Impact of Uncertainties on Resonant Overvoltages

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***Abstract*--A number of changes in the power system have increased the risk for more serious resonances in the harmonic frequency range. The changes also result in an increased uncertainty with regard to the frequency and damping of those resonances. Uncertainties could be related to variations with time, uncertain future developments in the grid, and the modelling of individual components. In this article, a distinction is made between discrete and continuous stochastic uncertainties. This article further investigates uncertainties affecting resonant overvoltages. Several study cases investigating the impact of different uncertainties on resonances and temporary overvoltages, performed in PSCAD, are presented. The results show that some uncertainties may have a significant impact on the resulting impedance characteristics and potentially on the resulting overvoltage levels.**

***Keywords*: electromagnetic transients, PSCAD, resonance, temporary overvoltages.**

I. INTRODUCTION

THE power system is facing a number of changes, including a large scale integration of renewable energy sources (RES), changes in the grid such as the introduction of more cables at higher voltage levels, and changes in load composition, e.g. due to an increase in energy-efficient appliances and the addition of PV panels. These changes will affect the power system in different ways; one consequence being the occurrence of resonances at lower frequencies, another consequence is the increased uncertainty regarding the frequency and damping of those resonances [1].

Because of the decreasing resonance frequencies, there is an increased risk of amplification of low-order harmonics, as well as an increased risk of resonance-related temporary overvoltages (TOVs). While an amplification of low-order harmonics may be counteracted by a shift in emission to higher orders [2], the same is not necessarily true for harmonic sources causing TOVs, since the mechanisms causing the harmonics (e.g. transformer inrush current) remain the same.

The other aspect that should be considered is the increased uncertainties related to both resonances and harmonic sources. According to IEC 60071-4 [3], TOV studies are typically done in a deterministic or quasi-statistic fashion, with the goal of finding or estimating the worst possible cases. However, considering a large amount of uncertainties, this may yield pessimistic results, which may unnecessarily hinder the integration of RES or otherwise hamper the development of the power system.

In this paper the impact of uncertainties on resonant overvoltages is investigated. In Section II, different uncertainties and their impact on resonances and resonant overvoltages are described. Section III provides an overview of the study cases investigating different uncertainties, while Section IV presents results from the simulations. Section V presents an example of TOVs following transformer energization and, finally, Section VI provides the conclusions of the study.

II. UNCERTAINTIES AFFECTING RESONANT OVERVOLTAGES

For resonant overvoltages to appear there must exist a resonance as well as a source that triggers the resonance. A typical example is energization of a transformer. Since the inrush current is rich in harmonic content it may trigger a parallel resonance around a harmonic frequency, causing high overvoltages. Another example is a series resonance triggered by a switching surge e.g. due to cable energization.

The following sections describe different uncertainties and their impact on resonances and resonant overvoltages. A distinction is made between uncertainties affecting the impedance and uncertainties affecting the harmonic source.

Some uncertainties exist during the planning phase and may disappear when a project is closer to realization. Other uncertainties could be due to variations in time, or due to a lack of detailed information, e.g. about customer loads.

Table I details the different types of uncertainties and their classification; a discrete stochastic variable is defined as having a finite (and typically limited) number of possible values, e.g. a number of different operational scenarios, while a continuous stochastic variable is defined as being able to take all values in a given interval [4].

TABLE I
CLASSIFICATION OF UNCERTAINTIES

	Variations with time	**Future development**	**Modelling**
Power system incl. large conventional generation sources	Discrete	Discrete	Continuous
Power electronics-based RES, HVDC	Continuous	Continuous	Continuous
Consumption	Continuous	Continuous	Continuous

A. *Uncertainties due to variations with time*

As the power system is expected to become more flexible, it will also become more uncertain regarding possible operational scenarios. If a large generator is out of service, this will weaken the grid, resulting in a lowering of resonance frequencies. If a cable or overhead line is out of operation, the

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This research is sponsored by the Swedish Energy Agency, Svenska kraftnät and Energiforsk – The Swedish Energy Research Center.

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Paper submitted to the International Conference on Power Systems Transients (IPST2019) in Perpignan, France June 17-20, 2019.

frequency dependent impedance seen from a particular bus may change drastically depending on how meshed the network is. On-line tap changers will impact the effective impedance of transformers following changes in the tap setting, which could happen several times a day.

