Power system impacts of decreasing resonance frequencies

Oscar Lennerhag

Independent Insulation Group Sweden AB
417 60 Gothenburg, Sweden
oscar@i2group.se

Math H. J. Bollen

Electric Power Engineering
Luleå University of Technology
931 87 Skellefteå, Sweden
math.bollen@ltu.se

Abstract—**As the energy system is transitioning to a more sustainable one several of the related changes will affect the power system in different ways. Renewable electricity sources, energy efficiency measures and increased operational flexibility lead to more serious resonances in the electricity network and an increased uncertainty in terms of frequency and damping of those resonances. This could have a large impact on the spread of harmonics and on temporary overvoltages. In this paper, some examples of changes in the grid are presented and their impact on the spread of harmonics and temporary overvoltages, as a consequence of changes in resonances, is discussed.**

Index Terms—**Electric Power Transmission, Power System Transients, Power System Harmonics, Insulation coordination, Power quality.**

I. Introduction

The electric power system is experiencing a number of changes as part of the transition to a more sustainable energy system. This includes a large-scale integration of renewable energy sources, changes in load composition (e.g. due to a switch to energy-saving appliances) and changes in the grid itself, such as replacement of overhead lines by underground cables. These changes impact the power system in several ways, e.g. with regards to the power quality, as discussed in [1] and [2]. Both papers mention, as a consequence of several of the changes, a reduction in resonance frequencies at all voltage levels, from low voltage to transmission.

The qualitative impact on resonance frequencies is rather well understood, as described in [1], [2] and other publications. The quantitative impacts are much less well studied however. In this paper the impact of the shift in resonance frequencies on overvoltages and the spread of harmonics will be discussed in more detail.

In Section II, the aforementioned changes and their impact on resonances in the grid are discussed. Section III and IV discuss the impact of the changes in resonances on the spread of harmonics and overvoltages, respectively. Section V presents conclusions and general considerations.

II. Changes in the grid

A. Replacement of overhead lines with cables

There are several reasons for replacing overhead lines with cables. Cables are less susceptible to outages related to adverse weather conditions. They may be the only option in densely populated areas where it may not be possible, or take too long time, to build overhead lines. As an example, the Danish TSO (Energinet.dk) plans to install cables in selected parts of the network, and the Dutch TSO (TenneT) is extending its 380 kV grid with underground cables to increase the capacity. In Sweden, the Swedish TSO (Svenska kraftnät) is planning to install cables at 400 kV and 220 kV in Stockholm in order to increase the security of supply and to meet future capacity demands. Another area where cables are predominately used is for connection of windfarms, especially for off-shore windfarms, but also increasingly for on-shore farms.

As overhead lines are replaced by cables more shunt capacitance is added to the grid, one consequence being a lowering of the resonance frequency. The impact of cables on the resonance frequency is investigated in [3], where it was deemed technically unacceptable to install a 10 km 400 kV cable circuit due to the resulting resonance frequency being too low. Another example is presented in [4], where the harmonic impedance for a wind farm connection is studied. It was found that the cable circuit was the dominating factor, with a resulting resonance frequency of 140 Hz. In [5], the authors investigate the influence of long EHV cables on resonances in the Dutch transmission system. It was concluded that the inclusion of cables in the case study increased the risk for resonances. More examples can be found e.g. in [6]-[8].

In order to get a first indication of the risk for low order resonances, the following expression can be used, where *L* is the inductive part of the source impedance and *C* is the total cable capacitance:

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

While such simplified expressions may not be accurate enough for studies on overvoltages or assessment of distortion

levels, they can be used as a first step to determine if there is a need for more detailed studies [7], [8].

As an example, consider a grid with the following parameters:

- S_{sc} = 7000 MVA; Short circuit power

- U_n = 400 kV; Rated voltage of the system

- c = 0.15 µF/km; Cable capacitance per km

- l = 10 km; Total length of connected cables

The resulting resonance frequency for this system would be 482 Hz. Table I shows the change in resonance frequency as the cable length increases.

