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# PERFORMANCE ANALYSES OF A THREE WINDING DOUBLE STACK PV TRANSFORMER

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**Abstract-** Transformers are the main components of electrical systems and are widely used in renewable energy systems that transfer the energy they produce to the grid. Recently, due to the lack of fossil fuels, governments have encouraged utilities to seek alternative energy sources. In this respect, PV (Photovoltaic) power plants have become more important in recent years. Accordingly, transformers are one of the most critical equipment of PV plants, and their safe operation and stability in the electrical network are important. This type of transformer is energized from the inverter and needs to be customized to work with each system. The main purpose of this study is to analyze and model the magnetic field behavior of a special type PV transformer. This transformer has two similar separate windings on the low voltage side and one winding on the high voltage side. The simulation results are compared with those obtained from the experiments. The effects of the unbalanced operation of the inverters on the transformer performance were also investigated in this study.

**Keywords:** PV (Photovoltaic), Three Winding, Transformer.

## 1. INTRODUCTION

Due to the lack of fossil fuel resources in recent years, all governments encourage researchers and public institutions to turn to renewable energy sources. As a result, solar photovoltaic energy is growing rapidly and plays an important role in energy production. The power produced in PV power plants is transferred to the grid by step-up transformer. Accordingly, the transformer is one of the most important components in PV power plants. Most customers are interested in having multiple LV (low voltage) windings on the same transformer to connect each winding individually to an inverter [1, 2]. Design considerations such as short-circuit impedance and losses for such transformers lead to a complex design phase, and the precise calculation of the operating losses of these transformers plays an important role in the design process and the safe operation of the network.

In this study, performance analyzes were made by analyzing the magnetic field behavior of 2000 kVA (1000+1000) kVA, which is the stacked LV winding configuration of the PV transformer [3] designed according to the new EU (European Union) transformer requirements. Then, an unbalanced case study was carried out to determine behavior of PV transformer in this situation.

## 2. SYSTEM DESCRIPTION

In this study, a 3-phase, Dyn5yn5, 2000 kVA, 20/0.49-0.49 kV, PV transformer with two low voltage windings and fed by two inverters is considered. Each LV winding has half of the rated power of the high voltage winding and operates separately while the HV winding works in parallel. Figures 1 and 2 show the winding configuration of the PV transformer.

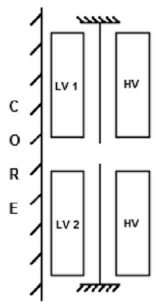


Figure 1. PV transformer winding

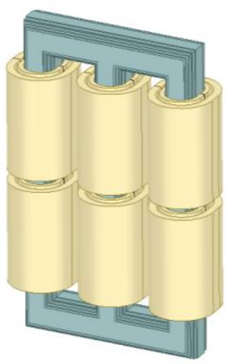

Figure 2. 3D modeling of the PV transformer

The brief design parameters of the studied transformer are demonstrated in Table 1.

Table 1. Transformer Specification

| Type | 2000 kVA, 20 /0.49-0.49 kV, 50 Hz |
|---|---|
| Secondary rated current (A) | 57.74 |
| Primary rated current (A) | 1178.27 |
| Vector group | Dyn5yn5 |
| Primary turn numbers | 21 |
| Primary conductor (mm) | AL- 555 x 1.5 |
| Secondary Turn numbers | 1485 |
| Secondary conductor (mm) | AL- 6.8x2.6 |
| Maximum flux density | 1.62 T |
| Core cross section (cm²) | 358.5 |
| Core Yoke distance (mm) | 441 |
| Core Leg distance (mm) | 1296 |
| Load Loss (W) | 14519 |
| No load losses (W) | 1462 |

## 3. SIMULATION STUDY

In this paper, a 3D transient analysis is performed employing the ANSYS Maxwell on a 3-phase, Dyn5yn5, 2000 kVA, 20/0.49-0.49 kV PV transformer. According to the simulation study, the results of the voltage and current of the secondary (High Voltage) and primary (Low Voltage) winding are presented in Figures 3-8.

