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Harmonics in a Wind Power Plant

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***Abstract*—Wind power generation has been growing at a very fast pace for the past decade, and its influence and impact on the electric power grid is significant. As in a conventional power plant, a wind power plant (WPP) must ensure that the quality of the power being delivered to the grid is excellent. At the same time, the wind turbine should be able to operate immune to small disturbances coming from the grid. Harmonics are one of the more common power quality issues presented by large WPPs because of the high switching frequency of the power converters and the possible nonlinear behavior from electric machines (generator, transformer, reactors) within a power plant.**

This paper presents a summary of the most important issues related to harmonics in WPPs and discusses practical experiences with actual Type 1 and Type 3 wind turbines in two WPPs.

***Index Terms*—harmonics, resonance, wind power plants**

I. Introduction

WITH the ever-increasing growth of wind power plants (WPPs) in size and their integration into global power grids, a deeper understanding of the impacts of wind power generation on power system operations is needed.

According to [1], worldwide wind capacity reached 336 GW at the end of June 2014, and an additional 360 GW was expected by the end of 2014, which is a 7% growth.

This continual growth has led to the development of new standards and grid codes aimed toward establishing the guidelines for the successful integration of WPPs into the grid. One of several technical aspects of WPP integration is the importance of maintaining the quality of the power generated by the wind turbines.

Like conventional plants, WPPs are required to provide energy to the electric system with good power quality (i.e., constant voltage and frequency, minimum disturbances, low harmonics emission) to ensure reliability and stability and satisfy customers connected to the power system network [2]. As WPPs have been integrated into the main grid, harmonic distortion [3] has been one of the issues related to power quality.

Wind turbine generators (WTGs) are classified into four basic types, known as Type 1 through Type 4 [4]. Type 1 and Type 2 WTGs use soft starters to reduce in-rush currents and voltage dropouts, which can produce harmonic currents that are low in magnitude and short in duration.

On the other hand, Type 3 (doubly-fed induction generator) and Type 4 WTGs are equipped with controlled back-to-back power electronic converters, and they may produce harmonics to the grid [5].

Harmonic distortion from WPPs could interact with preexisting harmonic network distortion and cause several issues if some of the harmonic frequencies involved excite a resonant point [5].

Harmonic resonance is caused by the interaction of inductive and capacitive elements. Inside a WPP, several elements can resonate with each other (transformers, power cables, capacitor banks, etc). When a frequency (voltage or current) experiences an inductive element reactance equal to a capacitive element reactance, a resonance occurs [6].

Harmonic overvoltages or harmonic overcurrents can appear on a power system because of parallel or series-resonant conditions, respectively. Wind turbine harmonic emissions are different from the emissions found in typical harmonic sources, such as industrial facilities or residential areas, and important efforts have been made to analyze them [3][5][13][14].

This paper presents different aspects of harmonics in real WPPs and practical experiences of harmonic issues with actual Type 1 and Type 3 WTGs.

Section II describes the fundamentals of harmonics generation and propagation in WPPs. Section III and Section IV present experiences with harmonic issues using actual WPPs that have Type 1 and Type 3 WTGs. Section V presents the summary and conclusions.

II. Fundamentals of Harmonics

The waveforms in alternating current electrical systems are ideally pure sinusoidal and have a constant magnitude and frequency to meet the expectations of the customers connected to the grid. A periodical deviation from this ideal condition, with a period of one cycle of the grid frequency, can be classified as a harmonic distortion.

Harmonics in power systems can cause several issues. The unwanted harmonic currents in Type 1 and Type 3 WTGs can cause unnecessary extra losses in the copper windings and torque pulsations, and they may even excite mechanical modes of the turbine components.

When problems related to resonance are addressed, two basic aspects should be considered: the harmonic circuit and the harmonic source.

Every harmonic current frequency injected into the electrical system experiences different impedances; hence, each harmonic current takes a different path into the system.

A. Harmonic Circuit

Many elements exist inside a WPP. The collector system consists of miles of underground cables, and every WTG has its own pad-mounted transformer, capacitor compensations (Type 1 and Type 2), and LC filters (Type 3 and Type 4); thus, resonance caused by harmonics can appear as an element of a WPP. Modeling the harmonic circuit in a WPP is not a trivial issue.

Transformers, power cables, generators, capacitors, and power factor correction devices such as static VAR compensators must be included in an analysis of harmonics to represent an actual system condition.

