IDENTIFICATION AND OPTIMIZATION OF THE SEQUENCE OF PARALLEL CONDUCTORS USING AN AUTOMATIC TOOL

Aldo CANOVA
Politecnico di Torino – Italy
aldo.canova@polito.it

Luca GIACCONE
Politecnico di Torino – Italy
luca.giaccone@polito.it

Vincenzo CIRIMELE
Politecnico di Torino – Italy
vincenzo.cirileme@polito.it

ABSTRACT

This paper presents a tool for the acquisition, processing and the automatic identification and optimization of a multi-conductor system. The tool registers the waveforms of the current in each subconductors, then magnitude and phase for each one are computed. By means of a simple indicator the subconductors sequence is identified and, finally, the optimal sequence that should be adopted for the minimization of the current unbalance and the magnetic stray field is automatically proposed. The paper analyzes the performance of the identification procedure testing it with several simulations and some experimental results on real cases.

INTRODUCTION

Parallel power conductors are widely used in the distribution of electricity 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 afor 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. Moreover, it is also shown that the unbalance is followed by an increase of the stray magnetic field [6].

It is possible to observe that both the unbalance and the stray magnetic field are related to the conductors sequence. Therefore, solutions to minimize both unwanted effects have been found showing that the two objectives are slightly conflicting. In other words, looking for the sequence that minimizes than stray magnetic field, one finds also a good approximation of the sequence that minimizes also the unbalance [6]. On this basis, it is possible to show that the minimization can be based on a geometrical parameter and the results can be easily related to the layout of the conductors [7].

During mitigation activities, it is quite common to find parallel conductors in the power system that generates the stray magnetic field. The main obstacle in applying the optimal transposition is often the absence of correct information of the conductor sequence and, without knowing the actual sequence, it is impossible to modify it into the optimal one. For this reason, this paper develops a tool that identifies the sequence of a system with parallel conductors and, afterwards, the optimal sequence to minimize the unbalance and the stray magnetic field is automatically suggested by the tool.

OPTIMAL TRANSPOSITION

A short introduction to the optimal transposition is given in this section the make the read of the paper easier. Detailed information can be found in the literature [6-7].

Let us consider six conductors in flat formation, 2 subconductors are used to handle the phase current and one neutral conductor is used. Here we label the phases with R (red), S (green) and T (blue) whereas the neutral conductor is called N (black). A three-phase balanced load is considered, and the solution is obtained using a circuital approach [6]. Figure 1(a) shows the most commonly used configuration R1-R2-S1-S2-T1-T2-N. On the left plot one can see that subconductors do not share the same amount of current. On the right plot it is shown that the phase currents, on the contrary, are well balanced. Figure 1(b) shows the results related to the optimal sequence R1-S1-T1-T2-S2-R2-N. All subconductors carry the same amount of current without affecting, obviously, the phase currents.

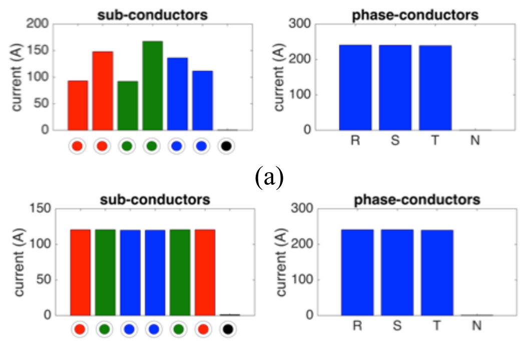


Figure 1 – Benefit of the optima transposition on the distribution of the current in subconductors.

The benefits of the optimal transposition can be observed also in the mitigation of the stray magnetic field. Considering an inspection line above the seven conductors as shown in Figure 2(a), the stray magnetic field of the standard and the optimal sequences is shown in Figure 2(b). A reduction of approximately 10 is obtained.

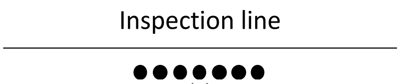
IDENTIFICATION OF THE CONDUCTORS SEQUENCE

The approach to identify the conductors sequence is introduced by an example that the authors faced before developing the tool under consideration. An existing distribution line made by 10 conductors feeds electricity to a cooling system. The true sequence is not known but it is known that each phase is made by 3 parallel conductors and there is one neutral conductor. The system of parallel conductors is shown in Figure 3(a) and Figure 3(b).