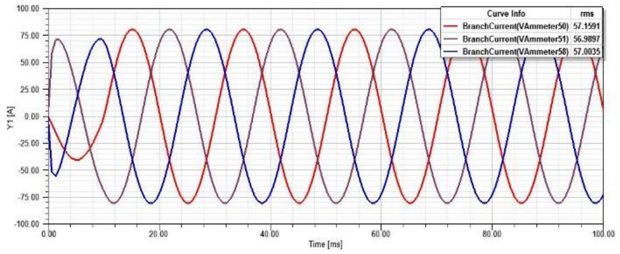


Figure 3. Secondary winding current

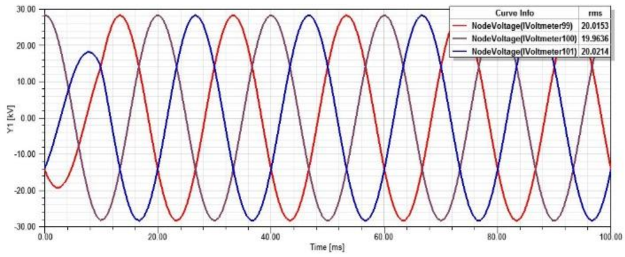


Figure 4. Secondary winding voltage

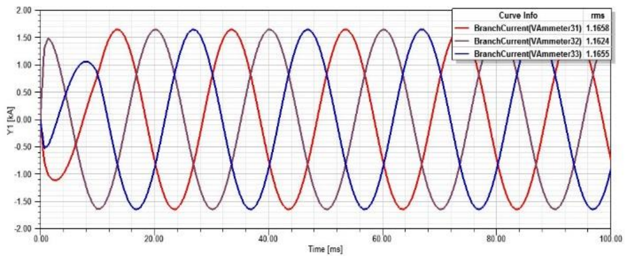


Figure 5. Lower primary windings current

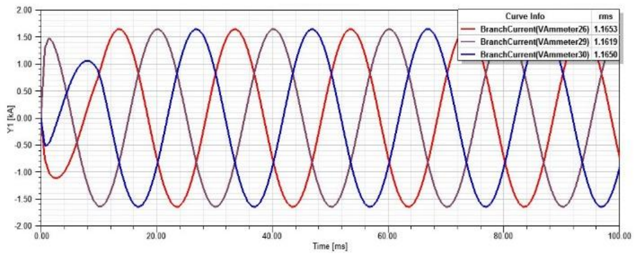


Figure 6. Upper primary windings current

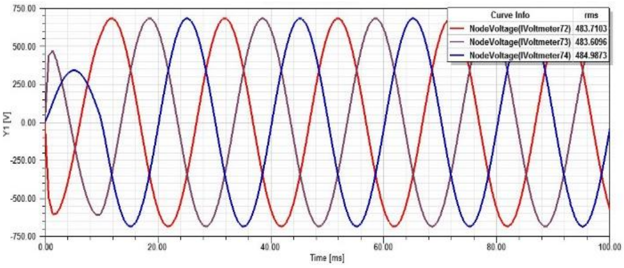


Figure 7. Lower primary windings voltage

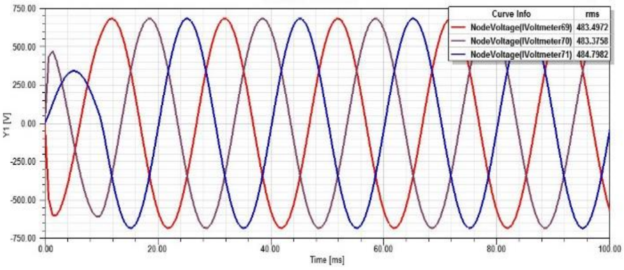


Figure 8. Upper primary windings voltage

## 4. TRANSFORMER LOSSES

Transformer losses are classified into two main groups as no load and load losses.

### 4.1. No Load Losses

No load losses are the losses which caused by the magnetization in the core of the transformer when it is energized with its rated voltage but not supplying load. No load losses mostly depend on the magnetic core material. The core loss of a transformer is consisting of Eddy Current and Hysteresis Losses [5-7].

$$P_{NL} = P_h + P_e \quad (1)$$

Figure 9 shows no load loss of studied transformer with the hysteresis and eddy losses which obtained from the simulation result.