Resonance is determined by the network impedance, and different configurations inside a WPP may lead to different resonant points; hence, it is important to analyze different operative cases in a single WPP harmonic analysis to account for every possible situation.

B. Harmonic Source

Knowing harmonic content at the point of common coupling of the WPP is important to ensure acceptable harmonic voltages at this point and also to assess possible resonance conditions and possible solutions aimed toward solving these issues.

In Type 1 WTGs, harmonic current generation primarily comes from the soft starter installed in the turbine to reduce the in-rush current during start-up; however, this harmonic current is low in magnitude and short in duration.

Harmonic currents could also appear in WPPs that have Type 1 and Type 2 WTGs—for example, as caused by the transformer during energization. A transformer's energization can cause a considerable amount of low-order harmonics, and the DC component can be part of the harmonic content.

Another source of harmonics in a power transformer is magnetic saturation, which is an undesired operating condition. Transformers are usually designed to operate very close to the saturation point. This condition can generate harmonics because of the nonlinear relation between voltage and current, especially when the transformer is operated in an overvoltage condition. Odd harmonics are associated with overexcited transformers; if it is assumed that triplen harmonics are blocked by the delta windings, then the harmonics being generated are of the orders 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th}, and so on—i.e., those of orders $6k \pm 1$, where k is an integer [7].

In most WPPs, however, triplen harmonics can be neglected, but these harmonic orders could appear as a result of an asymmetry on a grid's voltage.

In Type 3 WTGs, harmonics can be generated by power converters [8]. Converters are based on power electronics, which normally use nonlinear devices to control the real and reactive power of the WTGs, but they could produce nonsinusoidal voltages and currents [9].

In the study presented in [10], relatively high harmonic levels are shown for Type 3 WTGs. Predominantly low-order harmonics are present (5^{th}, 7^{th}, 11^{th}, and 13^{th}). According to [11], these low-order harmonics are introduced because of the interaction of a WPP with the source power system.

Harmonics injected by Type 3 WTGs at higher orders are associated with pulse width modulation (PWM) switching. The most significant components reported by [11] include the 39^{th} and 41^{st}.

III. WPPs WITH TYPE 1 WTGs

Induction generators are usually used in wind power turbines because of their low price compared to other kinds of generators and also because they are robust machines that require little maintenance.

A Type 1 WTG is considered a constant-speed induction generator turbine. Induction generators absorb reactive power from the grid to operate, and compensation capacitors are used to provide this reactive power. Because of the nature of wind, output power from WTGs varies with time and also the reactive power required by the generator; this is why the capacitor compensation is adjusted as the output generator's power changes.

To achieve this variable reactive power compensation, several mechanically switched capacitors are used by many vendors [4]; this may lead to a diversity of resonant conditions.

Fig. 1 shows a simplified diagram of a Type 1 WTG and its connection to the grid.

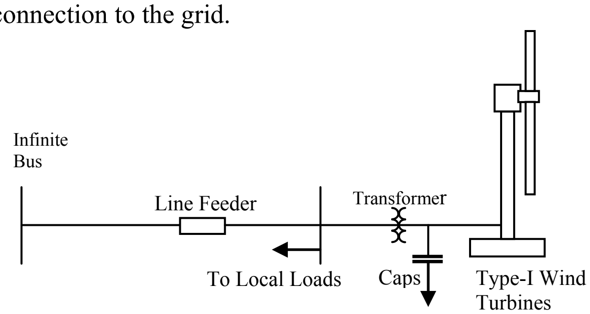


Fig. 1. System diagram for a Type 1 WTG

The system shown in Fig. 1 can be modeled with a per-phase equivalent circuit, as shown in Fig. 2, to study the harmonic. In this circuit, harmonic per-unit notation h is used; thus, $h = f / f_o$, where f is the frequency under analysis, and f_o is known as the fundamental frequency. As mentioned, the usually even and triplen harmonics are not present in WPPs; thus, only h = 5, 7, 11, 13, etc., will be considered.

