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Inverter Transformers for Photovoltaic (PV) power plants: Generic guidelines

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Abstract:

With a plethora of inverter station solutions in the market, inverter manufacturers are increasingly supplying the consumer with finished integrated products, often unaware of system design, local regulations and various industry practices.

In this paper, the author describes the key parameters to be considered for the selection of inverter transformers, along with various recommendations based on lessons learnt. This should enable the user to avoid potential pitfalls and failures while designing future utility scale PV power plants. The paper sets out critical codes and guides to be considered in order to empower the user to refer a single document for system design.

Keywords—Photovoltaic, Inverter Transformer, Harmonics

I. INTRODUCTION

Utility scale photovoltaic (PV) systems are connected to the network at medium or high voltage levels. To step up the output voltage of the inverter to such levels, a transformer is employed at its output. This facilitates further interconnections within the PV system before supplying power to the grid.

The paper sets out various parameters associated with such transformers and the key performance indicators to be considered. The next section describes the naming terminology of such transformers. In the third section, type of oil employed in transformers is discussed. Section four details the various codes, standards and parameters needed for simulation. Section five deals with harmonics, its effect on transformers and derivation of k factor. Section six lists out a few recommended practices.

II. TERMINOLOGY & SELECTION

A. General

The most commonly used terminology for a transformer employed at the output of an Inverter is “Inverter duty transformer” or simply “Inverter transformer”.

The term duty refers to the varying operational performance of the inverter during generation periods rather than the conventional definition of duty, defined as the ratio of active time to total time.

It is the recommendation of this paper that the transformer be sized as per the reference load cycle of the Inverter and be correlated with transformer temperature rise to define its name plate rating in line with IEC 60076-7.

III. TRANSFORMER OIL

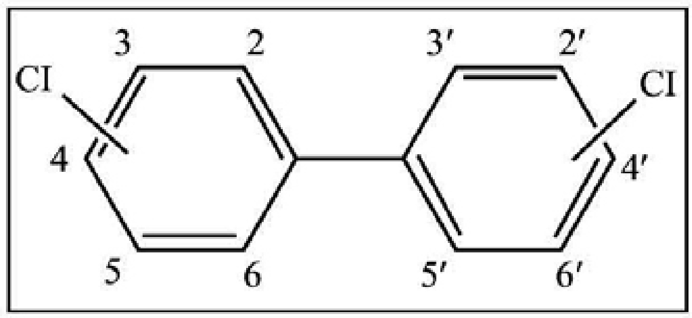
The primary function of transformer oil is to protect the winding and core of the transformer. It helps dissipate heat i.e. act as a coolant, prevents arcing and corona, protects the insulation and stops any kind of oxidation to take place within the transformer tank.

The transformer oil recommended for inverter transformers is PCB free, polycyclic, aromatic, hydrocarbon free mineral oil in line with IEC 60296.

A. What is PCB

Polychlorinated biphenyls are a subset of the synthetic organic chemicals known as chlorinated hydrocarbons. The molecular structure of PCB is identical to two benzene rings linked together.

Due to numerous physical and chemical properties, PCBs found widespread use. PCB attributes include fire resistance, low electrical conductivity, high resistance to thermal breakdown, high degree of chemical stability, and resistance to many oxidants and other chemicals [2]. Owing to the above properties, PCBs were widely used as dielectric fluids and heat transfer fluids in transformers and capacitors. However, their adverse effects on health restricted their use across the globe.



Although PCBs have beneficial chemical properties, acute exposures to high levels of PCBs have been associated with skin rashes, itching and burning, eye irritation, skin and fingernail pigmentation changes, disturbances in liver function and the immune system, irritation of the respiratory tract, headaches, dizziness, depression, memory loss, nervousness, fatigue, and impotence [3]. The US Department of Health and Human Services as well as the International Agency for Research on Cancer (IACR) consider PCBs to be probable carcinogens in humans (ATSDR 1997; IARC 1987).

Due to the above deteriorating effects of PCBs, it is imperative that the vendor submit a third party tested certificate indicating that the mineral oil is PCB free. It is also mandatory to submit such a certificate to the Energy Board of the country in which the transformer is being installed, for cases in which the equipment is being imported.

C. Dielectric Breakdown Voltage (BdV)

Dielectric breakdown voltage is a measure of the electrical stress that an insulating oil can withstand without breakdown. An AC voltage is applied across a sample of oil and is gradually increased until sparking is observed between the electrodes. The voltage at which the breakdown occurs needs to be recorded.