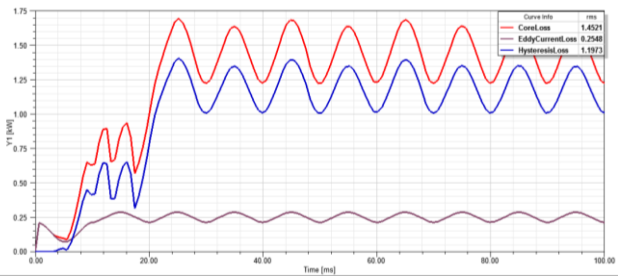


Figure 9. No load loss

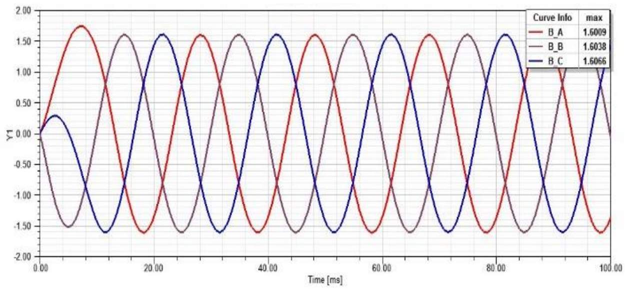


Figure 10. Magnetic flux density

Figure 10 shows the maximum magnetic flux density in the core of the transformer. When both LV windings are fed by the inverter, the magnetic flux density distribution in the working transformer is shown in Figure 11.

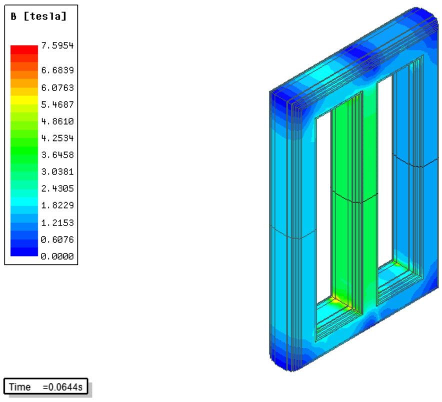


Figure 11. Magnetic flux density distribution (3D)

### 4.2. Load Losses

Resistance losses and total leakage losses in the windings form the load losses of the transformer. Total leakage losses also consist of eddy losses in the winding and leakage losses in the metal part of the transformer such as the tank and core clamps [5-7].

$$P_{LL} = P_{DC} + P_{EC} + P_{OSL} \quad (2)$$

In this study, the winding eddy current loss is neglected since the winding is defined as a helical model. Since the simulation only works with the active part of the transformer, other star losses such as connection and cable losses and losses in the tank and core clamps of the transformer are neglected.

The ohmic losses at 75 °C obtained from the simulation result are shown in Figure 12-15. Since the simulation study works only with the active part of the transformer, these losses include only ohmic losses and leakage losses in the winding of the transformer without lead losses.

