

# EXPERIMENTAL RESULTS AND ANALYSIS ON UNBALANCED REGIMES ON A WYE-DELTA TRANSFORMER

## REZULTATE EXPERIMENTALE ȘI ANALIZA LOR ÎN CADRUL UNOR REGIMURI NESIMETRICE LA UN TRANSFORMATOR STEA-TRIUNGHI

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**Abstract:** *Low voltage (LV) networks are frequently operating with substantial unbalanced regimes, thus bringing power quality issues which need to be addressed. The present work presents experimental results of non-symmetric regimes on a reduced scale star-wye transformer, by applying principles of similitude, and compares the results versus a theoretical analysis of operation in a non-symmetrical regime of the MV/LV transformers. In this respect, a setup using a reduced scale transformer has been used, with a total power of 8 kVA, which is a reduced scale equipment of an 400 kVA MV/LV transformer, by using adequate similitude factors, such as  $K_{SIMIL} = 50$  for the current and power on the LV side. Measurements have been made with high quality devices, using a precision electronic smart meter of class 0.2S on one side and a power quality analyzer on the other side of the transformer, both being integrated in a small SCADA system which acquired and stored the necessary records. The work presents also specific adaptations of the measurement system in order to allow a detailed analysis of regimes of work on both sides of the star-wye transformer. The aim of the analysis is also to show practical aspects which can make a better link between theory and practice.*

**Keywords:** unbalanced regimes, star-wye transformers, similitude, reduced scale, experimental results.

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**Rezumat:** Rețelele electrice de joasă tensiune (JT) se caracterizează prin regimuri care sunt adeseori puternic nesimetrice, producând probleme legate de calitatea energiei electrice. Lucrarea prezintă rezultatele experimentale ale măsurării regimurilor nesimetrice pe un transformator stea-triunghi realizat la scară redusă, pe baza aplicării unor principii de similitudine și le compară cu analiza teoretică a funcționării în regim de nesimetrie a unor transformatoare de medie joasă tensiune (MT/JT). În acest scop se folosește un ansamblu trifazat de transformatoare la scară redusă, cu o putere totală de 8 kVA, care reprezintă un transformator MT/JT de 400 kVA, utilizând factori de similitudine adecvați, cum ar fi  $K_{SIMIL} = 50$  pe partea de joasă tensiune. Măsurătorile sunt realizate cu aparate de măsurare de înaltă calitate, respectiv cu un contor de energie electrică de precizie și cu un analizor de calitate, ambele fiind integrate într-un mic sistem SCADA cu care s-au realizat înregistrările. În lucrare se prezintă și adaptări specifice ale sistemului de măsurare, care să permită o analiză în detaliu a regimurilor de funcționare pe ambele părți ale transformatorului stea-triunghi. Scopul analizei este să pună în evidență aspecte practice care să facă o mai bună legătura între modelul teoretic și experiența practică.

**Cuvinte cheie:** regimuri nesimetrice, transformator stea-triunghi, rezultate experimentale

## 1. Introduction

Low voltage (LV) networks are frequently operating with substantial non-symmetric regimes, thus bringing power quality issues which need to be addressed. The present work presents experimental results of non-symmetric regimes on a reduced scale star-wye transformer, by applying principles of similitude, and compares the results versus a theoretical analysis of operation in a non-symmetrical regime of the MV/LV transformers. To allow flexibility in performing tests, a reduced scale low-voltage (LV) electrical network has been used.

The measurements presented in this work use high quality measurement equipment, respectively a 0.2S high accuracy digital meter and a power quality analyzer, both being integrated in a SCADA system which was able to make records of relevant measurements.

Moreover, the paper presents some of the specific adaptations which have been chosen to allow a detailed analysis of the operational regimes on both sides of the wye-delta transformer of the reduced scale model. The analysis highlights also practical aspects which can make a better connection between theoretical model and practical experience.

Measurements have been realized on a laboratory-based reduced scale network which uses principles of similitude to obtain similar results with the ones to be obtained in a real system with a 400 kVA MV/LV transformer.

## 2. Using principles of similitude and reduced scale models

John Strutt, known also as Lord Rayleigh, introduced in 1915 the paper “The principle of similitude” [1], saying that he has “often been impressed by the scanty attention paid even by original workers in physics to the great principle of similitude”.

