HARMONIC VOLTAGES AND LIGHTNING EQUIPMENT FLICKER CAUSED BY PUMPING STATION – MEASUREMENTS, ANALYSIS AND MITIGATION

Trond TOFTEVAAG
SINTEF Energy Research – Norway
trond.toftevaag@sintef.no

Helge SELJESETH
SINTEF Energy Research – Norway
helge.seljeseth@sintef.no

Rune PAULSEN
Nord-Trøndelag Elektristitetsverk – Norway
rune.paulsen@nte.no

ABSTRACT

This paper discusses cause and effect of harmonic voltages and severe lighting equipment flicker that were observed by low voltage end consumers in connection with the operation of a pumping station connected to a 22 kV radial line of a typical MV distribution network of a Norwegian utility. The pumping station, consisting of three wound-rotor induction motors rated at 1.75 MW, 6.6 kV, forms part of a local medium-size hydro power scheme. The voltage disturbance is a 7.harmonic (and partly 5.harmonic) component fluctuating with a frequency of approximately 2 Hz, resulting in considerable flicker problems in lighting equipment at end customers, causing customer complaints.

INTRODUCTION

The voltage quality problem described in this paper caused customer complaints to the Norwegian Network operator NTE Nett AS even though flicker levels measured according to international standards were low. After customers complaining about what they experienced as very poor lighting quality with very visible flicker the network operator performed measurements to evaluate the situation. Measurements with instruments capable of measuring according to the Norwegian voltage quality regulation [1] (and according to EN50160 [2]) did not reveal any large flicker levels nor any large number of rapid voltage changes. Customers had however managed to capture and prove the very visible flicker on video during a period when low flicker levels in the voltage was measured.

SINTEF Energy Research was hired by NTE to investigate and troubleshoot this customer complaint case. SINTEF had in a limited number of previous cases verified flicker problems when both flicker levels and the occurrence of rapid voltage changes are moderate or even low. In those cases different types of harmonic distortion of the supply voltage had been the cause of the very visible and irritation flicker.

ADVANCED MEASUREMENT AT CUSTOMER

SINTEF performed measurements with Elspec G4500 and G4430 instruments at one of the complaining customers. These instruments are capable of recording and continuously storing the 3 phase voltages and currents so most voltage quality parameters can be investigated on a cycle to cycle basis to reveal rapid variations.

These advanced measurements verified moderate to low flicker levels and normal levels of rapid voltage changes. Se Figure 1 for cycle by cycle rms variations of the voltage and the variation in Pst. The time range shown has low Pst values of only between 0.15 and 0.33. During these hours flicker was very visible.

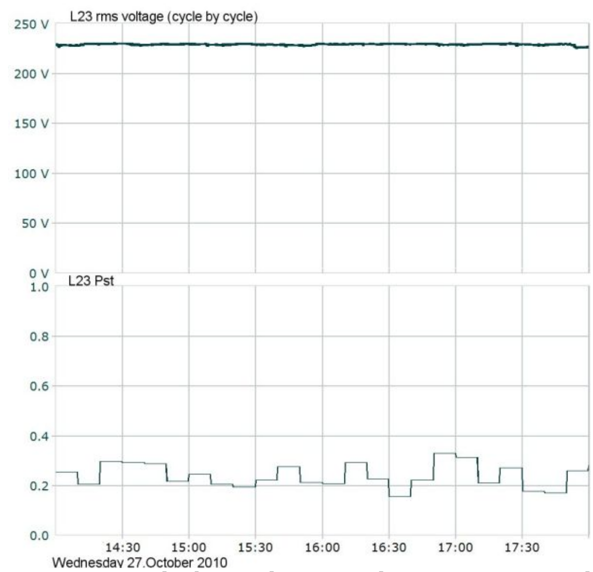

Figure 1. Cycle by cycle rms voltage variations and variations in Pst for a time interval with very visible flicker.

