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Transformers within photovoltaic generation plants: Challenges and possible solutions

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SUMMARY

Within South Africa, the drive for electrical energy from renewable sources has seen the exponential growth (since 2011) of independent power producers (IPPs). The renewable sources used for the majority of these IPPs are solar and wind. Due to conversions required in these plants, from direct current (DC) power to alternating current (AC), harmonics and transients affect the equipment installed. Variation in loading due to fluctuating availability of resources also affects the equipment within these systems. In this paper the focus will be on the effects of grid-connected photo-voltaic (PV) plants on the distribution transformers utilised within them. These transformers connect the IPP to the grid, and therefore it is important to understand the effects that such an installation could have on these units. This paper explores the existing literature on problems within PV systems, which include harmonics, non-linear loading and transients. It further analyses the effects that these problems could have on PV transformers. It also identifies the responsibilities of both the manufacturer and the utility, and elaborates on the role that each plays to ensure the compatibility of a transformer for a PV plant.

KEYWORDS

Distribution Transformers, Harmonics, Non-linear Loading, Photovoltaic, Power Quality, Renewable Energy, Transients

1. Introduction

Due to an ever-increasing demand for electrical energy, not only in South Africa but worldwide, the drive for renewable energy sources has been overwhelming. In South Africa, the key driver has been the implementation of the REIPPPP (Renewable Energy Independent Power Producer Procurement Programme), and renewable energy feed-in-tariffs (REFIT) [1]. This resulted in an expansion of the renewable technology market, especially PV (photovoltaic) and wind farm generating plants. Equally, there has been an increasing market for manufacturers of electrical distribution equipment, which includes transformers.

Step-up distribution transformers connect these PV plants to the electrical grid, by increasing the generated voltage to the required distribution voltage level. These step-up transformers are exposed to various electrical challenges within the system. One of these challenges is resulting harmonics; owing to the conversion from the DC generated power to the AC distributed power – via inverters.

Other challenges include voltage transients (switching, voltage dips and swells), caused by non-linear loads [2]. These transients can result in abnormal stresses in the insulation of the transformer. PV plant distribution transformers are also energised and de-energised more frequently, often daily [3]. The variation in the loading of these transformers poses some concerns about the transformer sizing. This load variation is due to the daily loading and generating capabilities of the PV plant itself.

There are various challenges within a PV system. It is therefore very important for both the transformer manufacturer and the client (IPP/utility) to be aware of the challenges involved. A lack of information and understanding from either party could result in a reduced lifespan of the transformer, consequently a reduced lifespan of the PV plant. This could in turn reduce the availability and profitability of the plant. Within an African context, this could even result in limited access to electrical energy.

The aim of the investigation is to holistically present the challenges experienced by distribution transformers that are connected to PV plants. The following section of this paper briefly looks at the basic components of a PV plant. Thereafter, some challenges for a transformer in this type of plant are discussed, with supporting literature. The analysis of the harmonic impact on transformers is covered in Section 4, where the data of an operating PV plant is used.

2. Basic components of a PV system

In a photovoltaic plant the solar radiation from the sun is converted to DC electrical energy, via solar panels. This DC power is converted to AC power and synchronised with the electrical grid (for a grid-connected setup). Various PV inverters can be used, depending on the plant configuration and size. For larger power plants, central inverters (0.1-1 MW) are typically used [4] (see Figure 1).

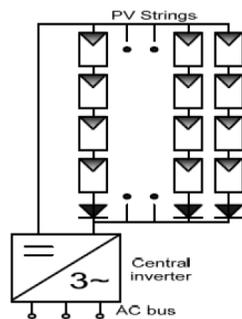


Figure 1: Central inverter arrangement for a PV plant [5]

In a centralised PV configuration a string of PV modules are connected to one inverter, which then supplies AC power to an AC bus. A number of central inverter arrangements can be connected in parallel to the AC bus [5]. The inverter-supplied AC power is fed to the grid via a distribution step-up transformer, being the link between the PV plant and the national or local grid (depending on the application). This document will focus mostly on grid-connected PV plants, but the issues mentioned might also be applicable to stand-alone PV systems.