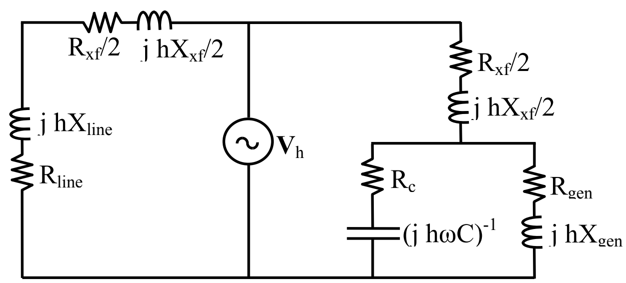


Fig. 2. System per-phase harmonic representation

The system was modeled as follows:

(1) Infinite bus and line feeder—An infinite bus and line feeder was represented by a Thevenin equivalent, and a simple R-L line model was used to model the line feeder.

(2) Transformer—A three-phase transformer with a 6% impedance was considered. Because the magnetizing inductance of a transformer is usually much larger than the leakage inductance, only leakage inductance was taken into account. For a large transformer ideally designed for maximum efficiency, an efficiency of 98% at full load and considering the copper loss equal to the core loss is a normal assumption [12]; thus, we can approximate the winding resistance, normally very small for efficient transformers.

(3) Capacitors—The compensating capacitor is represented by the capacitance C in series with its parasitic resistance R_C to represent the losses in the capacitor. An additional 1.5 MVAR to the original 400-kVAR manufacturer reactive compensation was considered.

(4) Induction generator—A 1.5-MW, 480-V, 60-Hz induction generator was represented by its per-phase equivalent, as shown in Fig. 2. Its operating slip is approximately 1% at 60 Hz (fundamental frequency). Slip as a function of harmonic frequency can be calculated as:

$$s_h = 1 - \frac{\omega_r}{h\omega_s} \tag{1}$$

where s_h is the slip for hth harmonic, h is the frequency per unit, ω_s is the synchronous generator speed, and ω_r is the rotor speed of the generator.

As shown in (1), for higher harmonic frequencies (h>5), s_h approaches 1, and for practical purposes, it is assumed to be 1. In this approach, the synchronous generator speed ω_s is assumed to be constant. Fig. 2 shows that impedance from the harmonic source can be calculated as:

$$Z(C,h) = \left(Z_{line} + 0.5Z_{xf}\right)||\left(0.5Z_{xf} + Z_C||Z_{gen}\right) \tag{2}$$

From (2), the admittance can be obtained:

$$Y(C,h) = \frac{1}{Z(C,h)} \tag{3}$$

The admittance is related to the harmonic current flowing in the system. Given a certain harmonic voltage, we can analyze the system admittance from the most dominant harmonic frequency (up to the 23rd harmonic, excluding even and triplen harmonics) by changing the capacitor size.

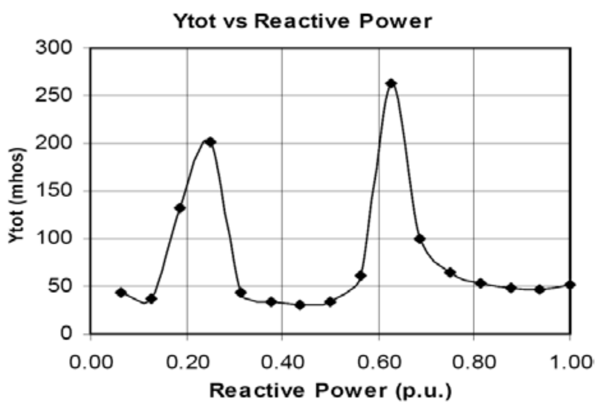


Fig. 3. Total admittance for higher harmonics as a function of reactive compensation

Data obtained from field measurements show only the total harmonic distortion and do not provide individual harmonics analysis; only a trend comparison can be done between Fig. 3 and Fig. 4.

Fig. 3 shows the circuit admittance as calculated using (2) and (3) for all higher harmonics of interest up to the 23rd harmonic (odd and non-triplen harmonics), and it can be compared to the measured data shown in Fig. 4. Fig. 3 shows admittance as a function of the total reactive power (per unit) as the size of the shunt compensator capacitors changed.

Fig. 4 presents the total harmonic distortion measured in the field as a function of total reactive power (per unit). As shown in Fig. 3 and Fig. 4, both graphs show similar behavior; as the reactive power compensation provided by shunt capacitors increases, the admittance calculated and the total harmonic distortion show resonance at different harmonic frequencies. As result of the analysis of calculated admittance and field measurements, we can say that two values of capacitances exist that amplify the total harmonic distortion, and both calculated and measured results show almost the same size of reactive power at which the two resonance frequencies occur.

