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Power quality issues in the electric power system of the future

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ABSTRACT

With the advent of new electricity production modes, power electronics, LED lamps and underground cables, new types of disturbances will appear, including an increase in distortion between 2 kHz and 150 kHz that is referred to as 'supraharmonics.' A shift of resonances to lower frequencies may partly compensate for the increased emissions at higher frequencies, but the transfer of disturbances will become less predictable. Equipment immunity also is likely to become less predictable.

1. Changes in society and in the grid

The electric power system (the "grid") is exposed to similar types of changes as the rest of society. For a development in society to impact the grid it has to have impact on electricity production, electricity consumption, or the grid itself. Some of the most important changes that have such an impact are:

- Changes in production
  - Change from large production units under control of a network operator to small units connected to the distribution network and/or to renewable sources whose availability and production is controlled by the weather.
- Changes in consumption
  - New types of consumption, with electric cars the example most often discussed in research and related forums. However the transition from gas heating to electric heating (most likely in the form of heat pumps) will be another such change that could have a huge impact on the grid.
  - New versions of existing consumption; many direct-driven electric motors are replaced by adjustable-speed drives where higher efficiency is the driving force. The replacement of incandescent lamps by compact fluorescent and LED lamps is another example.
  - Large numbers of small devices, where device chargers are the main part.
- Changes in the grid
  - The replacement of overhead lines by cables. At low and medium voltage levels, many countries have already close to 100% of the grid underground. Examples are Germany and The Netherlands, with 75% and 90% of medium-voltage networks underground, respectively. Other countries, like Sweden, are quickly undergrounding even their more remote rural networks. But even at a higher voltage level, including transmission, there is a clear trend towards more underground cables.
  - The number of HVDC links connecting to the transmission system is increasing, with some countries or areas having many such links within a relatively short distance. Other types of power electronics in the grid are also showing an increasing trend. For example, the Scandinavian grid is connected to the grid of continental Europe by 10 HVDC links.
  - Power line communication is being increasingly used to communicate with energy meters.
  - Finally, there is a whole spectrum of developments that go under the name "smart grids."

2. Power quality

Many of these changes have unintended consequences for the performance of equipment connected to the grid. The ultimate aim of the electric power system is to deliver energy to this equipment. Those unintended consequences therefore require serious attention. Those same changes could also have unintended consequences for the grid, including component overload, instability, and

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supply interruptions. The consequences for the grid will not be addressed in this article.

The study of the performance of equipment connected to the grid is part of the field of “power quality.” The ultimate aim of all work within power quality is to ensure a low probability of interference between the grid and equipment connected to it (“ensure a high probability of electromagnetic compatibility,” to use the terminology in the IEC standards on EMC). Unintended consequences for equipment connected to the grid translate into unintended changes in probability of interference. Such changes are due to:

- Changes in emission levels;
- Changes in immunity levels;
- Changes in transfer through the grid.

This article provides an overview of the unintended changes in emission, immunity, and transfer for four specific developments:

- Replacement of incandescent lamps by LED and compact fluorescent lamps; (This will be discussed in detail in Section 3.)
- The shift to renewable electricity production (Section 4);
- Increasing amount of equipment with an active power-electronic interface (Section 5);
- Replacement of overhead lines by cables (Section 6).

The overview will consider 11 different power-quality disturbances, as listed in Fig. 1. Most of the terms are standard power-quality terms. The term “supraharmonics” is new and refers to waveform distortion roughly in the frequency range 2 kHz to 150 kHz. Supraharmonics will be discussed in detail in Section 7.

3. New types of lighting

The replacement of incandescent lamps by compact fluorescent and LED lamps has accelerated significantly in many countries (Fig. 2) because of a number of political decisions followed by faster-than-expected technical developments.

3.1. Changes in emission

Many types of compact fluorescent and LED lamps show a highly distorted current. Concern has been expressed that the mass introduction of those lamps will result in large increases in voltage and current distortion. A number of studies have been carried out to investigate this concern (Blanco et al., 2013; Rönnberg et al., 2010, 2012), among others, with the main conclusion being that the increase is minor even in the worst case and in some cases the aggregation effects introduced by the lamps has led to a decrease in harmonic levels. After replacing 576 incandescent lamps with a combination of compact fluorescent and LED lamps in a hotel in Sweden, a slight increase could be observed for some individual harmonics in some phases while there was a decrease in other phases (Rönnberg et al., 2010). Similar observations were made when incandescent lamps were replaced at 12 semidetached houses (Rönnberg et al., 2012). The impact from other devices cannot be ignored and even though the lamps add harmonics, the effect will, due to aggregation, not result in an overall increase in harmonic magnitude for the installation.

An overview of both simulations and measurements is presented in (USAID, 2010) where it is concluded that the simulations generally predict a higher increase in distortion due to replacement of incandescent lamps by CFL than shown by measurements.

Measurements have, on the other hand, shown that most high-efficiency fluorescent lamps and many types of LED lamps are a source of supraharmonics (Blanco et al., 2013; Larsson et al., 2010; Martínez and Pavas, 2015). The measured magnitudes are in most cases low but this is a type of device, using a diversity of technologies, which will likely be connected in large numbers.

3.2. Changes in immunity

Compact fluorescent and LED lamps are less sensitive than incandescent lamps to steady-state overvoltages. The impact of other disturbances on life length of modern lamps is not very well studied. An additional temperature rise of components in lamps has been observed during high levels of supraharmonic voltage

	Emission	Immunity	Transfer
Voltage dips			
Voltage swells			
Harmonics			
Supraharmonics			
Interharmonics			
Slow voltage variations			
Fast voltage variations			
Voltage unbalance			
Transients			
Frequency variations			
DC components			

Fig. 1. Template for evaluation the impact of different changes on emission, immunity and transfer for 11 different types of voltage disturbances.

