In the past, the equipment was designed to operate under well-known conditions assuming a 'clean' sine wave of 50 or 60 Hz

Brian SPARLING

Managing existing transformers in the grid transition

A brief history of line and equipment ratings

In the past eight or more decades, the electric power industry used a rating system based on conservative assumptions to determine the capacity available which lines and substations could use to safely carry the load. These are known as static lines ratings (SLR) systems, and substation capacity has had similar determinations made based on static or nameplate data of the equipment. It remains in use but is a very conservative method. Two newer methods evolved over time. One is the seasonally adjusted rating (SAR) system and the ambient adjusted rating (AAR), but they still rely on weather-related assumptions rather than real-time information.

It worked well in the past when the system was designed to generate energy in larger centrally located power plants and when they delivered that energy in one direction, from the source to the load centers. The equipment was designed to operate under well-known conditions assuming a 'clean' sine wave of 50 or 60 Hz.

The changing nature of the power system: Digital versus static

There has been a lot of technical changes in our industry, beginning with the shift from analog simulation systems, to first electronic and then quickly into the microprocessor-based devices that are common today.

The application of intelligent electronic devices (IEDs) on power transformers has been ongoing for the past 25 years. An example can be found in dissolved gas analysis (DGA) monitors, from basic key-gas units advancing to multi-gas monitors with inherent ability to alarm when gassing patterns begin to change and provide diagnostics about the nature, and sometimes, about the severity of a developing fault. The systems have evolved to today's point, where virtually anything can be measured, computed locally, and communicated to centers where this actionable information is available for decision making.

With these "Smart Grid" IEDs, digital communication and data collecting/archiving systems throughout the grid,

Today, AC current is often 'polluted' with harmonics, as the inverters in many applications typically do not produce the clean sine wave that equipment, such as transformers, expect to see

the opportunity to make use of the information and enable the move from the "Static" to a "Dynamic" understanding of the capacity available in the system is achievable.

A tug-of-war is happening

At the same time, a tug-of-war is ongoing during this change and providing a technological challenge to all stakeholders. There is a growing need to provide more capacity on the existing grid due to the addition of renewable generation on both sides of the meter. Recent events involving voluntary (or at times) forced power shutdowns, of either distributed energy resources (DERs) or lines in areas of severe climatic stress, customers are moving to install their own sources of DER and/or storage.

This intervention of PV DER systems installed on the customer rooftop, or in large PV solar parks, has introduced some unique characteristics which carry over to the existing grid. PV systems produce energy locally when there is sunlight. The energy produced passes through an inverter changing the DC current to a usable AC current. A local utility may purchase excess energy that may be available from the home or business owner. This has the impact of imposing a reverse power flow into the network. In addition, the AC current may be 'polluted' with harmonics, as the inverters typically do not produce the clean sine wave that equipment such as transformers expect to see.

The issue is exacerbated with large PV parks - some of them are of significant size and go into the double or triple digits of MW capability. The issue is two-fold:

FIRST: The introduction of non-dispatchable PV DER, which at times cannot be controlled as larger power plants. The issue is how to handle this from a grid point of view, as there needs to be some backup or reserve of energy available to make up for the loss of generation;

- This involves "Solar Droughts" which occur when clouds accumulate to the point of reduced or no energy being produced by the solar panels.

- This issue is a little more controllable when dealing with the sunrise and sunset time periods (nighttime) when there is no power produced.

- The same issue can occur with Wind DER. There may be times of the day or year when there will be "wind droughts." Or more critically, when the wind velocity is too great for the wind turbines to operate safely.

SECOND: A problem is lurking in the system regardless of which PV or Wind DER is deployed. That is the harmonics produced by the inverters. These harmonics are imposed on the 50 or 60 Hz sine wave and will affect the performance of the transformers connected into the system. One of the effects is the overheating of the conductors in the windings of the transformer.

- The impact can, at times, affect the core in 5-limb shell-type distribution transformers, when connected directly to the output of a wind turbine machine. Work by the IEEE Transformers Committee produced a Tutorial on the early problems of distribution transformers [1] (many failed in the early days in North America).

- The Tutorial presented at the IEEE Transformers Committee Fall meeting of 2013, "Wind Power Transformer Design", by Philip J Hopkinson et al., covered not only the issues related to transformers but also included circuit breakers, grounding switches and the MV cables connecting these units to the main output or step-up transformer [2].

- This study and work done by IEC lead to the creation and publication in September 2018 of a new Dual Logo Standard IEC/IEEE 60076-16 Part 16, Transformers for Wind Turbine Application [3]. This addition to the Loading Guides of both IEC and IEEE should be referenced when specifying transformers connected to Wind Turbines and PV farms.

