Unbalanced Operation in Transformers Used in PV Plants

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Abstract- Renewable energy has become the most preferred energy sources today due to its environmental and economic advantages. One of the renewable energies is solar energy, in which Photovoltaic (PV) cells are used to convert solar energy into electrical energy. In this respect, Solar Power Plant (SPP) is one of the popular renewable energy sources and the integration of such power sources into electricity grids has been increasing in recent years. Transformers are one of the largest capital investments in solar power generation and the way they work is different from transformers used in a substation. Therefore, failure of transformers has significant economic effects on electrical networks. The PV type transformer is powered by the inverter and needs to be customized to work with every system. Consequently, the safe operation and reliability of this type of transformer is critical to the sustainability of the electrical grid. Consequently, identifying the probability of failure as a preventative action for grid protection is critical and should be addressed to improve electrical system reliability. The main purpose of this study is to analyze the effects of the unbalanced operation of the inverter on the performance of the special type transformer used in the PV plant and to show how the inverter operation can affect the operation of the transformer.

Keywords Photovoltaic (PV); Solar Power Plant (SPP); Transformer; Finite Element Method (FEM), Unbalance Condition

1. Introduction

Due to the large investments in renewable energies in various industries and electricity recently, solar power plants are growing day by day all over the world. Transformers are used in solar power and distribution systems and play a critical role in power generation [1-5]. Generally, in high power distribution transformers used in solar power plants, more than one inverter is used due to the inverter power rating limitation. The operation and regulation of each winding is controlled by a separate inverter. Therefore, the operating state of the inverters critically affects the performance of the transformer and more effort is required to ensure that the transformer operation meets the requirements of the power plant. In the last few years, several studies have been conducted to develop and experiment with transformer analyzes for specific conditions of PV power plant, as reviewed in [6-11]. Some studies have been carried out to show the additional losses associated with the current harmonic content by considering some correction factors [12-13]. The maximum load capacity of a transformer used in a solar power plant is investigated in [14]. In [15-16], the finite element method is used to calculate transformer losses used in solar power plants. Case studies on the effects of PV transformer energizing on the power quality of the grid are conducted in [17]. The design methodology for solar power generation transformers using comparative analysis is presented in [18]. In [19], various simulation results and practical measurements are used to evaluate the effect of current harmonics on the k-factor value of the distribution transformer. In [20], the electrical design of a special type of PV transformer fed with two separate inverters is made by taking into account the high frequency loss calculation. In [21-23], various studies have been carried out to evaluate the aging and lifetime of the PV transformer, taking into account the effects of weather conditions such as ambient temperature, solar radiation, solar cell temperature and current harmonics. In [24], transformer power is calculated according to the loading data of the solar installation. In [25], the design of the 100 kVA three phase transformer used in solar and wind application is carried out. The rated power of the solar power generation transformer is investigated based on the loss of life calculation in [26]. The study [27] presents comparative analyzes considering the harmonic spectrum of different transformers in the range of 100 kVA to 1500 kVA used in renewable energy applications.

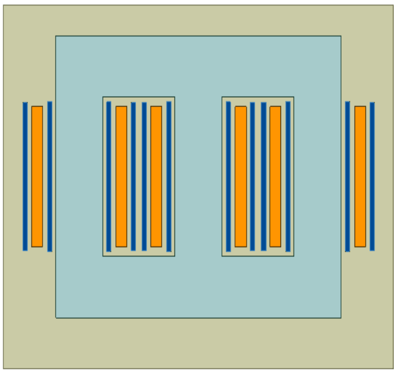
Although an acceptable number of studies have been carried out on the performance and loss analysis of solar transformers according to the reviewed literature, investigation of the behavior of the transformer in case of unbalanced operation of the inverters has not been done before.

This paper discusses a 5.1 MVA three-winding PV transformer to evaluate and demonstrate the importance of the unbalance condition on transformer behavior. The simulation model of the transformer is used to show the effects of the situation on the transformer. The simulation results reveal that a low level of unbalance operation has a significant effect on the transformer, which negatively affects the performance and safe operation of the transformer.