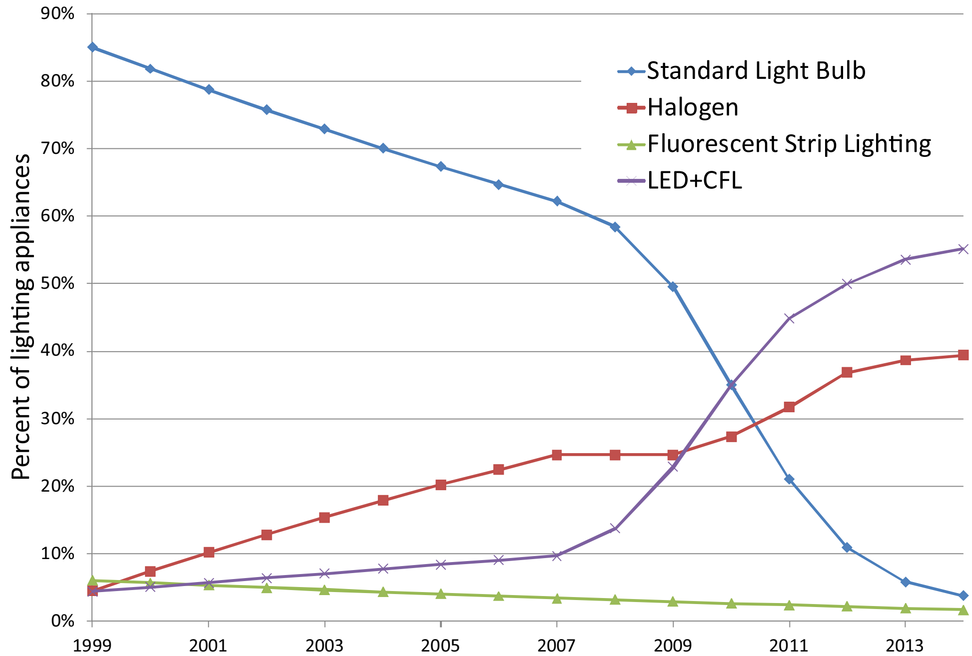

Fig. 2. Replacement of incandescent lamps by other types of lighting in the UK, 1999–2014 (UK Department of Energy and Climate Change, 2015).

(Meyer et al., 2013). It has also been shown that the functionality of the dimming function can be impacted by high levels of voltage distortion at higher frequencies (Pikkarainen et al., 2012). The large diversity in driver technology insures that no general conclusions can be drawn from this yet, but the subject certainly is worth further investigation.

Most compact fluorescent and LED lamps show less flicker than incandescent lamps, but some modern lamps are more sensitive than the classical ones. A higher sensitivity of LED lamps compared to the classical incandescent ones against rectangular voltage changes (contrary to sinusoidal ones) has also been observed by (Chmielowiec, 2011). Different studies in the recent literature have demonstrated the sensitivity of CFLs and LED lamps to interharmonics in terms of light flicker (Frater and Watson, 2007; Drapela and Taman, 2007; Kim et al., 2008; Slezingr et al., 2012; CIGRE WG C4.111, 2016; IEEE, 2016; Gallo et al., 2008) As a result, it is already clear that the existing flickermeter is not able to predict the impact of voltage fluctuations on lamps (Gallo et al., 2008) thus requiring alternative solutions (Lehman et al., 2011; Slezingr and Drapela, 2013).

An overview of the impacts of the new types of lighting on the probability of interference is shown in Fig. 3. In the figure, the minus sign indicates deterioration (an increase in probability of interference: an increase in emission, a reduction in immunity, or an increase in transfer). The plus sign indicates improvement; the letter “A” indicates that something is very much “on the agenda”,

	Emission	Immunity	Transfer
Voltage dips			
Voltage swells			
Harmonics	? A		
Supraharmonics	--	--	
Interharmonics		--	
Slow voltage variations		++	
Fast voltage variations		??	
Voltage unbalance			
Transients		-?	
Frequency variations			
DC components			

Fig. 3. Changes in emission, immunity and transfer of power-quality disturbances due to the introduction of new types of lighting.

e.g. in international working groups. The question mark indicates that the impact is not known or that the opinions are divided. An empty box means that no impact is expected.

4. New production units

There is a change taking place or expected in many countries, from large dispatchable production units to small units and/or renewable sources with intermittent availability. This shift will have an impact on several power quality phenomena; in some cases degradation is expected and in other cases the introduction of new types of production units will improve power quality.

4.1. Changes in emission

The presence of distributed generation will result in fewer and shallower dips especially due to single-phase faults (for dips due to faults upstream of the generator and the customer downstream) (Bollen and Häger, 2005) but may require additional steps in the protection coordination with slower fault clearing (longer dips) as a result (Bollen and Hassan, 2011).

Measurements with solar (Chidurala et al., 2015; Rönnberg and Bollen, 2013; Djokic et al., 2015) and wind power (Yang et al., 2014) installations show that their harmonic emission is small. But as such production units are additional equipment connected to the grid, some increase in harmonic emission may still be expected. In Fig. 4, the harmonic emission is shown for three modern wind turbines (in the 2–2.5 MW range) in comparison with the emission from an incandescent lamp. The comparison shows that the emission from modern wind turbines is, in terms of rated power, less than the emission from an incandescent lamp.

Wind and solar power installations are, however, shown to emit interharmonics (Yang et al., 2014; Yang and Bollen, 2016) and supraharmonics. Regarding supraharmonics, it is shown in (CIGRE/CIRED JWG C4.29, 2016) that the primary supraharmonic emission from small single-phase connected photovoltaic (PV) inverters (installed power below 4.6 kW) occurs at frequencies somewhere in the range between 15 kHz and 20 kHz. For three-phase connected inverters used for high-power units the switching often takes place at a lower frequency range starting at around 2 kHz (Moreno-Munoz et al., 2015; Wu et al., 2011; Rönnberg et al., 2015; Klatt et al., 2013). More recently smaller three-phase inverters have started to appear on the market with switching frequencies around 20 kHz. The magnitudes of both interharmonics and supraharmonics related to installed power are small but, unlike the harmonic emission, the impact and possible interferes due to those types of distortions are largely unknown.