Variable loading by DERs

The wind and PV farm concepts are simple. When the wind blows within a certain band of wind speed, they produce power. Likewise, for PV installations, they produce power when the sun shines. When there is a 'wind or sun drought,' they do not. Therefore, tim-

ing becomes a critical issue. When customers' demand is the greatest, either of these sources may not be available.

So how does this type of loading affect the performance of the transformer connected to the output of these DERs? Conventional distribution or GSU transformers are typically designed to a more constant load factor, loading that is close to their theoretical maximum rating. Under the aforementioned conditions, they are subjected to frequent thermal cycling, at times loaded beyond the rating plate. This occurs as a function of the varying loads, as well as "start and stop" sometimes initiated by either wind or solar droughts. This causes repeated thermal stresses on the windings, clamping structure, seals, and gaskets, which in turn causes accelerated aging of the solid insulation, as well as electrical connections, both internal and external.

Wind and PV sources often cause the overloads and variability of the load as well as higher harmonics generation, which is not optimal from the insulation aging point of view

Some consider that transformers are allowed to deliver energy that exceeds their basic rating if there is a possibility for them to "rest" when there is no wind, or when it is cloudy or night time, which allows them to "recover" until either the wind blows, or the sun reappears. This is, however, not the way the aging process works. Once a transformer has been overloaded, the solid insulation ages at an exponential rate. For every 6 or 7°C of winding hotspot temperature increase above the rated 98°C or 110°C, the aging rate doubles. The aging of the solid insulation is a chemical process and is non-reversible.

Figure 1. 2.5 MVA transformer/inverter package with MV switchgear [1]

Higher harmonic content can cause overheating of the insulation which can cause major reduction of its tensile strength thus significantly reducing the insulation lifetime

Harmonics and non-sinusoidal loads

Existing transformers in service were designed based on the principle of working with a uniform sinusoidal AC waveform. A purely uniform sinusoidal waveform is, in theory, possible. In the real world, the waveforms get distorted from the ideal to a THD (Total Harmonic Distortion), of 1 to 2 % at the point of generation.

Wind and PV generators will produce the THD by the solid-state controls, and inverters will have a cumulative effect. They add peaks on the voltage and current waveforms and occur at other than the fundamental frequency of 50 or 60 Hz. The harmonics creating these distortions are multiples of the fundamental frequency and are referred to by their multiple, i.e., 3rd, 5th, 7th, etc. These inverters are tested at their respective manufacturers, however once installed and operating for several years, how well are they functioning as originally specified becomes the question? It would be then logical to monitor continuously the harmonic content as one of the functions of a monitoring system for the transformer with other key parameters.

These damaging harmonics will increase the eddy and stray losses in the unit. Eddy and circulating currents in a winding conductor cause additional heating, which must be addressed with additional cooling.

The degree to which these harmonics increase the heating in the conductors, and thereby the insulation system, cannot be measured by existing WTI's, either legacy or electronic. Fiber optic sensors and systems that measure the conductor temperature in-site should be considered for new or refurbished transformers for this application.

Example of damaging harmonics

The section of wrapped conductor in Figure 2 was removed from a rectifier transformer that failed after a small short circuit the unit should have been able to sustain. Only 8 or 9 years old, the oil testing regime included testing of the oil for Furanic Compounds. The laboratory had reported an increased amount of 2FAL over the time period, however, the owner was not convinced that anything was wrong, as the temperature gauges had never reached the alarm setpoints.

The failure occurred without a fire; during the autopsy, this section of the conductor was removed, and the DP test was applied to the remaining paper.

As one can see, this paper had reached the "end of life" stage with little to no tensile strength remaining. The weakened paper had allowed the conductor to separate, due to the short circuit forces.

In the investigation for the root cause that followed, it was discovered that the OEM of the transformer and the OEM of the rectifier did not consult each other with respect to the expected THD that would be generated from the rectifier. The transformer's life (and its 19 siblings' lives) was greatly diminished due to this error, and all had to be replaced.