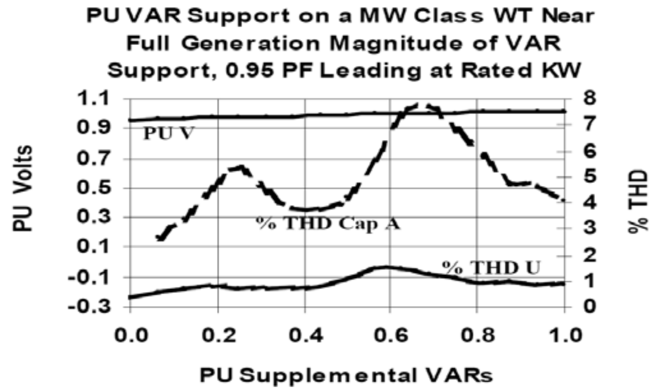


Fig. 4. Measured values of total harmonic distortion of the current as a function of the reactive compensation per unit

In other words, when the reactive power requirement from a WTG matches the critical values shown in Fig. 3 and Fig 4, resonance issues may occur at different high-harmonic frequencies when those particular harmonic frequencies are present or excite the circuit. In a simple way, the WPP becomes a tunable LC circuit. As the size of the capacitor compensation increases when the wind speed increases, the resonance frequency also changes. For example, at lower wind speeds corresponding to low power and low capacitance compensation, 7th harmonics may be encountered, and in high wind speeds corresponding to high power and thus high capacitance compensation, 5th harmonics may be encountered.

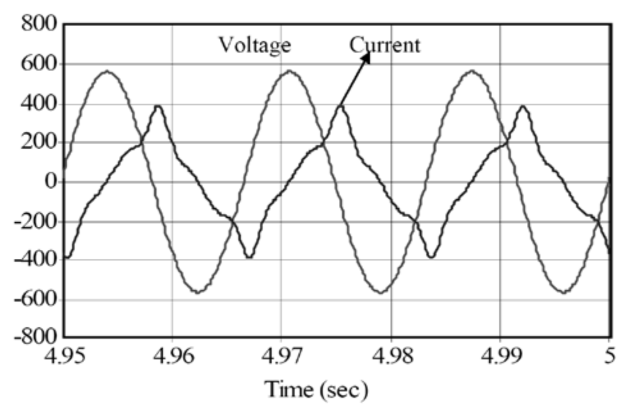


Fig. 5. Typical voltage and current waveform from a transformer under a saturation condition

The main sources of harmonics during normal operation of a WPP with a Type 1 WTG are usually power transformers operating in a saturated mode. This undesired condition occurs when the voltage output from the WPP reaches a point at which the distortion can produce a nonlinear behavior and may distort the line current. This distorted current could excite the resonant points, as shown before. Fig. 5 shows a typical voltage and distorted current waveform from a transformer under a saturation condition.

IV. WPPs with Type 3 WTGs

The power system shown in Fig. 6 contains three real WPPs: (1) 100 MW (WPP1), (2) 100 MW (WPP2), and (3) 85 MW (WPP3), respectively; all the wind turbines are Type 3, the collector power transformers are 230/34.5 kV Yg-D connection, and all the WTGs have a 34.5/0.69/0.69-kV D-Yg-Yg connection transformer. Some operating conditions of the WPPs produced severe current and voltage harmonic problems identified at harmonics 18th, 19th, and 20th as measured at Bus 7. The WPPs are represented by current sources as shown in Fig. 10.

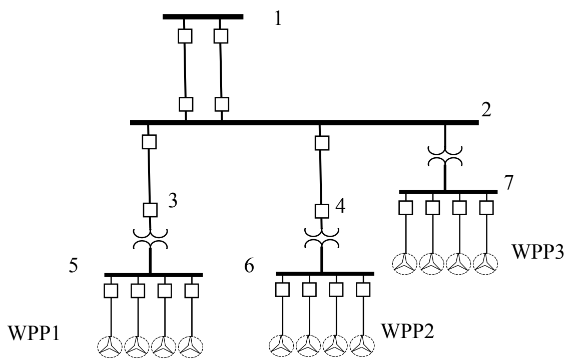


Fig. 6. Power system with three WPPs

A. Transformer In-Rush Current During Energization

Fig. 7 shows the three-phase voltage waveforms, and Fig. 8 shows the three-phase current waveforms. Both voltages and currents are measured at Bus 7. It is concluded that these are transient currents of the transformer during energization.