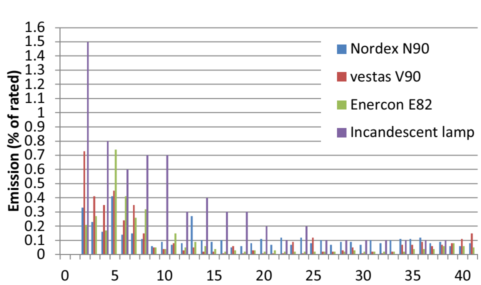

Fig. 4. Comparison of the harmonic current spectra from four wind turbines and from an incandescent lamp. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Small installations at low voltage (i.e. rooftop installations) and larger installations at higher voltage levels (i.e. solar plants) need to be treated differently with regards to supraharmonic interaction. Solar plants are often connected to high or medium voltage with few other loads connected, and any interaction will likely take place within the plant between inverters. Rooftop installations are connected at the customer site and close to other low-voltage devices. Possible interaction between the inverter and other devices is hence more likely to occur.

Voltage fluctuations, due to PV, at time scales that can produce flicker can also in most cases be neglected. However, cloud movements and multiple panels connected to the same low-voltage feeder may cause some noticeable flicker in certain situations (Lennerhag et al., 2014). Also the maximum power-point tracking technique can result in light flicker (Slezingr and Drapela, 2013; Langella et al., 2016).

Light flicker due to wind turbines was seen as a concern earlier (Saad-Saoud and Jenkins, 1999). The tower shadow effect results in some level of flicker when induction machines are used, but these have become a minor fraction of the turbines. A comparison shown in (Bollen and Hassan, 2011) concluded that the flicker level (P_{st}) due to a wind turbine was independent of the local fault level and did not exceed 0.2. The only exceptions were studies solely based on simulations. Other types of wind turbines do not show the tower-shading effect to the same extent.

Variations in wind speed and solar irradiation cause variations in production that are too slow to result in flicker but too fast to be considered in the slow voltage variations (averaging periods of 1 min or 10 min). In (Lennerhag et al., 2015) it is shown that these “very short variations” (Bollen and Gu, 2005) are expected to increase in magnitude and to change in character with massive introduction of solar power in low and medium voltage networks. An example is shown in Fig. 5. Further studies are needed in this range of time scales.

Single-phase production units, mainly PV, will increase both negative-sequence and zero-sequence voltage unbalance in the low-voltage network. The lack of diversity between the panels contributes to the concern that this could lead to an increase in unbalance (Bollen and Hassan, 2011). A reduction in the maximum size allowed for single-phase inverters combined with control of which phase the PV inverters are connected is recommended when the risk of high voltage unbalance is deemed unacceptably high (Schwanz et al., 2016). The results of a stochastic study with single-phase PV in a rural low-voltage network are shown in Fig. 6. The difference between European and North American networks should be considered regarding voltage unbalance, as the connection of three-phase converters is not possible in large parts of North American distribution networks.

4.2. Changes in immunity

The mass introduction of new production, in the form of small production units, has introduced a concern with their immunity for network operators. The impact of massive tripping of production units after a dip originating in the transmission system is a concern for system stability. A study was undertaken to determine inverter trip behavior as a function of voltage dip depth, duration, start point on wave, power generation of the inverter, and grid voltage (Iyoda et al., 2010). In (Mohseni et al., 2011) is shown that the analyzed PV inverter is very sensitive to the phase-angle jump associated with a voltage dip. The same is shown for a doubly fed induction generator (DFIG)-based wind turbine in (Bollen et al., 2006). Requirements on voltage-dip immunity (“fault-ride-through” or “low-voltage ride-through”) for production units are set in local grid codes and/or connection agreements. The requirements vary between network operators and countries,

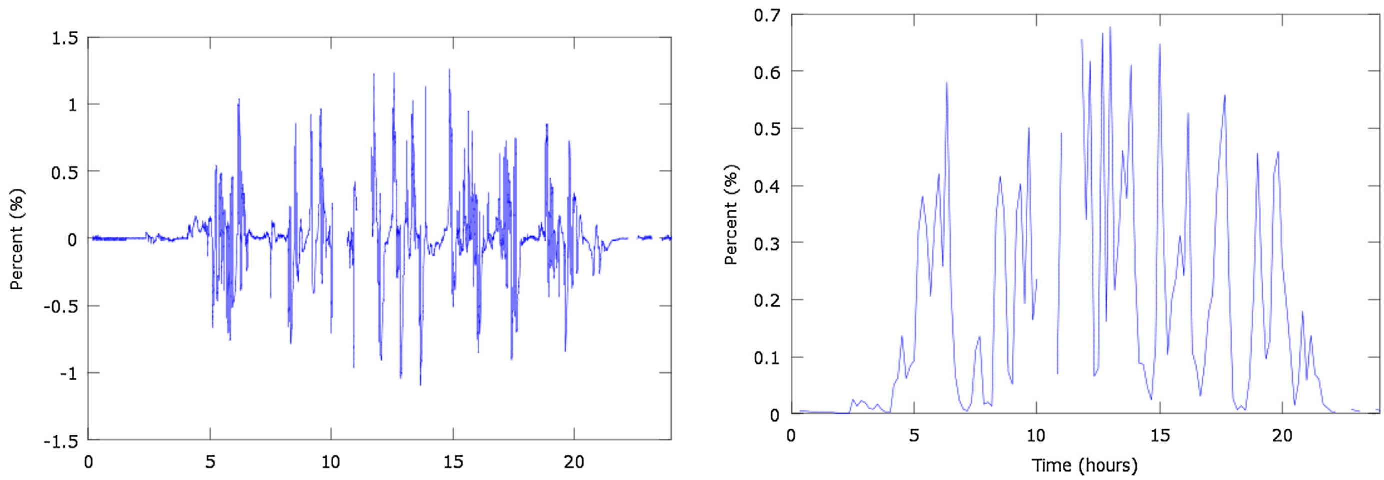

Fig. 5. 3-s (left) and 10-min (right) VSV-levels for a single PV unit during a day with partial cloud coverage (Lennerhag et al., 2014; Lennerhag et al., 2015).