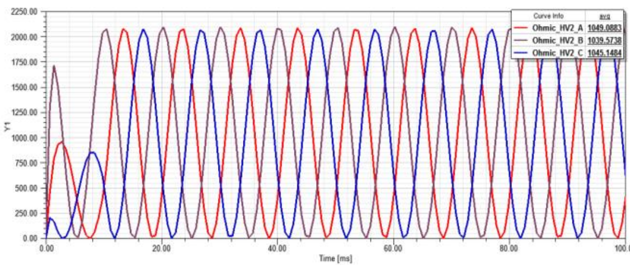


Figure 12. Ohmic loss in the lower HV winding

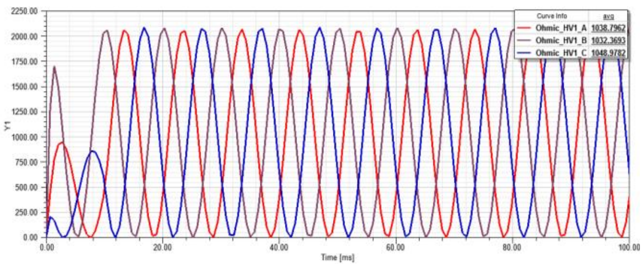


Figure 13. Ohmic loss in the upper HV winding

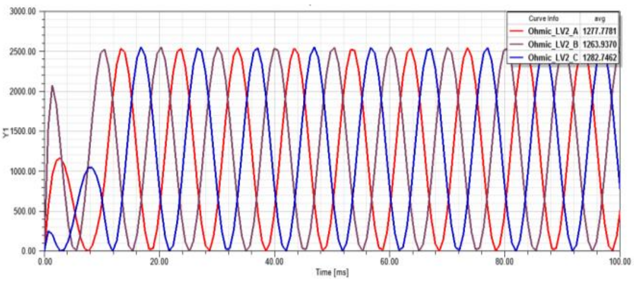


Figure 14. Ohmic loss in the lower LV winding

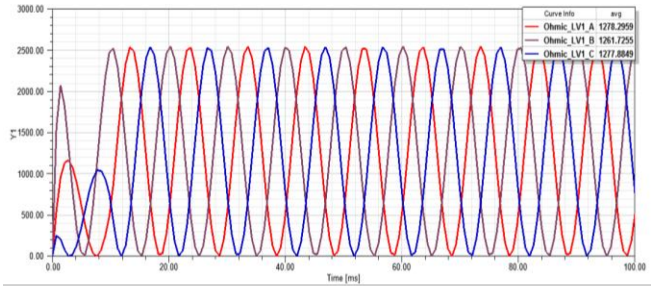


Figure 15. Ohmic loss in the upper LV winding

The results obtained from the simulation and the factory test results are compared in Table 2.

Table 2. Analyses results

| | | Test | Simulation | Dev % |
|---|---|---|---|---|
| Secondary Voltage (V) | | 20000 | 19999.6 | 0.002 |
| Primary Voltage (V) | | 490 | 484.1 | 1.2 |
| Secondary Current (A) | | 57.74 | 57.05 | 1.2 |
| Primary Current (A) | | 1178.27 | 1164 | 1.2 |
| Flux Density (T) | | 1.62 | 1.60 | 1.3 |
| No Load Loss (W) | | 1445 | 1452 | 0.5 |
| Load Loss (W) | HV Ohmic | 6439 | 6251 | 3 |
| | LV Ohmic | 8175 | 7638 | 7 |
| | Stray | 1254 | - | - |
| | Total | 15868 | 13925 | 14 |

## 5. UNBALANCED OPERATION STUDY

Two unbalanced conditions are applied to the subjected transformer for determination of the transformer performance under these situations.

### 5.1. Unbalanced Phase Angle

To evaluate the performance of the transformer during the unbalanced phase condition the upper LV winding operate at 5 degree phase shifting. Figures 16-21 show the results of the voltage and current of the secondary and primary winding of the transformer during this condition.

