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Optimal layout of parallel power cables to minimize the stray magnetic field

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ABSTRACT

This paper deals with three-phase power lines operated by parallel power cables. In these systems each phase is made up of several parallel subconductors and it is well known that the sequence of the subconductors influences the magnetic field generated by the power line. This paper proposes a new approach to identify the optimal arrangement of the power cables that minimizes the stray magnetic field. Unlike the design methods covered by the literature, this paper proposes a deterministic procedure that is based mainly on a simple geometrical indicator. This geometrical quantity makes it possible to analyze all the configurations in order to create a small subset of candidate solutions. From this subset the optimal solution is then identified quickly and easily by computing and comparing the stray field. A full validation of the proposed approach is performed by comparing it with a standard method based on genetic algorithm. The results of the validation also provide a useful table that covers all the cases from 2 to 6 subconductors for each phase. Furthermore, it is shown that the geometrical indicator makes it possible to obtain a good cable arrangement in a direct way, without performing any magnetic field evaluations.

1. Introduction

Power delivery of electrical energy often requires cables with high ampacity. Two chief examples are industrial sector, where a large amount of power is required, and medium-voltage/low-voltage (MV/LV) substations where the conversion from medium to low voltage is accompanied by the increase of the current values on the LV side. Dealing with the necessity of the delivery of high current values, a possible solution is the adoption of busbar systems because of their compactness and their ease of installation. The main drawback of this solution is the high frequency of the maintenance required to assure proper behavior of the system. An alternative solution is to use a power line made of parallel cables. Parallelism of more than one cable is unavoidable in order to reach the desired ampacity and, at the same time, to have the possibility to follow a desired path with flexible cables that can be folded easily. The literature has analyzed the systems made of parallel power cables because of the possible issues that can arise. First of all, the total current is not always shared equally by the subconductors belonging to the same phase [1–3], and this occurs for systems realized with busbars [4] or cables [5,6]. The unbalance of the currents inside subconductors gives rise to other issues related to mechanical and thermal design. The electrodynamic stresses are not divided equally among the subconductors and those with higher currents heat up more than expected [3,7]. Although it is possible for all these aspects to be taken into account by means of appropriate methodologies covered by the literature [8–11], awareness and evaluation of the problem alone do not solve the issue itself. Therefore, a dedicated design methodology is necessary.

Another highly important issue nowadays is the emission of the magnetic field by electrical installations. Most countries have a regulatory framework on the exposure to electric and magnetic fields based on the ICNIRP guidelines [12] or on the IEEE standards [13]. For this reason the minimization of the magnetic field generated by parallel power cables has been already analyzed in the literature. Reference [14] shows the magnetic behavior of several power line layouts pointing out, for each case, the best and the worst cable arrangement. Reference [15] focuses on underground power cable duct banks. The paper identifies the best passive shield that minimizes the total cost (including the losses) depending on the cable configuration. The target of the optimization is very challenging ($B < 1\ \mu$T), therefore, the authors highlight the importance of a proper management of the power cables to minimize as much as possible the magnetic field before the shield has to be designed and applied. Reference [5] is mainly related to the methodology for approaching the optimization problem. The authors want to test the performance of the optimization technique called Vector Immune System (VIS) [16] solving a multiobjective combinatorial problem.

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Table 1
Parameters used to describe a power line arrangement.

N_T	total number of cables
N_S	number of subconductors composing each phase
N_R	number of rows
N_C	number of columns
Δ_x	distance between two consecutive cables along x direction
Δ_y	distance between two consecutive cables along y direction

They seek the minimum magnetic field emission and the minimum unbalance of the currents. Even if power lines with parallel cables are simply used as a case study, some interesting conclusions are drawn in this reference. First of all, they find that the two objectives are slightly conflicting and therefore, the minimum magnetic field arrangement also becomes the most convenient one for the thermal and mechanical aspects.

In this paper we exploit the main conclusions of reference [5] in order to provide a simpler and effective method for the identification of the best arrangement of parallel power cables. The authors of [5] affirm that the optimal sequences are characterized by a geometrical symmetry. This concept is used to define a geometrical indicator based on the barycenter of the three phases. This indicator is used to analyze all possible permutations for a given number of subconductors. This analysis aims to select some candidate solutions in which the best sequence is subsequently identified quickly and easily. In the rest of the paper this methodology will be described in detail and validated by comparing the results with a standard approach based on genetic algorithm (GA). Moreover, it will be shown that the simple geometrical interpretation of the problem provides interesting results without any dedicated optimization technique or special efforts.

2. Nomenclature

In this paper three-phase balanced power systems operated by parallel power cables are analyzed. A generic arrangement is uniquely described by the parameters summarized in Table 1.