When cycle by cycle variations in harmonic voltages was investigated, THD was well below the limits given in the Norwegian regulations and EN50160. There was however significant levels of THD with an interesting pattern of variation. The by far largest contribution to the THD level was the 7.harmonic component in the voltage. In Figure 2 the 7.harmonic voltage component is shown together with the rms voltage variations and the Pst from Figure 1. The 7.harmonic limit value in both the Norwegian voltage quality regulation and the EN50160 is 5 % and in this case even the cycle by cycle levels of the 7.harmonic component were lower than 4 %. The 7.harmonic maximum levels were by itself not the problem. The experienced flicker problem is caused by some unexpected variations in the 7.harmonic voltage.

In Figure 3 the parameters in Figure 2 is zoomed in to view a shorter time range to reveal the interesting pattern in variation of the 7.harmonic component. These variations are of quite low frequencies (slow) and are not easily recognized by the human eye. In Figure 4 the rms voltage variations and Pst is removed and replaced by the voltage wave shape envelope curve.

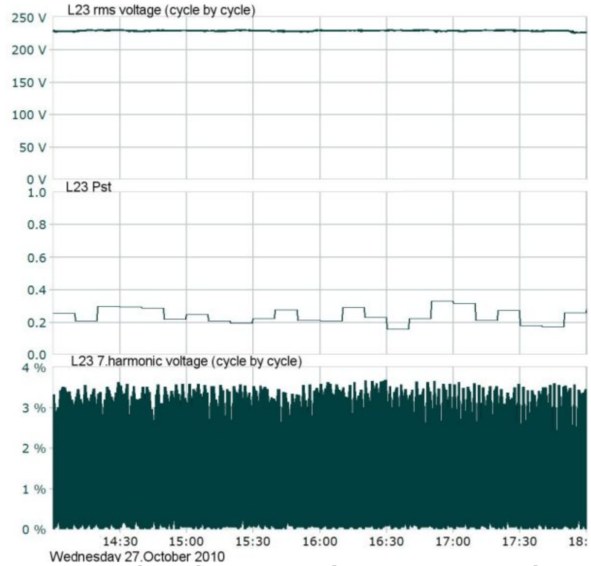

Figure 2. The 7.harmonic voltage component shown together with cycle by cycle rms voltage variations and variations in Pst for a time interval with very visible flicker.

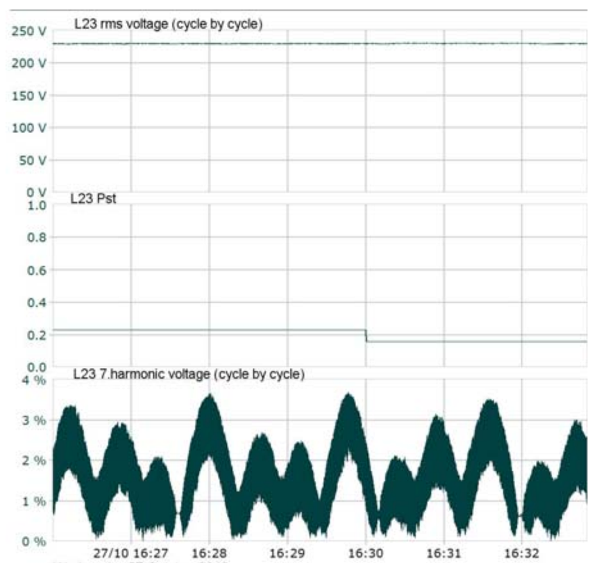

Figure 3. The parameters in figure 2 zoomed in to view the interesting variation pattern of the 7.harmonic component.

The wave shape envelope curve indicate that the 7.harmonic component significantly influence the wave shape peak values. However the variations visible in figure 4 is as stated previously so slow that they are not easily perceived as flicker. The red rectangle in Figure 4 indicates the time range for Figure 5. Figure 5 represents a shorter time range than figure 4 and shows in more detail how the 7.harmonic components impact on the voltage wave shape at a frequency more easily perceived as flicker. The most significant frequency component in terms of causing visible flicker is the approximately 2 Hz variations in the 7.harmonic component and is in particular electronically controlled lighting equipment that is affected.