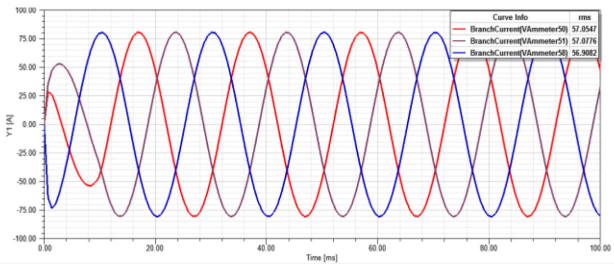


Figure 16. Secondary winding current

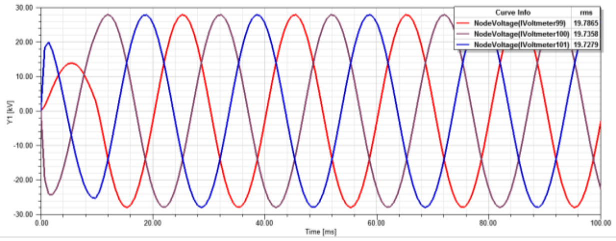


Figure 17. Secondary winding voltage

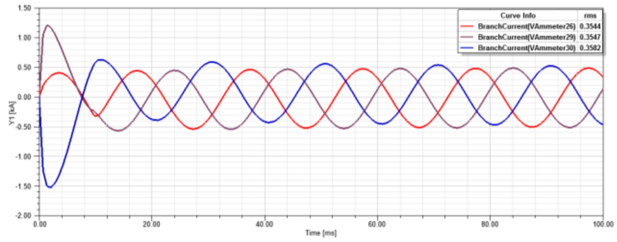


Figure 18. Upper primary windings current

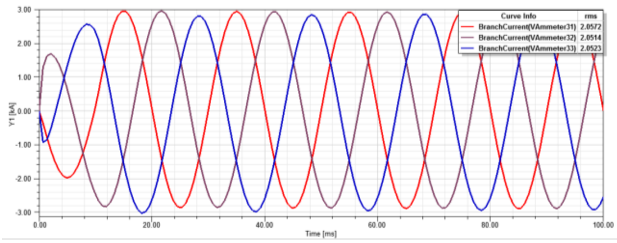


Figure 19. Lower primary windings current

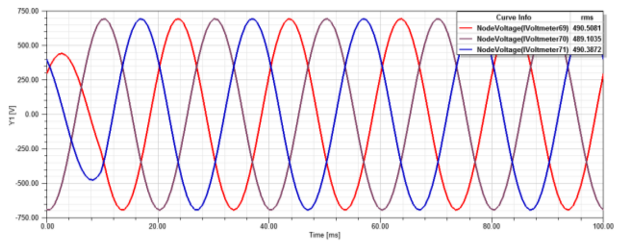


Figure 20. Upper primary windings voltage

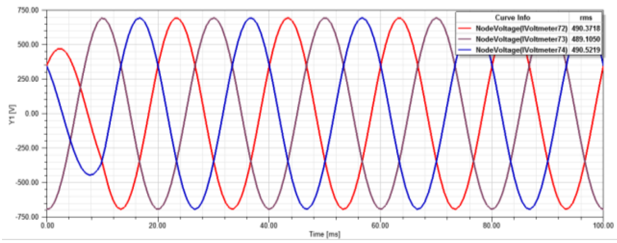


Figure 21. Lower primary windings voltage

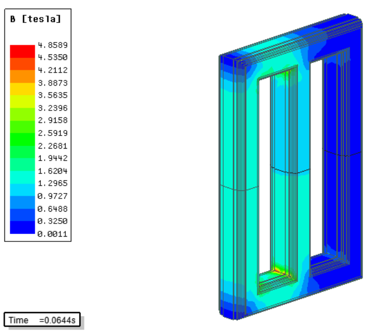


Figure 22. Magnetic flux density distribution (3D)

### 5.2. Unbalanced Voltage

In the unbalanced voltage condition, the voltage which applied to the LV winding are different from each other. Respecting this, the upper LV winding voltage is %5 less than the lower LV winding rated voltage. The results obtain from simulation during this condition are given in Figures 23-29.