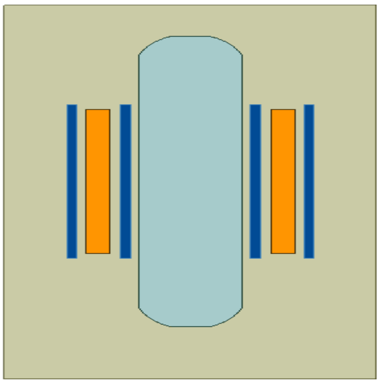
2. Explanation of the System

A 3-phase, Dyn11yn11, 5.1 MVA, 34.5/0.66-0.66 kV with circular concentric winding PV transformer is discussed as a case study in this article. In this transformer, each low voltage winding is at half rated power and is fed by a separate inverter, while the high voltage winding operates at full power and is located between two low voltage windings. Figure 1 shows the 2D model and position of the windings of the subjected transformer.

Various possible winding configurations and loss analyzes of a three-winding transformer used in PV power systems are given in [28-30]. Each of these winding configurations has different advantages and disadvantages. The most important advantage of the concentric winding configuration used in this study is its compact design, and its disadvantage is the difference in the impedance value of the low voltage windings.



(a)



(b)

Fig. 1. 2D model of the transformer (a) Front view, (b) Side view

The electrical and mechanical design details and specifications of the relevant transformer are given in the Table 1.

Table 1. Transformer Specification

Type	5.1 MVA, 34.5/0.66-0.66 kV		
Secondary rated current	85.35 (A)		
Primary rated current	2230.6 (A)		
Vector group	Dyn11yn11		
Primary turn numbers	13		
Primary conductor	AL-710x1.6 (mm)		
Secondary turn numbers	1177		
Secondary conductor	AL-9.7x2.6 (mm)		
Maximum flux density	1.65 T		
Core cross section	667 (cm²)		
Core yoke distance	1458 (mm)		
Core leg distance	1048 (mm)		
	LV1 (mm)	HV (mm)	LV2 (mm)
Winding inner diameter	315	443	649
Winding outer diameter	377.9	617.5	714
Winding axial height	740	747	740
Load Loss	≤ 52 (kW)		
No load losses	≤ 3.8 (kW)		
Short circuit impedance	7 % ± 10 %		

3. Unbalanced Operation Study

Since PV transformers are fed with two separate low voltage windings from the low voltage side, different unbalanced operation situations can be considered in this type of transformers depending on the inverter operation. In this study, two unbalance cases are considered to show transformer performance under these conditions. One of the unbalanced operating situations is voltage level unbalance, and the other one is difference in phase angles of the low voltage windings. In the normal and stable operating condition of the transformer, the voltage values applied to each low voltage side are equal and there is no phase angle shift between them. The effects of unstable operating conditions on transformer performance are examined in the following sections.

3.1. Unbalanced Voltage Level

In unbalanced voltage operation, the voltage values applied to the low voltage windings of the transformer are different from each other. In this study, 5% voltage difference is considered to show the effect of voltage unbalance. As a result, the LV1 winding voltage level is 5% less than that of the outer winding, which is equal to its rated value. The simulation results of the relevant condition are given in Figure 2-7. As can be seen from the figures, the voltage unbalance in the low voltage windings causes the current values to be unbalanced, which adversely affects the performance of the transformer.