After the problem was identified and verified the network operator continued measurements in multiple locations to narrow down and identify the source of the very varying 7.harmonic voltages. The source was found to be 3 large high-voltage asynchronous machines in a pump station.

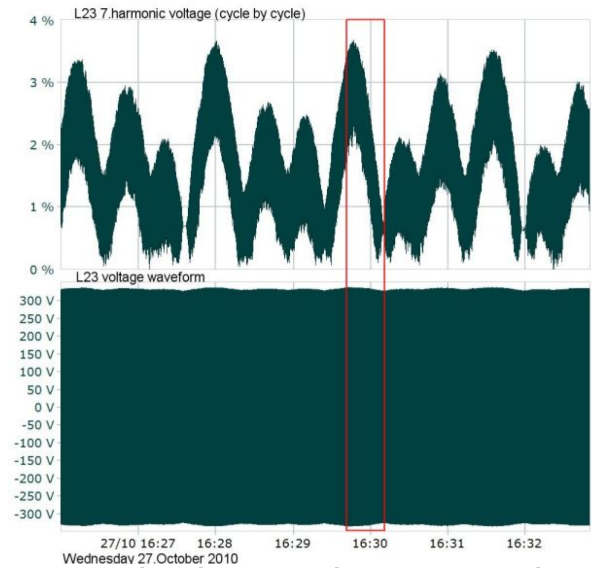

Figure 4. The 7.harmonic voltage component shown together with the voltage wave shape (envelope curve). The red rectangle indicates the time range in figure 5.

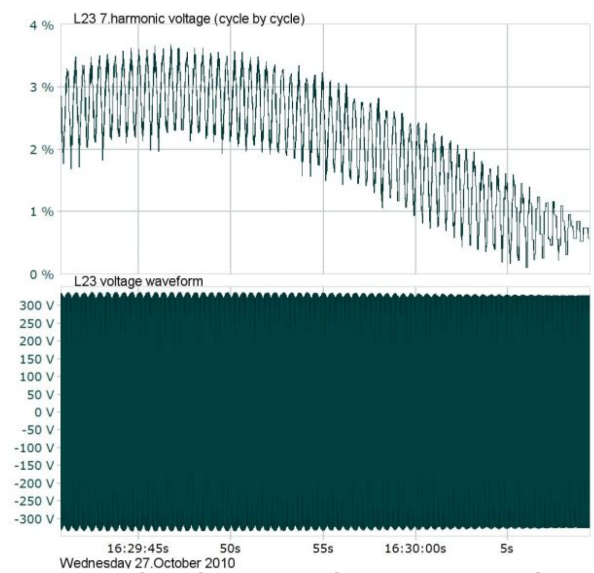

Figure 5. The 7.harmonic voltage component shown together with the voltage wave shape (only envelope curve visible). The time range equals to the red rectangle in Figure 4. The upper curve clearly shows the (approx.) 2 Hz variations in the 7.harmonic component.

MEASUREMENTS IN PUMP STATION

In cooperation with the grid owner SINTEF performed measurements in the pump station (October 2012) with the aim to collect more information about the electric behaviour of the electric motors in different operating modes. The pump station consists of 3 identical high voltage induction motors. A single-line diagram of the pump station is shown in Figure 6, where also the measuring points are depicted. The instruments used were Elspec G4430 (22 kV) and G4500 (6.6 kV), respectively.