RES utilizing power electronic converters impact the grid, both regarding the resonance frequency (e.g. due to capacitive elements in filters) and emission [5]. RES are intermittent by nature and the amount of RES that will be in operation at any given time is not known in advance. It should also be noted that new sources of generation typically provide less short-circuit power to the system compared with traditional sources; thus, replacement of conventional generation sources with RES will further impact the resonance frequencies.

The consumption also varies with time, and even if it may be possible to predict general load patterns it is not possible to accurately predict what equipment will be connected at any given time.

In modern high-voltage cables, the electrical charge may remain for a long time following de-energization, unless the cable is discharged through an earthing switch or inductive voltage transformers (IVTs). This could be a concern in case of a series resonance that is triggered by cable energization, since the switching surge will be affected by any remaining charge, the worst-case being energization when the source voltage is of opposite polarity to the charge.

B. *Uncertainties related to future developments*

Reliability is an important criterion in all phases of power system planning. In order to ensure required redundancy, parallel cables may be installed even if a single cable is sufficient to handle the transferred power. This will lead to an effective increase of the capacitance of that particular route, which will result in a lowering of the resonance frequency. Depending on the substation layout it may be that parallel cables in the same corridor are energized by a common breaker, which will also impact the resulting switching surges.

Another important aspect of reliability is the capacity of the power system. The capacity needs will impact the dimensioning of different components, which consequently will impact their electrical parameters. In the case of cables, the capacitance depends on the conductor radius, the thickness of the insulation and semi-conductive layers, and the permittivity. Any changes will impact the resonance frequency and the switching surge. As in the case of reliability, parallel cables may be installed for capacity reasons, which may further increase the capacitance. Capacity needs will also impact the design parameters of e.g. transformers, which may also impact resonances and the risk for TOVs, e.g. in the case of a series resonance between a transformer and a cable connected to its secondary side.

At the planning stage, the final route of a certain section may be unknown. This will impact the choice of technology, where e.g. tunnel cables, underground cables or overhead lines may be used, and also the length of the route. These aspects will affect the electrical parameters, and thus the resonance frequency.

Other aspects related to cable installations are the cable layout (e.g. trefoil or flat formation), and the screen bonding configuration. The cable layout can have a large impact on the frequency, magnitude and the number of resonances in the positive sequence, and the type of screen bonding also has a significant effect on the positive sequence impedance [6].

Another uncertainty is related to the future development of the load composition. PV inverters and appliances equipped with power electronics add capacitance to the LV network, and they also provide less damping compared with non-electronic (resistive) loads [5]. However, it is not known beforehand e.g. which customers will install PV panels, and the impact on the damping is difficult to assess due to a lack of comparative measurements of the network impedance [7].

One uncertainty in the future development of the power system is the location and amount of RES. As was mentioned in a previous section, RES utilizing power electronic converters will impact the grid in several ways; another impact of RES is e.g. the shunt capacitance introduced by wind farm collection grids.

HVDC links will also have an impact on the system, both regarding resonances and as a source of emission, but it is often unknown where HVDC links will be installed in the future.

C. *Uncertainties related to component modelling*

Uncertainties related to component modelling typically stem from a lack of detailed information, or in some cases a lack of detailed models.

Transformer energization is a possible source of TOVs since the inrush current is rich in harmonic content. The magnitude of the inrush current depends on the saturation characteristics of the transformer and the time instant of energizing, as well as any remanence [8]. Standardized transformer no-load tests do not provide the necessary information for modelling the deeply saturated region, and assumptions are typically required. The time instant of energizing depends on the breaker characteristics and whether synchronized switching is applied. With non-synchronized switching, the breaker closing instant may occur randomly at any time during the power-system period, with some spread between the individual poles e.g. due to mechanical scatter.

Synchronized switching is used e.g. to reduce the inrush current of transformers or the switching surges when energizing lines or cables. Implementations of synchronized switching typically consider the impact of mechanical spread on the closing instant when determining the optimal closing targets. In the case of transformer energizing, the synchronized switching scheme will differ depending on the transformer type and the configuration of the windings, since this will affect the optimal closing targets with regards to the desired flux [9]. Some implementations of synchronized switching may estimate the remanence based on the voltage at the time of de-energizing. In such cases, the mechanical spread and the possibility of errors in the estimation of the remanent flux should be considered. Other implementations may use controlled de-energization in order to create a predictable flux. In case of uncontrolled de-energization, e.g. due to a fault, the subsequent energization will still be according to the predefined pattern with a risk of high inrush currents.