Generally there are two configurations, with regards to the PV transformers, which are utilised within a PV plant. The first is the connection of an inverter, or a string of parallel inverters feeding a low voltage bus, to the primary (low voltage) winding of a two-winding transformer. This arrangement can be seen in Figure 2, which has two two-winding transformers feeding a medium voltage bus. The parallel arrangement is typically used for smaller (kVA) inverters.

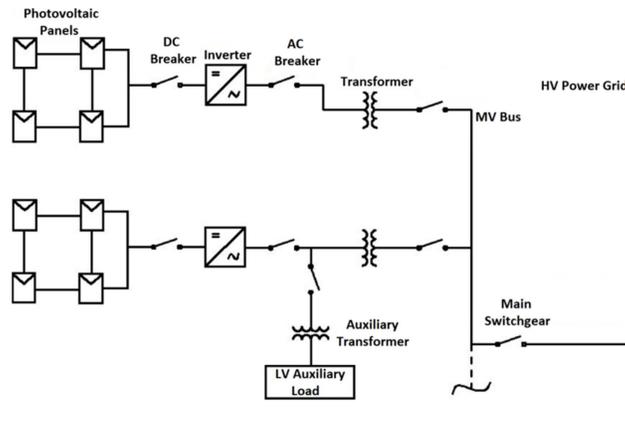


Figure 2: Example of a configuration with two-winding transformers [6]

The second arrangement is given in Figure 3, where a three-winding transformer is used. In this arrangement, the transformer has two primary (LV) windings, which are fed from two separate inverters. It is important to consult with the inverter manufacturer to review the parallel operation of these inverters, with either a two- or three-winding transformer. Some inverter designs would require galvanic isolated low voltage windings. Other important aspects to consider is to have equal impedences between each LV winding and the HV winding and also ensure that the impedance between the two LV windings is high enough to ensure decoupling of these windings [6].

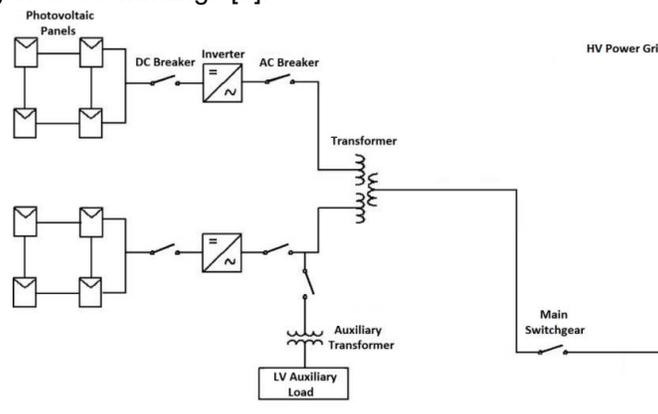


Figure 3: Example of two inverters feeding one three-winding transformer [6]

In any PV plant configuration, the interaction between the transformer(s) and the inverter(s) are of high importance. Resonance in this system could result in harmonics, which could damage the transformer and also reduces its life span. The following section looks at some challenges that transformers could be exposed to in a PV plant application.

3. Identified challenges

This section presents the challenges facing distribution transformers that are connected to PV plants. The challenges are derived from literature and individually presented.

3.1. Harmonics

In a grid connected PV plant, the inverters produce harmonics due to the electronic switching required to convert DC power to AC power. These harmonic currents and voltages could reflect on the AC bus at various voltage levels and with that be fed to the step-up distribution transformer. In this section the effects these harmonics can have on the transformer are discussed.

The AC waveforms generated by the PV inverter(s) are sinusoidal, but the voltage to ground has a pulsed nature. This voltage includes harmonics and spikes, which should be taken into consideration when a PV transformer is designed [6]. In applying Faraday's law in the frequency domain, it becomes clear that the flux magnitude is proportional to the amplitude of the voltage harmonic and inversely proportional to the harmonic order [8].