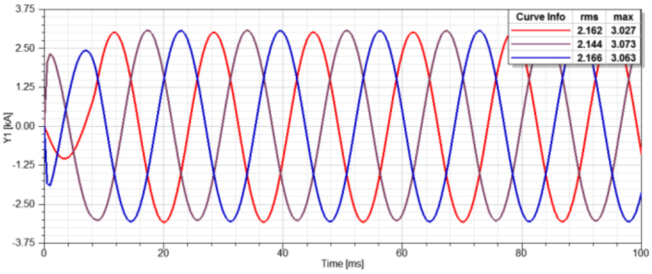


Fig. 2. PV transformer LV1 winding current

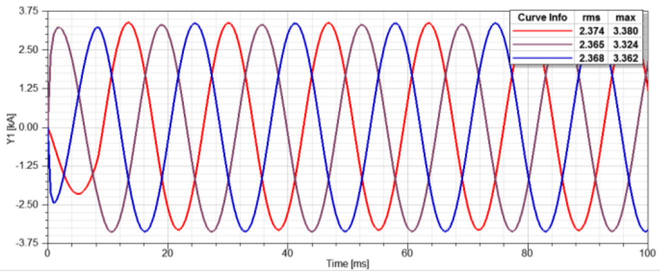


Fig. 3. PV transformer LV2 winding current

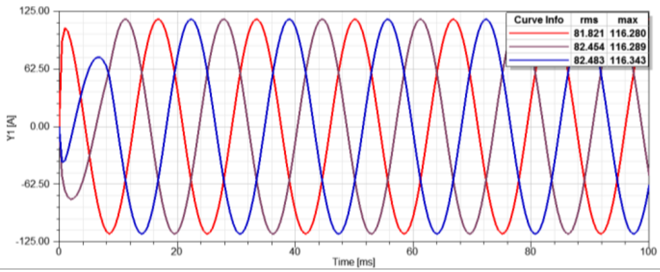


Fig. 4. PV transformer HV winding current

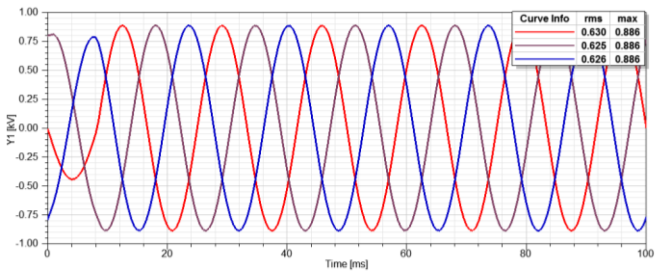


Fig. 5. PV transformer LV1 winding voltage

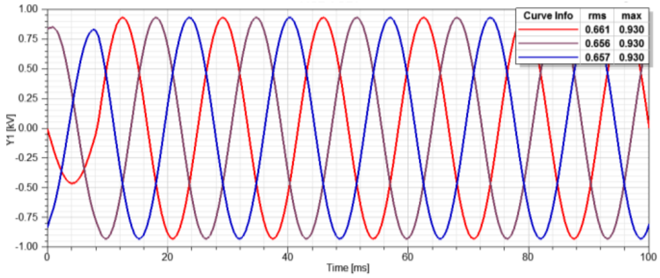


Fig. 6. PV transformer LV2 winding voltage

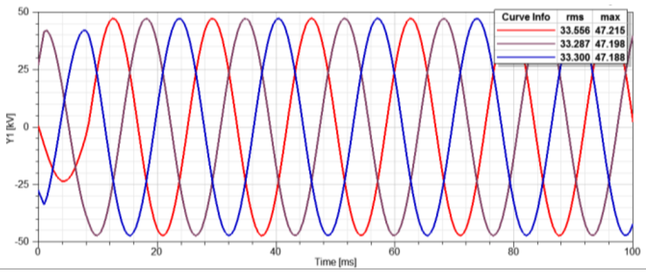


Fig. 7. PV transformer HV winding voltage

3.2. Unbalanced Phase Angle

The voltages of the low voltage windings may not be synchronized due to difference in phase angles of the inverters. In this study, a phase difference of 5 degrees is taken into account to evaluate the corresponding effects on the operation of the transformer. The LV1 winding voltage lags the LV2 winding voltage by 5 degrees. Figures 8-13 show the results of the voltage and current of the secondary and primary windings of the transformer during this condition. It can be seen from the figures that when the voltage phase angles of the two low voltage windings are different, the current of the outer low voltage winding (LV2) is greater than that of the inner low voltage winding (LV1). This excess current value causes overheating resulting in transformer breakdown.