Due to a lack of information, and in some cases computational constraints, downstream networks and end customer loads are typically considered in a simplified manner. One of the biggest uncertainties is related to the modelling of customer installations and the related impact on the damping. The choice of model, i.e. a parallel or series model, or a full representation of the network at lower voltage levels, including loads, can also have a large impact on the resulting resonances [6], [10].

Due to practical variations in cable manufacturing process, the thickness of different layers in a cable tend to vary within certain acceptable tolerances. These variations impact the overall electrical parameters of the cable. Consequently, the resulting impedance profile and frequency content of the switching surge could be affected. The values below are approximate tolerance values:

- ± 5% for the core conductor thickness
- ± 5% for the insulation thickness
- ± 20% for the semi-conductive layer thicknesses

It should be noted that the above tolerances could be manufacturer specific and may not necessarily be taken as a general norm of the industry.

Tolerances also have an impact on the design of passive filters [11].

Due to e.g. the skin and proximity effects, the resistance will vary with frequency, and the results may differ significantly depending on the modelling approach used [6].

The modelling of power electronic converters, e.g. RES and HVDC links, requires specific information related to e.g. the converter controls, for all operating points of relevance [6].

III. STUDY OUTLINE

In order to illustrate the impact of some of the mentioned uncertainties the example grid presented in [12] and [13], is used for simulations in PSCAD. The example grid is characterized by having a large share of cables at 400 and 220 kV, one consequence being low-order resonances. The 400, 220 and 130 kV voltage levels of the example grid are modelled in detail in PSCAD, together with Frequency Dependent Network Equivalent (FDNE) representations of the downstream networks. Cables and lines are modelled using frequency dependent models. The average load is used for the reference case.

The following sections present the study cases, representing a selection of uncertainties described in the previous sections.

A. Impact of the share of cables

In this study case, the impact of the share of cables is investigated. This represents a hypothetical case where it is not yet known if it is possible to build overhead lines, or if cables have to be applied instead.

With the example grid as a reference, cables CA 1, CA 2, CA 3, CA 4 and CA 5 at 400 kV are replaced by overhead lines of the same length. The overhead lines use the same parameters and configuration as OHL 2. Then, the share of cables is increased by replacing the overhead lines by cables one by one, starting with CA 1 and ending with CA 5, while the resulting frequency dependent impedance is analyzed.

B. Impact of cable tolerances

In this study case the impact of dimensional tolerances on the cable capacitance is studied. This is done by running 1000 Monte Carlo iterations while varying the thickness of each cable layer uniformly within the limits specified in Section II. Consider a single-phase cable with parameters as CA 1. It is divided into 9 segments with the length 710 m (i.e. the total cable length is around 6.4 km) as described in [12], and the variations are assumed to be independent for each segment. The resulting capacitance for each segment is then calculated using (1), where ε_r is the relative permittivity, ε_0 the vacuum permittivity, r_c the outer radius of the core conductor, th_{sc} the thickness of the inner semi-conducting layer and th_i the insulation thickness [14].

$$C = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\left(\frac{r_c + th_{sc} + th_i}{r_c + th_{sc}}\right)} \tag{1}$$

The total cable capacitance (for the entire single-phase cable) is calculated by adding the capacitances of all segments, for each iteration.

As a comparison, the worst-case is also considered, where all segments vary in the same way and with the maximum deviation from the nominal thickness, yielding the maximum variation in capacitance.

C. Impact of changes in operational scenarios

In this study case, CA 4, CA 5, CA 11 and OHL 3 are disconnected one at a time and the resulting frequency dependent impedance is analyzed.

D. Impact of a weakening of the grid following a large-scale introduction of RES

This study case investigates the consequence of replacement of conventional generation by RES, with the assumption that RES will not provide significant short-circuit power. From the reference case, the short-circuit power of the grid is adjusted downwards from 100% to 50% by changing the impedance of network equivalents G1-G5, and the resulting frequency dependent impedance is analyzed.

E. Impact of variations in load

In this study case, the impact of variations in load is investigated. Based on [12], the resulting harmonic impedance is compared for three load levels: no load (the downstream networks are disconnected, e.g. in a black-start condition), an estimated average consumption (reference case) and the maximum consumption. Aside from changes in the load itself, it should also be noted that capacitor banks at 20 or 10 kV are more prevalent in the case of maximum consumption. FDNEs were used to represent each downstream network.

F. Impact of remanence and time instant of transformer energization

In this study case the impact of the instant of transformer energization and remanence on the resulting inrush current are studied by energizing one of the transformers at bus 9.

