully during the design process of the active shield. In addition, the mitigation system must have a controller to guarantee the optimal compensation at any time due to variations on the loading conditions of the MF source. In this sense, previous works [7], [8] employed control techniques based on the implementation of a proper transfer function in an electronic system, which is generally an analogical system. Nonetheless, the introduction of a microcontroller could extend the possibilities of control, which would be not limited to a transfer function anymore.

In this regard, this paper deals with the design and application of a low-cost microcontroller-based system for the active shielding of the MF generated by power lines or MV/LV substations. A first prototype was previously developed and validated in [9], which is now improved by adding new hardware and software features in order to provide better mitigation results. In particular, the new prototype is more flexible and adaptable to different MF sources and its loading conditions thanks to the implementation of a "Perturb and observe" control algorithm. In the following sections, the software of the new prototype is fully described, and several numerical results are also presented.

PROTOTYPE DESCRIPTION

A first prototype for the active shield was already developed and successfully applied to the mitigation of the MF generated by a three-phase line [9].However, an improved version (Figure 1) has been developed with the following new features:

-Possibility to drive *n* shielding loops.
-Possibility to measure and manage the MF in *m* points.
-Possibility to run the Perturb and Observe algorithm.

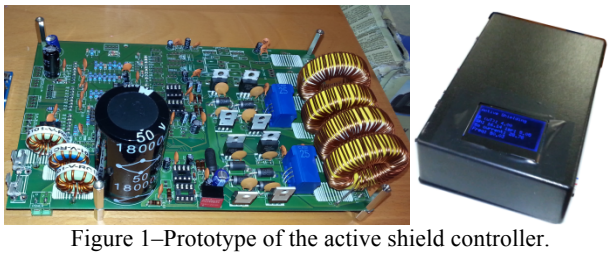

Figure 1–Prototype of the active shield controller.

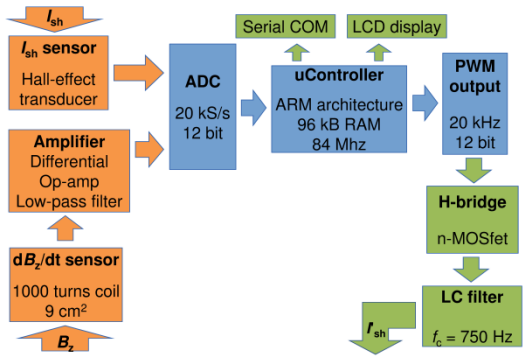

Figure 2- Scheme of the hardware implementation.

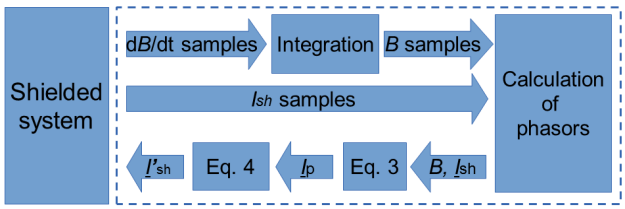

Figure 3–Scheme of the control algorithm.

This prototype does not require any coupling with the source since it needs just an online measurement of the MF (B) at a particular point Q (Figure 2). This feature is based on the knowledge of the geometry of both shield and the source. It is worth noting that the information about the geometry is usually available since it is required to perform the design of the loops. Thus, the control algorithm (Figure 3) is mainly based on two equations:

$$B_j = B^j_p + B^j_{sh} = \alpha^j \cdot I_p + \beta^j \cdot I_{sh} \quad (1)$$

$$I'_{sh} = \gamma \cdot I_p \quad (2)$$

Where B_j is the j-th component of the MF at the point Q, α^j and β^j are complex numbers which takes into account the contribution of the source currents (I_p) and the shield currents (I_{sh}), γ is a complex number that depends on the geometry of the source and on the result of the optimization procedure, and I'_{sh} is the new current that should be injected in the shielding loop as a function of the current of the MF source.

Experimental validation

The performance of the prototype was analyzed on a simple case study composed by a three phase power line (Figure 2).Some measurements were carried out along the inspection line to check the validity of the optimal solution and the performance of the control system.