TABLE I.   RESONANCE FREQUENCY VS CABLE LENGTH

Length	10 km	25 km	50 km	75 km	100 km
f_{res}	482 Hz	305 Hz	215 Hz	176 Hz	152 Hz

A move towards underground cables also presents operational challenges, including the need for reactive compensation. HVAC cables generate large amounts of reactive power (as an example, a 400 kV cable with parameters as shown above would generate 7-8 MVAr/km), making reactive power compensation a necessity for long cables. If a compensation rate of 100% is used the cable will not affect the reactive balance of the system it is connected to, but lower compensation rates are often used in practice [9].

One risk associated with high degrees of compensation is the so called "Zero Miss" phenomenon [10], [11]. Zero Miss can be explained using a simplified circuit such as the one shown in Fig. 1, which shows a cable (represented by capacitance C) being energized together with a compensating shunt reactor (represented by inductance L and resistance R).
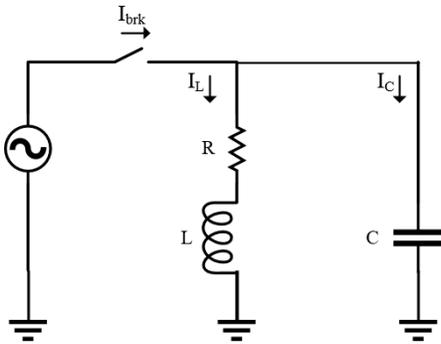

Figure. 1. Example circuit showing the energization of a compensated cable

When a capacitance is energized together with an inductance, the resulting ac currents (I_C and I_L) will be in phase opposition, thereby reducing the total ac current through the circuit breaker (I_{brk}). Depending on the voltage at the switching instant I_L may also contain a dc-component, and due to this the total current through the breaker may not cross zero for several seconds. If a fault occurs shortly after energization it is not possible to open the breaker without risk of damage. However,

since the dc component is limited by the size of the inductor, there is no risk for Zero Miss as long as the compensation rate is below 50%. An example of the resulting currents for a compensation rate of 100% and 50% is shown in Fig. 2.
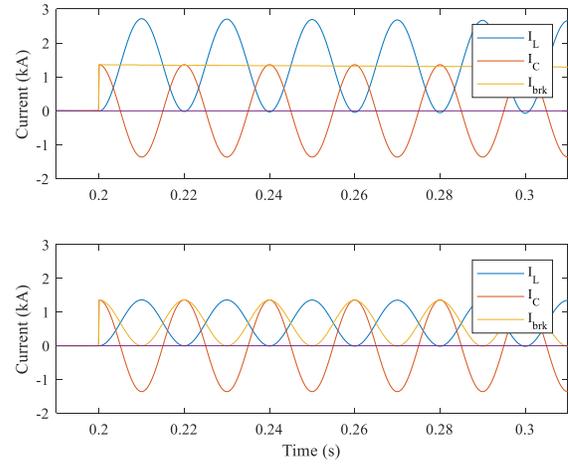

Figure. 2. Example of Zero Miss phenomenon, 100% (top) and 50% (bottom) compensation

There are several ways to mitigate the effect of Zero Miss, such as synchronized switching and the use of pre-insertion resistors [10]-[12].

B. Replacement of conventional generation with renewable energy sources

New sources of generation typically provide less short-circuit power to the transmission grid. Because of this, a large-scale replacement of traditional production units with renewable energy sources will lead to a general weakening of the transmission grid, one consequence being lower resonance frequencies [1].

Fig. 3 shows an example of how the resonance frequencies as seen from a 400 kV bus in a system with a large amount of underground cables are affected following a weakening of the grid. In this case, an overhead line connecting a large powerplant was disconnected and the short-circuit power was reduced from around 8 GVA to 6 GVA.
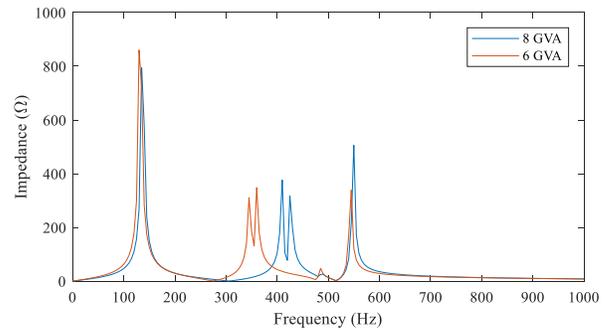

Figure. 3. Impedance and frequency for the case with 8 and 6 GVA, respectively

As can be seen from the figure, the reduction in short-circuit power leads to a reduction in resonance frequencies, with a shift in the first resonance from 138 Hz to 130 Hz. In this case, the main change is in the second resonance peak, shifting from around 450 Hz to around 350 Hz, with a possible amplification of the 7th harmonic as a result.