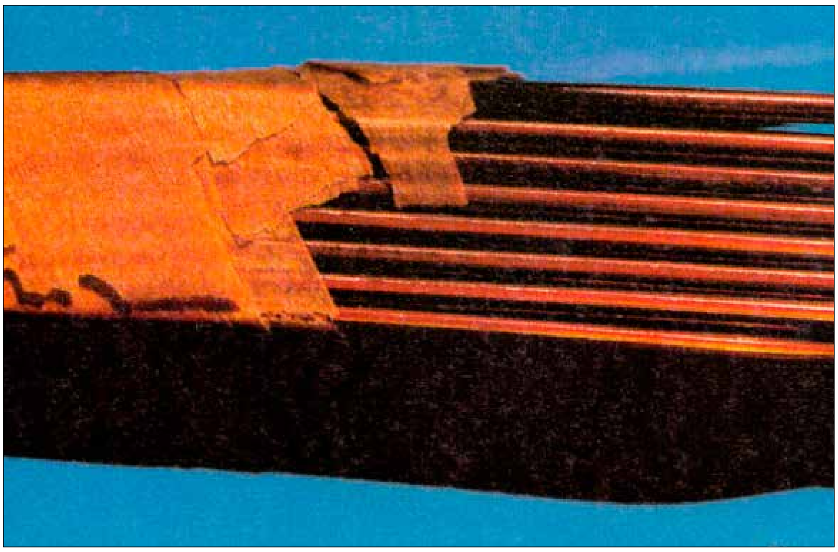


Figure 2. Example of a total loss of tensile strength in paper due to excessive harmonics

Example of a unit affected by harmonics from a PV farm

The case of an 8 / 10 MVA, 44 kV ONAN/ONAF, without OLTC. This unit is connected to a solar farm, with a total output of 14 MW. Total harmonic distortion has been measured at 12 %, mostly around the 5th and 7th harmonic. Installed in 2011, it has had regular DGA sampling performed from the beginning, with rather high dissolved gas. A partial record of the DGA results is shown in Table 1.

Interpretation of these results using Duval triangle 4 and Duval pentagon 1 both indicate a stray gassing of mineral oil fault with a temperature of <200°C, trending towards the PD area on the Pentagon.

Details of the construction of the transformer reveal a 5-limb wound core shell-form design. A common design applied to standard distribution transformers of type voltage class and MVA size in North America. This is quite typical of any transformers first installed in these applications and remains one of the reasons for many failures.

As pointed out in the IEEE Tutorial [2] referenced before, with this type of con-

Table 1. DGA results of 8 / 10 MVA 44 kV transformer

Date	CO	CO_2	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2
Apr 20, 2018	219	3235	4157	587	8	176	ND
Feb 26, 2018	188	3586	3379	517	7	156	ND
Nov 22, 2017	214	3242	3516	587	9	223	ND
Oct 19, 2017	235	2734	3469	569	12	206	ND
Aug 23, 2017	197	2600	2589	536	10	224	ND
Jul 10, 2017	165	4624	2754	531	9	197	ND
May 29, 2017	171	3457	3407	531	9	179	ND

struction, core grounding seems to need more attention with the following recommendations:

1. For 5 leg wound cores
   a. Ground the inside of the core or
   b. Shielding of the core

2. Use 3-leg stacked cores (generally immune to the situation)

3. Use 4 and 5-leg stacked cores which may need some shielding

It would also be prudent for new transformers required for these specific applications, that the purchaser insists that the designs meet the criteria of the new IEC/IEEE Dual Logo Standard [3].

Managing existing units in these applications will require an increased level of condition monitoring, from the point of view of the rate of insulation aging, and accumulation of the harmonic content which is now available with some online monitoring systems. Testing of the oil includes DGA (if not monitored online), as well as oil quality, and Furanic compound analysis. This will provide information as to when a unit may be a suitable candidate for replacement (built under new knowledge) before an unexpected failure occurs.

Loading practices should be reviewed and altered for future projects, such that units will be applied properly, given the possibility of planned overloading beyond nameplate for even short durations. The OEM selected certainly needs to be aware of these conditions.

Managing existing units will require an increased level of condition monitoring of all the aspects of the insulation aging rate as well as the accumulation of the harmonic content

The other aspect is to utilize the knowledge gained from continuous monitoring of these harmonics as to the degree of how the damaging harmonics can be mitigated, with the use of improved rectifiers or inverters and filters, applied to the existing site, to minimize the harm they are producing on these existing assets.

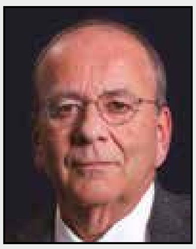
Bibliography

[1] Courtesy of Elecnor Australia Pty. Ltd.

[2] IEEE Tutorial Fall Meeting 2013, Wind Power Transformer Design, Philip J. Hopkinson, PE

[3] IEC/IEEE Standard, Power transformers – Part 16: Transformers for wind turbine applications

Author



Brian D. Sparling, a Senior Member of IEEE, is a Senior Technical Advisor with Dynamic Ratings Inc. Brian has over twenty years of experience in the field of power and distribution transformers. For the last 28 years, he has been involved in all aspects of on-line monitoring and diagnostics and condition assessment of power transformers. He has authored and co-authored more than 33 technical papers on several topics dealing with the monitoring and diagnostics of transformers. He has worked on many guides and standards with the Canadian Electricity Association, IEEE Transformers Committee, and the CIGRÉ A2 Transformer committee.