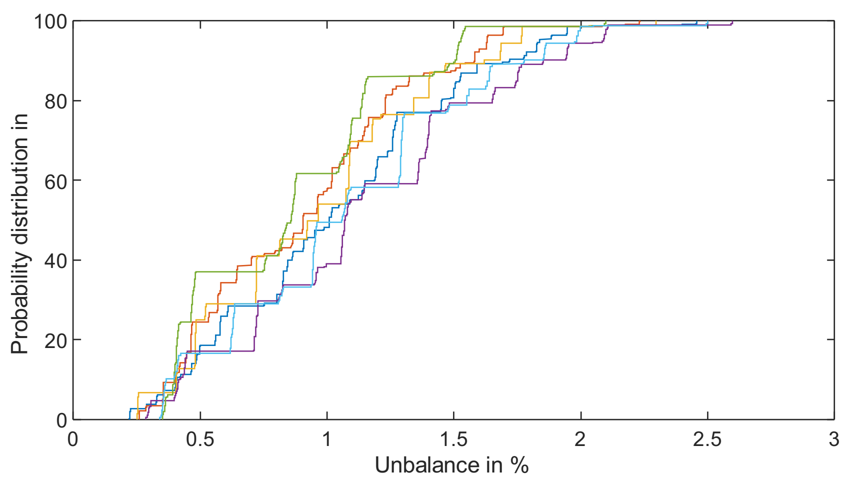

Fig. 6. Probability distribution function of the voltage unbalance for 5 inverters at random busses and phases in a 6-customer network; the different colors refer to different customers (Schwanz et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

but most of them only consider magnitude and duration of the dip. It is unknown to which extent immunity requirements including only magnitude and duration give a guarantee against massive tripping of production units.

4.3. Changes in transfer

The replacement of conventional production by other types of production changes the source impedance at the original location of the production unit. The change in transfer impedance depends on the type of disturbance and on what has replaced the conventional production unit.

The shift to new sources of generation using existing technology, i.e. those that do not give active voltage support to the grid, will result in a general weakening of the transmission grid. This was used in (Bollen et al., 2006) to show an increase in the number of dips in the transmission grid when 20% of energy is supplied by wind power. The same effect is shown in (Altschäffl and Witzmann, 2015). Weakening of the transmission grid will result in lower resonant frequencies. However, this does not necessarily result in an increase in harmonic levels. The transfer increases for lower frequencies but it decreases for higher frequencies. Weakening of the grid may actually improve the distortion levels for higher frequencies, but it will deteriorate the situation for lower frequencies (Bollen and Hassan, 2011).

The weakening of the transmission grid will also result in a further spread of fast voltage variations due to fluctuating loads and unbalance due to large single-phase installations like electrified railways.

An overview of the impact of new production units on the probability of interference is shown in Fig. 7.

5. Power electronics interfaces

The number of electronic devices connected to the grid has increased a lot during the last decades, as shown in Fig. 8.

5.1. Changes in emission

The use of more advanced power-electronic interfaces (using active switching instead of passive diode rectifiers) results in a current waveform with low harmonic content. Most of the new equipment connected to the grid will be equipped with such an active interface. A study on harmonics from electric vehicle

	Emission	Immunity	Transfer
Voltage dips		A	--
Voltage swells		(A)	
Harmonics	?		-/+
Supraharmonics	--		
Interharmonics	--		-/+
Slow voltage variations	--		
Fast voltage variations			--
Voltage unbalance	--		--
Transients			--
Frequency variations	--	A	
DC components	?		

Fig. 7. Impact of new production units, like renewable electricity production, on the emission, immunity and transfer for 11 different types of power-quality disturbances.

chargers (Lepka et al., 2015) concluded that their harmonic emission is small. Also, existing types of equipment (like televisions and computers) is likely to have an active front end in the future. In (Larsson et al., 2009) the trend of harmonics from computers has been investigated during the years 2002–2008. The measurements show a clear trend of decreasing levels of harmonics (in relation to the fundamental component) from computers.

With active power-electronic circuits finding their way to equipment, the impact of the background voltage distortion on the emission becomes more complicated and emission can increase as well as decrease with increasing voltage distortion (Blanco et al., 2015; Carbone, 2004) whereas it would decrease with non-active equipment interface.

The terms "primary emission" and "secondary emission" have been introduced to describe this (Rönnberg et al., 2011a), where primary emission originates in the device under study and secondary emission originates elsewhere. The terms are further explained in (Bollen and Rönnberg, 2016), where the term "interaction" is used to refer to non-linear phenomena.

5.2. Changes in immunity

There is a range of different grid interfaces in use for low-voltage equipment, with different configurations, control strategies, etc. This is also expected to lead to different immunity to power-quality disturbances. The immunity may be better or worse that for classical equipment, but describing and quantifying the immunity will certainly become more complex and less predictable.

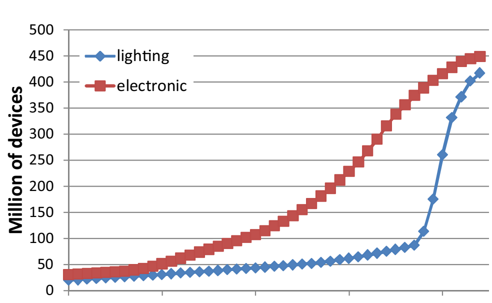

Fig. 8. Growth in the number of electronically-based lamps (blue) and the number of other electronic devices (red) UK households (UK Department of Energy and Climate Change, 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. Changes in transfer

Replacement of non-electronic loads by electronic loads removes part of the damping at resonant frequencies. Most power-electronic equipment with active interface also adds capacitance to the low-voltage network. Both impact the transfer of certain disturbances through the low-voltage grid.