A large-scale integration of wind power will result in additional capacitance e.g. due to the capacitor banks used for power-factor correction or the medium-voltage cables used in the collection grid [4], [13]. Power electronics based distributed energy resources also have a capacitive element (e.g. due to grid side filters), which will affect resonance frequencies [14].

C. Changes in load composition

PV inverters and appliances equipped with power electronics add capacitance to the low voltage network (e.g. due to grid side filters), resulting in a shift in resonance frequency [15]. The same is true for new types of lighting [1], [2].

Aside from changes in the resonance frequency, the replacement of non-electronic (resistive) loads by electronic loads will also reduce the damping at resonance frequencies. However, the damping is generally difficult to assess and as there are no comparative measurements of the network impedance that can be used to indicate the change in damping, simulations have to be used instead [16].

In [17], the impact of different components in the downstream network on the harmonic impedance as seen from the high voltage side of a 220/70 kV transformer is investigated. It was found that the 70 kV cables were the dominating factor with regards to the harmonic impedance, but also that the increasing use of capacitors in LV equipment may have an impact, and should therefore be considered. It should be noted that this case study focused on the modelling of the downstream network (70 kV and below), but in practice, more cables at sub-transmission level will also impact the impedance as seen from transmission level.

In [18] the authors investigate the effect of parameters of the downstream network and model simplifications when studying switching transients in an EHV (380 kV) network. When studying overvoltages caused by switching transients the impedance around the oscillation frequency is of great importance since it determines the amplification, and thus the resulting overvoltages. Any uncertainty regarding the resonance frequency will impact the results. Equivalent models and other simplifications are compared with a detailed model of the downstream network, and it was concluded that for this case study, parameters of the end customer loads have only a minor effect on the switching transients at transmission level, compared to the modelling of the 150 kV network.

III.   IMPACT ON THE SPREAD OF HARMONICS

Following a decrease in resonance frequencies there is a risk of amplification of lower-order harmonics. In [19] a significant amplification of background harmonics is reported following the energization of a wind farm, even if there was no active harmonic injection from the wind turbine converters at the time of measurement. The reason was determined to be the

underground cable used for the connection shifting the resonance frequencies towards the 7th order harmonic.

Another example is shown in Fig. 4, which shows the 7th harmonic voltage and current (expressed as a percentage of the fundamental) following the connection of a downstream capacitor bank in an industrial installation. The capacitor bank is switched on shortly after 2008-02-29, after which a clear increase can be seen in the harmonic voltage and current. The switching of the capacitor bank can be seen from the reactive power in the upper curve; when reactive power consumption is low, the capacitor bank is connected and the 7th harmonic is high.
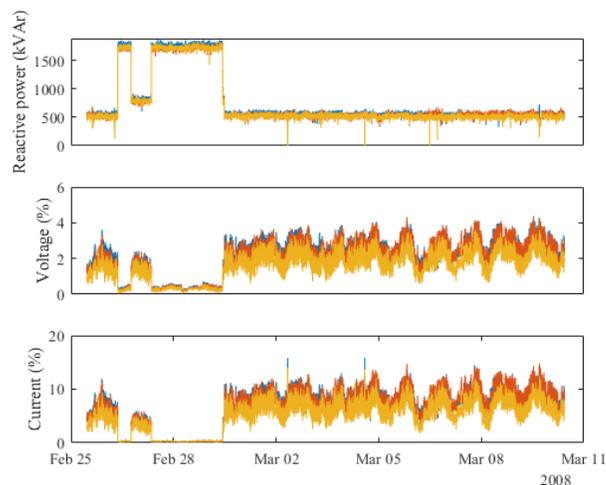

Figure. 4. Reactive power (top), 7th harmonic voltage (middle) and 7th harmonic current (bottom) following the connection of a capacitor bank