1) Significance of BdV

The dielectric breakdown test on the insulating oil of a transformer can help determine its level of contamination. If in-service oil testing is performed, it can help determine the remaining life and operational safety of the transformer. If in-service oil testing is performed, it can help determine the remaining life and operational safety of the transformer and help prevent equipment fires. For in service equipment, it is recommended to test the oil at least once a year.

2) Key parameters to be tested

Following parameters need to be analysed during testing of transformer oil:\Make, Appearance of Oil

- ✓ Density, Resistivity
- ✓ Kinetic Viscosity & Inter facial tension
- ✓ Flash & Pour Point
- ✓ Neutralization Value
- ✓ Corrosive Sulphur Test
- ✓ Water Content
- ✓ Antioxidant additives
- ✓ Oxidation Stability,
- ✓ Neutralization Value & Sludge %
- ✓ Breakdown Voltage and Dissipation Factor
- ✓ Impulse Withstand Level
- ✓ Gassing tendency
- ✓ Ageing characteristics at 115 Deg. C for 96 hours

3) Standard for testing mineral oil

a) International Electrotechnical Commission (IEC)

IEC 60296 is applicable to specifications and test methods for unused mineral insulating oils. It applies to oil intended for use in transformers, switch gear and similar electrical equipment in which oil is required for insulation and heat transfer. As its title indicates, this standard applies only to new, unused oil as received from the manufacturer, which must have a dielectric breakdown voltage of 30 kV or more, determined using the IEC 60156 test method. Oil that has been vacuum filtered in a laboratory must have a minimum dielectric breakdown voltage of 70 kV.

For oil which has been filled but not yet energized or for in-service oil, IEC 60422 needs to be referred as it prescribes the acceptable dielectric breakdown values for different equipment voltage level.

a) International Electrotechnical Commission (IEC)

TABLE I. - ASTM STANDARDS FOR MINERAL OIL TESTING

STANDARD	DESCRIPTION
ASTM D3487	Standard Specification for Mineral Oil Used in Electrical Apparatus
ASTM D664	Acid Number
ASTM D877	Dielectric breakdown voltage
ASTM D924-08	Liquid power factor
ASTM D971	Interfacial tension
ASTM D1169	Specific resistance
ASTM D1275	Corrosive sulfur
ASTM D1524	Visual examination

IV. CODES, STANDARDS & PARAMETERS FOR SIMULATION

A. Codes and Standards

The regulations which need to be followed for individual components of the transformer and the complete unit are listed in Table II, followed by the mandatory type test requirements needed for such units.

TABLE II. - CODES AND STANDARDS

REFERENCE DESIGN CODES	
Bushing	IEC 60137
Radiator	EN 50216-6
Mineral Oil	IEC 60296, IEC 60156
K-factor & Harmonic rating	IEEE C57.110-1998
Transformer unit	IEC 60076, IEEE C57.159

B. Parameters for software simulation

Certain transformer parameters are critical to simulate the PV plant performance via software and should be furnished by the vendor along with the general technical datasheet.

Electromagnetic transient or EMT studies help evaluate the transformer inrush characteristics and determine if any specific switching sequence during energization may cause failures.

When the applied voltage to a transformer is sinusoidal, the core flux rises from -Φm to +Φm during the positive half cycle of the applied voltage. If the transformer is switched ON at an instant when the instantaneous value of applied voltage is at its positive peak, then the flux would rise from its natural zero value up to +Φm during the next quarter cycle (Magnetizing lags voltage by 90deg). The magnetising current required would remain normal and the switching of the transformer would be trouble free.

However, if the instantaneous value of applied voltage at switching instant is zero and going towards positive, then the core flux would rise from its natural zero value to +2Φm in the next half cycle. This phenomenon is also known as doubling effect.

This flux doubling is accompanied by a huge magnetizing inrush current which may reach 5 times the full load current or higher, leading to massive winding forces and a possible dip in the system. Magnetizing inrush is highly unsymmetrical and stays for quite a few cycles, decaying according to the time constant of the system. The inrush current is expected to delay quickly if the system is switched on resistive load or capacitive loads. However, it would delay slowly if switched on NO load or with inductive load (which is the case for most Grid connected Solar Power Plants).

Below parameters are required to perform successful EMT studies.