First, non-synchronized switching is investigated. In this case, phase L1 is energized randomly over one half-period. The energizing instants of phases L2 and L3 are assumed to be normally distributed (3σ = 1ms) around the time instant of energization of phase L1. The simulations are performed for different levels of remanence where the remanence is assumed to take on a typical shape of +φ, 0 and -φ (in any order), with a magnitude of 0, 0.5 and 0.8 pu, where 0.8 pu is considered as a realistic maximum value [15]. For the cases with remanence the Jiles-Atherton model is used [16].

Synchronized switching is also investigated. As the transformers in [12] are 3-limb and have a delta winding there will be magnetic coupling between the phases. The employed switching strategy must consider the coupling in order to achieve a symmetrical flux [15]. For such a configuration, a possible strategy is to energize L1 at the positive voltage peak, L2 at 112 degrees after L1 and L3 at 85 degrees after L1 [17]. The mechanical spread of each phase is considered (3σ = 1ms). The simulations are repeated for varying levels of remanence, where the case without remanence simulates energization after a controlled de-energization. In case of remanence, it is assumed that the de-energization is uncontrolled, yielding a remanent flux between 0.5-0.8 pu.

IV. RESULTS

A. Impact of the share of cables

The frequency dependent impedance (positive sequence) seen from bus 9 for an increasing share of cables for branches CA 1-CA 5 is shown in Fig. 1.

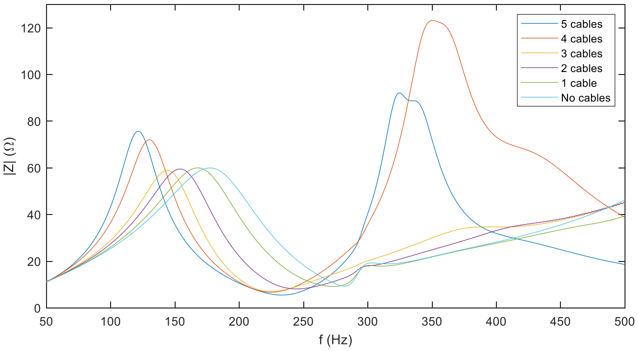

Fig. 1. Frequency dependent impedance (positive sequence) for an increasing share of cables for branches CA 1-CA 5.

It is evident from the figure that the share of cables has a significant impact on the resulting resonances, with a shift in the first parallel resonance from around 180 Hz (no cables) to around 120 Hz (5 cables). In some of the cases, the parallel resonance has its peak close to 150 Hz, which could result in TOVs following transformer energization. Additional resonances can also be seen e.g. around 300-400 Hz where, again, the impact of different amounts of cables is large.

B. Impact of cable tolerances

Fig. 2 shows a histogram of the calculated capacitances for a single-phase cable, divided into 9 segments of 710 m. The left figure shows the distributions of the capacitance for each of the 9 segments, and the right figure shows the distribution of the total capacitance for the same cable.

Each individual cable segment has a σ of 5.2 nF, which corresponds to around 3% of the mean, whereas the total single-phase cable (consisting of all 9 segments in series) has a σ of 15.6 nF, which corresponds to around 1% of the mean.

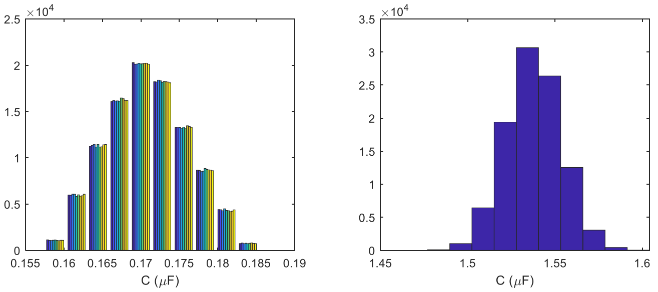

Fig. 2. Histogram of calculated capacitances for the 9 segments (left) and for the whole cable (right).

If two independent normal distributions with standard deviations σ_A and σ_B are added together the corresponding standard deviation σ_{tot} will be equal to [4]:

$$\sigma_{tot} = \sqrt{\sigma_A^2 + \sigma_B^2} \quad (2)$$

Considering that CA 1 is made up of three parallel cable circuits, with 9 single-phase cables in total, the standard deviation of the total capacitance for the whole cable system will be 46.8 nF, which is 9 times the standard deviation of one segment. However, the total capacitance of the cable circuit will be 81 times that of one segment. Thus, the standard deviation for the whole cable circuit will be 0.34% of the mean, and the impact of tolerances on the resonance frequency can be considered negligible.