Fig. 5 shows the measured current through a 130/10 kV transformer before and after the switching of a capacitor connected to the 10 kV bus. Following capacitor energization, a clear increase in harmonic content can be seen in the measured current.
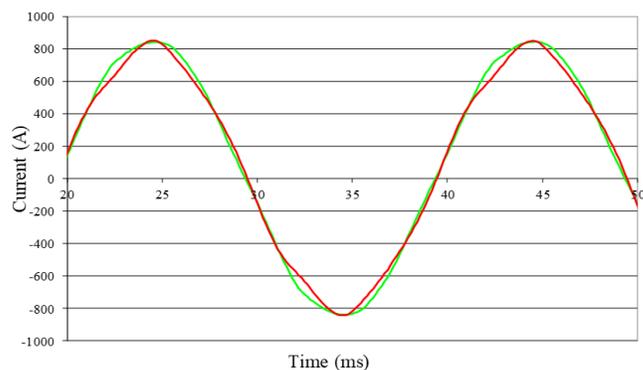

Figure. 5. Current through a 130/10 kV transformer before (green) and after (red) capacitor energization

Aside from changes in resonance frequencies, new equipment also behaves differently with regards to harmonic emission, and the emission from modern power electronics is expected to be small. However, as modern converters typically use switching frequencies above 1 kHz, the emission is

expected to increase for frequencies above the classical harmonic range [1], [2], [20]. Thus, a shift in resonances to lower orders may be counteracted by a general shift in emission to higher harmonic orders.

With regards to the impact of resonances on the spread of harmonics the following should be considered: the resonance frequency, the resistance (damping) at the resonance frequency, and the emission around the resonance frequency. If there is sufficient damping or a lack of emission, resonances are generally not a problem.

IV. IMPACT ON TEMPORARY OVERVOLTAGES

As resonances are decreasing in frequency, it is important to consider the risk of resonance-related temporary overvoltages as a part of insulation coordination studies. Temporary overvoltages are defined as having a frequency in the range of 10 – 500 Hz with duration from several seconds up to 1 hour [21]. Although the risk of temporary overvoltages can impact the selection of surge arrester rated voltage, the surge arresters are not usually used as a means of mitigation for this type of overvoltages. If protection against temporary overvoltages by arresters is desired, it leads to additional considerations with regard to arrester energy capability [22].

There are several causes for temporary overvoltages including resonances, ground faults or system islanding [12], [23]. With regard to temporary overvoltages caused by resonances, a useful distinction is between series resonances, parallel resonances and ferroresonance.

A. Parallel resonance

A parallel resonance is characterized by large impedance at the resonance frequency. If such a resonance is excited by a harmonic current source this may lead to significant voltage distortion. A typical example of a parallel resonance circuit is shown in Fig. 6, which illustrates the energization of a transformer through a cable.
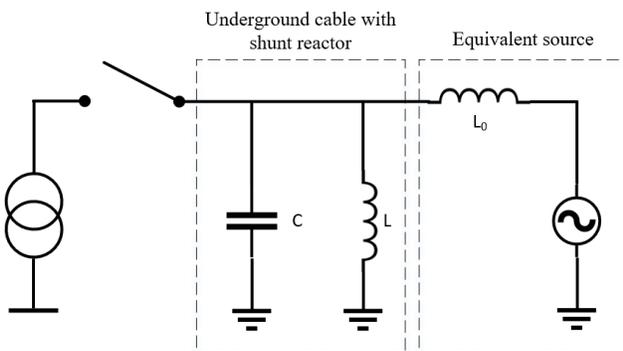

Figure. 6. Parallel resonance triggered by transformer inrush, adapted from [12]

When the transformer is energized, it will act as a source of harmonic current which may excite the parallel resonance circuit formed by the cable capacitance, the shunt reactor and the equivalent source impedance. Transformer inrush current is characterized by a high harmonic content, long duration and poor damping, and in a case of low order resonances a situation such as the one shown above may lead to sustained temporary overvoltages [12], [23]-[26].