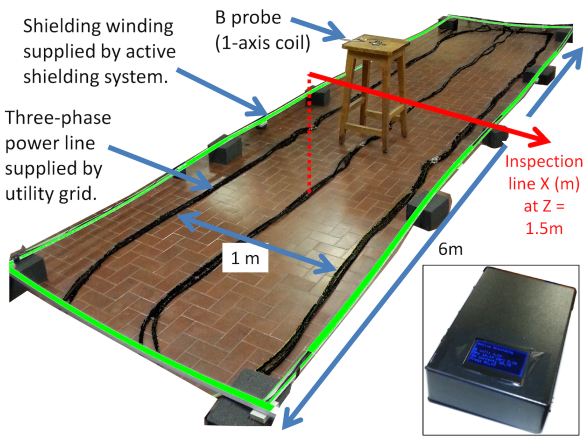

Figure 2 - Experimental case study for active shielding test.

The main results are reported in Table **1**, where data are related to a source current equal to I_p = 25 A. As can be observed, the results are in good agreement with the analytical calculations derived from the optimization procedure, hence validating the rationale on which the whole system is based: design, modeling and control system. However, the small differences observed are mainly caused by possible deviations in the 3D model in comparison to the actual installation. For this reason, a "Perturb and Observe" algorithm has been implemented in order to obtain a more accurate setpoint during the runtime.

Table 1 - Comparison between measurements and simulations with and without active shielding system.

x (m)	Source B simulation (μT)	Source B measure (μT)	Shielded B simulation (μT)	Shielded B Measure (μT)
0	1.910	2.078	0.346	0.430
0.5	1.743	1.867	0.338	0.356
1	1.358	1.385	0.263	0.279
1.5	0.959	0.957	0.179	0.168
2	0.654	0.648	0.117	0.120
2.5	0.447	0.443	0.078	0.072
3	0.311	0.340	0.053	0.070

PERTURB AND OBSERVE ALGORITHM

As mentioned earlier, a "Perturb and Observe" algorithm has been implemented in the new prototype. Its goal is the searching of the actual optimum shielding current under conditions that are different from the design ones. In fact, the setpoint calculated offline by the optimization process could be not perfect due to:

- Imperfections on the 3D model which is not exactly compliant with the actual geometry or the properties of the materials.
- The presence of unbalanced three-phase currents.

In addition, the measures of the MF and I_{sh} may be affected by errors that lead to a setpoint different from the optimal one. To overcome these issues, the new algorithm will perturb the parameter γ during the runtime and will evaluate the effect on the total MF in order to search the best setpoint. This new algorithm has been named 'Minimum Field Tracker' (MFT). Its approach is similar to the Maximum Power Point Tracker (MPPT) used in the inverters for photovoltaic applications but, instead of working on a scalar quantity (which is the duty cycle of the buck converter for the MPPT), it works on a vector quantity. The variables that are perturbed during the runtime are:

- The magnitude of γ for each shielding loop.
- The angle of γ for each shielding loop.

For example, an active shield with one shielding loop has 2 online optimization variables.

The MFT works in this way:

- A measure of MF is performed in an opportune point R. The ratio between the MF and the evaluated I_P is calculated. This ratio is used as a fitness for the evaluation of the effect of the perturbations.
- One of the variables is perturbed by a fixed quote (for example: ± 1 \%).
- A new measure of MF is performed. The fitness is calculated again.

- If the fitness is better, a new perturbation of the variable with the previous sign is performed.
- If the fitness is worst, a perturbation with the opposite sign respect to the previous one is performed.
- When 5 consecutive changes of sign occur, the obtained perturbation of the variable is kept, and the algorithm starts to perturb and observe the next variable, in the same way.
- When the whole set of variables have been perturbed, the cycle starts again from the first variable.

