DISTURBANCES DUE TO VOLTAGE DISTORTION IN THE KHZ RANGE – EXPERIENCES AND MITIGATION MEASURES

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SUMMARY
Disturbances in power systems due to oscillations of several kilohertz (1 .. 15 kHz) superimposed to the fundamental became more and more important in recent years. The paper discusses causes for this development such as the increased use of PWM converters (e.g. for drives or FACTS devices) or reduction in system damping together with ordinary converter load leading to an excitation of natural system frequency known as commutation oscillations. Measurement results as well as examples from several cases of disturbances investigated by the authors will be presented. The effects of these disturbances vary in a wide range such as malfunction of electronic office equipment, blown power supply units, malfunction of electronic controls or unacceptable noise.

INTRODUCTION
For many years, in respect to voltage waveform distortion, the main focus was on low-frequency disturbances in the harmonic range up to the 50th harmonic. In many practical investigations, harmonics will be considered up to the 25th only. A large number of papers deals with such voltage perturbations and they are well covered in many national and international standards in order to allow a co-ordination of disturbances and the immunity of equipment. However, as practical experiences show, the amount of problems with steady-state voltages in the frequency range of several kilo-Hertz have been steadily increasing over the last few years. The authors found two major sources of such disturbances. One source are frequencies generated by self-commutated converters with an operating pulse frequency of several kHz. The other main source are oscillations of a subsystem at its natural frequency caused by the commutation of "ordinary" line-commutated converters (commutation oscillations).

SELF-COMMUTATED CONVERTERS
Self-commutated converters are used increasingly at the system side of variable speed drives (known as active front end – AFE), for the connection of d.c. generating devices such as solar power panels or for special applications such as active filters [1,2]. The power rating of devices with a pulse frequency in the kHz range is still limited to a few MVA due to the limitations of power electronic components, in particular due to sharply increasing losses for higher switching frequencies for high power components. Therefore, most converters are connected to the LV level. However, it can be predicted easily, that the number and power rating of equipment producing substantial distortion in the kHz range will increase in the near future.

The effects of these disturbances vary in a wide range such as malfunction of electronic office equipment, blown power supply units, malfunction of electronic controls or unacceptable noise.

COMMUTATION OSCILLATIONS
Commutation oscillations are caused by the sudden voltage dip caused by the 2-phase short-circuit during commutation of a line-commutated converter. This voltage dip causes the feeding system to oscillate at its natural frequency, which is determined mainly by line capacitances and the inductance of the feeding system (Fig. 3). Typical frequencies of such oscillations in the LV system were found in the range of several kHz up to more than 10 kHz. In most cases, substantial magnitudes of commutation oscillations can be found only in the subsystem where the converters are connected. The main factor determining their duration and magnitude is the system damping. Since most of the damping in this frequency range is provided in many cases by transformers, the development towards transformers with
lower and lower losses supports the appearance of commutation oscillations. This is supported by a special case, where the authors found commutation oscillations caused by a large converter as the source of disturbances. The busbar where the converter was connected was fed by two similar transformers with their age being the main difference. One was taken from an old plant and the other one was new. Commutation oscillations were found during the supply via the new transformer only.

In the last few years, the authors investigated many disturbances mainly in industrial plants. The following examples in respect to disturbances, which were found to be caused by voltage components in the kHz range, give an idea about the variety of possible problems.

- During the operation of a converter-fed pump with a rating of several MW, loud noise caused by various electronic devices disturbed the enthusiasm for employee's work in a nearby office building. It was found out, that the supplying LV network was connected to the same MV busbar as the pumps. These drives caused commutation oscillations in the range of about 12kHz and with a magnitude of about 40%, which could be measured at the socket outlets of the office building. In the case of one computer monitor the cause of the noise was investigated and was found out to be a mechanical oscillation of ferrite cores used in the power supply of the monitor probably to protect it against voltage surges. As a solution, the feeder transformer supplying this LV network was shifted to another busbar without any converters. The plant is operational by now without any further problems and without implementation of any further mitigation measures.

- During the operation of one individual machine tool in a LV system with several ten machines connected at a mechanical engineering company, commutation oscillations similar to the one's of Fig. 3 were measured. A photocopier produced copies with white stripes across the copies during the operation of the machine. No other disturbances were detected.

- Many LV converters are protected by varistors against overvoltage surges. These varistors are often rated such that they start conducting already at voltages slightly above 110% rated voltage. With commutation oscillations at the top of a sine wave (Fig. 3) and a fundamental voltage of 105% rated voltage, 10% magnitude of the commutation oscillations are already sufficient for the varistors to carry a short-term current at each fundamental cycle. Since the varistors are designed for short-term load due to transients only, after a certain time varistors fail due to thermal overload.