As there are no available comparative network impedance measurements that could quantify the reduction of damping due to changing types of equipment, simulation results can be used as a reference, as presented in (Langella and Testa, 2016; Ćuk et al., 2012; Barakou et al., 2016). The potential impact on the transmission grid of the change in damping and capacitance with low-voltage equipment is shown in Fig. 9 (Barakou et al., 2016). Interpretation of the results from natural events is difficult and no clear conclusions can be drawn from such studies yet (Ribeiro et al., 2011).

A recent measurement of network harmonic impedance in a low-voltage network with about 400 customers found an average capacitance of about 12 μF per household (Hauptmann, 2015). Not only consumer equipment but also PV installations are capacitive at harmonic frequencies. According to (Enslin and Heskes, 2003), the capacitance of a PV inverter is between 0.5 and 10 μF and for a domestic customer (without PV) between 0.6 and 6 μF. Both the series resonance seen from the upstream medium voltage network as well as the parallel resonance seen from the low-voltage grid will be impacted by the additional capacitance. An estimation of the reduction in resonant frequency for a low-voltage network with 220 customers is shown in Fig. 10. The figures shows resonant frequencies below harmonics 15 are to be expected in a low-voltage network even without PV. Resonant frequencies as low as harmonic 7 are possible for networks with PV.

An overview of the impact of active interfaces on the probability of interference is given in Fig. 11.

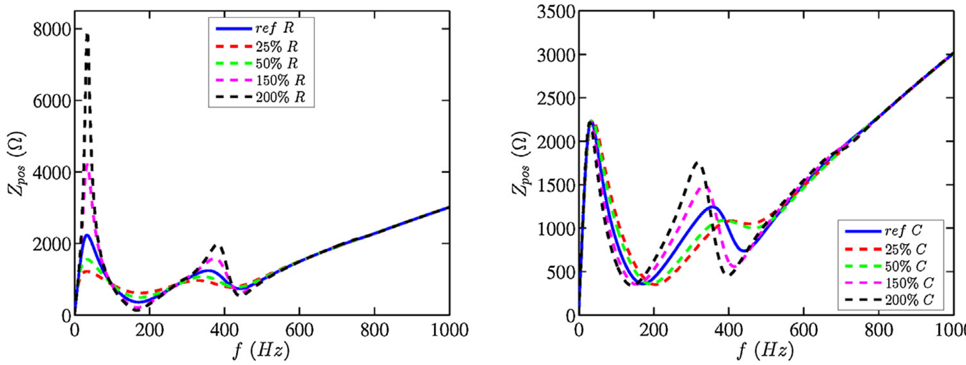

Fig. 9. Impact of resistance (left) and capacitance (right) of domestic customers on the impedance of the load as seen from the transmission system (Barakou et al., 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

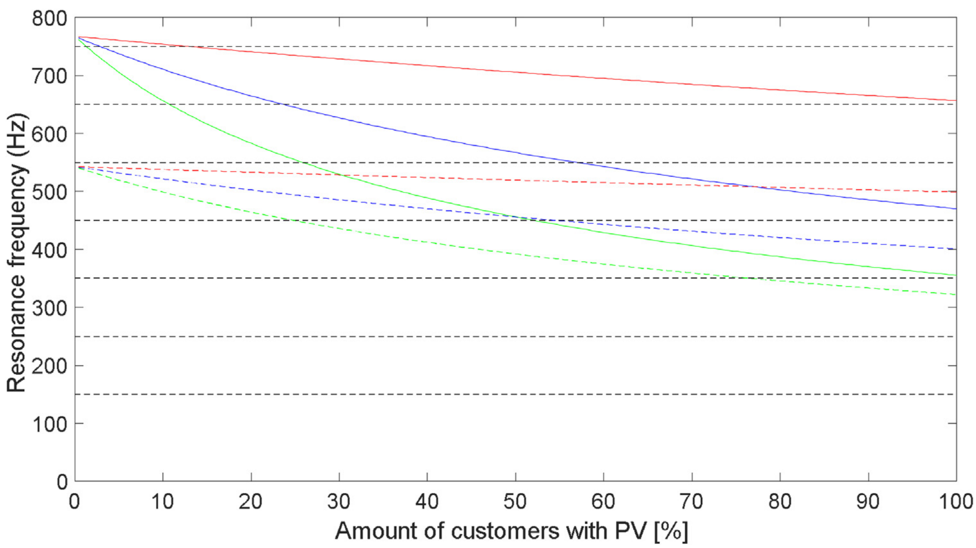

Fig. 10. Resonant frequency of a low-voltage network as a function of the fraction of customers with PV; 2.2 (red); 10 (blue) and 22 (green) μF/PV; 6 (solid) and 12 (dashed) μF/customer. The horizontal dashed lines indicate the low-order odd harmonic frequencies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

	Emission	Immunity	Transfer
Voltage dips	++	?	
Voltage swells		?	
Harmonics	++	?	--
Supraharmonics	--	?	
Interharmonics	-- (?)	?	--
Slow voltage variations		?	
Fast voltage variations		?	
Voltage unbalance		?	
Transients		?	--
Frequency variations		?	
DC components	--	?	

Fig. 11. Impact of the large-scale shift to active electronic interfaces on emission, immunity and transfer for 11 different types of power-quality disturbances.

	Emission	Immunity	Transfer
Voltage dips	++		
Voltage swells	++		
Harmonics			--
Supraharmonics			
Interharmonics			--
Slow voltage variations			
Fast voltage variations			
Voltage unbalance			
Transients	++		--
Frequency variations			
DC components			

Fig. 12. Impact of the shift from overhead lines to cables on emission, immunity and transfer for 11 different types of power-quality disturbances.