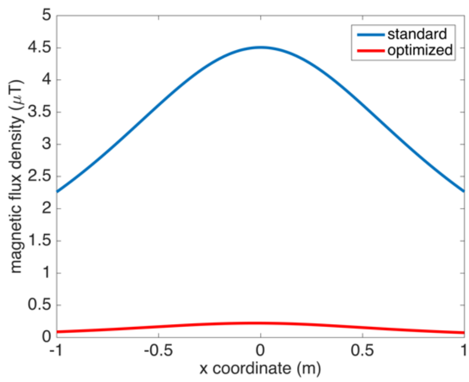
The identification started by measuring the currents in all subconductors (magnitude and angle) by a commercial power meter. A phasor diagram of these currents is shown in Figure 4(a). The association of the subcurrents to phases R, S or T was made manually selecting, for the same phase, the currents closer to each other. The selection is shown in Figure 4(a) with the dashed lines: conductors 5-6-10 belong to phase R, conductors 3-4-8 belong to phase S, conductors 1-2-9 belong to phase T, conductor 7 is the neutral conductor.

By summing up together the currents belonging to the same phase the results in Figure 4(b) is obtained. The three phase-currents calculated in this way have the same magnitude and the phase shift between them is 120°. Since the load is balanced this confirms the correctness of the identification.

After the identification, the conductors were transposed obtaineing the desired mitigation results but this step is not shown here because this example is provided to highlight the lack of information about the original sequence and the procedure followed to identify the conductors. The tool presented o this paper makes it possible to identify the sequence translating this approach into a deterministic procedure.



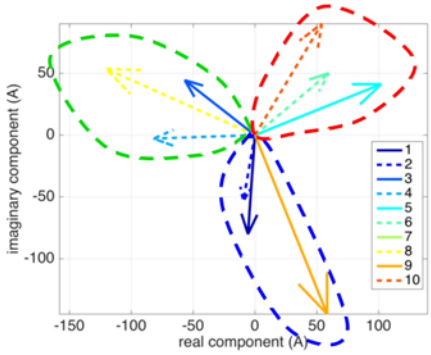
(a)



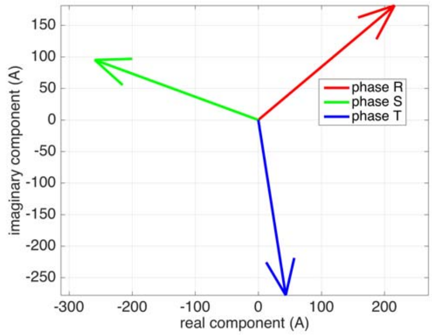
(b)

Figure 2 – Benefit of the optimal transposition on the generation of the stray magnetic field. Inspection line represented in (a) and stray magnetic field along the inspection line represented in (b).

Figure 3 - Example of parallel conductors feeding a cooling system.



(a)



(b)

Figure 4 – measurement of all currents in subconductors and manual identification of the possible phasors belonging to the same phase (a). Phase currents obtained by summing up together the subcurrents belonging to the same phase (b).

TOOL FOR OPTIMAL POSITIONING

The tool for identifying and then optimizing the sequence of parallel conductors is shown in Figure 5(a). It is currently based on the NI USB-6008 card that is programmed using LabVIEW. As it will be explained later, the identification algorithm is simple enough to allows a low-cost extension of the tool using open hardware (e.g. Arduino boards). The upper part of the front panel provides information about the measured currents in time domain and in frequency domain. In the frequency domain both subconductors and phase currents are shown. The phasors are defined using the first harmonic of the waveforms.

The lower left part is the input section, the place where the user is asked to provide information about the layout of the conductors and the current probes. For the purpose of this analysis the layout of the conductors is of key importance. It is described by using the dimension of a matrix, rows (N_R) and columns (N_C). For example, considering a system of 6 conductors with two subconductors for each phase, two possible layouts are shown in Figure 5(b) and Figure 5(c). Figure 5(b) corresponds to the layout with N_R=2 and N_C=3 (shortened in 2x3) and Figure 5(c) corresponds to the layout with N_R=1 and N_C=2 (shortened in 1x6).

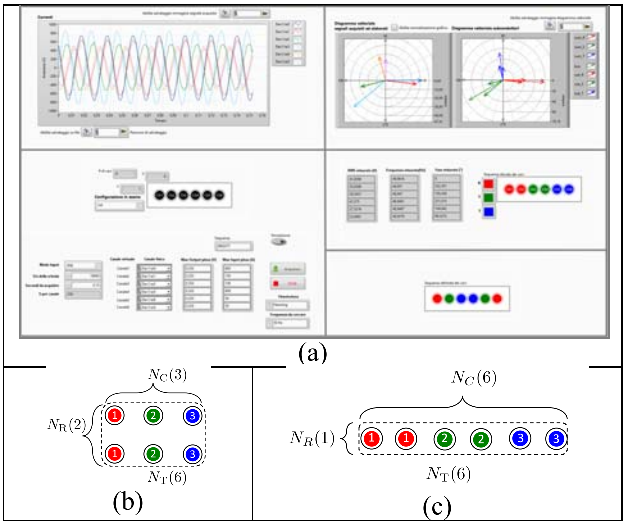


Figure 5 - Front panel of the identification and optimization tool (a). Example of conductor sequence 2x3 (b). Example of conductor sequence 1x6 (c).