The point R could coincide with Q, which is the measure point used for feedback of total MF and for estimation of the source current I_P. In this case, only one MF sensor is employed. If the point R is different from point Q, a second sensor is required. The selection of the point R influences the performance of the Perturb and Observe algorithm. The convenience of using two different points instead of only one is case dependent.
A simulation tool for the online optimization MFT has been developed in Matlab. In particular, the simulator is characterized by:
- The actual parameters α and β, intended as parameters of the physical model for the calculation of the MF in a point P due to a source that is carrying the current I_P and a shielding loop carrying the current I_{sh}.
- The parameters α_i and β_i set in the optimization algorithm. They are intentionally different from the actual parameters α and β in order to test the online optimization procedure.
- The parameter γ_i set in the optimization algorithm. This can be intentionally different from the optimum parameter in order to test the online optimization procedure.
- The parameters err_B and err_{I_SH}: these parameters take into account the error of the measure of B and I_{sh}. In this way it is possible to test the optimization procedure also in the case of non-negligible errors on online measure.

Simulations

Two different situations have been considered to analyze the performance of the MFT.

Case study 1: A three-phase power line in flat configuration
Figure 2shows the geometry of the source and the shielding coil as well as the point chosen for the evaluation of B. The parameters chosen in the simulations are:

-error of 10 % for MF measurement
-error of 10% for the feedback of the shielding current.
-error of 5% on the drive of shielding current.
-error of 10% of the MF model of the source
-error of 30% of the parameter γ.

The parameters set in the simulation are reported in Table 2, and the result of the simulation is reported in Figure 3.

Table 2 - Parameters set in the simulation.

Parameter	Value
α	-0.2432 + j0.14151
B	-0.36022
$\gamma_{optimum}$	$0.6133 \cdot e^{j147.8}$
$\gamma_{initial}$	$0.3677 \cdot e^{j123.6}$

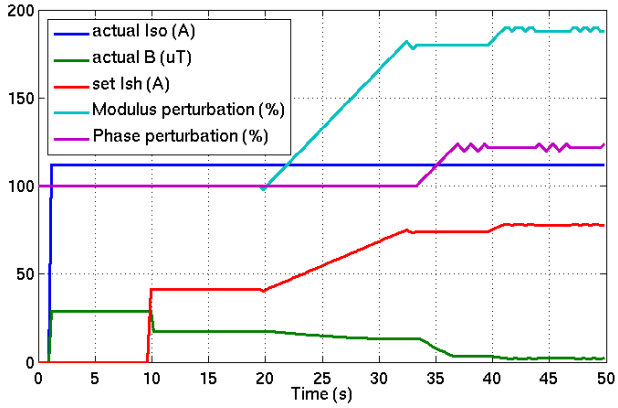

Figure 3 – Simulation of the MFT algorithm.

Several aspects should be highlighted from this study:
- At the beginning of the test the active shield is turned off and the MF at the inspection point Q is 28μT.
- The active shield is firstly turned on with the online optimizer MFT disabled, thus it works based on the parameter γ_i provided by the user, which is not the actual optimum. In this situation the MF at the inspection point Q is about 17μT.
- Then, the online optimizer MFT is enabled. At first, the phase of γ is perturbed from the 100% of its value to the 170%. Next, the magnitude of γ is perturbed from the 100% of its value to the 123%. The MFT continues to perturb the phase and the modulus forever.
- After some cycles, the online optimization reaches a stable setpoint, and the value of γ becomes $0.65 \cdot e^{j151}$, which is very close to the optimum value $0.61 \cdot e^{j148}$. The final MF at the inspection point Q is 1.8μT.

Case study 2: MV/LV substation
Another simulation test is performed on a more complex case study: a substation composed by two 630 kVA MV/LV cast resin transformers, one MV switchgear with seven cells and one LV switchgear. In this case, the active shield is composed by four loops.
We want to remark that the application of a shielding system to a substation is a very complex task, because the loading condition of the substation can vary without homogeneity in all the components. Theoretically, for each working condition there is an optimal shield configuration. However, it is obvious that the shield must be designed once for all. Here we propose the MFT algorithm to solve this problem. Indeed, we will show, by

means of the analysis of two configurations, that the MFT is able to set the right shielding currents in the loops even when they are asked to shield a MF source that differs from the one used in the design.