In [2] it is stated that for power systems engineers, models are critical to the planning and economic design of this massive infrastructure, pointing that physical modeling has always had a role as well, stretching to use the laws of similitude to use more convenient frequency, impedance base, and physical size. The method presented in the paper [3] aims to establish in laboratory conditions, using the similitude criteria, the real value and the duration of a three phase short-circuit current acting in wind farms connected to the electric grids, while paper [4] gives some prerequisites of using similitude for studying distribution networks with a laboratory-scaled grid.

In the paper [5], experimental determinations have been obtained, for medium voltage faults on the lines radially connected to the main line emerging from a wind farm, using the similarity relations, allowing the determination of the electrical quantities from the real network. Similarity is used in many fields. For instance, the study from [6] explores the vulnerability of Internet-exposed services and the prevalence of Brute Force Attacks (BFAs) as an intrusion method. Within this study, are also evaluated similarity metrics based on Bloom Filters (BFs).

In the paper [7] are described different prototypical labs and their application are described, where users can exploratively learn the method of differential balancing, including similitude mechanics and visualization types in fluid mechanics, while in [8], based on the similarity theory, a reduced-scale model is proposed to study the voltage distribution characteristics in ultra-high voltage direct current converter transformer windings under the impulse voltage.

The paper [9] presents a reduced scale model for grounding resistance calculation using finite element method FEM method. In the paper [10], by using the finite element simulation platform, a reduced-scale model of two-span transmission line and its prototype finite element simulation model are established. The basic principle which has been used is that the main test data measured by the model and prototype in the test are similar or meet a certain proportion. In [11] it is presented an original smart-grids test bed aimed at teaching novel feeder automation functions to students from both university and industry origins, by using reduced-scale loads, generators, and a supervisory control and data acquisition system and paper [12] compares steady state and dynamic behavior of a large 117-inverter based, 147-MW solar PV plant

connected to IEEE 39-bus system, considering also reduced scale solar PV plant models.

In the paper [13], the operation of an MMC converter in an MTDC network containing three converter is verified experimentally in a reduced-scale pilot. In the tests, the energy buffering of the MMC converter was considered to sustain either AC or DC grids', by using the framework of the Multi Terminal DC pilot. In paper [14], the authors present a reduced-scale reconfigurable dc distribution testbed that contains a number of converters, inverters and adjustable link impedances.

In [15] it is made a real-time grid-impedance measurement, and experiments are conducted on a reduced scale 3 kVA laboratory testbed.

All these works show the broad spectrum of applications and how promising are the principles of similitude in various domains as well for studying various aspects of the power grid in the energy domain.

### **3. A reduced scale network, based on similitude factors**

A reduced scale network (RSN) has been constructed and used for making various tests and by using principles of similitude.

It is a low voltage network using five LV nodes (N1 – N5) which is supplied through a delta-wye three-phase transformer. While the delta part of the transformer is intended to represent a medium voltage connection in node N0, this node and the delta part of the transformer are still implemented in LV, for laboratory purposes.

The applied principles of similitude are targeting:

- A much lower power and current in the LV part of the scaled network
- A much lower voltage implemented for the primary of a real MV/LV transformer.

The following sections give the main formulas used in order to study such a reduced scale network and to obtain results regarding the operational status of the grid which can apply on a real and powerful network.

#### ***3.1. Similitude between currents of a real electrical network versus currents of a reduced scale network at the same voltage level***

For the reduced scale model having a different current level than for the real system, it is needed to introduce a current similitude factor.

For this, we apply the following rule: the current of the real system and the current of the reduced scale model need to produce the same voltage

drop on an impedance  $Z$ , if the reduced scale model is at the same voltage level as voltage level of the real system:

$$Z_{Real} \times I_{Real} = \Delta U_{Real} = Z_{Simil} \times I_{Simil} = \Delta U_{Simil} \quad (1)$$

for:

$$K_{Simil_I} = \frac{I_{real}}{I_{Sc\_Red}}$$

where  $I_{real}$  is the current in the real network, while  $I_{Sc\_Red}$  is the current in the reduced scale network.

