

# ANALYSIS OF VOLTAGE TRANSIENTS IN A MEDIUM VOLTAGE SYSTEM

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## ABSTRACT

Power system transients can be caused by lightning, switching actions and faults in the power system. The transients can reach high magnitudes and depending on raise time, peak value, wave shape and frequency of occurrence the impact on power system components and end user equipment can be severe. The damages can be operational problems, accelerated ageing (fatigue) and immediate damage to equipment.

In this paper voltage transients in a medium power system are investigated. Data from a long term measurement in a 10.5 kV system are used to analyze voltage transients. By comparing the voltage magnitude before and after a transient event it may be possible to obtain information about what event caused the transient. This is important when protection and prevention against transients are discussed. For example capacitor energizing and capacitor de-energizing can cause changes in the voltage profile, either in the voltage magnitude or in the harmonics.

The paper includes an estimation of rate of occurrence of transients in a station during a long measurement period. Other interesting parameters for transients are also studied.

## INTRODUCTION

A previous investigation refers to change in supply voltage after transient impact [1]. Different events cause either a rise or a decrease in voltage. The rate of occurrence and the amplitude of the transients are important parameters when damages due to fatigue causes in isolation materials in transformers are investigated [2].

### **Voltage Transformers, measurement accuracy**

When measuring on medium voltage level the measuring equipment cannot be directly connected to the terminals. Voltage transformation is required to connect to the measuring equipment. Magnetic voltage transformers are frequently used in medium voltage systems. These transformers are designed to operate at fundamental frequency. For voltages up to about 11 kV and frequencies below 5 kHz the accuracy of most voltage transformers is within 3% [3]. As most of the measurements analyzed in this article concern capacitor energizing events where the main frequency is about 1 kHz the accuracy is acceptable. The sampling rate of the measuring equipment used in the measurements is 6400 Hz, 128 samples per period. At 6400 Hz the Nyquist frequency is 3200 Hz. Due to the voltage transformer and the anti-aliasing filter the maximum detectable frequency in the measurement is approximately 2000 Hz. The measurements were initially made for general power quality purposes and not

especially for transient analysis. For this a voltage divider and another type of measuring equipment is required. Measurements with a voltage divider and high sampling measurement equipment are conducted at the moment within a Ph. D. project at Chalmers University of Technology. The results are not yet available.

The collected data contains a lot of useful information such as peak value, duration and rate of occurrence. From the data collected a lot of interesting conclusions can be drawn despite the lack of higher frequency components.

## **VOLTAGE TRANSIENT CHARACTERISTICS**

### **Transients in general**

Voltage transients in power systems are caused by switching actions, lightning and faults in the system. Different phenomena create different types of transients. Oscillatory transients are caused mainly by switching phenomena in the network. The most common switching action is capacitor bank switching. The most severe transients are caused by capacitor energizing while capacitor de-energizing only causes a minor transient [4]. Non synchronized energizing of capacitors is worse than synchronized. Oscillatory transients are characterized by duration, magnitude and spectral content [1]. There are subclasses of oscillatory transients depending on the dominant frequency [5].

Impulsive transients are caused mainly by lightning strikes. The worst impulsive transients are created when the lightning strikes directly on the power line. However the majority of direct strikes lead to a fault, which shows up as a voltage dip at the equipment (monitor or end-user equipment) terminals. Voltage dips are not treated in this paper. Impulsive transients are characterized by rise and decay time. The impulsive transients are divided into subclasses according to their duration [5]. Transients in general are rapidly damped when they propagate due to the resistive part of the system. Therefore transients in general are a local phenomenon. Exceptions are transients of relatively low frequency that originate in the transmission or subtransmission network, e.g. the switching of a 130-kV capacitor bank. Such a transient spreads in the same way as a voltage dip and may be observable hundreds of kilometers away from its origin.