Configuration 1: all transformers and switchgears at 70% of their rated currents. The loops positions and the shielding currents are obtained by an optimal design based on Genetic Algorithms (GA) [10]. The geometry of the substation, the optimum configuration of the shielding loops and the inspection plane are reported in Figure 4.

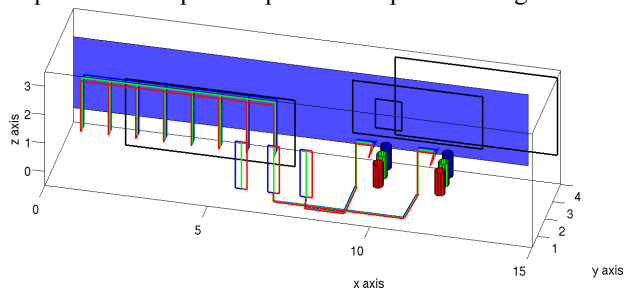

Figure 4–Geometry of the substation (red, blue and green conductors represents the phase conductors L1, L2 and L3), the optimum active shield (black conductors) for *Configuration1*, and the inspection plane (blue).

The MF with and without the active shield on the inspections plane is shown in Figure 5 and Figure 6. The MF reaches values higher than 10μT in the region close to the two transformers. However, the active shield allows a significant reduction of the MF, since the MF values are lower than 3μT in most of the inspection plane.

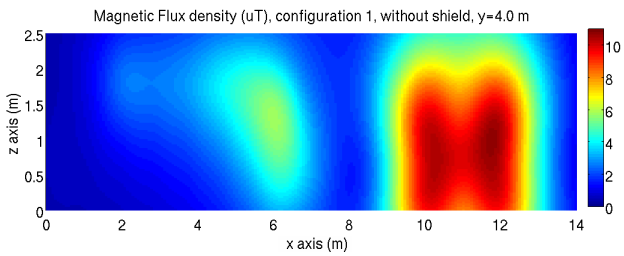

Figure 5 - MF on the inspection plane of the *Configuration 1* without shield.

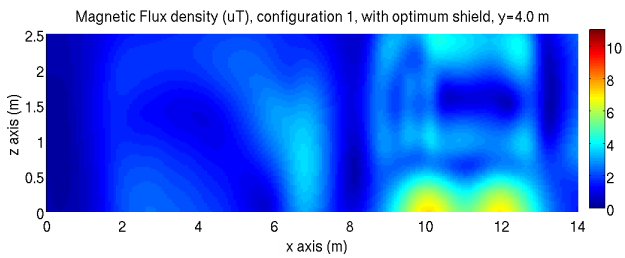

Figure 6 - MF on the inspection plane of the *Configuration 1*with its optimum shield.

On the other hand, since the analyzed problem is linear, the MF at a given point is proportional to the loading factor of the substation. This also means that the geometry obtained by optimal design holds for any loading condition obtained by varying the source currents by the same factor. In this case, if all the shielding currents are modified by this factor, the shield performance is guaranteed. Conversely, if the working condition of the substation varies without homogeneity (e.g. one transformer works at 70% and the other at 20%), the shielding geometry would not be the optimum one anymore, and the shielding effect is not assured. In all these cases, the MFT can find the currents that minimize the MF even if the shield geometry is not the best one. This situation is analyzed next.

Configuration2: one transformer switched off, the other transformer at 70%, four MV cells at 4A and three MV cells at 18A.In this situation, the unshielded MF is as shown in Figure 7. Once again, the maximum MF value is higher than 10μT.

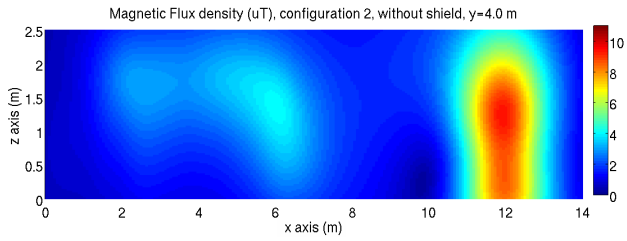

Figure 7 - MF on the inspection plane of the *Configuration 2* without shield.