It results the relation:

$$I_{Real} = K_{Simil_I} \times I_{Simil} \quad (2)$$

And we can write that:

$$Z_{Real} \times K_{Simil_I} \times I_{Simil} = Z_{Simil} \times I_{Simil} \quad (3)$$

Which brings the relation between the two impedances as being:

$$Z_{Real} \times K_{Simil_I} = Z_{Simil} \quad (4)$$

$$K_{Simil_U} = \frac{U_{real}}{U_{Sc\_Red}} \quad (5)$$

For a real current  $I_{real} = 50$  A, which corresponds to a current in the reduced scale model  $I_{Sc\_Red} = 1$  A, we have:

$$K_{Simil_I} = \frac{I_{real}}{I_{Sc\_Red}} = \frac{I_{real}}{I_{Simil}} = \frac{50}{1} = 50 \quad (6)$$

This is the current similarity factor which has been chosen for the reduced scale grid.

### 3.2. *Similitude between voltages of a real electrical network versus voltages of a reduced scale network*

For the reduced scale model having a different voltage level than for the real system, it is needed to introduce a voltage similitude factor, as follows:

$$K_{Simil_U} = \frac{U_{real}}{U_{Sc\_Red}} \quad (7)$$

For  $U_{real} = 20$  kV and  $U_{Sc\_Red} = U_{Simil} = 0,4$  kV, we have the following voltage similitude factor:

$$K_{Simil_U} = \frac{U_{real}}{U_{Sc\_Red}} = \frac{20000}{400} = 50 \quad (8)$$

This is the volage similarity factor which has been chosen for the medium voltage part of the reduced scale grid.

The  $K_{Simil_U} = 50$  allows to have a 400 V AC three-phase system on the transformer side which represent the real system phase to phase voltage of 20 kV.

#### 4. Tests and results

The reduced scale network used for the tests is presented in Figure 1.

It is a three-phase LV network which is supplied by a three-phase transformer. The transformer has been constructed by using three single-phase transformers having on the primary winding  $U_{N_{prim}} = 400 V$  and on secondary  $U_{N_{sec}} = 230 V$ . The three single-phase transformers are connected on primary side in delta, while on the secondary side they are connected in wye.

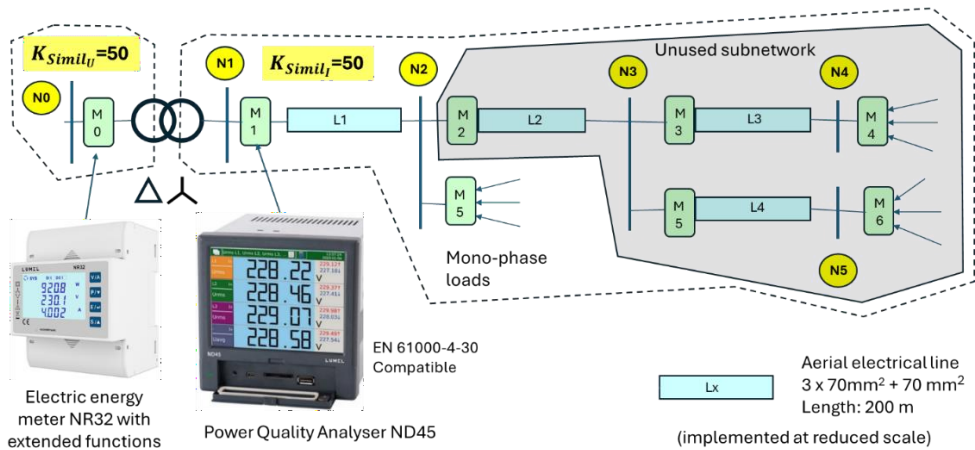


Figure 1. Reduced scale network used in the tests.

In order to test the behavior a MV/LV transformer with delta connection on MV and wye connection on LV side, tests have been made by connecting on the LV part of the transformer only single-phase loads. This brought three different scenarios, which are presented below.

#### Test 4.1 – Single-phase load between phase “a” and the neutral of the wye connection on the LV side.

The situation is depicted in Figure 2. It has been used a pure resistive load ( $X=0$ ).