- An industrial LV system supplies mainly a large amount of small and medium size variable speed drives for pumps, motor operators etc. Most of the rectifiers feeding the drives are equipped with shunt capacitors at the system side probably for surge protection purposes, but without commutation reactor. Busbar voltage and its spectrum as well as supply current are depicted in Fig. 4. The voltage waveform contains components in the lower kHz-range of up to 0.9%. Most of the loads connected operated without any problems, but some of the small drives failed regularly and had to be replaced. The magnitude of higher harmonics was reduced substantially after installation of small commutation reactors for the majority of the drives.

**EXAMPLES**

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Fig. 2: Busbar voltage with a self-commutated converter connected; pulse frequency 3kHz (above: time characteristic, below: spectrum)

Fig. 3: Commutation oscillations with about 6kHz measured at an industrial LV busbar with a machine tool operating
An individual machine tool connected at a remote place via a small dedicated transformer is working trouble-free. One day, a precision measuring device is connected to a socket outlet in the control section of the machine due to a lack of other power supply possibilities in the vicinity. Accelerating the main spindle drive creates immediately a black cloud coming out of the expensive measuring device, being not able to measure anymore before an expensive repair. The experiment was repeated several times with the same result. The voltage during the acceleration of the drive at the socket outlet shows Fig. 5. Although the manufacturer of the machine offered (optional) a filter in order to reduce system perturbations, the owner decided to omit this costly accessory.

Also a case of radiated disturbance is worth reporting: a PWM voltage-source converter is installed in a utility building as a state-of the art solution for dynamic reactive power compensation. Several electronic control devices in the same building use the so-called DCF 77 time signal radiated at 77.5 kHz as a time base for internal clocks. The building is located in a valley resulting in a very low receiving level. After commissioning of the converter, unusual disturbances were observed and correlated to the missing time signal. It was found out, that the time signal is located in the vicinity of multiples of the switching frequency (in this case 3 kHz). Thus spectral lines close to 78 kHz are generated by the converter reducing the DCF 77 signal level. An effective solution was not the installation of additional filter circuits – which are difficult to design and are even more difficult to connect properly – but to change the switching frequency of the converter to 5 kHz. Thus the DCF 77 signal is located exactly in the middle between the neighbouring sidebands leading again to an undisturbed operation.

International standardisation in the frequency range above the 50th harmonic is rather weak, leaving many uncertainties to equipment manufacturers, utilities and private network operators. IEC 61000-2 proposes the following compatibility levels in informative annexes only for voltages in the frequency range between 50th harmonic and 9kHz:

- 0.2% for individual frequencies
- 0.3% for a frequency band with 200 Hz bandwidth

Certainly, voltages with such magnitudes will safely avoid any disturbances due to these frequencies in the system. However, especially with regard to self-commutated converters, such stringent limits might be prohibitive for many useful applications. The experience of the authors suggests that voltage limits in the range of 0.5% to 0.6% of the fundamental would not increase the number of disturbances remarkably, but would substantially reduce the effort for filtering required or would even only allow the application itself. In the case of the LV busbar voltage depicted in Fig. 2, an entire LV subsystem with various kinds of loads is operating without disturbances although the magnitudes of the individual frequencies reach up to 0.8%. IEC 61800 requires the consideration of overvoltages due to commutation oscillations of up to 150% of the peak value of the fundamental voltage (periodically) or even 250% (non-periodically) for the design of LV converters. This design criteria will certainly ensure safely, that the converters are robust and are unable to disturb each other. However, the examples given above show, that average equipment and even converters for industrial use fail already at much lower disturbance levels. At least, the design of all equipment to be connected in an industrial environment in parallel to...
converters according to these immunity requirements will result in additional costs for each individual device and needs to be specified explicitly.

MITIGATION MEASURES

In case of the self-commutated converters, a L-C-L – filter is the usual means in order to reduce line conducted system perturbations (Fig. 6). However, the reduction of voltage distortion in the supply system is limited both by economical and technical aspects in the filter design. Generally the expenditure for the filter must not exceed a fraction of the converter costs. In addition the rating of this passive component should be small in comparison to the converter rating to minimise the influence on the desired operating characteristic of the converter.

In the higher frequency range, special constructive measures have to be carried out to come as close as possible to the theoretical filter action. As a consequence, standard filter components for this frequency range exist only for low power ratings. Additionally, various special screening measures as well as special EMC filters may be applied in order to reduce radiated disturbances.

In order to reduce commutation oscillations, several possibilities seem to be useful:

- Many, especially small variable speed drives are connected without or with a small commutation reactor only. Installation of reactors of a sufficient size reduces the depth of commutation dips and thus the stimulation of such oscillations.

- Damped (high-pass) filter circuits increase the damping of the subsystems especially for higher frequencies and such reduce the tendency of the subsystem to oscillate. However, impact on low-frequency harmonics should be considered carefully, which might be amplified by new resonance points substantially.

- A common means of avoiding disturbances is also the use of a "dirty" and a "clean" busbar. All disturbing equipment with generally higher immunity against disturbances is connected to one busbar/subsystem, sensitive equipment is combined with loads with low disturbance emission. Where the possibility of the creation of such subsystems exists, it is often the least-cost alternative in order to keep the system running without any disturbances.

REFERENCES