6. From overhead lines to cables

The replacement of overhead lines by cables will add more shunt capacitance to the grid, with a lowering of the resonant frequency as a result. This holds true especially for transmission cables, where resonant frequencies below 150 Hz have been reported (Wiechowski and Eriksen, 2016). The lower resonant frequencies will result in higher harmonic voltage levels for lower-order harmonics (Wiechowski and Eriksen, 2016; Bollen et al., 2014; Wu, 2014; Bollen et al., 2015; Jansen et al., 2015). The transfer for higher-order harmonics may however become less when the resonance shifts to lower frequencies.

The shift of resonant frequencies to lower values could result in strong amplification of harmonic orders 5 and 7. The consequences

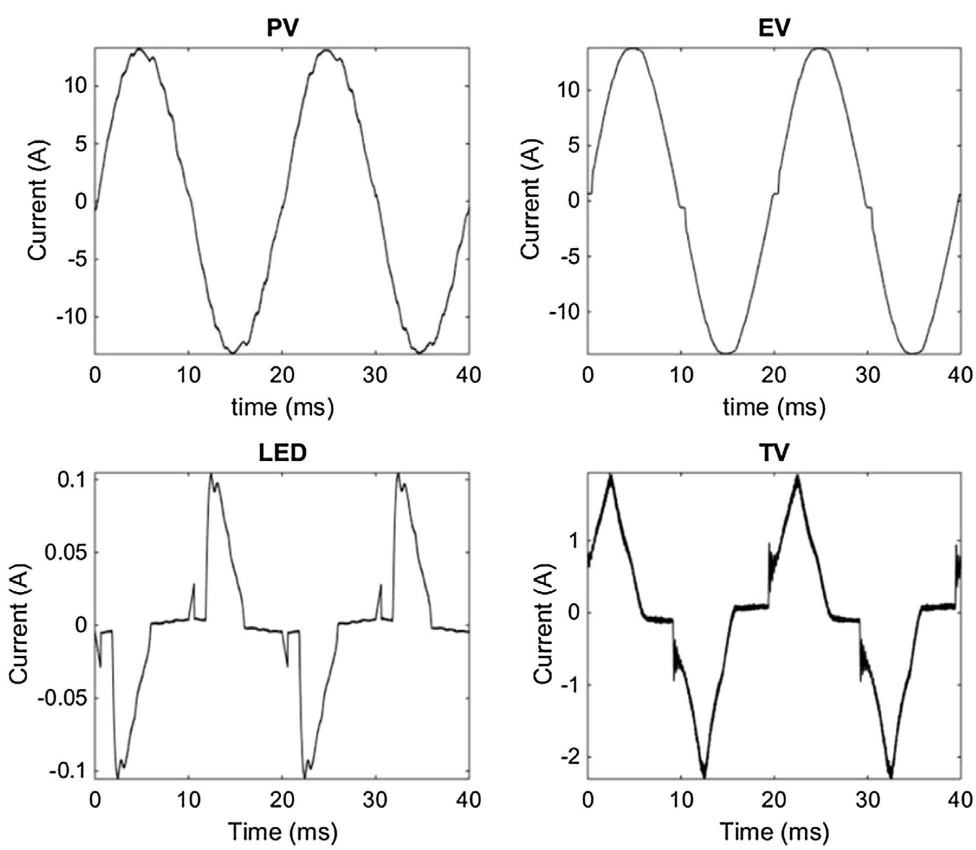

Fig. 13. Current drawn by four different household devices, shown in time domain: Photovoltaic inverter (top left), Electric vehicle charger (top right), LED lamp (bottom left) and an LCD TV (bottom right). Note the difference in vertical scale.

of this remain unclear; particularly, the damping is not well mapped at transmission levels. Even larger amounts of AC cables could result in resonances close to harmonic order 2 or 3. The transfer of harmonics could become significantly impacted by non-linear phenomena like the core saturation (magnetizing current) of transformers or the interaction between HVDC converters and transformers.

An important reason for the replacement of overhead lines by cables is that the latter are less prone to weather impacts. The shift from lines to cables will give a reduction of the number of voltage dips due to faults at the distribution level. The number of dips due to faults at the transmission level will not be impacted, as cables will still be orders of magnitude less in total length than overhead transmission lines.

A significant reduction is expected in the number of swells due to earth faults in low- and medium-voltage networks. The zero-sequence impedance of cables is less than of overhead lines, which gives a lesser overvoltage. Also, the number of faults will be significantly less for underground cables than for overhead lines; swell will thus be less common and less severe.

An overview of the impact of this replacement on the probability of interference is given in Fig. 12.

7. Supraharmonics

An important conclusion from the review presented in the previous section is that the emission of supraharmonics will increase in the future electric power system. In this section, we will therefore give a brief overview of the existing knowledge on emission, immunity, and transfer for supraharmonics

7.1. Emission

Active power-electronics use switching frequencies starting above 1 kHz. This results in the emission at frequencies above the classical harmonic range. Emission from equipment in this frequency range is shown, among others, in (Rönnberg et al., 2008; Larsson and Bollen, 2010; Rönnberg, 2011; Schöttke et al., 2014). Measurements of supraharmonic emissions from PV inverters are presented in (Rönnberg et al., 2014). Wind power is also expected to contribute emissions in this frequency range, but very limited measurements are available on this. Some of the measurements presented in (Yang, 2015) show the presence of significant emission from wind turbines at frequencies above 2 kHz. The number of papers presenting studies of emissions in this frequency range is increasing rapidly. Some examples of devices that have been found to emit supraharmonics are:

- Industrial-size converters (9–150 kHz)
- Oscillations around commutation notches (up to 10 kHz)
- Street lamps (up to 20 kHz)
- EV chargers (15–100 kHz)
- PV inverters (4–20 kHz)
- Household devices (2–150 kHz)
- Power line communication for automated meter reading (9–95 kHz).