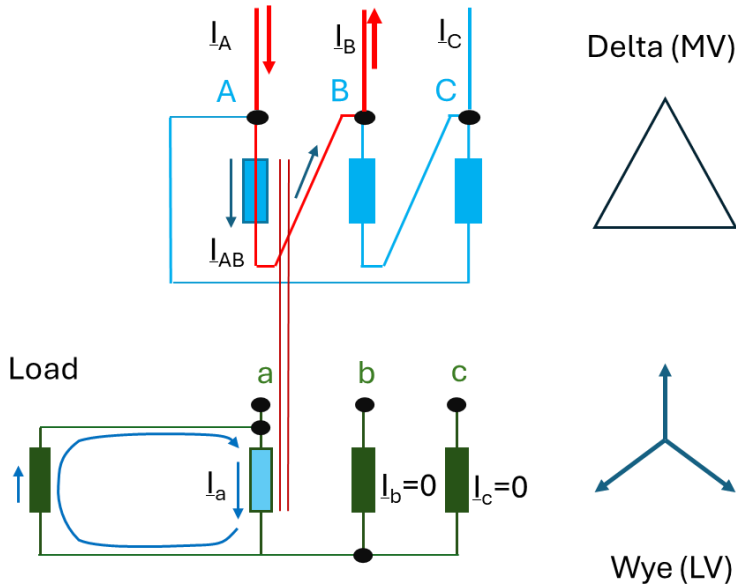


Figure 2. The voltage drops on an electrical line

It can be seen that the current  $I_a$  is obtained based on the magnetic coupling of the secondary between a and null (a-n) and the primary connected between phases A and B.

Moreover, as for each reduced scale single-phase transformer of the three-phase transformer the primary winding has a nominal voltage of  $230 \times \sqrt{3} \cong 400 \text{ V}$ , while the secondary has a nominal voltage of 230 V per phase, the relation between the currents is given by:

$$I_{AB} = \frac{I_a}{N_{Trafo}} \tag{9}$$

where the ratio  $N_{Trafo}$  is given by:

$$N_{Trafo} = \frac{U_{Primary}}{U_{Secondary}} = \frac{400}{230} = 1.73 \tag{10}$$

Then:

$$I_{AB} = \frac{I_a}{N_{Trafo}} = \frac{I_a}{1.73} \tag{11}$$

The currents on phases A and B are:

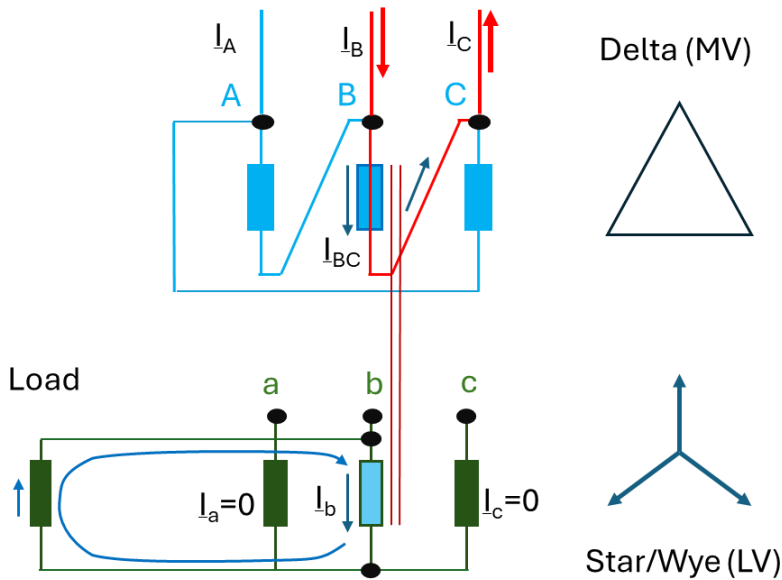
$$I_A = I_B = I_{AB} \tag{12}$$

Moreover, there is no current  $I_c$ , thus it can be considered  $I_c = 0$ .

This situation on the primary side of the transformer occurs when the single-phase load is connected on the secondary side between phase “a” and the neutral “n” of the wye. The secondary currents are  $I_a = U_{a-n}/Z_{Load}$ ,  $I_b = 0$  and  $I_c = 0$ .

**Test 4.2 – Single-phase load between phase “b” and the neutral of the wye connection on the LV side.**

The situation is depicted in Figure 3. It has been used a pure resistive load ( $X=0$ ).



**Figure 3.** The voltage drops on an electrical line

In this second test it can be seen that the current  $I_b$  is obtained based on the magnetic coupling of the secondary between phase b and null (b-n) and the primary connected between phases B and C of the transformer’s primary windings.

**Test 4.3 – Single-phase load between phase “c” and the neutral of the wye connection on the LV side.**

The situation is depicted in Figure 4. . It has been used a pure resistive load ( $X=0$ ).

