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Transformer Model Identification by Ārtap: A Benchmark Problem

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Abstract

The paper presents how Ārtap can be used for determining the equivalent circuit parameters of a one phase transformer as a benchmark problem. The following unknown parameters of the equivalent circuit are identified: primary resistance and primary leakage reactance, secondary resistance and secondary leakage reactance, finally magnetizing resistance, and magnetizing reactance. The known quantities from measurement are the primary voltage, primary current, power factor, secondary voltage, and the load resistance. Algorithms implemented in Ārtap are used for determining the transformer parameters and the results are compared with the analytical solution.

Keywords

Ārtap, transformer measurement, transformer equivalent circuit model, parameter identification

1 Introduction

Transformers are passive components, which transfer electrical energy from one electrical circuit to another. There is plenty of type of transformers exist in the industry. Many aspects can classify them: by their rating, manufacturing technology, application, etc. [1–3]. The design optimization and the accurate modeling of transformers can be numerically expensive and complex engineering task, where many physical domains should be harmonized simultaneously [4, 5]. The challenging part of the transformer optimization problem highly depends on the application and the applied technology. For instance, in the case of the modern, solid-state transformers, the determination of the minimal losses and optimal value of inductances needs an accurate calculation of the medium, high-frequency harmonics and the caused non-linearities [6–11]. Or in the case of large power transformers, the thermal and the electrical properties should be examined together with the mechanical stresses in their windings [3, 4, 12–14].

The accurate calculation of these quantities needs cutting edge numerical solvers, which should be validated by measurements. There are open benchmark problems published and maintained by the Compumag Society [15]. These problems are related to simple, analytically formulated problems or measurements. These benchmarks aim to compare some selected electromagnetic quantities with these given precise measurements or analytical formulations. However, in electrical optimization tasks, the machine parameters cannot be calculated directly from the geometry. The paper presents a simple, small, shell-type benchmark transformer manufactured by a simple technology, where the primary and secondary windings are wounded together. This means that the realized winding system contains randomly positioned windings. This cheap manufacturing technology is very generally used because it is precise enough to produce transformer windings with the given losses, where the transformer's short circuit impedance is not important. It can be manufactured with higher tolerances, but this is not important in many applications. These transformers no-load and short-circuit performance can be modeled by the transformer's well-known T-model parameters [16] and the no-load and short-circuit measurements of the transformer.

This parameter estimation's main difficulties are that the leakage impedances in the applied transformer model are significant, more than ten times higher than the transformer's main impedances. Moreover, these quantities are not fully physically independent parameters. Therefore, finding the optimal solution of the given equation system

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is a challenging task for the state-of-the-art bio-inspired metaheuristic algorithms [17]. Due to the no-free launch theorem of the mathematical optimization, these different meta-heuristic searches should be compared on the same optimization task to determine which one is the most suitable for the given optimization problem [18, 19].

The presented transformer parameter identification problem can be used to benchmark the different optimization techniques on this problem and benchmark state-of-the-art numerical solvers. The source code and the results of this simple benchmark problem can be accessible from Ārtap's example directory.

2 Ārtap framework

The Ārtap framework [20, 21] is a MIT licensed robust design optimization tool, written in Python (Ārtap is available for downloading from the web page of [22]). The development of the framework is motivated by an industrial brazing process, where several multi-physical Finite Element Method (FEM) based solvers, Neural networks and Model Order Reduction tools have to be used together to make an optimized design of an inductor [23–26]. Ārtap is designed to provide a collection of numerical solvers and optimization tools for robust design optimization of electrical machines [19, 26-29]. Ārtap provides a simplified interface for integrated optimization and numerical libraries. It has a simple, three-layered architecture (Fig. 1), where the task of the user is to define the Problem class and rewrite the *evaluate()* function. Through the algorithm class, the different optimization solvers can be invoked automatically, with a single command. Moreover, it contains an integrated FEM - solver (Agros suite [30, 32]) and several interfaces to commercial numerical libraries (like COMSOL Multiphysics [33]) and surrogate modelling tools [19-21].

In this paper, these optimization algorithms are used to analyze the performance of the different optimization solvers.

3 Transformer measurement setup

A photo of the transformer measurement setup can be seen in Fig. 2, the block diagram is depicted in Fig. 3. Measurements have been performed at the Laboratory of the e-Mobility Competence Center of the Széchenyi István University, Győr.