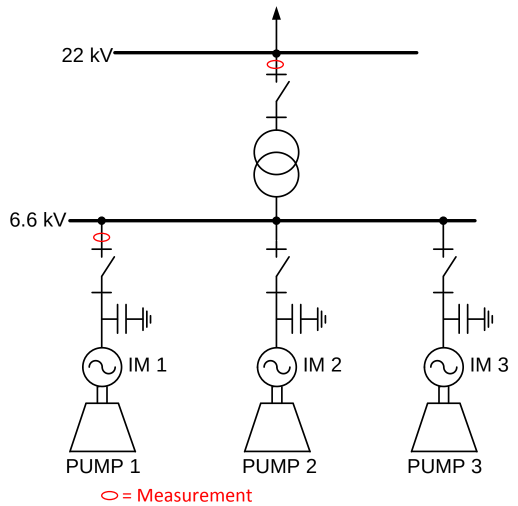

Figure 6. Single-line diagram of the pump station. The measuring points are depicted in the figure. Measurements performed with Elspec G4430 and G4500.

Data for the induction motors:

- Rated voltage: 6.6 kV
- Rated frequency: 50 Hz
- Rated power: 1.75 MW
- Rated speed: 742 rpm
- Rotor: wound rotor and slip-rings
- Starting: resistors (external) in rotor circuit (motor-controlled brush-lever and 7 step starting resistors)
- Capacitor for compensation: 600 kvar (per motor)

The pump unit sets have horizontal, dry-mounted, double-wheel pumps.

The measurements show in principle the same pattern(s) as have been observed from the previous measurements performed in this context (i.e. in both the grid and in the pump station). The main observations from the measurements in the pump station are:

- There is a pronounced 7.harmonic component in both voltage and current both at 6.6 kV level and at 22 kV level. See Figure 7 for further details (relates to 6.6 kV level).
- The 7.harmonic component (in both voltage and current) increase with number of motors that are in operation. See Figure 8 for further details. This also relates to the 7.harmonic in current of motor No. 1.
- There is a pronounced approx. 2 Hz variation in the 7.harmonic component. This 2 Hz variation is also visible in the instantaneous value/curve of the fundamental line voltage (see e.g. Figure 5). The frequency of the 2 Hz variation is not constant during the measuring period (in the October 2012 measurements: approx. 4 hours): the frequency increases from approx. 1.9 Hz to approx. 2.1 Hz during this period.
- The amplitude of this 2 Hz component, as identified via the 7.harmonic in the voltage at 6.6 kV level, increases with the number of motors in operation, from approx. 1 % for one motor via approx. 3 % for two motors to approx. 7 % for three motors in operation. See Figure 8 for further details.
- The 7.harmonic component (in voltage and current) exhibits a pronounced low-frequency "wave-pattern" when 2 or 3 motors are in operation. The frequency of this "wave-phenomenon" is higher when three motors are in operation than when two motors are in operation. See Figures 3 and 4, and also Figure 7 for further details.

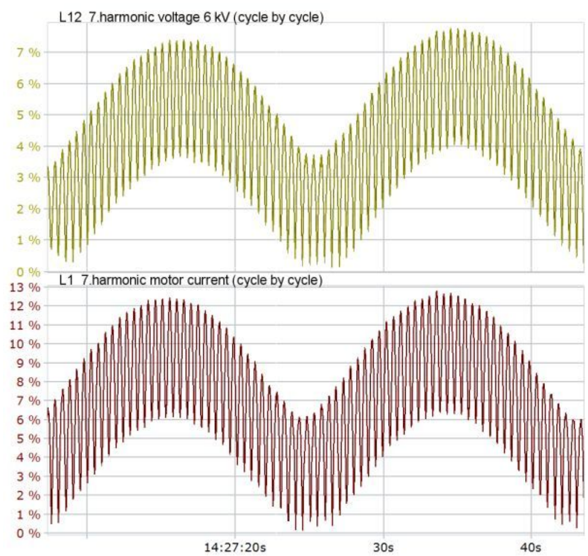

Figure 7. The 7. harmonic component in voltage and current, respectively, at 6.6 kV level. The 2-Hz variation is clearly visible. Three motors in operation at approx. rated power.