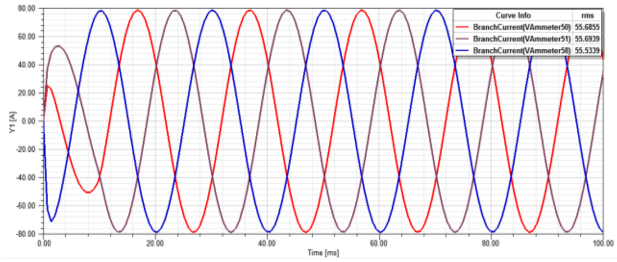


Figure 23. Secondary winding current

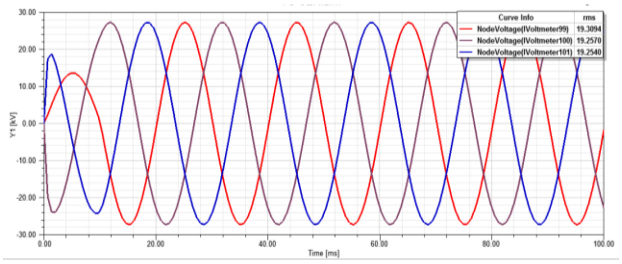


Figure 24. Secondary winding voltage

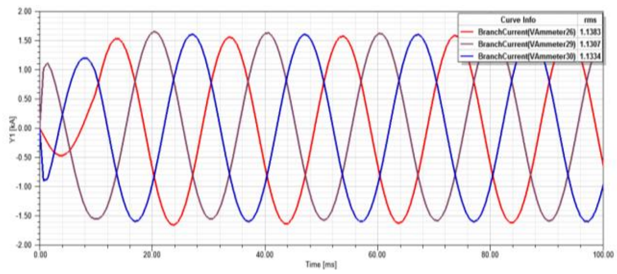


Figure 25. Upper primary windings current

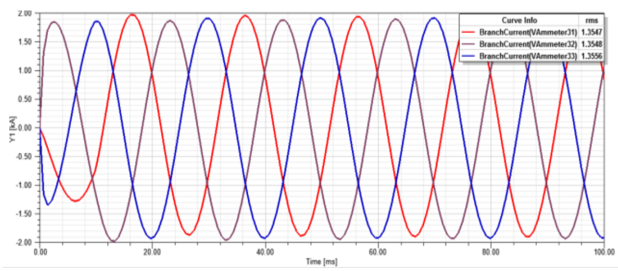


Figure 26. Lower primary windings current

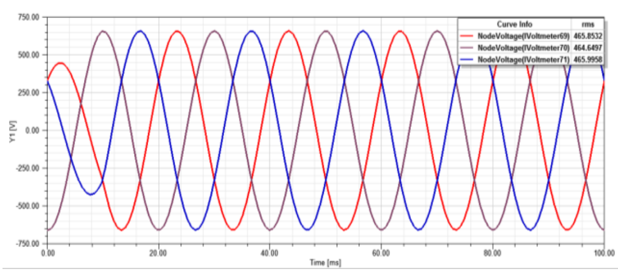


Figure 27. Upper primary windings current

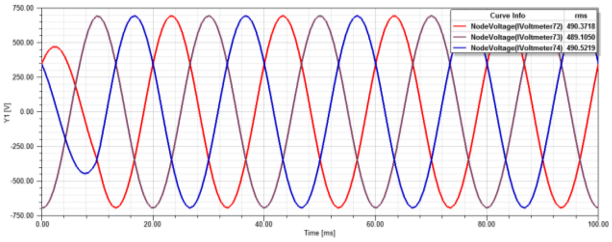


Figure 28. Lower primary windings current

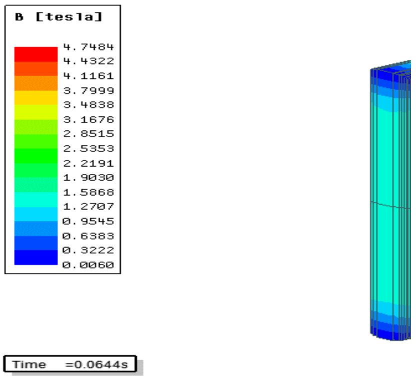


Figure 29. Magnetic flux density distribution (3D)

The analyses results of the unbalanced operation condition and the normal operation condition of the PV transformer are illustrated in Table 3.

Table 3. Analysis results of unbalance conditions

| | Secondary Voltage | | Upper Primary Voltage | | Lower Primary Voltage | |
|---|---|---|---|---|---|---|
| | (V) | (A) | (V) | (A) | (V) | (A) |
| Normal Operation | 19999 | 57.0 | 484 | 1164 | 484 | 1164 |
| Unbalanced Phase | 19600 | 57.0 | 490 | 355 | 490 | 2053 |
| Unbalanced Voltage | 19273 | 55.6 | 465 | 1133 | 490 | 1354 |

According to the simulation results, in the case of unbalanced phase, the upper LV winding current is 355 A, while the lower LV winding current is 2053 A. It is also seen that the unbalanced voltage condition affects the voltage and current of each winding.

## 6. CONCLUSIONS

In this paper, a 3-phase, Dyn5yn5, 2000 kVA, 20/0.49-0.49 kV PV transformer is studied to determine and calculate its operating losses. Finite element method was used to show the 3D model of the transformer. The results obtained from the simulation and the experimental results are compared. It is seen that the results are in good agreement and the analysis of transformer using Ansys program helps to better understanding behavior of the transformer prior to the production of transformer and will useful for transformer design carried on by manufactures.

In addition, the performance of transformer was analyzed considering unbalance operation conditions such as difference in phase angle and difference in amplitudes of the three phase voltages produced by the inverters supplying the LV windings. According to the simulation results, in the case of unbalanced phase angle, the phase shift of 5 degrees has a significant effect on the current of the LV winding of the transformer, causing the winding to overload and overheat, resulting in deterioration of the insulating material and insulating oil.

Also, the 5% voltage magnitude unbalance condition causes the voltage and current of the winding to change, which adversely affects the safe operation of the transformer. For these reasons, the utility should be aware of the impact of unbalance and make special consideration in choosing identical inverter parameters feeding this type of PV transformer to improve the safe and secure operation of the grids.

## NOMENCLATURES

### 1. Symbols / Parameters

$P_T$ : Total losses in transformer

$P_{NL}$ : No load losses in transformer

$P_{LL}$ : Load losses in transformer

$P_e$ : Eddy losses in the transformer core

$P_h$ : Hysteresis losses in the transformer core

$P_{DC}$ : Ohmic losses in winding of transformer

$P_{EC}$ : Eddy losses in winding of transformer

$P_{OSL}$ : Stray losses in the metallic parts of the transformer

## ACKNOWLEDGEMENTS

Thanks to SEM Transformer company, Ankara, Turkey for their support and all the necessary high performance test equipment.

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## BIOGRAPHIES

**Amir Jahi** received his M.Sc. degree in Electrical and Electronics Engineering from University of Gazi, Ankara, Turkey in 2013. Currently, he is a Ph.D. student in Electrical Engineering at the same University and working as Electrical Design Team Leader at SEM transformer Inc. company, Turkey. Generally, he is interested in researching about transformers.

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