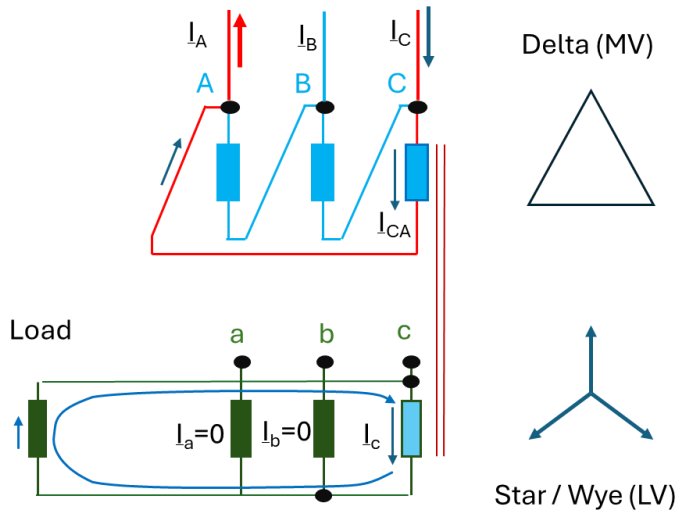


Figure 4. The voltage drops on an electrical line

In the third test it can be seen that the current  $I_c$  is obtained based on the magnetic coupling of the secondary between phase c and null (c-n) and the primary connected between phases C and A of the transformer’s primary windings.

#### 4.4 – Results and assessment

The currents and phases of currents related to their phase voltages have been measured and recorded each 2 seconds, for a period of at least 30 seconds. Tables 1 and 2 show average values of currents (in Amperes, [A]) and of angles (in degrees, [°]) during stable load-flows in no-load status and with single-phase loads on each secondary phase of the transformer.

The  $\Delta I$  [%] errors are calculated with the formulas:

$$\Delta I_A \% = (I_A - I_B) / I_A \times 100 \quad (13)$$

$$\Delta I_B \% = (I_B - I_C) / I_B \times 100 \quad (14)$$

$$\Delta I_C \% = (I_C - I_A) / I_C \times 100 \quad (15)$$

According to Figures 2, 3 and 4, the following relation should apply in theory for the primary currents:

- In Test 4.1 we should have  $I_A = I_B$  and  $I_C = 0$
- In Test 4.2 we should have  $I_B = I_C$  and  $I_A = 0$
- In Test 4.3 we should have  $I_C = I_A$  and  $I_B = 0$

*Table 1. Values of currents on primary and secondary of the three-phase transformer*

	$I_A$ [A]	$I_B$ [A]	$I_C$ [A]	$\phi_1(I_A-U_A)$	$\Phi_2(I_B-U_B)$	$\Phi_3(I_C-U_C)$	$\Delta I$ [%]
<b>No loads on the secondary of the transformer</b>							
Primary [A]	0.1073	0.0992	0.1131	41.455	154.694	-84.522	
Secondary [A]	0	0	0				
<b>Load on phase A</b>							
							$\Delta I_A$ %
Primary [A]	3.4762	3.4118	0.1104	42.513	94.87	-85.832	1.85%
Secondary [A]	5.8526	0	0				
<b>Load on phase B</b>							
							$\Delta I_B$ %
Primary [A]	0.1167	3.4506	3.3923	-24.774	153.857	-83.315	1.69%
Secondary [A]	0	5.8267	0				
<b>Load on phase C</b>							
							$\Delta I_C$ %
Primary [A]	3.4193	0.1023	3.4699	34.062	155.938	-144.067	1.46%
Secondary [A]	0	0	5.85				

The results from the measurements show that current deviations from the expected theoretical values (of having equal currents on two phases, depending on the single-phase load on the secondary part of the transformer), with errors between 1.46% to 1.85%. Considering the accuracy of 0.2 to 0.5% of the measurement equipment (smart meter on primary side and a quality analyzer on the secondary side), these are higher than expected errors.

In order to obtain results with a much lower deviation from theory, to comply with the expectancies due to high accuracy of the used measurement equipment, it has been realized that the small currents on the primary side of the transformer during a no-load situation may be the cause of the increased error. These currents are due to the magnetization of the transformer core, are small and have measurable angles compared with their voltages, thus allowing them to be represented as well as phasors. These currents need therefore to be added to the currents from the tests with loads on different phases, by using full phasor diagrams (each current represented by module and angle).