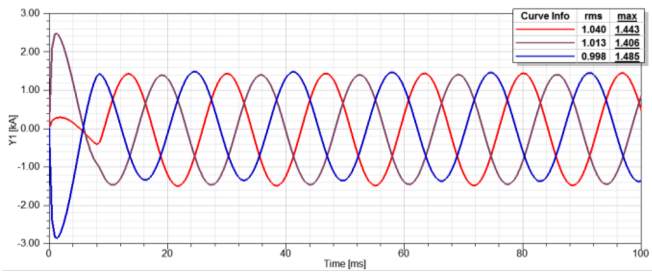


Fig. 8. PV transformer LV1 winding current

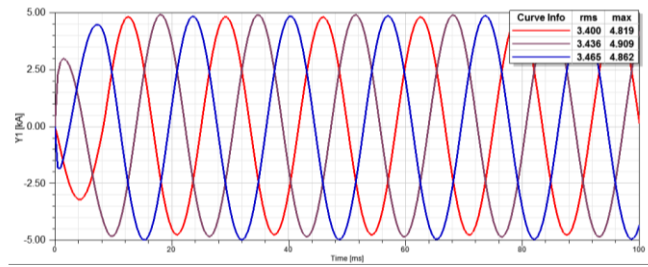


Fig. 9. PV transformer LV2 winding current

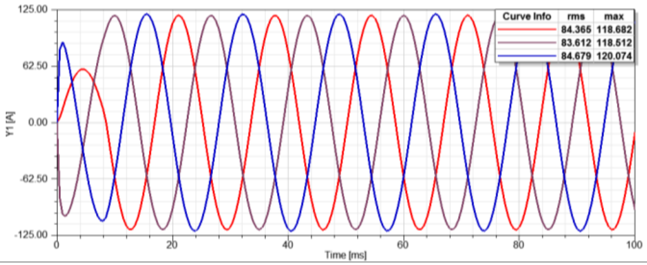


Fig. 10. PV transformer HV winding current

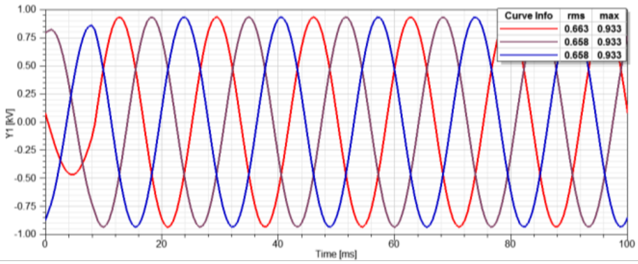


Fig. 11. PV transformer LV1 winding voltage

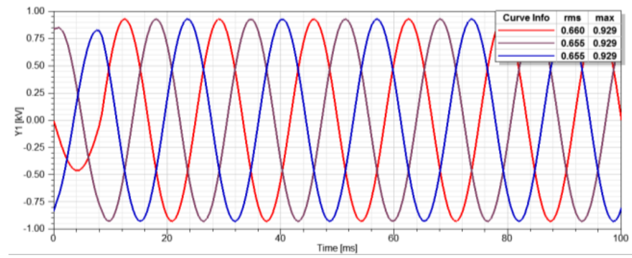


Fig. 12. PV transformer LV2 winding voltage

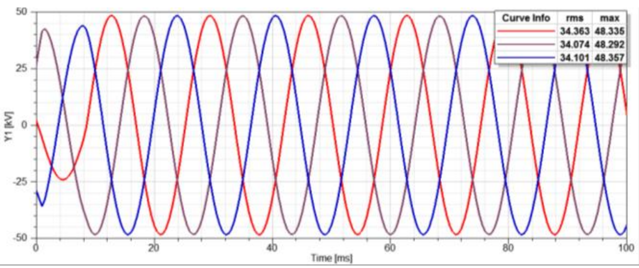


Fig. 13. PV transformer HV winding voltage

4. Results and Discussions

The analysis results of the unbalanced operating condition are compared with those of the normal operating condition of the PV transformer in Table 2.

According to the simulation results, it has been observed that the 5-degree phase difference has a significant effect on the current value of the low voltage winding. This will cause the LV2 winding to overload and overheat, causing aging of the insulating materials and eventual transformer failure. In addition, 5% voltage unbalance situation causes unbalance in current values, negatively affecting the safe operation of the transformer.

Table 2. Analysis results

	LV1 Voltage		HV Voltage		LV2 Voltage	
	(V)	(A)	(V)	(A)	(V)	(A)
Normal Operation	660	2230	34500	85.3	660	2230
Unbalanced Voltage	627	2157	33381	82.2	658	2369
Unbalanced Phase	659.6	1017	34179	84.4	656.6	3433

5. Conclusion

The main objective of this study is to analyze and examine the problems that may occur in transformers using more than one inverter in solar power plants. A special type of PV transformer is selected as a case study for evaluating the effects of the unbalance condition on the transformer performance.

Based on the results obtained from the simulation study, manufacturers of PV transformers fed from two or more inverters should pay great attention to the balanced operation of the inverters. Therefore, the output voltages of the inverters must be fully controlled and synchronized in terms of phase angle and voltage level.

The output voltage of the inverters is not completely sinusoidal and contains different harmonics, which causes problems in the performance of PV transformers. Harmonics cause an increase in transformer losses, resulting in an increase in the operating temperature of the transformer and a decrease in its useful life. For these reasons, it is necessary to use properly designed filters at the outputs of the inverters.

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