The nominal values of the type DB-0.25 transformer under test manufactured in Hungary are known from the nameplate: primary voltage is 230 V, power is 250 VA.

The one phase transformer under test is supplied by the primary voltage U_1 via a toroid transformer, i.e. U_1 can be controlled. The secondary coil of the transformer is loaded by a variable resistor with resistance R_L. The primary voltage U_1 and current I_1, furthermore the secondary voltage U_2 and current I_2 are measured by a power analyzer. Here, RMS-values are presented.

The Tektronix PA3000 is a four-channel powerful and versatile precision power analyzer designed to accurate measurements of electrical power. In this measurement setup the RMS-value of the voltage and the current, the frequency, the effective power, the reactive power, and the virtual power as well as the power factor have been collected by the power analyzer.

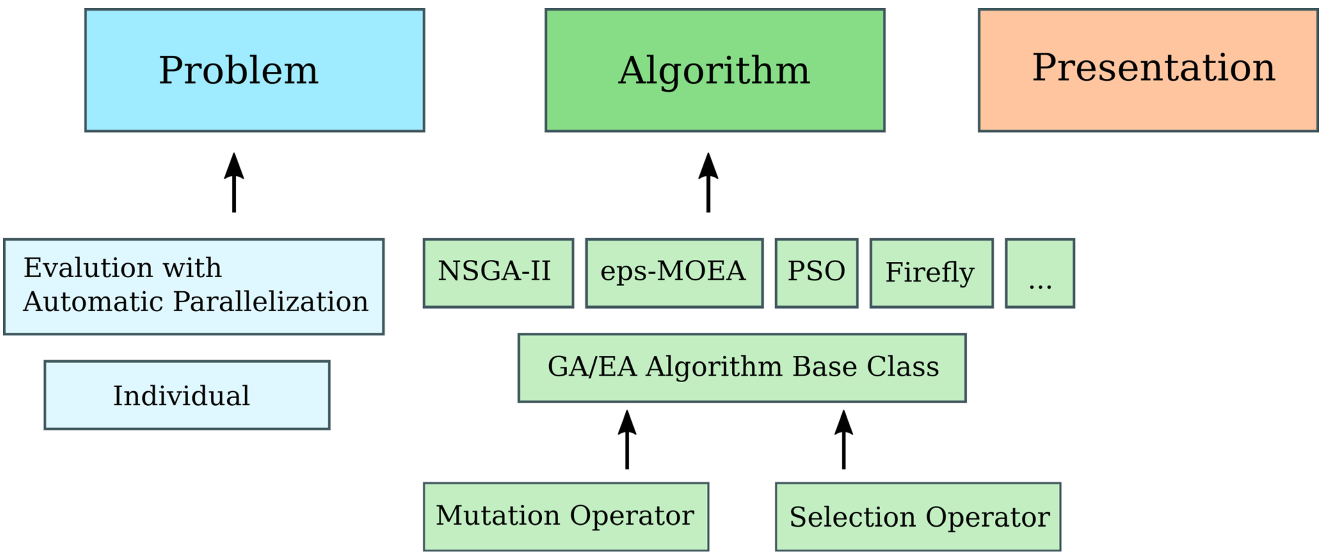

Fig. 1 Structure of the Ārtap framework

Fig. 2 The transformer measurement setup

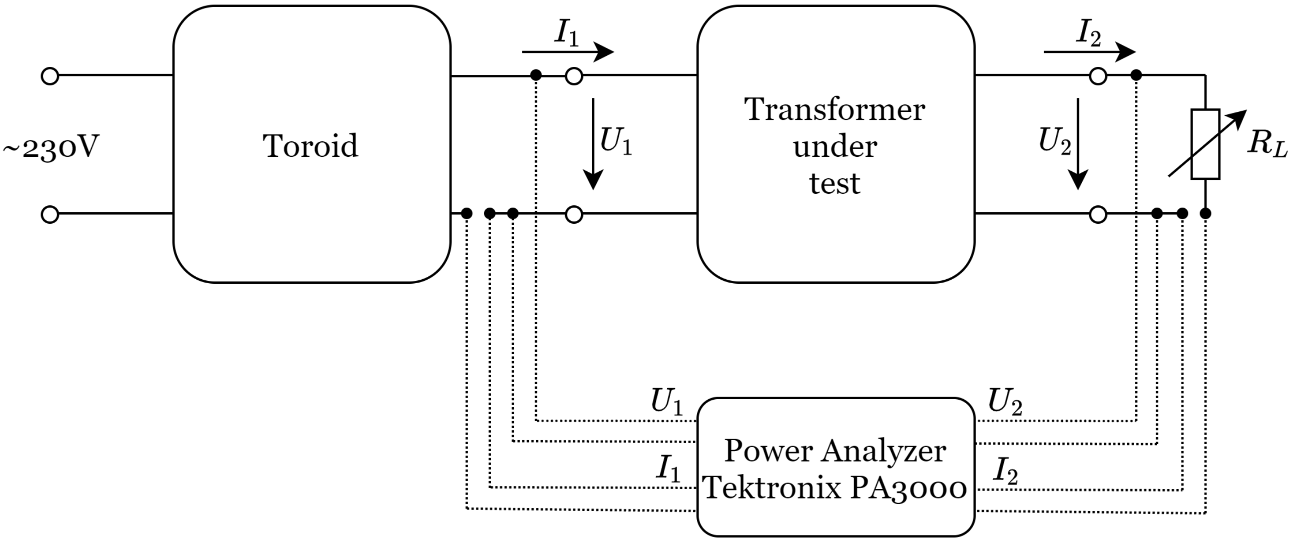

Fig. 3 Block diagram of the transformer measurement system

The measured data set based on five different loads for model identification is shown in Table 1.

4 Analytical parameter identification

The well-known equivalent circuit model of the transformer loaded by a resistor R_L is shown in Fig. 4 [16].

There are six parameters in the circuit, namely: primary resistance R_1 and primary leakage reactance X_1, secondary resistance R_2 and secondary leakage reactance X_2, both referred to the primary side, furthermore the magnetizing resistance R_m and magnetizing reactance X_m.

The known quantities from measurement are listed in Table 1:

- the primary voltage U_1,
- the primary current I_1,
- the power factor $\cos \varphi$,
- and the secondary voltage U_2 across the load resistance R_L.

Table 1 Measured data

U_1 [V]	230.34	229.36	229.02	228.13	48.634
I_1 [A]	0.116	0.3485	0.57078	1.2748	1.1055
$\cos \phi$	0.2136	0.9267	0.9693	0.9921	0.9922
U_2 [V]	13.026	12.414	11.951	10.95	0.0
R_L [Ω]	∞	2.3448	1.2745	0.4992	0.0

Open circuit and short circuit measurement results are plotted in Fig. 5 and in Fig. 6, where the power at nominal voltage and the power at nominal current are highlighted.

Analytical parameter identification is known from the textbooks. From the open circuit measurement results, the parallel connected R_m and X_m can be obtained as:

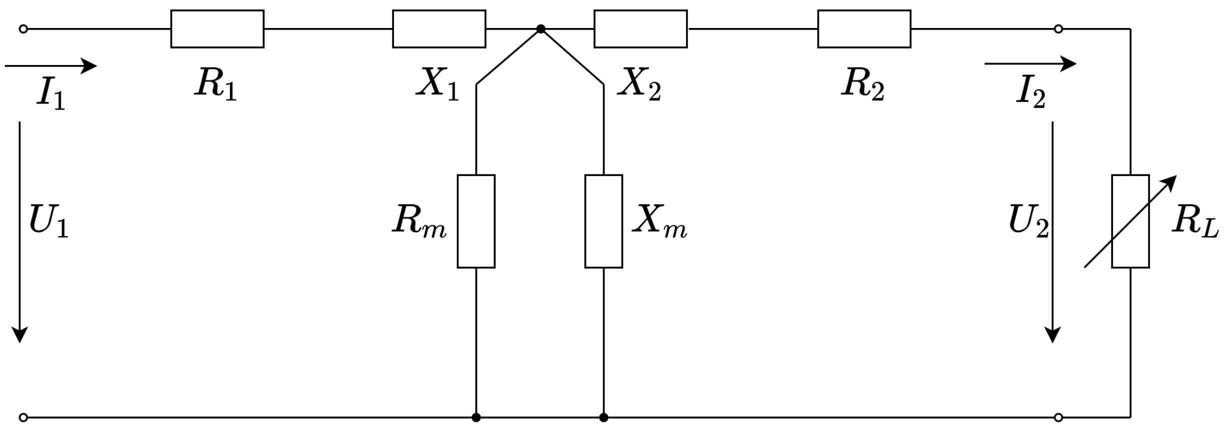

Fig. 4 Equivalent circuit model

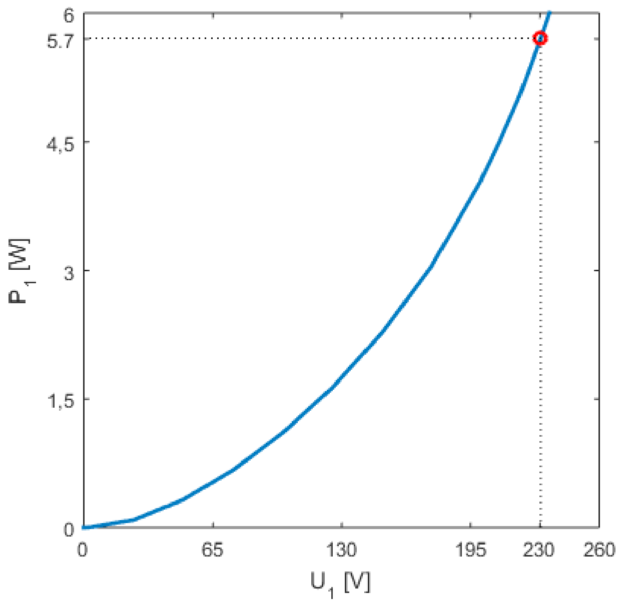

Fig. 5 Open circuit measurements result

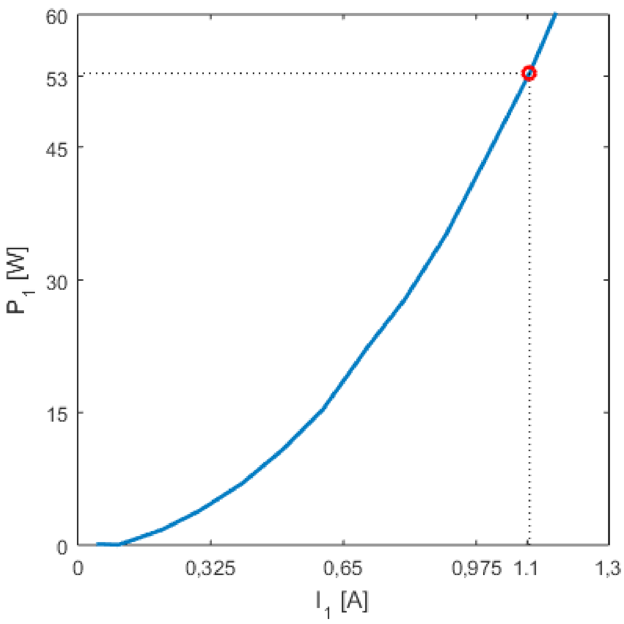

Fig. 6 Short circuit measurement result

$$R_m = \frac{U_1^2}{P_1}, \quad X_m = \frac{U_1^2}{Q_1}, \tag{1}$$

where $P_1 = 5.7$ W and $Q_1 = 26.1$ VAr, i.e. $R_m = 9308\ \Omega$ and $X_m = 2033\ \Omega$. The ratio can also be calculated:

$$a = \frac{U_1}{U_2} = \frac{230.34}{13.026} = 17.68 \cong 18, \tag{2}$$

Short circuit measurement data can be used to get the value of the horizontal elements:

$$R_1 + R_2 = \frac{P_1}{I_1^2}, \quad X_1 + X_2 = \frac{Q_1}{I_1^2}, \tag{3}$$

where $P_1 = 53.35$ W and $Q_1 = 6.7$ VAr, i.e. $R_1 + R_2 = 43.65\ \Omega$ and $X_1 + X_2 = 5.48\ \Omega$. It can be supposed, that $R_2 = R_1$ and $X_2 = X_1$, i.e. $R_1 = R_2 = 21.8\ \Omega$ and $X_1 = X_2 = 2.7\ \Omega$.

5 Parameter identification by Ārtap

An objective function must be set up to solve the parameter identification numerically.