The two main sources of supraharmonics that have been identified are power-electronic converters with active or passive switching (non-intentional emission) and transmitters of power-line communication (intentional emission). With the

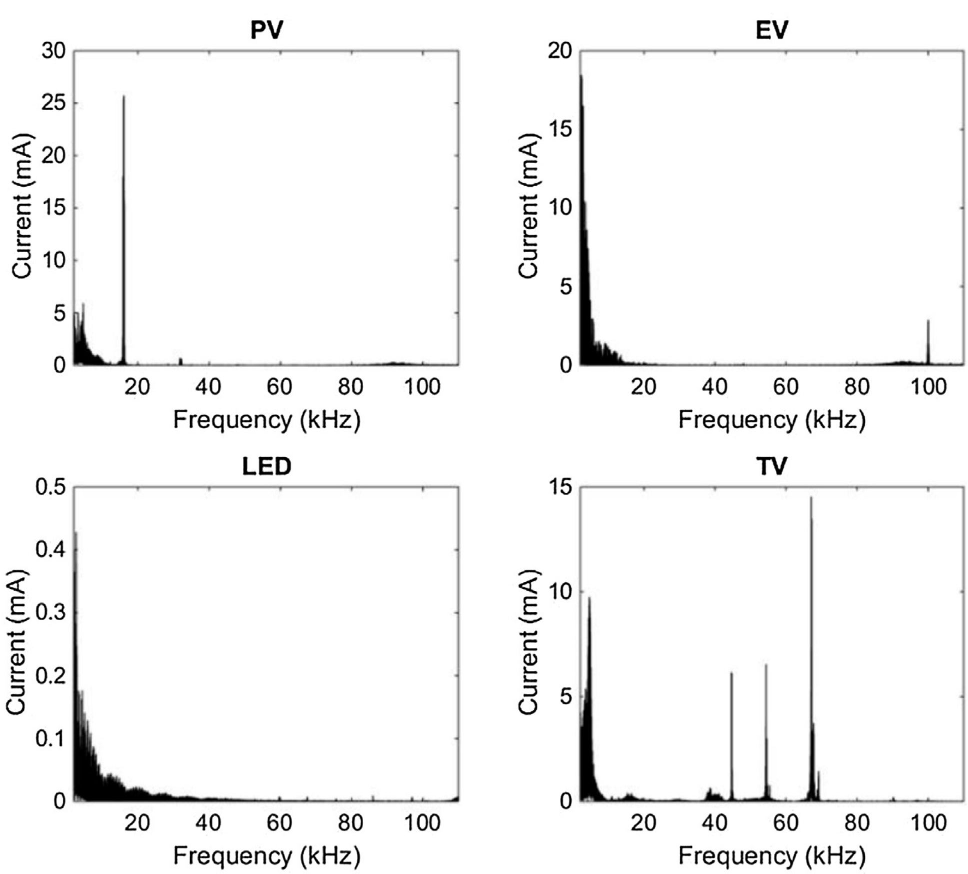

Fig. 14. Current drawn by four different household devices, shown in frequency domain: Photovoltaic inverter (top left), Electric vehicle charger (top right), LED lamp (bottom left) and an LCD TV (bottom right) shown in the frequency domain. Note the difference in vertical scale.

introduction of self-commutated valves, emissions have shifted from harmonic to supraharmonic frequencies. Products have been designed for satisfying emission limits at harmonic frequencies but instead having increased emissions at higher frequencies.

In Figs. 13–15, some examples are shown of the emissions of household devices in the time domain (Fig. 13), frequency domain (Fig. 14) and time-frequency domain (Fig. 15). It should however be emphasized that these are just examples; there are, for instance, LED lamps with completely different emissions patterns (Ćuk et al., 2010; Uddin et al., 2012; Rönnberg and Bollen, 2012) and the same holds for other types of devices.

7.2. Immunity

The immunity of equipment against supraharmonics is an important aspect to study. It will among others determine where the balance should be between requirements on emissions and requirements on immunity.

Measurements have shown that connected devices will interact with each other in several ways; the full consequence of this interaction is still not understood. Five types of interaction between power line communication and end-used equipment were identified in (Rönnberg et al., 2011b) that illustrate the complexity of the interaction. Three types out of the five directly apply to any kind of interaction (i.e. they are not specific to interaction between a communication device and any other device)

- A voltage signal results in large currents through a device. This can result in overheating of components or other interference with the functioning of the device.
- Non-linear devices exposed to a voltage at a supraharmonic frequency results in currents at other frequencies, typically at integer multiples of the original frequency.
- Distortion of the voltage waveform feeding a device results directly in mal-operation of the device.

Several incidents of equipment malfunctioning or behaving in unwanted ways due to the presence of supraharmonics have been reported (SC 205A Mains Communicating Systems TF EMI, 2013; CLC/TR, 2015). Examples include clocks running too fast, hair dryers turning on by themselves, and flickering lights. In addition, a device subjected to frequencies below 20 kHz (i.e. in the audible range) can produce audible noise due to stimulation of a mechanical resonance. Animals are able to hear higher frequencies than humans and could therefore be impacted by supraharmonics at even higher frequencies.

The main components that are expected to be damaged by supraharmonic currents, driven by supraharmonic voltages, are the electrolyte capacitors commonly used in EMC-filters and as smoothing capacitors connected after a diode rectifier (Rönnberg, 2011). Currents of any frequency will contribute to the heating of this capacitor. Overheating of an electrolyte capacitor will reduce its life expectancy. As the capacitor reaches the end of its lifetime, the equivalent series resistance (ESR) of the capacitor will start to increase and as a consequence also the output ripple voltage (Lenk, 2016). This could lead to complete failure of the capacitor and