On the right, below the phasor diagrams, the results are shown and divided in two boxes. The upper box shows the identification of the subconductors. Figure 5(a) is the screenshot of a laboratory validation where a system like the one represented in Figure 5(c) was tested. Numerical values of the currents are provided and also a graphical representation of the conductors is given using colors to identify the phase membership. The second box provides the optimal sequence for the layout considered. As already introduced, the optimal sequence depends only on the layout of the conductors [7]. It is apparent that, by knowing both the actual and the optimal sequence, one can easily proceed to optimally transpose the conductors.

Identification algorithm

The correct identification of the sequence of conductors would require the solution of an inverse problem. Nowadays, this is certainly not an issue, however, we tried to follow a different strategy in order to provide the results quickly and to limit as much as possible the requirement of the hardware that performs the identification.

The algorithm is based on the same assumption made in the example presented earlier: *currents belonging to the same phase are close to each other in the phasor diagrams*. This suggests the possibility to define an indicator that quantify the phase shift between currents of the same phase, in fact, after several tests, we defined the following phase shift indicator:

$$\nu = \frac{1}{3}\sum_{h}^{R,S,T}\left|\frac{1}{n_{sc}}\sum_{i=1}^{n_{sc}}\frac{\bar{I}_{hi}}{I_{hi}}\right| = \frac{1}{N}\sum_{h}^{R,S,T}\left|\sum_{i=1}^{n_{sc}}\frac{\bar{I}_{hi}}{I_{hi}}\right| \qquad (1)$$

being, υ the phase shift indicator, n_{sc} the number of subconductor for each phase, N the total number of conductors, I_{hi} the current of the subconductor i (i runs from 1 to n_{sc}) of the phase h (equal to R, S, or T).

It is easy to show that $\upsilon \leq 1$ and it reaches the maxim value of 1 only when, for each phase, al the subconductors carry currents with the exact same angle. This indicator can be intended as a degree of vicinity of the currents in subconductors of the same phase. The higher is υ, the closest are the currents in subconductors belonging to the same phase.

The identification algorithm makes use of the indicator υ to identify a sequence of conductors with given current in the following way:

- Given N conductors, the total number of groups made of n_{sc} conductors is given by:

$$N_G = \binom{N}{n_{sc}} = \frac{N!}{n_{sc}!\,(N-n_{sc})!} \qquad (2)$$

- The total number of three-phase systems (i.e. number of sequences) for this N conductors with n_{sc} subconductors for each phase is given by:

$$N_T = \binom{N_R}{n_{ph}=3} = \frac{N_R!}{n_{ph}!\,(N_R-n_{ph})!} \qquad (3)$$

N_T increases very fast with the increase of N. However, it turns out that many of the possible three-phase systems are equivalent to mirroring or circular rotation [6-7]. Therefore, filtering all the repetitions one can reduce N_T to the number of unique three-phase systems (N_U) as shown in Table 1.

Table 1 - Number of the unique three-phase systems than can be obtained with N conductors.

N	6	9	12	15
Ns	15	84	495	3003
Nr	455	95284	20.09E6	4.51E9
Nu	15	280	5775	126126

- For a given number of conductors (eg. N=6) a matrix including all possible three-phase system is generated in the following form.

$$M_s = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 2 & 3 & 5 & 4 & 6 \\ 1 & 2 & 3 & 6 & 4 & 5 \\ 1 & 3 & 2 & 4 & 5 & 6 \\ 1 & 3 & 2 & 5 & 4 & 6 \\ 1 & 3 & 2 & 6 & 4 & 5 \\ 1 & 4 & 2 & 3 & 5 & 6 \\ 1 & 4 & 2 & 5 & 3 & 6 \\ 1 & 4 & 2 & 6 & 3 & 5 \\ 1 & 5 & 2 & 3 & 4 & 6 \\ 1 & 5 & 2 & 4 & 3 & 6 \\ 1 & 5 & 2 & 6 & 3 & 4 \\ 1 & 6 & 2 & 3 & 4 & 5 \\ 1 & 6 & 2 & 4 & 3 & 5 \\ 1 & 6 & 2 & 5 & 3 & 4 \end{pmatrix}_{15\,x\,N} \quad (\text{columns } R \mid S \mid T) \quad \rightarrow \quad \text{evaluation of } \upsilon \text{ for each rom}$$