In most power systems, the effect of current harmonics is more significant, when compared to voltage harmonics. Current harmonics could result in additional losses in both the windings and structural components of the transformer, as will be seen in the results section. The winding eddy current losses, due to a non-sinusoidal current, vary with the square of the root mean square (rms) current and the square of the frequency, as given in equation (1) [9].

$$P_{EC} = P_{EC-R} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_R} \right)^2 h^2 \quad (1)$$

Where P_{EC} is the winding eddy-current loss [W], P_{EC-R} is the winding eddy-current loss (rated conditions) [W], h is the harmonic order, h_{max} is the maximum harmonic number, I_h is the rms current at harmonic h [A] and I_R is the current under rated frequency and load conditions [A]. With an increased rms current the I^2R losses of the transformer increase accordingly. As stated previously, the eddy-current losses within the transformer, subjected to current harmonics, are affected by the harmonic frequency ([10], [11], [12] and [13]). These increased winding losses will add to the temperature rise within the windings of the transformer. Additionally, harmonic currents can also add to the no-load losses within the core of the transformer by possibly 15% [14]. Studies also show that the stray losses in structural components increase by a harmonic exponential factor of 0.8 or less [9].

A rise in the losses of a transformer increases the heat generation, which would increase the top oil temperature. This means that customers must specify the harmonics generated by the specific inverters, and for complex systems the simulated harmonic results of the bus to which the transformer will be connected. These harmonic values must then be used in loss calculations and transformer cooling designs [15].

3.2. Loading

The electrical energy production capability of a PV plant, without energy storage capabilities, is directly related to the irradiation available on each day. Figure 4 shows an example of the loading of a transformer at a PV plant – note that the figure represents a clear day. The loading curve has the same shape as the irradiation curve for that specific installation. The loading of the transformer is usually controlled by the inverter, through a dampened reaction process.

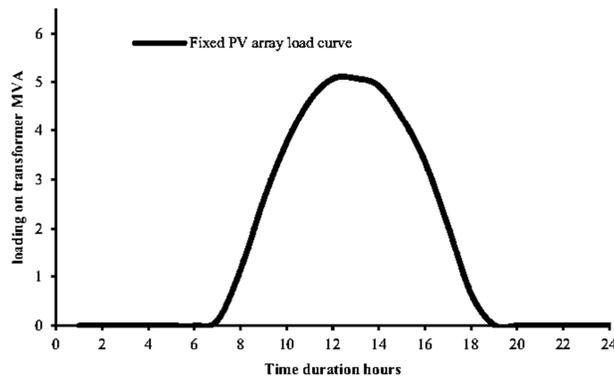


Figure 4: Example of a peak generation day load curve of a 6.5 MVA transformer [16]

A transformer in a PV plant may be loaded for up to 14 hours in summer of which around 6 hours could be at full load. This loading of the transformer could result in thermal and mechanical force cycling, which may damage the transformer [6]. The variant no-load operation of the transformer in a PV system impacts the loss capitalisation [15]. The client must ensure that the capitalisation for the transformer takes into consideration this loading curve.

Another important aspect which must be addressed is the sizing of the PV transformer, owing to the solar irradiation variation and with that the load of the transformer. The transformer must be rated based on the energy generation cycle of the plant, the output of the inverter(s), as well as other factors like harmonics and weather patterns [17]. The “white cloud” phenomenon causes irradiation spikes. The frequency, duration and amplitude of these spikes could also affect the transformer sizing [6]. An oversized transformer will be able to supply the maximum solar energy to the utility grid, but will increase capital costs of the plant (increased inverter and distribution line costs). Transformers that are not optimally sized for the variation in irradiation could cause grid instabilities. This could result in frequent shut-down of PV plants, which does not have energy storage capabilities [18]. Transformer sizing is important in order to optimise the capitalisation costs of the transformer and with that a PV plant. In [16], [18] and [19] guidelines are given for transformer size selection.