To illustrate this, transformer energization was simulated in PSCAD/EMTDC using the system parameters described in Section II. The resonance frequency of the parallel resonance circuit can be calculated using the following expression:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} + \frac{1}{L_0 C}}$$ (2)

Based on the parameters given in Section II, and assuming a compensation rate of 100%, this will give a resonance frequency of around 160 Hz. Fig. 7 shows the corresponding frequency scan (note that the lack of damping leads to a very high impedance at the resonance frequency).
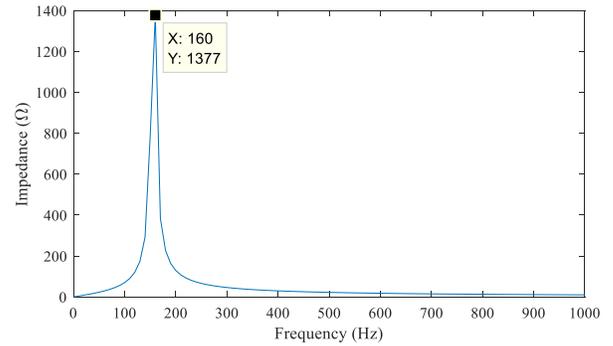

Figure. 7. Impedance versus frequency

Since the transformer energizing current contains a 3rd harmonic component there is a risk for temporary overvoltages. Fig. 8 shows the resulting voltages following transformer energization at t = 0.5 s.
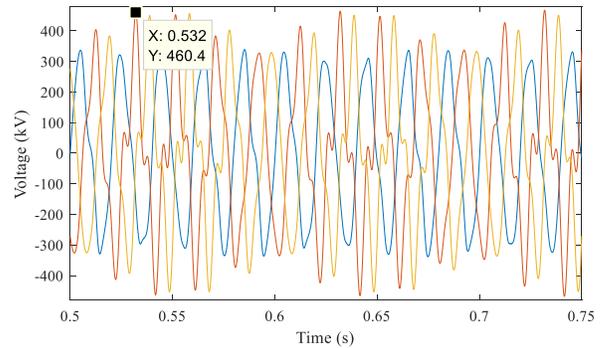

Figure. 8. Example of temporary overvoltages following transformer energization

As can be seen the voltage is heavily distorted. In this case, the maximum voltage was approximately 1.37 p.u.

B. Series resonance

A series resonance is characterized by small impedance at the resonance frequency. In case of existing voltage distortion this could lead to large harmonic currents flowing through the circuit and high harmonic voltages in the circuit. One example of a series resonance circuit is a transformer in series with a

cable, where the leakage inductance of the transformer creates a resonance circuit with the cable capacitance.

As an example, consider the circuit in Fig. 9. As the cable is energized, it will act as a harmonic voltage source that could potentially trigger the series resonance circuit formed by the transformer inductance and the cable capacitance (C_c), one possible consequence being high overvoltages on the secondary side of the transformer.
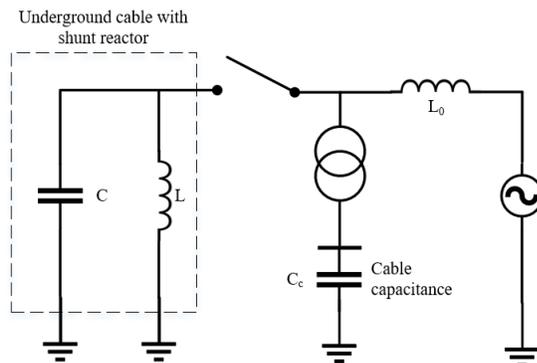

Figure. 9. Series resonance triggered by cable energization, adapted from [12]

C. Ferroresonance

Ferroresonance can be described as non-linear oscillations due to interaction between the leakage inductance of a transformer and a cable capacitance. One possible cause of ferroresonance is if one pole of a breaker is opened with the other two remaining closed. Due to mutual coupling between the phases, the open phase of the transformer will still be energized, resulting in overvoltages in all phases, the highest appearing in the open phase [12], [27].

V. CONCLUSIONS

This paper outlines a selection of future changes in the grid and their impact on power system resonances. As more capacitance is introduced to the grid, along with a general weakening of the power system due to the replacement of conventional generation sources, resonance frequencies are expected to decrease, and in some cases resonance frequencies around 100-150 Hz have been reported. This shift in resonance frequencies could have a large impact on the spread of harmonics and temporary overvoltages.