1) Inrush current curve

Inrush current is a form of transient over current present during the energisation of transformers. It depends on the residual flux of the transformer, magnetic characteristic of the core & voltage waveform at the time of switching.

TABLE III. - VOLTAGE DISTORTION LIMITS

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69kV and below	3.0	5.0
69.001kV through 161kV	1.5	2.5
161.001kV and above	1.0	1.5

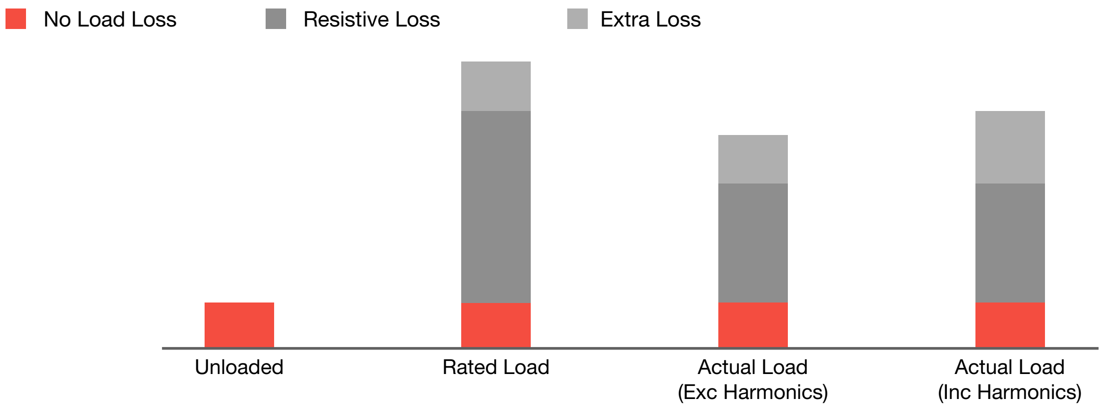
The permissible harmonic current distortion limits for a transformer connecting the user to the utility system will not be subjected to harmonic currents in excess of 5% of the transformers rated current. When the harmonic current flowing through the transformer exceeds the design level of 5% of the rated current, the heating effect in the transformer should be evaluated by applying the methodology contained in IEEE C57.110-1998. This evaluation will ensure that the transformer insulation is not stressed beyond design limits.

A. Effect of harmonics on transformers

The overall effect of harmonics is an increase in the transformer heat which can have a significant impact in reducing the operating life of insulation of a transformer. Some effects of harmonics on transformers are listed below:

- ✓ Copper losses or winding eddy-current loss in thepower frequency spectrum tends to be proportional to the square of the load current and the square of frequency (Skin Effect). If the rms value of the load current is increased due to harmonic components, the I^2R loss will be increased. This characteristic causes excessive winding loss and hence abnormal winding temperature rise in transformers supplying non sinusoidal load currents.
- ✓ Other stray losses in the core, clamps, and structural parts will increase at a rate proportional to the square of the load current. And hence, with the increase in harmonic components, load current increases and eventually ends up heating the transformer.

- ✓ There is a potential risk of resonance (parallel and series) between transformer inductance and supplied capacitive loads, at certain harmonic frequencies which can tremendously magnify harmonic levels.
- ✓ Laminated transformers cores can vibrate at certain harmonic frequencies, causing audible noise and overheating.
- ✓ Transformer windings are affected by Proximity Effect: effect of reduced "effective" area due to this effect, similar to Skin Effect, is proportional to frequency, so for higher order harmonics the AC resistance of winding conductors will be further increased, i.e., added losses.



For all effects described above, transformers need to be de-rated in the presence of harmonics, or specially designed to handle harmonics, identifying them by a rating parameter called 'K factor', function of the harmonic's capability. The 'k factor' transformers could be a more optimal solution (cost and weight), rather than derating (for example, can be designed with only oversizing neutral for triplen harmonics) [6].

There are several approaches to account for the increased losses caused by harmonics in selecting a transformer. The first one, devised by transformer manufacturers in conjunction with Underwriters Laboratories in the United States, is to calculate a factor for the increase in eddy current loss; this is known as 'K-Factor'. The second method is to estimate by how much a standard dry transformer should be de-rated so that the total loss on harmonic load does not exceed the fundamental design loss; this is known as 'factor K'. The 'factor K' method (used in Europe) is described in the Harmonisation document HD 538.3.S1. A third way to calculate the influence of harmonics is described in the IEC 61378-1 "Transformers for industrial applications".[7]

B. Derivation of K-factor – US Practice

The K-Factor rating assigned to a transformer and marked on the transformer case in accordance with the listing of UL, is an index of the transformer's ability to supply harmonic content in its load current, while remaining within its operating temperature limits.