The following objective function has been performed [33]:

$$F = F_1 + F_2 + F_3, \tag{4}$$

where:

$$F_1 = \sum_{i=1}^{n} \left(\frac{I_{1,calc}}{I_{1,meas}} - 1 \right)^2, \tag{5}$$

$$F_2 = \sum_{i=1}^{n} \left(\frac{\cos \varphi_{1,calc}}{\cos \varphi_{1,meas}} - 1 \right)^2, \tag{6}$$

$$F_3 = \sum_{i=1}^{n} \left(\frac{U_{2,calc}}{U_{2,meas}} - 1 \right)^2. \tag{7}$$

There are three components of the objective function. Here $I_{1,\mathrm{calc}}$ and $\varphi_{1,\mathrm{calc}}$ are the RMS-value and the phase of the primary current given by the equivalent circuit model. These calculated values are compared to $I_{1,\text{meas}}$ and $\varphi_{1,\text{meas}}$, i.e. to the RMS-value and the phase of the measured primary current. In the last term of the objective function $U_{2,\text{calc}}$ and $U_{2,\text{meas}}$ are the simulated and the measured secondary voltages.

The primary current can be got by:

$$I_{1,\text{calc}} = \frac{U_1}{Z_e}, \tag{8}$$

where U_1 means the measured input voltage, and Z_e is the equivalent input impedance,

$$Z_e = R_1 + jX_1 + R_m \times jX_m \times \left(a^2 R_L + R_2 + jX_2\right). \tag{9}$$

For further use, the last term, i.e. the equivalent impedance of the parallel elements is denoted by $Z_{p.}$ The secondary voltage can be derived from the voltage divider rule as:

$$U_{2,\text{calc}} = U_1 \frac{Z_p}{Z_e} \frac{a^2 R_L}{a^2 R_L + R_2 + jX_2} \frac{1}{a}. \tag{10}$$

The Ārtap code is as follows. First, some packages must be imported, as seen in Algorithm 1.

Next, the problem is defined. The parameters of the problem are given with their bounds, then the above mentioned objective function is implemented in Python. Measured data set is necessary to calculate the objective function. The code segment is very easy to understand as it is given in Algorithm 2.

The next step is to run the selected algorithm with some parameters, like the population number or the population size when applying genetic algorithms. In Algorithm 3, the SMPSO technique is applied.

Only the second line must be changed to apply another genetic algorithm based solver, e.g.:

$$\text{algorithm} = \text{NSGAII}\left(\text{problem}\right)$$

or

$$\text{algorithm} = \text{EpsMOEA}\left(\text{problem}\right).$$

At the end, the results of optimization can be got for further use, for example to check the identified model behavior. It is illustrated in Algorithm 4.

Algorithm 1 Import packages

```
from artap.problem import Problem
from artap.algorithm_genetic import NSGAII
from artap.algorithm_swarm import SMPSO
from artap.results import Results
import cmath, math
```

Algorithm 2 Problem definition

```
class TransformerDataFit(Problem):
    def set(self):
        self.name = 'Transformer'
        self.working_dir = '.'
        self.parameters =
        [{'name':'R1','bounds':[0.1,100]},
         {'name':'X1','bounds':[0.1,100]},
         {'name':'Rm','bounds':[2000,12000]},
         {'name':'Xm','bounds':[1000,4000]}]
        self.costs =
        [{'name':'F','criteria':'minimize'}]
    def evaluate(self, individual):

# Five measured data
U1 = [230.34,229.36,229.02,228.13,48.634]
I1 = [0.116,0.3485,0.57078,1.2748,1.1055]
pF = [0.2136,0.9267,0.9693,0.9921,0.9922]
U2 = [13.026,12.414,11.951,10.95,0.0]
RL = [math.inf,2.3448,1.2745,0.4992,0.0]

# Model parameters
R1 = individual.vector[0]
R2 = R1
X1 = individual.vector[1]
X2 = X1
Rm = individual.vector[2]
Xm = individual.vector[3]
a = U1[0]/U2[0]

# Objective function
F = 0.0
for i in range(len(U1)):
    if i == 0:
        Zp = 1.0/(1.0/Rm + 1.0/(1j * Xm))
    else:
        Zp = 1.0/(1.0/Rm + 1.0/(1j * Xm) +
        1.0/(a*a*RL[i] + R2 + 1j * X2))
        Ze  = R1 + 1j * X1 + Zp
        aZe = abs(Ze)
        fZe = cmath.phase(Ze)
        F = F+(U1[i]/aZe/I1[i]-1.0)** 2.0
            + (math.cos(fZe)/pF[i]-1.0)**2.0

    if i < len(U1)-1:
        if i == 0:
            U2c = U1[i]*Zp/Ze
        else:
            U2c = U1[i]*Zp/Ze*a*a*RL[i]/
                (a*a*RL[i] + R2 + 1j * X2)
            U2c = abs(U2c) / a
            F = F+(U2c/U2[i]-1.0)**2.0
return [F]
```