Figure 5 gives the phasor summation in the case of a single-phase load on phase b.

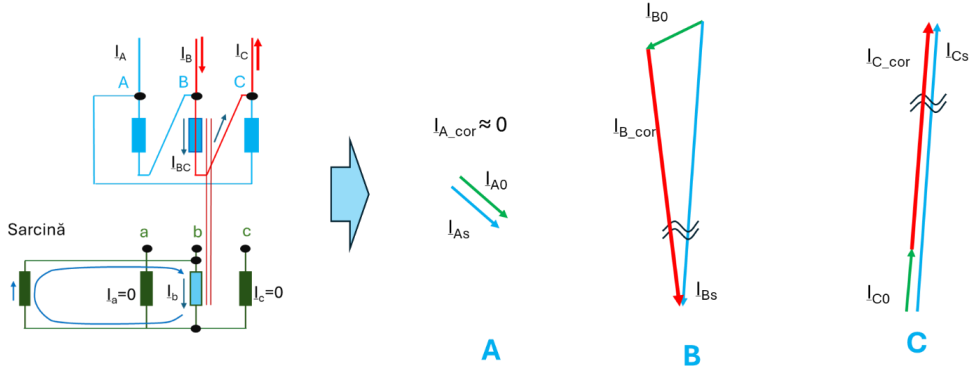


Figure 5. The voltage drops on an electrical line

Considering the needed corrections, Table 2 shows the new values of the primary, compared to theoretical values. One can see that the difference from theoretical values have decreased substantially, showing that the method of correction gave successful results.

Table 2. Values of currents on primary and secondary of the three-phase transformer with corrections

	$I_A$ [A]	$I_B$ [A]	$I_C$ [A]	$\phi1(I_A-U_A)$	$\Phi2(I_B-U_B)$	$\Phi3(I_C-U_C)$	$\Delta I$ [%]
No loads on the secondary of the transformer							
Primary [A]	0.1073	0.0992	0.1131	41.455	154.694	-84.522	
Secondary [A]	0	0	0				
Load on phase A							
Primary [A]	3.36313	3.363039	0.1104	42.513	94.87	-85.832	-0.003%
Secondary [A]	5.8526	0	0				
Load on phase B							
Primary [A]	0.1167	3.3514	3.3505	-24.774	153.857	-83.315	-0.028%
Secondary [A]	0	5.8267	0				
Load on phase C							
Primary [A]	3.363387	0.1023	3.36352	34.062	155.938	-144.067	0.004%
Secondary [A]	0	0	5.85				

The results show much lower current deviations comparing to the expected theoretical values, with errors between 0.004% to 0.028%, which are

much better results to be obtained from the accurate measurement equipment used in the experiments.

## 5. Conclusions

Based on the measurements, the primary currents have been found to have values with an error of 1.46 – 1.85% compared with the theoretical values. Such errors are too high considering the measurement equipment, which is in classes between 0.25S and 0.5. In order to see the root of these errors, it has been deduced that the primary currents for the transformer without secondary loads (no-load regime) are superposing with the currents due to the secondary loads, so a correction has been made by considering these currents as well. Table 2 shows that after a correction considering phasors of the superposing currents, the new error compared with the theoretical one has decreased to a maximum of only 0.028%. The study has highlighted the importance of experimental tests, which in this case it shown the necessity to consider the additional influence of no-load currents. By adjusting the phasors of the load currents with the phasors of the no-load currents, the experimental results have been accurately obtained at values close to the theoretical ones.

The measurements and their interpretation have been made on a reduced scale network by using also principles of similitude for currents and voltages.

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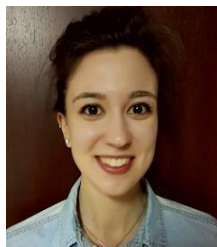
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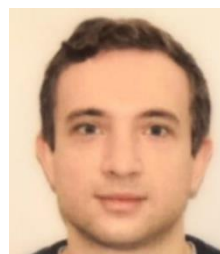
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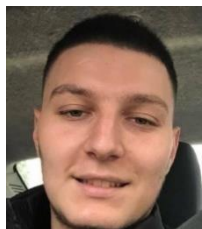
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