Transformers are generally designed for a more constant loading operation and might not be designed for daily switching, which may be required in a PV system. Frequent switching of a transformer poses additional challenges, like inrush current. Loading variation of PV plant transformers also poses other challenges, which includes voltage regulation (higher frequency tap changing). In the following section some of these challenges are discussed.

3.3. Intermittent challenges

3.3.1. Voltage transients and Insulation

The inverter in a PV plant usually regulates the voltage supplied to the LV side of the transformer, which varies by $\pm 5\%$ of the nominal voltage. This reduces problems with regards to LV insulation, which can be designed according to standard transformer design principles. With the exception of a possible electrostatic shield, which might be required and specified by the inverter manufacturer, the LV (primary) side of the transformer has no real special design considerations with regards to transients.

The electrostatic ground shield has the main purpose of minimising the transfer of voltage disturbances (like harmonics) from the primary (LV) winding to the secondary (HV) winding. It also assists in limiting overvoltage transfers from HV to LV, and to the inverter [6]. As mentioned in Section 3.1, inverter output voltage usually contains voltage harmonics caused

by the electronic switching. The voltage harmonics could result in partial discharge at certain frequencies [20].

Voltage transients could affect the design of the secondary (HV) side of the transformer. These transients on the HV side could be a result of multi-stage capacitor bank switching or from breaker operation. For the latter, re-ignition could result in transients and single phase switching. Protection equipment can be installed on the transformer or circuit breaker to eliminate re-ignition, which if not addressed could cause transformer failure [6].

3.3.2. Inrush Current

PV transformers can be exposed to high inrush current during switching, in which case the source winding usually carries all the current. This inrush current is caused by residual flux within the core of the transformer, which is added to the flux introduced by the source voltage [21]. The inrush current can be between four and forty times the rated full-load current, but is mostly between seven and twelve times the full-load current. This could also affect the power quality of the system, through resulting voltage dips [22]. Generally, inrush current does not cause any significant problems for systems up to 2 MVA [6]. Again, this is an aspect which needs to be taken into account when defining transformer specifications.

3.3.3. Supply Current and Voltage Unbalance

Load unbalance on the LV side of a three-winding transformer can also cause problems. If unbalanced currents are supplied from the inverters, abnormal flux patterns may result in increased heating within the windings. Unbalanced voltages on the other hand, could result in excessive core or winding temperature rise, excessive noise and possible core saturation (resulting in increased excitation current and core temperature) [6].

3.3.4. Voltage Regulation

The output voltage of a transformer can be adjusted by the tap changer (on-load or off-load), which is usually connected on the HV side of the transformer. It could also be required to install a tap-changer on the LV side of the transformer, to accommodate solar panel deterioration over time [6]. A large percentage (26%) of transformer failures are due to the failure of on-load tap changers [23]. Frequent switching in PV plants, will require increased maintenance on the tap changer. Failing to do so could increase the risk of failure [24].

3.3.5. DC bias

Another possible challenge, which should be taken into account and analysed is the possibility of a DC biased transformer. According to [9], harmonic currents regularly have a DC component which could be transferred to the winding connected to the inverter. The DC current could increase the magnetisation current of the transformer, which can lead to a saturated core [25]. This could then result in increased circulating currents in structural parts of the transformer, and an increase in the core temperature and audible sound. Another result could be resonance between the capacitance connected in the system and the non-linear self-inductance of the transformer [6]. The expected DC current from the inverters should also be included in the transformer specification, to enable the designer to study the effect it could have on the design.