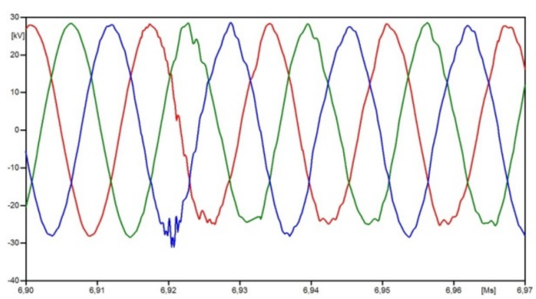


Fig. 7. Measured phase voltages at the 34.5-kV bus at the WPP3 transformer

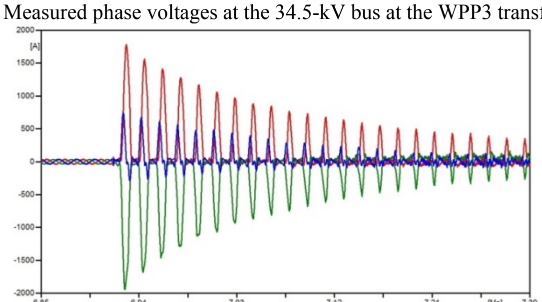
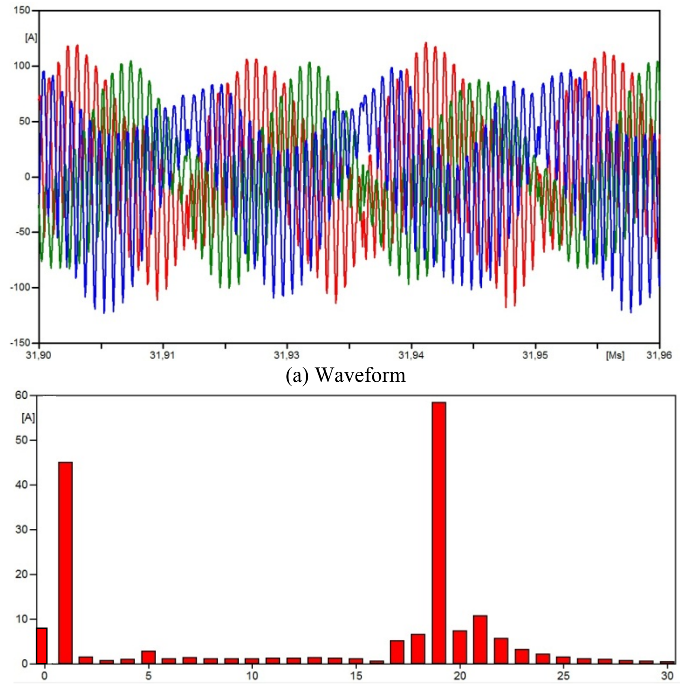


Fig. 8. Measured line in-rush at the 34.5-kV side of the WPP3 transformer bus

B. Current Harmonics in Lightly Loaded Cables

Another severe harmonic problem appeared when the WPPs were operating at 80% of nominal capacity, and the operator of the WPP3 started reducing its generation from 80% to 0%. As the power generated by WPP3 was reduced, the harmonic content increased. Measured current and harmonic content under null generation condition is shown in Fig. 9, which is the worst registered condition.



(a) Waveform

(b) Harmonic content

Fig. 9. Measured harmonic currents in the WPP3 when the plant reduced its output to 0%