Algorithm 3 Solver settings 1

```
problem   = TransformerDataFit()
algorithm = SMPSO(problem)
algorithm.options['max_population_number'] = 500
algorithm.options['max_population_size'] = 100
algorithm.run()
```

Algorithm 4 Getting the results of the optimization

```
results       = Results(problem)
res_individual = results.find_optimum()
print(res_individual.vector)
```

Some technique requires the setting of the initial conditions, for example the Nelder-Mead method. In this case the following modification must be performed to set for example the parameter R1:

$$\{\text{'name'}:\text{'R1'},\ \text{'initial\_value'}:1,\ \text{'bounds'}:[0.1,100]\}.$$

The Nelder-Mead algorithm can be run by the lines given in Algorithm 5.

After inserting:

```
from artap.algorithm_scipy import ScipyOpt.
```

Here, the setting *tol* is for the tolerance, and the number of iterations has been set to 100. The algorithm can be changed very easily, just the name must be rewritten.

Table 2 presents the comparison of some results obtained by different algorithms. SMPSO, NSGAII and EpsMOEA are genetic algorithms, giving more or less the same values. Nelder-Mead method requires to set some initial conditions, and the result depends on it. For example, Nelder-Mead (1) is with the initial conditions: [10,10,10000,1000], and Nelder-Mead (2) is with the initial conditions: [1,2,10000,1000]. The difference between initial conditions is quite small, however the results are different. The algorithms CG, Powell, COBYLA and BFGS have been run with the initial conditions of [1,2,10000,1000] (these algorithms can be run easily by changing the algorithm name). The algorithm LN_BOBYQA is also very sensitive to the initial conditions, which can be applied by implementing the three lines of Algorithm 6.

Algorithm 5 Solver settings 2

```
algorithm = ScipyOpt(problem)
algorithm.options['algorithm']    = 'Nelder-Mead'
algorithm.options['tol']          = 1e-3
algorithm.options['n_iterations'] = 100
algorithm.run()
```

Algorithm 6 Solver settings 3

```
from artap.algorithm_nlopt import NLopt, LN_BOBYQA
algorithm = NLopt(problem)
algorithm.options['algorithm'] = LN_BOBYQA
```

Table 2 Comparison of the results obtained from different algorithms

Algorithm	$R_2 = R_1$	$X_2 = X_1$	R_m	X_m
Analytic	21.8	2.7	9308	2033
SMPSO	20.54	5.49	9536	1995
NSGAII	20.57	5.52	9542	1998
EpsMOEA	20.56	5.53	9543	1998
Nelder-Mead (1)	20.57	5.51	9544	1998
Nelder-Mead (2)	1.64	21.8	9265	2019
CG	20.64	4.69	9988	2269
Powell	20.56	5.54	9545	1999
COBYLA	21.35	6.89	9999	1048
BFGS	20.55	6.22	9990	2050
LN_BOBYQA	22.45	1.30	11560	2068
GN_DIRECT_L_RAND	20.45	5.65	10333	2056

The algorithm of GN_DIRECT_L_RAND can be tried out by changing the name in the last line.

6 Conclusions

The paper presented a simple one phase transformer benchmark problem to show, how the different optimization techniques can be used to determine the equivalent circuit model. Due to the no-free lunch theorem of the mathematical optimization, the different optimization algorithms should be benchmarked on this or a similar problem to decide which one is the most suitable for the given optimization task. The optimization problem was modeled by the Ārtap framework which software was provided a simple interface to invoke the different optimization solvers. The results of the different metaheuristic solvers are compared with the exact analytical solution. This global optimum is very close to the results of the optimization both in the case of the genetic and the particle swarm optimizer-based solutions.

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