4. Result and analysis

Three main challenges facing distribution transformers in PV plants have been articulated in the previous sections. The main focus of this section is on the impact of harmonics on transformers in a PV plant. Simulations of PV generation plants have been reported widely in literature [26]. Thus, PV system studies in DlgSILENT are quite common. Nevertheless, the

model for the purpose of this study was established from an existing plant where harmonic currents were measured. For brevity, the analysis is explained and conducted using three stages. The first stage includes the power system analysis, which is carefully conducted to determine the total harmonic distortion at feeding points in the network. The resultant harmonic spectrum is used in the second stage to calculate the harmonic loss factors. The first thereof is the winding eddy current loss factor (F_{HL-WE}), given in equation (2). In the power frequency spectrum, the eddy losses are proportional to the square of the load current and the square of frequency. Thus, it is this characteristic that can cause excessive winding losses leading to abnormal winding temperature rise [27].

$$F_{HL-WE} = \frac{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^2}{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_1}\right)^2} \quad (2)$$

In equation (2), I_h is the harmonic order current [A], h the harmonic order and I_1 the rated current [A]. A factor is also calculated for the stray losses (F_{HL-STR}), using equation (3). Stray losses in the core, clamps, and other structural parts will also increase at a rate proportional to the square of the load current. It is well published that eddy current losses in bus bars, connecting and structural parts increase by a harmonic exponent factor of 0.8 or less [28].

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_1}\right)^2} \quad (3)$$

It is also important to comment on dc losses; the rms value of the load current is increased by the harmonic components, and therefore the I^2R losses will increase accordingly [27].

Third stage - in this stage the factors of the previous stage are used to calculate the new loss components. In a practical manner, the original losses that would have been calculated using a 2-D finite element method (FEM) or other advanced tools are multiplied by the factors to realise the harmonically affected loss values.

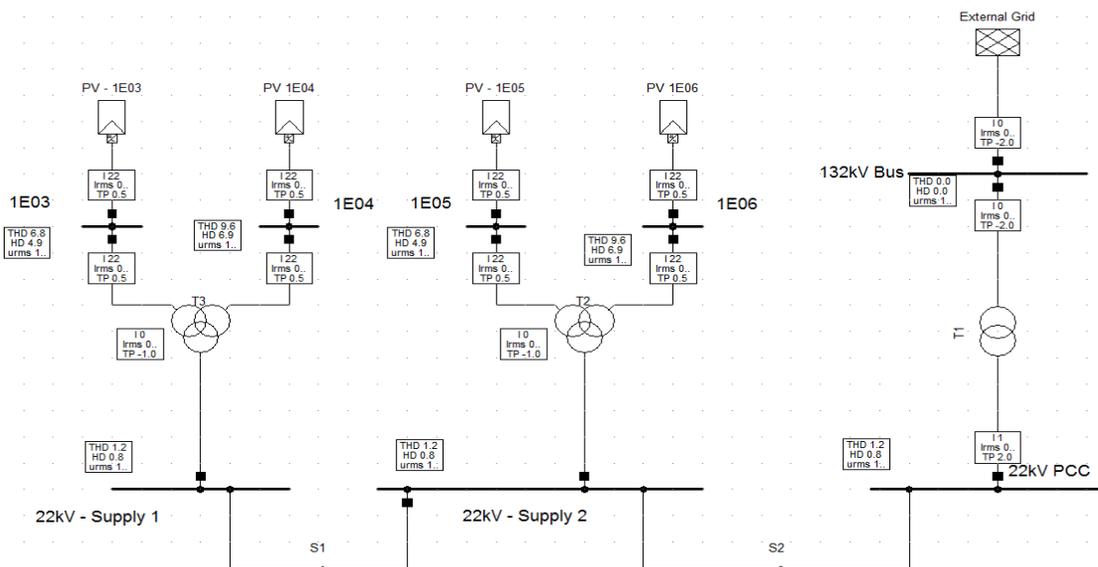


Figure 5: Harmonic PV plant model analysis with the measured spectrum applied

In implementing stage one, Figure 5 shows the model in DlgSILENT. This model was used to determine the harmonic spectrum that the three transformers connected in the network will be exposed to. Two scenarios were considered: a) Use of the inverter supplier's harmonic spectrum, and b) Use of plant measured inverter harmonic spectrum.

The maximum total harmonic distortion (THD) observed in Figure 5 is 9.6% on one of the LV winding sets, while the other is 6.8% - case b. The difference is due to the different impedances of the LV windings. The detailed spectrum resulting from this analysis is depicted in Figure 6 and Figure 7. In addition, this includes the supplier's spectrum.