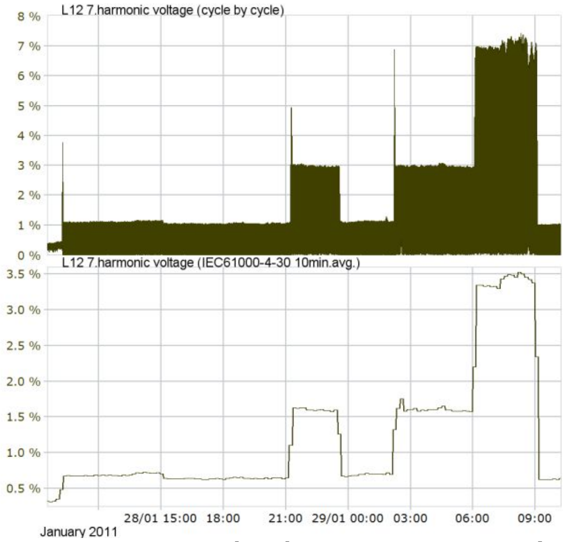

Figure 8. Upper curve: The 7. harmonic component in voltage at 6.6 kV level for one motor (left part), two (middle) and three motors in operation. Lower curve: 10 min average of the 7.harmonic component, calculated according to IEC61000-4-30 [3].

Also "classical" vibration measurements have been performed regularly on the machinery in the pump station. None of these measurements contains information that could help in explaining th**e** 2-Hz component in the electrical measurements.

INVESTIGATIONS

It has not been possible to collect detailed information about the design of the induction motors in question. The main approach has therefore been to study available literature, primarily textbooks ([4], [5], [6]), with the aim to try to find explanations on the flicker caused by the approx. 2 Hz component in voltage and current. Also [7] has been studied. Resonance between the grid and the motors including the capacitors, have been considered. Normally such resonances are of a much higher frequency. The "wave-pattern" observed in the 7.harmonic component when two or all three motors are in operation is assumed, though, to be rotor-related (wound rotors), since the rotor speeds most likely will be different during normal operation of the motors.

The frequency of the rotor related 7.harmonic component of voltage induced in stator becomes 347.6 Hz, when assuming rotor speed of 744 rpm (slip=0.008), based on [8]. Similarly the frequency of the rotor related 5.harmonic component of voltage induced in stator becomes 247.6 Hz, i.e. a difference of exactly 100 Hz compared with the 7. harmonic component. A modulation between the 7.harmonic components of stator and rotor related induced voltages, respectively, should be expected to occur in this case, with the resulting superposition sum wave having an amplitude envelope that varies according to the difference frequency, i.e. at 2.4 Hz in this case (larger value for larger slip). The same difference frequency will apply to the 5. harmonic component. This implies that also the resulting superposition sum waves of the above 7. and 5. harmonic components, respectively, will add up (depending on possible phase shift). A "classical" frequency analysis of the motor current (IM1) reveals that it contains 7. and 5. harmonic components according to the above calculations, i.e. both fundamental frequency and rotor speed related components, the 7. harmonic component having the largest amplitude.

CONCLUSIONS

This paper discusses cause and effect of harmonic voltages and severe lighting equipment flicker that were observed by low voltage end consumers in connection with the operation of a pumping station connected to a 22 kV radial line of a typical MV distribution network of a Norwegian utility. The pumping station consists of three wound-rotor (slip ring) induction motors rated at 1.75 MW, 6.6 kV. The work and investigations described proves that severe flicker can be present in the network and supplied to customers even though low flicker values are measured (Pst and Plt). Measurements have documented that the motors in the pump station represents the most likely source of the voltage disturbances. The quite regular (approx.) 2 Hz variation observed in the Elspec curves of the 7. harmonic component and the voltage wave shape is believed to be related to the resulting superposition sum wave for the 7.harmonic components of stator and rotor related induced voltages, respectively, <u>and</u> the superposition sum wave of the 5. harmonic, both waves having an amplitude envelope that varies according to the difference frequency, i.e. at 2-3 Hz in this case.

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