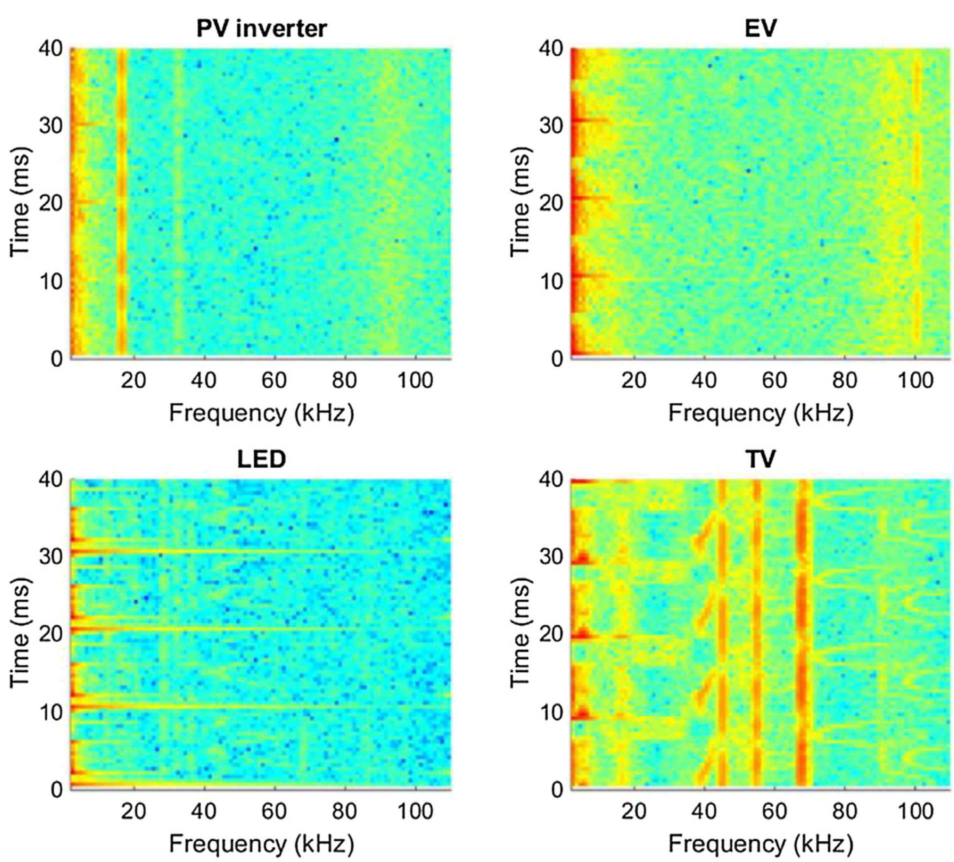

Fig. 15. Current drawn by four different household devices, shown in time-frequency domain: Photovoltaic inverter (top left), Electric vehicle charger (top right), LED lamp (bottom left) and an LCD TV (bottom right).

possible damage to other components. The function of a device will often not be affected if the EMC filter fails. The result will simply be that the emission at unwanted frequencies increases.

Several studies also indicate that high levels of supraharmonic voltages at higher voltage levels could result in insulation failures in cables (Paulsson et al., 2003; Sonerud et al., 2009). A well-published and −studied example is the failure of cable terminals after the connection of a VSC HVDC installation (Paulsson et al., 2003). The failures occurred in compact type cable terminations, rated at 24 kV, with resistive/refractive stress grading. The problem was resolved by installing another type of cable termination, generally called the "geometric type," whose insulation characteristic is expected not to be dependent on frequency. Additionally, various power system components have higher losses (e.g. conduction losses due to the skin effect, eddy current losses in ferrite cores, etc.) for higher frequencies, which can cause overheating and accelerated aging.

7.3. Transfer

The transfer of supraharmonics from one device to another device (i.e. the elements in the transfer-impedance matrix) depends on the impedance in the wiring connecting devices and on the impedance of those devices. For small low-voltage installations (i.e. inside of a building) series inductance and resistance are what matters; for large installations and at higher voltage levels, the series capacitance will also play a role. Whereas the wiring of the grid can be considered linear impedances, this is not always the case for devices connected to the grid. Connected devices can be classified into three main types:

- Type I: devices whose impedance is a function of frequency but that can be seen as constant impedance over the duration of one cycle of the fundamental frequency. This includes devices equipped with EMC-filters of LCL-type or CLC-type (e.g. computers or television sets). The impedance of these devices will hence vary with frequency but not with time (at least not on a time scale of one cycle of fundamental frequency).
- Type II: devices whose impedance varies with time over one cycle of the fundamental frequency. This includes devices equipped with a diode rectifier (e.g. LED lamps) (Rönnberg, 2011). The impedance of devices of type II will vary with frequency and time (on a time scale of one cycle of fundamental frequency). The instance of the transition from high impedance to low impedance corresponds to the instant at which the diodes start to conduct.
- Type III: purely resistive devices, whose impedance is neither dependent on time nor dependent on frequency.

The impedance of all types of devices (and thus the transfer between devices) will vary with time on a longer times scale as devices are connected and disconnected. The impedance at supraharmonic frequencies of neighboring devices is in many cases lower than the impedance of the grid. A substantial part of the emission will therefor flow between connected devices.

8. Findings and recommendations

The on-going changes in the power system have impacts on emissions, immunity as well as the transfer of disturbances. All this impacts the probability of electromagnetic interference. There is no situation where an immediate large increase in the probability of electromagnetic interference is expected. However, several changes in emissions, immunity, and transfer require further study and serious monitoring of developments; this should be an important guidance for power-quality research.

Further studies, including fundamental research, are needed for disturbances that are expected to increase because of the large-scale introduction of active power electronics: interharmonics; DC components and low-frequency subharmonics ("quasi-DC"); and components above 2 kHz ("supraharmonics"). The latter in particular is an important new research and study area.

Another observation from the review is that the amount of capacitance connected to the grid is expected to increase at all voltage levels. This will result in a shift of resonances to lower frequencies. The increased emission at higher frequencies may be (partly) compensated by the shift in resonance to lower frequencies. At the same time, however, the transfer of disturbances will become less predictable.

The immunity of new types of devices against all types of voltage disturbances requires study and may require a new approach to standardization.

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