### **Other ways to characterize and identify different transients**

The distinction between oscillatory and impulsive transients is somewhat artificial. Many transients can show oscillatory as well as transient behavior and change characteristics as they propagate through the network. Therefore other ways of characterization of transients are helpful when studying transients.

Efforts have been made to characterize transients in other way than the standardized.

Classification can be made depending on the origin of the transient, for example lightning transients, capacitor energizing transients or capacitor de-energizing transients.

The purpose of a capacitor bank energizing action is to add reactive power to the system. This increases the voltage. By studying the voltage before and after an oscillatory transient one can obtain additional information about the cause of the transient [1].

- Capacitor energizing causes voltage increase. How large the increase is depends on the size of the capacitor bank.
- Open-ended line energizing causes a small voltage increase.
- Capacitor de-energizing causes a decrease in voltage.

- Shunt-reactor energizing causes a decrease in voltage.
- Shunt-reactor de-energizing causes an increase in voltage.

With good knowledge of the different components in the power system studied, it is possible to tell what event caused the actual transient.

The initial change in voltage for the transient is also a way to characterize a transient.

Capacitor energizing causes an initial decrease (towards zero) in voltage due to the fact that an uncharged capacitor is initially a short circuit. For a lightning impulse the initial voltage can either increase (away from zero) or decrease depending on the polarity. Normal capacitor de-energizing only causes minor transients. Restrike during capacitor de-energizing causes high-frequency transients of high amplitude that often show a repetitive character.

A transient created in one of the three phases in the system is also visible in the other two phases only smaller in amplitude. This is due to mutual coupling between the phases.

### **Direction estimation by studying transient characteristics.**

By studying the first oscillations after a voltage transient caused by a capacitor energizing event it is possible to decide where the origin of the transient is located, i.e. where the capacitor bank is located in the system, upstream or downstream from the measuring point. If a voltage change creates a current change that seen from the measuring point is moving in the same phase (in the same 'direction') the capacitor bank is located upstream in the system. If the voltage and the current are moving in different directions the capacitor bank is located downstream in the system. This analyze is only possible to perform on the first two or three oscillations after the initial transient, later the signals become too distorted [6].

## **ANALYSIS OF LONG TERM MEASUREMENTS**

### **General considerations**

The measurements were recorded at the 10.5 kV side of a 50/10.5 kV transformer. Transients were recorded during a period of 5 months. A total of 47 transients were detected.

Most of the transients are due to capacitor bank energizing. The predominant frequency is determined by the size of the capacitor bank C and the source inductance L:

$$f = \frac{1}{2\pi\sqrt{LC}} \text{ or}$$

$$f = f_0 \sqrt{\frac{MVA_{sc}}{MVA_c}}$$

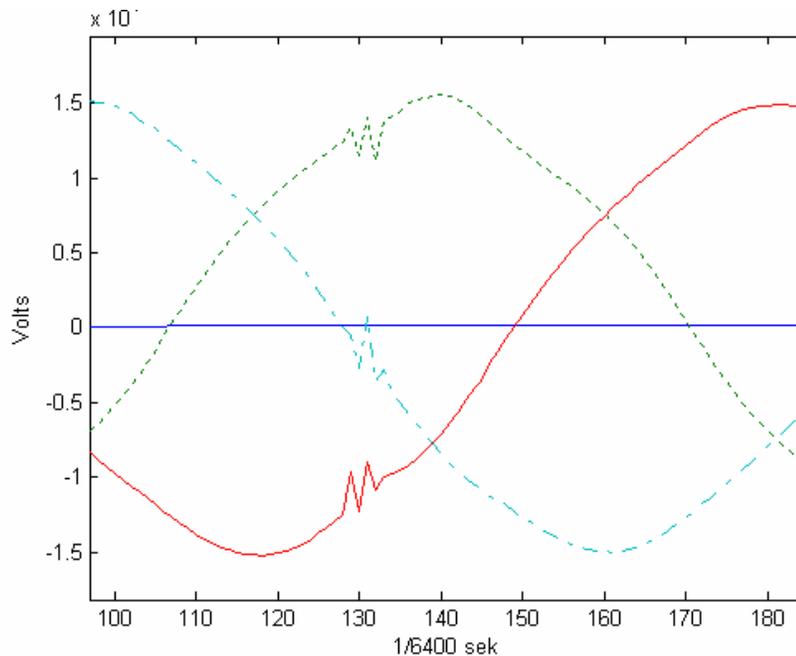
where  $MVA_{sc}$  is the short circuit of the source,  $MVA_c$  is the capacitor bank rating, and  $f_0$  is the power system frequency (50 Hz). The frequency for capacitor energizing ranges from 250 Hz through 1 kHz depending on the components in the system.