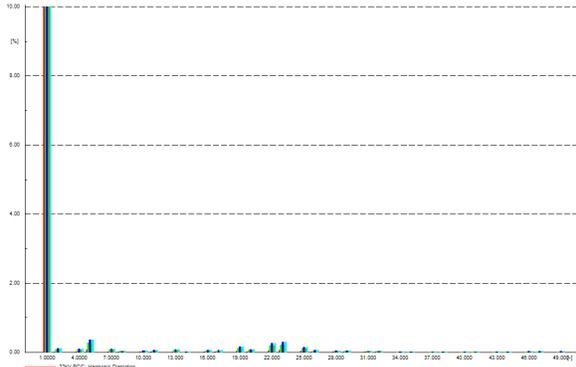


Figure 6: Total harmonic distortion for the supplier's spectrum (case a)

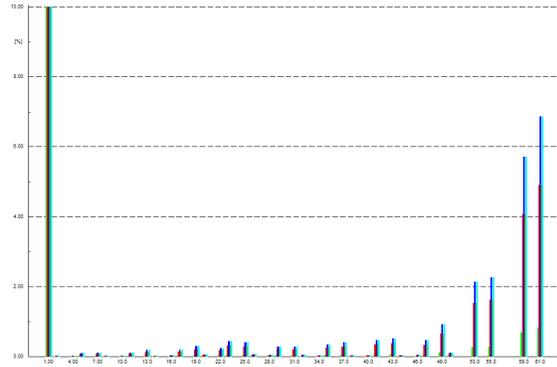


Figure 7: Total harmonic distortion for the measured spectrum (case b)

The measured spectrum in Figure 7 shows that the transformers will likely see significant higher order harmonics that are odd, from 53th to 61st harmonics. The supplier spectrum goes up to the 50th order harmonic; on the contrary, the measured spectrum goes up to 61 order harmonic. It is also apparent from this figure that the whole network is influenced by the spectrum. Again, this signifies the collaborative effort required between the OEM and the PV plant operator. Furthermore, as per stage three, the calculation of winding transformer losses was done using a 2-D FEM analysis. The 2-D model of transformer 1 is shown in Figure 8 and Figure 9.

In practice, the evaluation of the total losses is complex. However, such a computation in 2-D FEM modelling for winding eddy loss components are shown in Figure 8. The metal part losses often rely on the combination of analytical and empirical formulations, although lately the use 3-D FEM is quite common. The losses depicted in Table 1 were calculated using in-house proprietary software of Powertech Transformers (Pty) Ltd.

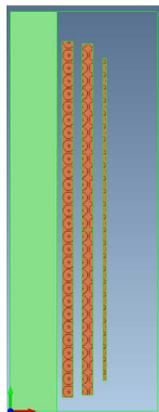


Figure 8: 2-D FEM geometric configuration

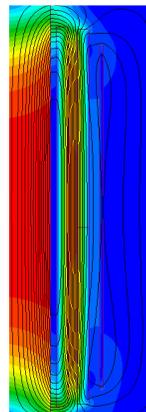


Figure 9: Flux density distribution between windings and core

The integration of the two previous stages yields the results in Table 1, where case b) was considered. In addition, case a) was also simulated although not reported in this section. The losses as calculated using the formation in stage 1 and stage 2 are denoted as Losses (H).