If the dimensional variations are the same for all segments (the worst case), this results in a possible capacitance variation of ±8% for the cable circuit. In the unlikely case that all cables in the example grid vary in the same way (and with the maximum deviation) this would result in a variation of around ±4 Hz for a resonance close to 100 Hz.

When performing studies, information on tolerances should be obtained from the manufacturer (if possible) so that the impact can be evaluated.

C. Impact of changes in operational scenarios

Fig. 3 shows the resulting impedance profile seen from bus 9 for different operational scenarios.

With CA 4 or CA 5 out of service, the first parallel resonance is shifted slightly to higher frequencies, and with OHL 3 out of service the resonance frequency decreases, with the resulting peak close to 100 Hz. Around 250-500 Hz the impact of CA 4 or CA 5 being out of service is significant.

D. Impact of a weakening of the grid following a large-scale introduction of RES

Fig. 4 shows the resulting impedance profile seen from bus 9 for different network strengths.

As a result of a lowering of the network strength a clear shift downwards in frequency can be seen for the first parallel resonance.

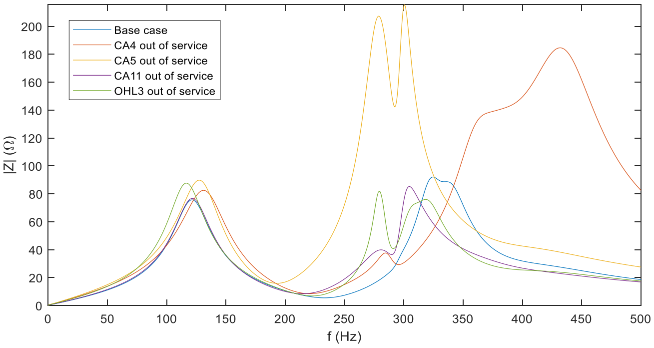

Fig. 3. Frequency dependent impedance (positive sequence) seen from bus 9 for different operational scenarios.

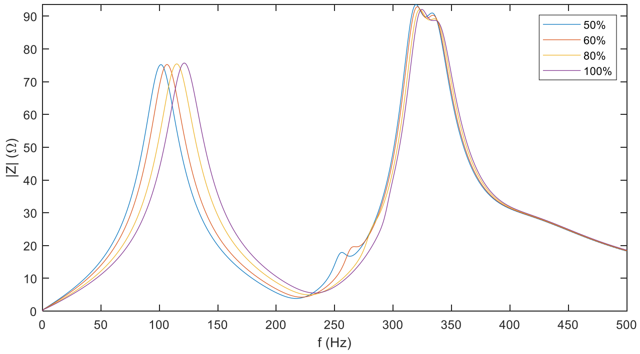

Fig. 4. Impedance profile for varying levels of network strength

E. Impact of variations in load

Fig. 5 shows the resulting positive sequence impedance magnitude seen from bus 9 for the different load scenarios.

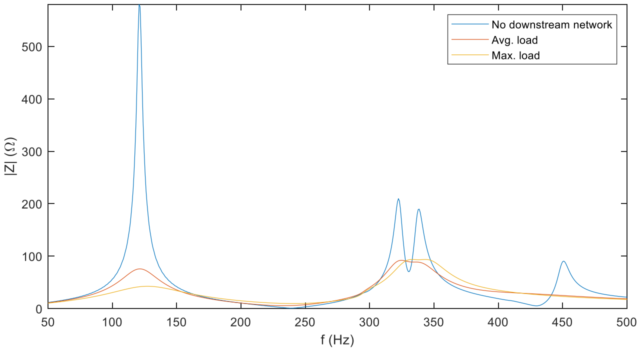

Fig. 5. Impedance profile for the no load, max. load and avg. load cases.

The figure shows that excluding the downstream networks and customer loads will lead to a severe underestimation of the damping, which could result in unrealistically high overvoltages. The maximum consumption case results in more damping at the first parallel resonance compared to the average consumption case, but aside from that the difference between the two cases is small.

In order to study the impact of the downstream networks on the impedance profile the downstream networks were connected, but without the LV loads. A comparison with the case without downstream networks is shown in Fig. 6.

The figure shows that while the downstream networks shift the resonance frequencies slightly, they do not provide significant damping.