For the switching of a single capacitor bank the resonance frequency  $f$  is linked to the voltage rise  $\Delta U$  (in per unit) through:

$$f \times \Delta U = f_0$$

In this station the energizing is synchronized. Synchronized switching is used to reduce switching stress. The controller is designed to automatically close the switch at strategic points that corresponds to the zero point of the AC voltage and the bank's configuration. For grounded neutral banks the capacitors are energized at each respective phase zero voltage crossing point. For isolated neutral capacitor bank configuration, two phases are simultaneously closed in the zero points of their phase-to-phase voltage. The next moment of closing of the third phase follows a quarter period later. Theoretically the switching transients can be totally eliminated, but deviations in the characteristics of the controller system and circuit breaker may affect the result [7]. In stations without synchronized coupling the influence from the switching transients are more severe. Fault related transients are not so common. Rate of occurrence varies and depend and amplitude depends on the characteristics of the system.

Fig.1. shows a typical transient at the location. Most of the transients recorded do not have large amplitudes compared to the voltage level.

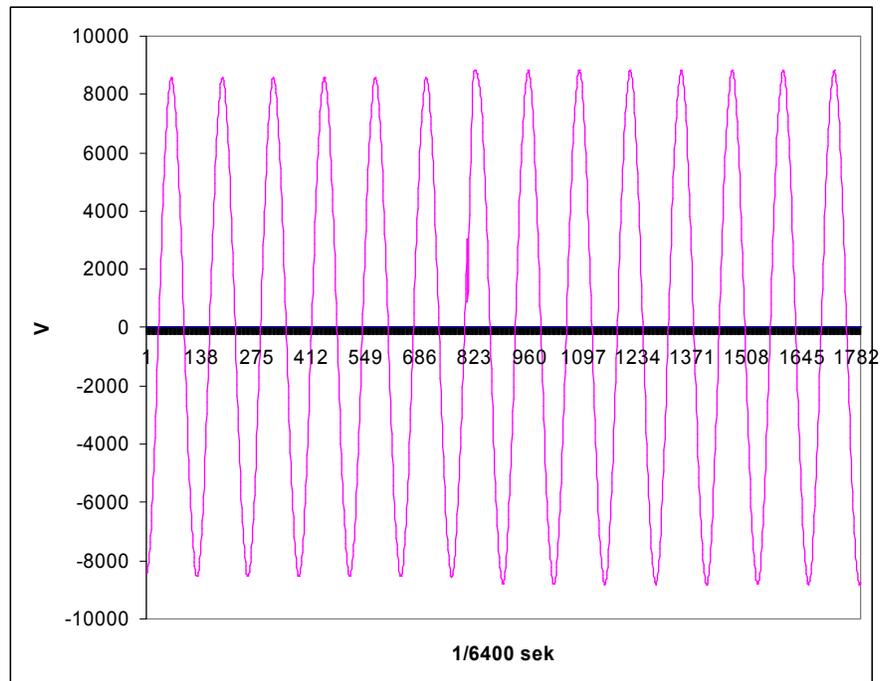


*Fig.1. Example of transient recorded at the 10 kV side of a 50/10.5 kV transformer*

The largest part has amplitudes less than 500 V. The transients can be transferred through the transformer to a higher voltage level and through the system to a lower voltage level. Depending on the transformer characteristics and the power lines the transients can either be magnified or damped due to the frequency dependence of the components [1]. Some frequencies are transferred and other frequencies are suppressed in the system. This is an important fact if a transient is present in only one of the phases it will be transferred to the other phases due to mutual coupling between the phases. This is visible in Fig.1.