It is worth noting that the parameters listed in Table 1 are not independent to each other. Indeed, the following relation always holds: $N_T = N_R N_C = 3N_S$. It is convenient to introduce all the parameters to provide clearer and more effective explanations of later notions.

After describing the arrangement of the power line, information about the position of the cables has to be provided. The three phases are identified with the numbers 1, 2 or 3. Moreover, they are also identified by a color that is red, green or blue, respectively. Bearing all this in mind, a cable sequence is described by N_T elements; each sequence includes N_S elements equal to 1, 2 and 3 (remember that $N_T = 3N_S$). With reference to Fig. 1 we analyze the

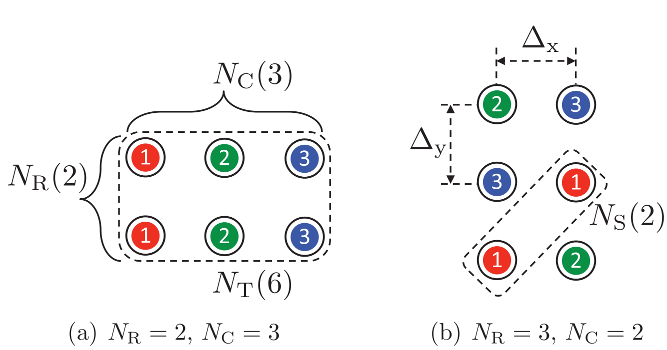

Fig. 1. System of $N_T = 6$ cables arranged in two configurations: ($N_R = 2, N_C = 3$) (a) and ($N_R = 3, N_C = 2$) (b). (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

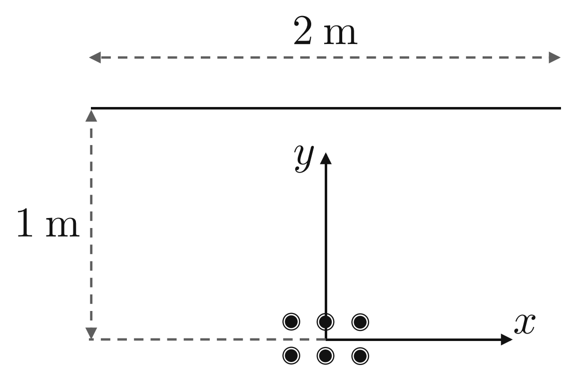

Fig. 2. Description of the inspection line used to compute the magnetic flux density. The same inspection line is used throughout all the paper.

example of a power line with $N_T = 6$ cables arranged in two configurations: (N_R, N_C) = (2, 3) in Fig. 1(a) and (N_R, N_C) = (3, 2) in Fig. 1(b). The sequence is filled reading the matrix of cables by rows. Starting from the bottom, we move from the lower left cable until the upper right. According to this rule, Fig. 1(a) and (b) both correspond to the sequence (123123). This example is given to highlight that the same sequence corresponds to significantly different cable positions depending of the arrangement defined by N_R and N_C. Finally, since the optimal sequence of the conductors is independent of the variables Δ_x and Δ_y, in this paper they are both fixed to the value of 5 cm.

3. General aspects

3.1. Objective function

In this paper, given an arrangement of cables, we identify a sequence that minimizes the generated magnetic field. Without loss of generality, all the magnetic field computations will be referred to the same inspection line as described in Fig. 2. The barycenter of the whole system corresponds with the origin of the system of coordinate. The 2 m long inspection line is centered with respect to the origin and it is 1 m far from the origin/cables.

To identify the optimal sequence, the inspection line is discretized in Q points. The magnetic flux density is evaluated with the Ampére's law at each point and the objective function (OF) is given by:

$$\mathrm{OF} = \min\{\max\{B_j\}\}, \quad j = 1 \ldots Q \tag{1}$$

being B_j the rms value of the magnetic flux density at the jth point.

3.2. Problem assumptions

Assuming that the above introduced optimal sequence is found, in order to reorganize the system of conductors it is essential to know the original sequence. Even if this concept can be obvious, sometimes it is the main obstacle for the implementation of the optimal sequence. In fact, if the analysis is related to an already working circuit, the existing conductors sequence might be not known. In these cases it has to be identified by means of measurements. However, the identification is not always an easy task.

The proposed methodology is very suitable for the design of new cable arrangements. For parallel cables, it is well known that the mutual coupling between each other depends only on the geometry. This coupling can lead to a significant unbalance of the currents among subconductors. The problem is well investigated in the literature because of the above mentioned issues regarding thermal and mechanical aspects [3,4,17]. In this