Table 1: The application of harmonic factors on load losses in kW (case b)

	Transformer 1 (20 MVA) 132/22 kV			Transformer 2 (1.25MVA) 315V/22 kV			Transformer 3 (1.25MVA) 315V/22 kV		
	Factor	Losses	Losses (H)	Factor	Losses	Losses (H)	Factor	Losses	Losses (H)
DC Losses	1.00	108.00	108.01	1.00	10.64	10.68	1.00	10.64	10.68
Winding LV1	1.47	5.10	7.50	17.27	0.14	2.44	17.28	0.14	2.44
Winding LV2				32.88	0.27	8.98	32.88	0.27	8.98
Winding HV	1.47	3.90	5.73	1.47	0.34	0.49	1.47	0.34	0.49
Winding Reg.	1.47	0.00	0.00						
Structural Parts	1.00	5.10	5.12	1.12	0.85	0.95	1.12	0.85	0.95
Total		122.10	126.36		12.24	23.53		12.24	23.53

The 20 MVA transformer experienced an overall increase in total losses of 3%. Transformer 2 and 3 show an increase of 92% of the total losses. This indicates a significantly high component of the losses, which resulted from the high k-factor on the LV windings. In context, the transformer will see these increased losses when fully loaded. Nevertheless, it is clear from the results that the increase of the factor will impact the transformer design; this also seems to influence the grid supply, other transformers in the vicinity. Although, the transformer connected to the direct harmonic source is the most impacted. The increase of the losses will impact the cooling design; the study in [29] shows that an increase of the average winding to oil temperature gradient by as much as 18.4% leading to the hotspot increase of 8.2% can be expected. The above simulation results further show that the total harmonic distortion meets the power quality specification, however the individual transformer designs are still sensitive to the spectrum. Therefore, this paper underscores the importance of the collaboration between the transformer supplier and the PV plant operator or representative consultants.

5. Recommendations

In general, the first party in the procurement of a transformer for a PV plant is the client, who could be a utility, smelter, mine or IPP. In practice, these clients are mostly represented by a third consulting party, who often assists with the specification of the transformer and factory acceptance testing. The second party involved is the supplier/manufacturer of the transformer, and for a PV transformer it is very important that both parties are aware of the previously discussed challenges that involves transformers in this operating environment. The net effect of this understanding is a higher quality transformer.

The first problem is the effect of harmonics that are produced by the PV inverter; most inverter manufacturers have the harmonic spectrum that is generated by these units. A harmonic analysis study, using simulation software should be used in determining the

harmonic impact. The transformer manufacturer should incorporate the additional losses in the load loss and cooling evaluation; this has a de-rating effect [30], [31] and [32].

The transformer in a PV plant will be subjected to loading variations; hence could be energised and de-energised frequently. The client should do a thorough study on the possibility of long-term no load operation, frequent energising, frequent tap changing and the variation in irradiation and loading at the specific site. This could impact no-load and load losses, which influence the cost capitalisation. It must be specified whether both LV windings will be loaded equally, or one will be loaded and the other slightly loaded. In the latter, the transformer needs to be designed to be able to operate with an asymmetrically loaded primary.

The client should also estimate the energising and de-energising frequency of the transformer. This could influence switching transient requirements and also inrush current. Some of these matters could be addressed in the protection scheme of the transformer, but the manufacturer should also be made aware of this frequent switching. The transformer designer could also supply the required information to the client for inrush current studies.

In order to ensure that a reliable and efficient transformer is designed for a PV plant it is of utmost importance that both the manufacturer and client exchange the required data and information. Without proper communication and cooperation from either party a transformer will be specified, which will most likely not have the desired performance when in operation.

6. Conclusion

This paper considered the literature review of the challenges that a step-up transformer might be subjected to in a PV plant. It was shown that harmonics (current and voltages), variation in irradiation and loading, as well as the manner in which the transformer is operated (frequent switching, no-load operation, etc.) could have an effect on the performance of the transformer.

Both the client (utility, IPP or Industrial Company) and the manufacturer have a role to play in ensuring the quality and compatibility of the transformers for PV applications. The analysis required for assessing the impact of harmonics demonstrated the two roles. It is important that both parties are aware of the challenges and the results this might have on the long-term costs and operation of a transformer and plant. Doing this could reduce down-time, improve grid stability and improve the rate of return for PV plants.

With the increased drive for renewables and their grid penetration capacity, it is important that stable operation of these plants be a priority. Both the client and manufacture of transformers for these plants have a role to play, and must assist and cooperate with each other in order to achieve this.

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