In this example N = 6 and we have, according to Table 1, 15 rows. Each row is made of numbers from 1 to N. These numbers represent the position of the conductors. For instance, the meaning of the last row is: conductors 1 and 6 belongs to phase R, conductors

2 and 5 belongs to phase S, conductors 3 and 4 belongs to phase T.
It is worth stressing that, this matrix only depends on the number of conductors (N) and not on the layout of the N conductors. The layout has influence on the current distribution that has to be identified. Coming back to the last row of the matrix M_S, the sequence 1-6-2-5-3-4 corresponds to the three-phase system R1-S1-T1-T2-S2-R2.

- In the next step the measured currents labelled from 1 to N are associated to each row of the matrix M_S. The indicator υ is computed for each possible three-phase system (rows of the matrix).
- The row with the maximum value of υ is the three-phase systems where the current of the subconductors of the same phase are closer to each other. Therefore, it is selected as the correct sequence and provided as output.

Accuracy of the identification

The simplicity of the algorithm makes it possible to use it with very low requirements. However, the downside is that this algorithm is not immune from identification mistakes. Several simulations have been done to test the accuracy of the algorithm and we observed that a wrong identification can occur mainly in the case of strong unbalance of currents. Moreover, also the presence of the neutral conductor can increase the probability of a wrong identification. In both cases, an overlapping of the subconductor currents in the phasor currents can happen. For example, Figure 6 show a case of N = 12 and n_{sc}=4 where the subconductor currents are very unbalanced. The most important thing here is that the rationale of the proposed approach does not hold because, as shown in the magnified portion of the phasor diagram, currents belonging to different subconductors overlap. Hence, the sequence with the highest value of υ is not the true one.

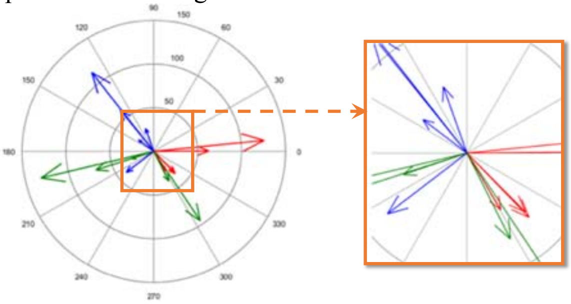


Figure 6 - example of true distribution in a system with N=12 and n_{sc}=4. The zoom shows that subconductor currents of different phases can overlap.

To test the accuracy of the identification procedure, several simulations have been carried out. The three-phase system is modelled using a circuital approach [6] and, for a given sequence of the conductors, the identification under different loading conditions is performed. The load is represented by three impedances and the loading conditions are modified by varying independently the modules and the angles of the three impedances. The max deviation for the module is 20% of the rated value and the max deviation for the angle is 40° with respect to the rated value. The two ranges of variation are discretized and combined obtaining 91125 possible loading conditions. All these loads are tested with two different sequences: the one with all subconductors of the same phase physically located close to each other (called standard sequence) and the sequence that creates the highest unbalance of subconductor currents in the system (called worst unbalance).
To understand the performance of the approach, we define the following additional quantities:

- average phase current

$$\bar{I}_{ave_h} = \frac{1}{n_{sc}} \sum_{k}^{n_{sc}} \bar{I}_{h,k} \quad ; h = R, S, T \tag{4}$$

- average current

$$I_{ave} = \frac{1}{3}\left(\sum_{k}^{n_{sc}} \left|\bar{I}_{ave_R}\right| + \sum_{k}^{n_{sc}} \left|\bar{I}_{ave_S}\right| + \sum_{k}^{n_{sc}} \left|\bar{I}_{ave_T}\right| \right) \tag{5}$$

- unbalance:

$$UNB = \frac{\sum_{h}^{R,S,T} \sum_{k=1}^{n_{sc}} \left|\bar{I}_{ave_h} - \bar{I}_{h,k}\right|}{I_{ave}} \tag{6}$$

- failure probability of the approach:

$$\chi = \frac{number\ of\ failed\ identifications}{number\ of\ total\ identifications} 100 \tag{7}$$

Several layouts are tested (see Table 2) and, for the purpose of illustration, here only one layout is analyzed with full details. It is considered the worst unbalance sequence with N=15, n_{sc}=5, layout 1x15, one neutral conductor. This is the case that creates more issues to the proposed identification approach. The phase shift indicator υ is plotted versus the unbalance indicator UNB in Figure 7. The plot includes 91125 points, one for every loading condition. Successful identifications are plotted in green whereas wrong identifications in red. The failure probability χ is equal to 55.17%. It is worth noting that this is the worst case whereas, in average, the failure probability is in almost always lower than 10% (see Table 3). However, a method to improve the identification is proposed in next section.