### Voltage rise due to capacitor energizing, one phase study

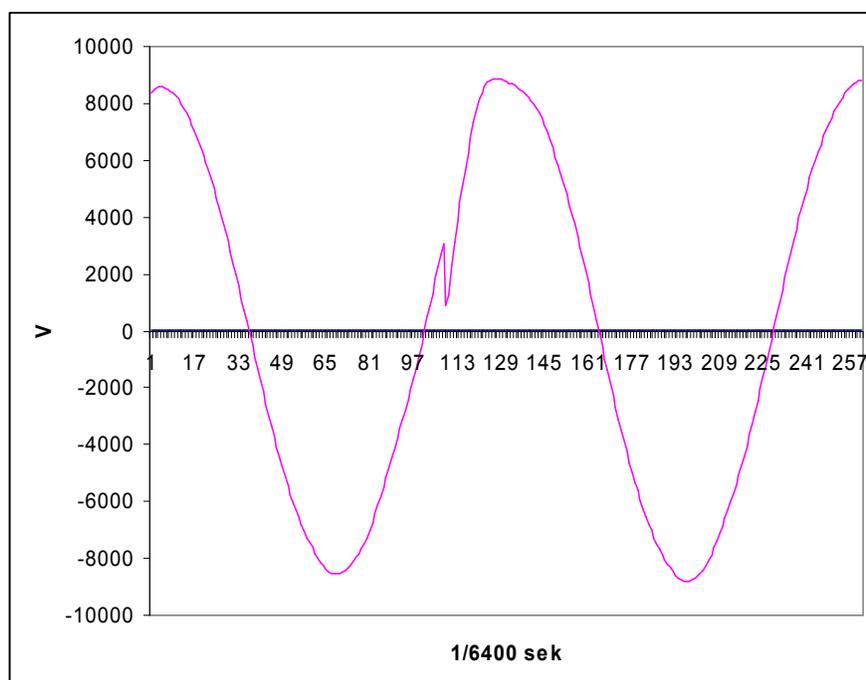
In Fig.2. there is a transient caused by capacitor energizing. The voltage rise due to capacitor energizing is approximately 0.04 p.u. The value corresponds to the results from measurements taken in a 22 kV network where the voltage rise is 0.03 p.u. [1].



*Fig.2. Voltage rise due to capacitor energizing, one phase.*

Fig.3. shows this transient on a larger scale. Note also the change in voltage distortion before and after the transient. A harmonic resonance is present somewhat above the fifth harmonic (250 Hz) leading to a rise in fifth harmonic voltage due to the presence of the capacitor bank. A sharp rise in harmonic distortion is another indication for capacitor energizing having been the cause of the transient. The energizing of the capacitor bank causes an initial decrease in voltage (towards zero). The magnitude of the transient is 2.172 kV or 0.15 p.u. The oscillations following the first initial change in voltage is not visible in the measurement example due to low sample rate. This shows that transient analysis need higher sampling rate in the measurement equipment to really show what happens. The voltage will recover through a high frequency oscillation. The initial oscillations can propagate through transformers and be magnified. The predominant frequency of the transient can coincide with a natural frequency in the transformer and thereby amplify the transient in the transformer. A transient can, from its point of origin be propagated through the distribution system and be transferred through the transformer inductive/capacitive couplings to other voltage levels. Measurements have been carried out on overvoltage transference from transformer primary winding to secondary winding on distribution and rural networks [8]. Impulsive wave is transferred with a considerable magnification regarding the winding rated voltage and showing a great change

in waveform. Magnitude of transferred impulsive wave is function of the transformer constructive characteristics. Depending on the characteristics of the system there can be oscillations that are severe for equipment connected to the system.