One risk associated with a decrease in resonance frequencies is amplification of low-order harmonics. However, even though resonance frequencies are expected to decrease, this may be counteracted by a shift in emission to higher orders following the introduction of new kinds of equipment with active front-ends [20]. It should be noted that the actual impact on the spread of harmonics can be difficult to determine, e.g. due to uncertainties related to modelling and aggregation of harmonic sources.

It is recommended to continuously measure harmonics in order to capture any trends in harmonic distortion that may be related to a shift in resonances.

Another concern related to low-order resonances is the risk of high temporary overvoltages following switching events such as the energization of transformers or cables.

In case of large cable projects, the impact on harmonics as well as the risk of high temporary overvoltages should be evaluated as a part of the planning process [7], [8].

Another aspect that should be considered is how the changes in the grid affect the damping, as it may have a large impact on the severity of the overvoltages and the spread of harmonics. The modelling of loads is of great importance since different load models may give vastly different results, both with regards to damping and the resonance frequency.

Changes in the grid also introduce more uncertainties e.g. with regard to operational scenarios. Small changes in parameters or other prerequisites could have a large impact on the results considering both harmonics and overvoltages. Since it is largely impractical to study each combination in a deterministic fashion, there is a need for tools that make it possible to perform studies in a stochastic manner. One such example is shown in [28].

REFERENCES

[1] S. Rönnberg and M. Bollen, "Power quality issues in the electric power system of the future," *The Electricity Journal,* vol. 29, pp. 49-61, Dec. 2016.

[2] S. Rönnberg, M. H. J. Bollen, R. Langella, F. Zavoda, J.-P. Hasler, P. Ciufo, V. Cuk and J. Meyer, "The expected impact of four major changes in the grid on the power quality – a review," *Cigre Science & Engineering,* vol. 8, pp. 5-13, Jun. 2017.

[3] N. Cunniffe, M. val Escudero, A. Mansoldo, E. Fagan, M. Norton and C. Ellis, "Investigating the Methodology and Implications of Implementing Long HVAC Cables in the Ireland and Northern Ireland Power System," in *CIGRE Session*, Paris, France, Aug. 2016.

[4] W. Wiechowski and P. B. Eriksen, "Selected Studies on Offshore Wind Farm Cable Connections - Challenges and Experience of the Danish TSO," in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, Pittsburgh, PA, Jul. 2008, pp. 1-8.

[5] H. Khalilnezhad, M. Popov, L. van der Sluis, J. A. Bos and J. P. W. de Jong, "Influence of Long EHV AC Underground Cables on the Resonance Behavior of the Dutch Transmission System," in *IEEE PES General Meeting*, Boston, USA, Jul. 2016.

[6] L. Wu, "Impact of EHV/HV Underground Power Cables on Resonant Grid Behavior," Ph.D. dissertation, Eindhoven University of Technology, Eindhoven, Oct. 2014.

[7] M. Bollen, S. Mousavi-Gargari and S. Bahramirad, "Harmonic resonances due to transmission-system cables," *Renewable Energy and Power Quality Journal (RE&PQJ),* vol. 12, pp. 463, Apr. 2014.

[8] M. Bollen, S. Ackeby, H. Jansson and M. Jonsson, "Using transfer impedances to study harmonic resonances due to AC cables in a transmission system," in *CIGRE Symposium*, Lund, Sweden, May 2015.

[9] C. L. Bak and F. F. da Silva, "High voltage AC underground cable systems for power transmission – A review of the Danish experience, part 1," *Electric Power Systems Research,* vol. 140, pp. 984-994, Nov. 2016.

[10] F. F. da Silva, C. L. Bak, U. S. Gudmundsdottir, W. Wiechowski and M. R. Knardrupgård, "Methods to Minimize Zero-Missing Phenomenon," in *IEEE Transactions on Power Delivery,* vol. 25, no. 4, pp. 2923-2930, Oct. 2010.

[11] F. F. da Silva, C. L. Bak, U. S. Gudmundsdottir, W. Wiechowski and M. R. Knardrupgård, "Use of a Pre-Insertion Resistor to Minimize Zero-Missing Phenomenon and Switching Overvoltages," *2009 IEEE Power & Energy Society General Meeting,* Calgary, AB, Jul. 2009, pp. 1-7.