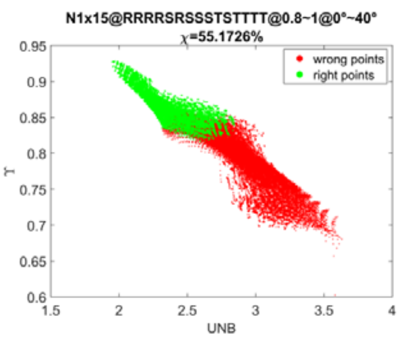


Figure 7 - phase shift indicator υ is plotted versus the unbalance indicator UNB for the worst unbalance configuration with N=15, n_{sc}=5, layout 1x15, one neutral conductor. The true sequence is shown in the tile of the figure.

Two-step identification approach

In this subsection a simple but effective procedure to improve the proposed approach is described. Basically, the failure probability can be significantly reduced repeating the identification twice as shown in Figure 8. In other words, a first identification is performed and the conductors are transposed according to the obtained result. The proposed approach is then used to check/identify again the sequence. If the previous result is confirmed nothing else has to be done. Otherwise, a new transposition has to be performed according to the second result.

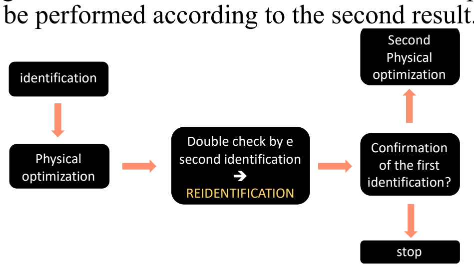


Figure 8 - flow chart of the two-step approach.

We consider again the worst unbalance sequence with N=15, n_{sc}=5, layout 1x15, one neutral conductor. With the two-step approach Figure 7 turns into Figure 9. The green points do not change because a single identification is sufficient. The red points in Figure 7 are tested again and, with a second transposition, many of them are correctly identified (blue points in Figure 9). A small percentage of cases, 4.47%, are still related to a wrong evaluation (red points in Figure 9). It is worth noting that, this simple procedure reduces the failure from 55.17% to 4.4%.

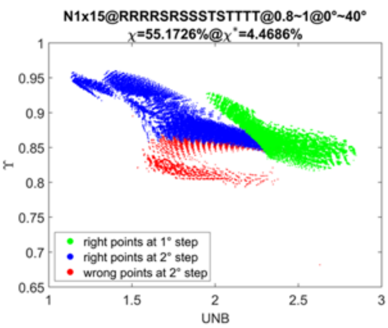


Figure 9 - phase shift indicator υ is plotted versus the unbalance indicator UNB for the worst unbalance configuration with N=15, nsc=5, layout 1x15, one neutral conductor. The true sequence is shown in the tile of the figure.

Summary of the results

The above procedure has been performed for all the layouts in Table 3 considering the standard sequence and the worst unbalance sequence. Both cases are also tested with and without the neutral conductors. Table 3 provides the average failure probability with the single-step approach and

Table 4 the improvements related to the two-step approach. In the analysis of these results, one must remember that these values are obtained considering the worst case unbalance (its use is very unlikely) and with a strongly unbalanced load (also very unlikely).

Table 2 - all tested layouts

N	layout
6	1x6
	2x3
9	1x9
	3x3
12	1x12
	2x6
	3x4
15	1x15
	3x5

Table 3 - failure probability with single identification

	χ (%) Standard sequence	χ (%) worst unbalance sequence
with neutral	5.7%	12.4%
without neutral	0%	2.6%

Table 4 - failure probability with two-step identification

	χ (%) Standard sequence	χ (%) worst unbalance sequence
with neutral	1.5%	2%
without neutral	0%	0%

CONCLUSION

In this paper a tool for the identification and optimization of parallel conductors with unknow sequence is proposed. Although the identification problem can be solved with an inverse problem, a simpler approach is preferred to avoid prohibitive computational requirements for a "low-cost" implementation of the tool. The downside of this simple approach is the failure probability with can be quite high if the system is complex (high number of conductors, high unbalance, presence of the neutral conductors). To improve the accuracy of the identification a two-step approach is proposed. Several simulations are carried out to show the how the failure probability is significantly reduced using the two-step approach.

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