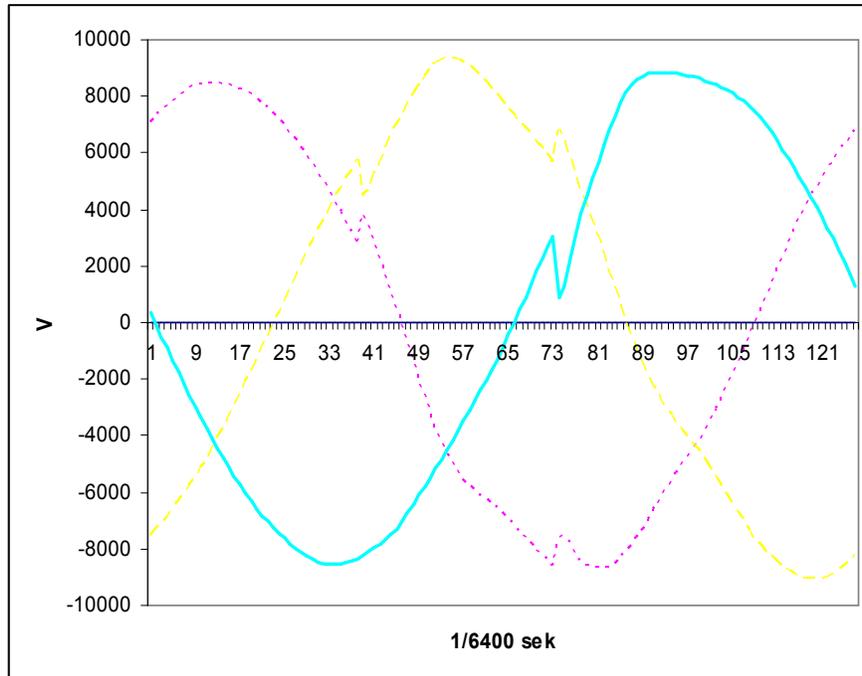


*Fig.3. Voltage rise due to capacitor energizing on a larger scale.*

Transient overvoltages can cause breakdown of insulation, and the result can be either a temporary disturbance of device operation or instantaneous failure. Insulating level will be weakened and this will eventually lead to failure in the material. Air and liquid are self healing but for solid material there will be permanent damage. The trend towards changing oil filled transformers to dry type transformers will probably increase the problem with fatigue in transformer materials due to transients.

### **Capacitor energizing, three phase study**

Fig.4. show a capacitor energizing event for three phases. Two subtransients are visible, the first one corresponds with the first switching action (two breakers are closed around zero crossing of their voltage difference). The second subtransient corresponds to the second switching action (the third breaker is closed 90 degrees later when the difference between the voltage in this phase and the average of the two other phases is around zero). The first subtransient is of the same amplitude but opposite direction in the two phases involved. The second subtransient has the largest amplitude in the phase that was not involved in the first subtransient, i.e. the phase of the third breaker to close. In the other two phases the second subtransient is half the amplitude and opposite in sign.



*Fig.4. Capacitor energizing, three phases*

### **Location of capacitor banks**

Fig.5. shows a measurement where the capacitor energizing event where the capacitor bank is located downstream from the measuring point. The top curve shows the voltage and the current transients. The middle curve shows the same transient with the 50 Hz component removed and the signal filtered by a 1500 Hz low-pass filter. The lower curve shows RMS values for the voltage and current. In all curves the voltage and current are moving in different directions. In this case it is verified that the capacitor bank is located in a factory, i.e. downstream in the system. For safe prediction all these curves are needed.