Before analyzing the effect of the MFT, it is of interest to know what is the best mitigation result that can be obtained under this loading condition. This is done by considering *Configuration 2* as a completely new source to be shielded, obtaining its optimal active loop design as described in [10]. In this way, the optimal active shield provides the results shown in Figure **8** where the MF values are lower than 2μT in almost all the plane. In the following, this situation will be considered as a reference "best" case in order to check the MFT performance.

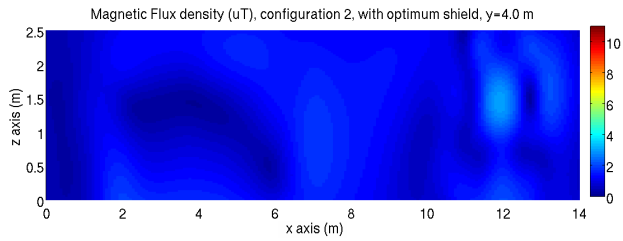

Figure 8 - MF on the inspection plane of the *Configuration 2* with its optimum shield.

Now let's analyze the performance of the active shield optimized for *Configuration 1* under the loading conditions of *Configuration 2*. This is shown in Figure 12, where the mitigated MF obtained without MFT algorithm is represented. These results confirm that the shield is non-optimal for this configuration. In fact, the MF values are significantly high at some points.

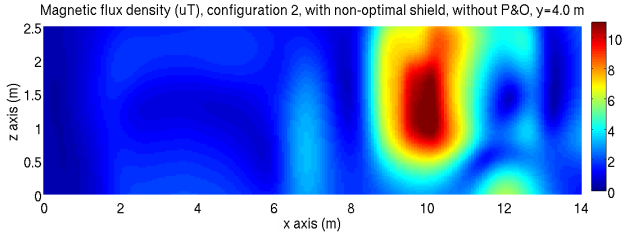

Figure 9 - MF on the inspection plane of the *Configuration 2* with the non-optimum shield, without Perturb and Observe algorithm.

However, better results are obtained if the MFT algorithm is now turned on, as shown in Figure 10.This result shows how the MFT algorithm compensates the non-optimum configuration of the active shield and leads to results that are clearly comparable to the optimum ones provided by the "best" case represented in Figure 9.

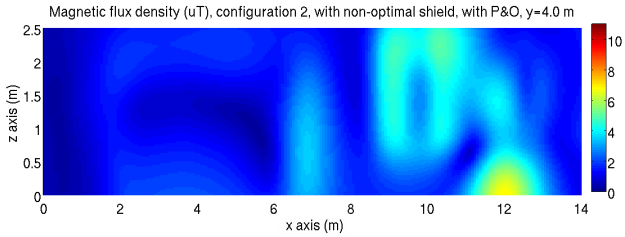

Figure 10 - MF on the inspection plane of the *Configuration 2* with the non-optimum shield, with Perturb and Observe algorithm.

It has to be remarked that the fitness function of the MFT algorithm is the average MF measured in three representative points. Since the MFT algorithm minimizes the MF in these points, it is necessary to choose their location properly (i.e. if a point is too close to a shielding coil, the MFT algorithm will tends to minimize its current).

CONCLUSIONS

This paper presents the new features of a previously developed prototype of a low-cost active shielding system. The prototype is based on a low-cost hardware (~ 100€), and now it's been improved by extending the hardware features and adding a Perturb and Observe algorithm, called MFT (Minimum Field Tracker). The MFT makes the shielding system more flexible and adaptable to complex MF sources, like MV/LV substations, where the loading conditions may vary without homogeneity in all the components. The performance of this new algorithm is analyzed in two situations: in a three-phase line in flat configuration and in a MV/LV substation. From the results it is derived that the MFT algorithm is able to improve the mitigation results by compensating possible differences between the data employed in the design stage and the actual installation.

On the other hand, since the active shielding is designed once for the most frequent loading conditions of the MF source, the control algorithm has to react to changes in the working conditions of the source, even if they vary without linearity. In this situation, the new algorithm has proven to be quite efficient, recalculating the right shielding currents to be injected in an active shielding which was optimized for very different loading conditions, and leading to a shielding factor which is comparable to the optimum.

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