For specification in general, the U.S. practice is to estimate the K-Factor which gives ready reference ratio K for eddy losses which is driving non-linear loads as compared to linear loads.

$$K = \sum_{h=1}^{\infty} I_h(p.u)^2 h^2$$

Ih (p.u) = the rms current at harmonic "h" (per unit of rated rms load current)

h = the harmonic order

UL recognizes K-factor values of 4, 9, 13, 20, 30, 40. The K-factor number tells us how much a transformer must be de-rated to handle a definite non-linear load or, conversely, how much it must be oversized to handle the same load.

TABLE IV. - K FACTOR RATING CHART

K Factor	Industry/Equipment
K=1	For Resistance heating motors, distribution transformers, motor generators (without solid state drives) etc.
K=4	For welders, Induction heaters, Fluorescent lights, UPS with/optional input filtering, etc
K=13	For Telecommunication equipment, UPS without input filtering
K=20	For main frame computers, solid state motor drive (variable speed drives), desktop computers and multiwire receptacle circuits in critical care areas and operating/recovery rooms of hospitals

C. Floating Neutral

Harmonics is one of the reasons for PV systems to be floated. Unwanted neutral currents in the output cause minute, short duration imbalances in phase switching times of an Inverter and is the reason Inverters do not have solid neutral connections. Allowing the transformer neutral to "float" prevents these disturbances from causing harmonic distortion in the host electrical system.[8] This harmonic distortion would make it extremely difficult for an inverter with a solid neutral connection to meet the harmonic distortion requirements of the UL 1741 standard.

Additionally, a solid neutral connection can interfere with the inverter's ability to detect phase voltage problems, and lead to unwanted nuisance currents in the isolation transformer. Extensive design modifications and testing would be required to overcome these problems. Given the difficulties associated with adding a solid neutral connection, it is worth ascertaining whether there is any real benefit to having a solid neutral connection in an inverter [9].

VI. RECOMMENDED PRACTICES

A. Electrostatic Shielding

It is recommended to install an electrostatic ground shield between the primary and secondary winding of an Inverter Transformer. Due to reasons listed out in the section above, the winding connected to the inverter circuit is kept ungrounded.

The electrostatic ground shield between the primary and secondary windings is intended to prevent capacitive coupling of these windings. The main advantage is that the electrostatic ground shield minimizes possible transfer of the high frequency voltage disturbances (harmonics, pulsations, surges that are created in the voltage inverting process) from the primary (LV) winding to secondary (HV) winding and the power system. The other advantage of the electrostatic ground shield is to reduce a transfer of the high voltage transients (overvoltage) to the primary (LV) windings and the inverter system connected to the primary winding. Without the electrostatic ground shield, a very high percentage of the high voltage transients on the secondary (HV) side may transfer to the primary side (LV) of the transformer. The electrostatic shield also filters the voltage gradient of the pulsed primary (LV) voltage.[1]

It is recommended that the design of the electrostatic shield considers the effect of the eddy losses due to the magnetic field. Either aluminium or copper shields can be used. Normally, the thinner the shield metal the less are the eddy losses. Higher conductivity shielding (copper foil) has less eddy losses than lower conductivity (aluminium strip) material.[1]

It is recommended that care be taken in the design of the electrostatic shield so as not to create a harmonic heating problem. For example, in the stacked windings arrangements of the three-winding transformer, it is recommended that the electrostatic shield be constructed in two separate parts (top and bottom) in order to avoid additional eddy losses and abnormal temperatures in the situation of the unbalanced loads between two inverters.[1]

B. Surge Arrestors

PV plant transformers are typically terminated on compact, gas filled units termed Ring Main Units or RMUs, which do not have any space to install surge arrestors. Hence, it is recommended that the surge arrestors be installed on the HV side of the transformers to deal with transient over voltages and lightning surges. The arrestors maybe retrofitted on the HV side bushing of the transformer and should consider the system configuration. Selection of surge arrestor should be made in coordination with grounding of main transformer or grounding of HV network.

The electrostatic shielding, surge arrestors and SPDs installed at the input and output of the Inverter should help provide protection to both the AC and DC systems and safeguard it against all contingencies.

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