In Fig.6. an energizing event is taking place upstream in the system from the measuring point. In this case the voltage and the current are in the same phase. The capacitor bank is located in the feeding network. This analyze has to be done in the first oscillations after the energizing event [6].

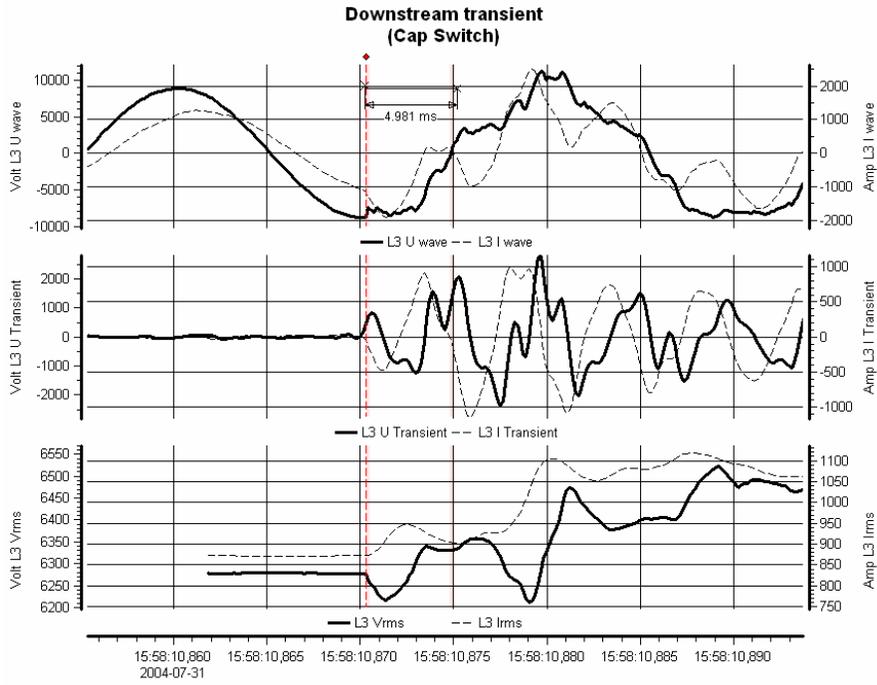


Fig.5. Downstream voltage/current transient due to capacitor switching

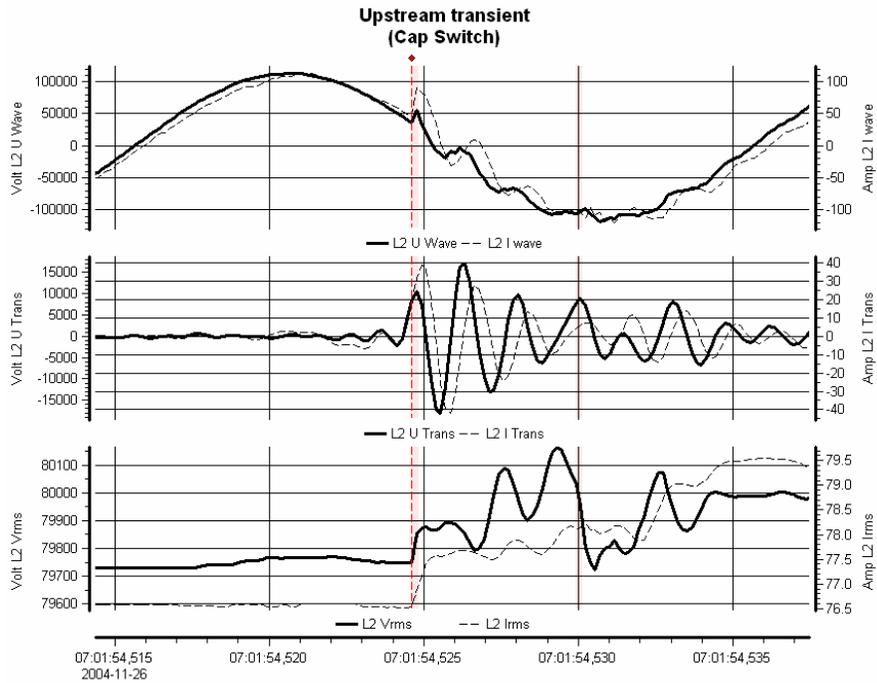
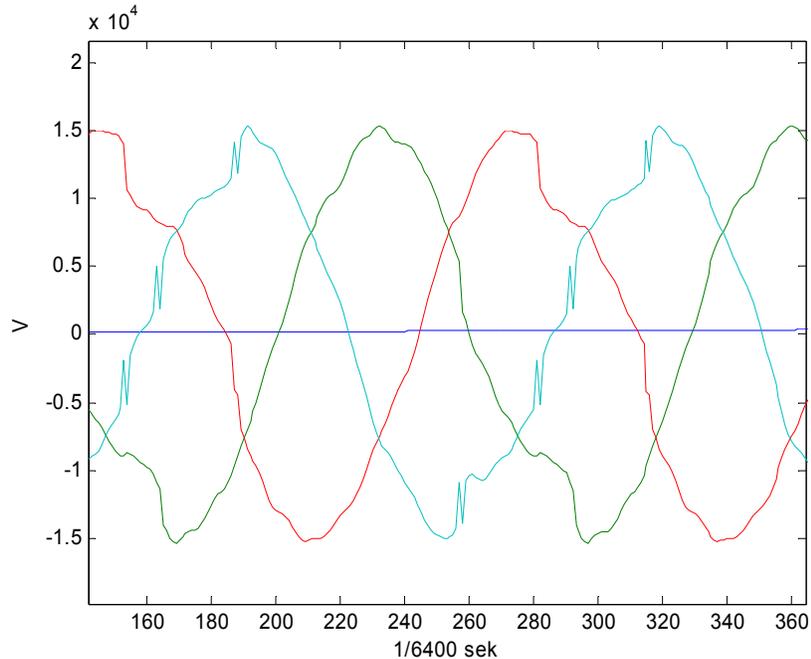


Fig.6. Upstream voltage/current transient due to capacitor switching

## Transformer saturation

In Fig.7. there is an example of transients during transformer saturation. The transients are repetitive and therefore the duration is a matter of definition. If the transients are seen as one event the duration is half a cycle, i.e. 10 ms which is a long duration for a transient. The transients are visible in one of the three phases and the amplitude is approximately 0.2 p.u.



*Fig.7. Transients during transformer saturation*

## CONCLUSIONS

A lot of useful information can be taken from power quality measurements without special focus on measuring transients. Capacitor energizing transients are oscillatory with a frequency below 2000 Hz. By studying the initial change in voltage and the voltage profile before and after a transient event a characterization of the transient is possible. The number of transients occurring in a power system is determined by system configuration and the components in the power system. The components in the power system (lines, transformers, etc) are also frequency dependent. The number of transients can vary widely between different parts in the system. One important factor is if the capacitor energizing in the system is synchronized or not. In the studied system there is both synchronized and not synchronized energization of capacitor banks. At locations with synchronized energization the number of transients is lower and the transients present have smaller amplitude. During the same period the number of recorded transients at two different locations in the system was 5 compared to 47. For transformers the number of transients occurring in the system is important. The trend of changing oil filled transformers with dry type transformers will probably increase the fault rate due to fatigue in material as solids are not self healing. For deeper analysis of transient behavior measurement equipment with higher sampling rate is needed. A voltage transformer

is only showing accuracy at lower frequencies. In low voltage measurements the accuracy is better due to the fact that the voltage can be measured directly and no voltage transformer is needed. For higher accuracy at other voltage levels a voltage divider is needed in the measurements.

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