[12] CIGRE Working Group C4.502, "TB 556 - Power System Technical Performance Issues Related to the Application of Long HVAC Cables," CIGRE, Paris, 2013.

[13] M. H. J. Bollen, L. Yao, S. K. Rönnberg and M. Wahlberg, "Harmonic and Interharmonic Distortion due to a windpark," in *IEEE PES General Meeting*, Minneapolis, MN, Jul. 2010, pp. 1-6.

[14] M. Bradt, B. Badrzadeh, E. Camm, D. Mueller, J. Schoene, T. Siebert, T. Smith, M. Starke and R. Walling, "Harmonics and resonance issues in wind power plants," *2012 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Orlando, FL, May 2012, pp. 1-8.

[15] E. C. Aprilia, V. Cuk, J. F. G. Gobben, P. F. Ribeiro and W. L. Kling, "Modeling the Frequency Response of Photovoltaic Inverters," *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Berlin, Oct. 2012, pp. 1-5.

[16] V. Cuk, J. F. G. Cobben, W. L. Kling and P. F. Ribeiro, "Considerations on Harmonic Impedance Estimation in Low Voltage Networks," *2012 IEEE 15th International Conference on Harmonics and Quality of Power (ICHQP)*, Hong Kong, Jun. 2012, pp. 358-363.

[17] F. Barakou, M. H. J. Bollen, S. Mousavi-Gargari, O. Lennerhag, P. Wouters and E. Steennis, "Impact of Load Modeling on the Harmonic Impedance seen from the Transmission Network," *2016 IEEE 17th International Conference on Harmonics and Quality of Power (ICHQP)*, Belo Horizonte, Brazil, Oct. 2016, pp. 283-288.

[18] F. Barakou, M. H. J. Bollen, S. Mousavi-Gargari, P. Wouters and E. Steennis, "Downstream network modeling for switching transients in EHV networks containing cables," *2017 IEEE Manchester PowerTech*, Manchester, Jun. 2017, pp. 1-6.

[19] J. Kilter et al., (2016, Dec.). Critical PQ phenomena and sources of PQ disturbances in PE rich power systems. MIGRATE [Online]. Available: https://www.h2020-migrate.eu/_Resources/Persistent/f337 837c7a68765f3d38a310427e67d1c0f44cce/MIGRATE_D5-1_V1_TUT.pdf.

[20] S. K. Rönnberg, M. H. J. Bollen, H. Amaris, G. W. Change, I. Y. Gu, L. H. Kocewiak, J. Meyer, M. Olofsson, P. F. Ribeiro and J. Desmet, "On waveform distortion in the frequency range of 2 kHz–150 kHz—Review and research challenges," *Electric Power Systems Research,* vol. 150, pp. 1-10, Sep. 2017.

[21] *Insulation co-ordination - Part 1: Definitions, principles and rules*, IEC Std. 60071-1, Ed 8.1, Mar. 2011.

[22] *Surge arresters - Part 5: Selection and application recommendations,* IEC Std. 60099-5, Ed. 2.0, May 2013.

[23] A. Ametani, T. Ohno and N. Nagaoka, *Cable System Transients: Theory, Modelling and Simulation*, Singapore: John Wiley & Sons, 2015.

[24] J. Arrilaga and N. R. Watson, *Power System Harmonics*, Second edition, Chichester: John Wiley & Sons, 2003.

[25] D. Pohv and W. Schultz, "Analysis of Overvoltages Caused by Transformer Magnetizing Inrush Current," *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-97, no. 4, pp. 1355 - 1365, Jul. 1978.

[26] R. A. Turner and K. S. Smith, "Resonance Excited by Transformer Inrush Current in Inter-connected Offshore Power Systems," *2008 IEEE Industry Applications Society Annual Meeting*, Edmonton, AB, Canada, Oct. 2008.

[27] CIGRE Working Group C4.307, "TB 569 - Resonance and Ferroresonance in Power Networks," CIGRE, Paris, 2014.

[28] P. Poujade, B. Caillault, M. Martinez Duro, V. Renouard and F. Zgainski, "Simulation of the effect of parameter uncertainties on transient overvoltages during power restoration: comparison with field measurements," in *International Conference on Power Systems Transients (IPST2017)*, Seoul, Republic of Korea, Jun. 2017.