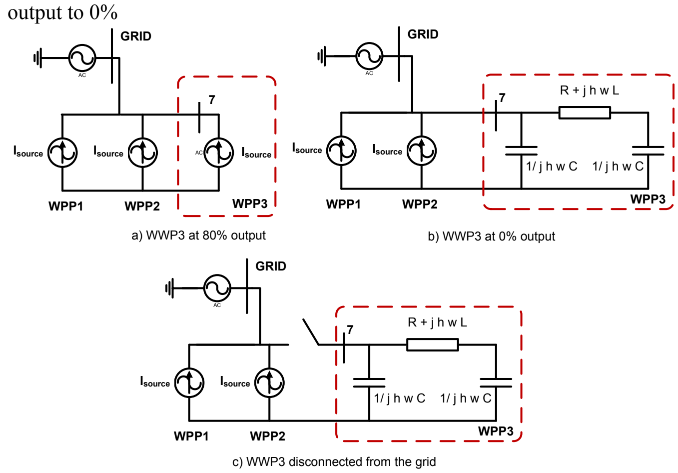
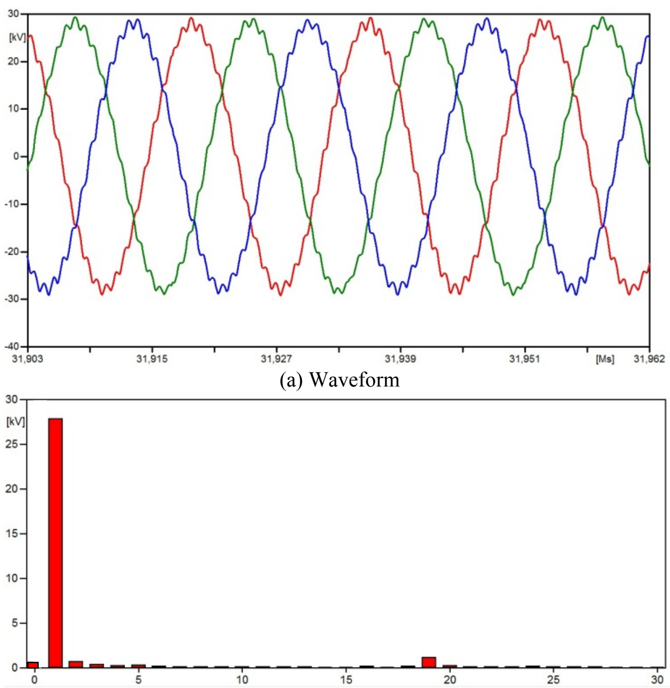


Fig. 10. Simplified circuits to illustrate the higher harmonics as measured at Bus 7

This phenomenon can be explained by using the illustration presented in Fig. 10. As shown in Fig. 10a, the circuit connected all three of the WPPs to the grid. Because a WPP consists of a doubly-fed induction generator operated with a current-regulated PWM (based on a push-pull three-phase converter controlled to shape the output sinusoidal 60-Hz currents), the harmonic contents, as expected, are very small. All of the WPPs (including WPP3) became the source of 60-Hz currents. (Any higher harmonics were blocked from entering the WPPs.)

As shown in Fig. 10b, WPP3 had 0% of output power, even though the circuit breaker was still connected to Bus 7. Thus, the equivalent impedance of WPP3 experienced by Bus 7 consisted of the equivalent of the collector systems. This unloaded cables and transformer inductances within the plant, which formed an LC circuit, and eventually became the sink of the harmonics current as measured at Bus 7. Thus, a small harmonic voltage could generate large harmonic currents into Bus 7.

The harmonic current flow continued until the circuit breaker to WPP3 was disconnected (as in Fig. 10c). As shown in these figures, a large resonance at the 19th harmonic occurred. This was confirmed by the voltage waveform at Bus 7 (shown in Fig. 11), the source of harmonics at the WPP3 during no load.



(a) Waveform

(b) Harmonic content

Fig. 11. Measured phase voltage in the WPP3 when the plant reduced its output to 0%

V. Conclusion

In this paper, we presented the harmonics issues in WPPs with different types of WTGs. The source of the harmonic currents and the network forming the harmonic paths were illustrated. Theoretical calculations were also included to supplement the measured data.

The source of the harmonics in the WPP with Type 1 WTGs was in the magnetic saturation of the transformer, and its harmonic network was formed by the tuned LC circuit of the capacitor compensations and the line inductance and leakage inductance of the transformer. The size of the capacitance C changed as the required compensation increased when the wind speed increased. The LC was tuned to different frequencies (notably, the 5th and 7th harmonics) for the WPP we studied.

The source of the harmonics in the WPP with Type 3 WTGS was in the PWM switching of the power converters (notably the 19th harmonic), and its harmonics network was formed by the interconnected underground cables and transformer leakage inductances across the WPP when there was no generation and the circuit breaker was still connected. After the unloaded cables in WPP3 were disconnected from the grid by the disconnection of the circuit breaker, the harmonic currents disappeared.

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