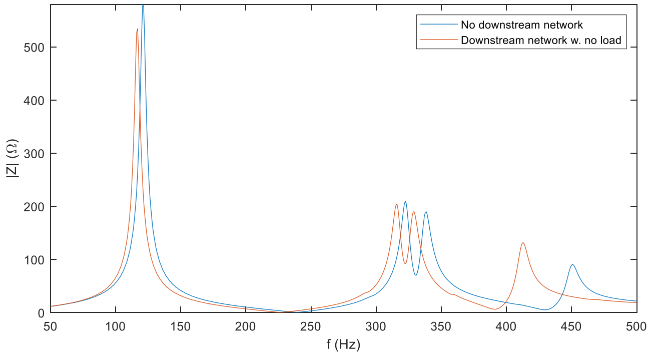

Fig. 6. Impedance profile for the case without downstream networks and the case with downstream networks (without loads).

F. Impact of remanence and the time instant of transformer energization

Table II shows the resulting peak inrush current for the studied cases (the highest current of the three phases is shown).

As can be seen from the results, synchronized switching gives a large reduction in inrush current. However, the presence of remanence (e.g. following uncontrolled de-energization) can still cause high inrush currents even if synchronized switching is used.

If the remanent flux is estimated, the inrush current may be further mitigated, but the effect of mechanical spread must still be considered together with eventual errors in the estimated flux.

TABLE II
PEAK INRUSH CURRENTS FOR DIFFERENT LEVELS OF REMANENCE

Strategy	**Remanence (pu)**	**Mean current (kA)**	**Max. current (kA)**
Random closing	0	1.2	2.0
Random closing	0.5	1.5	3.0
Random closing	0.8	1.9	3.7
Synchronized switching	0	0.06	0.6
Synchronized switching	0.5	0.9	1.5
Synchronized switching	0.8	1.6	2.3

V. EXAMPLES OF RESONANT OVERVOLTAGES

Simulations are performed to investigate the risk of high TOVs following transformer energization. The example grid in [12] with average load is used, but the source impedances are increased to move the first parallel resonance to 100 Hz. Based on Table II, the case with the highest resulting peak inrush current for synchronized switching is simulated and the resulting TOVs are studied. The simulations are repeated without downstream networks and loads.

Fig. 7 shows the resulting voltages following transformer energization. In the case with loads, the energization does not result in any significant overvoltages.

Without the damping from the downstream networks and loads, the situation is significantly worsened. The highest recorded voltage is around 1.4 pu, which could be a cause for concern. Such a situation could occur in black start scenarios, where the grid is weakened and there is little damping.

It should be noted that the studied case for synchronized switching assumes uncontrolled de-energization; following controlled de-energization, synchronized switching will generally result in significantly reduced inrush currents compared to random closing.

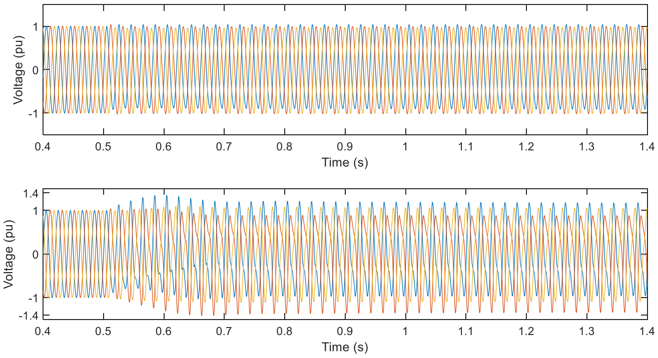

Fig. 7. Overvoltages following transformer energization using synchronized switching with 0.8 pu remanence, with loads (upper) and without loads (lower).

VI. CONCLUSIONS

This paper describes uncertainties that impact resonances and resonant overvoltages. Based on the studied examples it is found that some of the uncertainties can have a large impact on the results. However, even small changes can be significant if they result in the shift of a resonance closer to or away from a frequency with strong emission.

The downstream networks and customer loads should be included when performing studies to avoid severely underestimating the damping. Even in case of a black start, any auxiliary loads should be considered as they may impact the results. Different consumption levels may impact the damping and should be evaluated. If detailed information is not available, studies without downstream networks and loads will give pessimistic results, and, as is shown in [18], may lead to incorrect values for the resonance frequency.

Future grid expansion options and operational scenarios should be considered based on the risk of resonant overvoltages.

Cable tolerances appear to have a negligible impact on low-order resonances, but more information about actual tolerance values is needed before any general conclusions can be drawn.

When studying transformer energization, the mechanical spread of breakers should be considered, as well as detailed information about equipment used for synchronized switching. As detailed data as possible should be obtained for transformer saturation characteristics.

In cases with few significant uncertainties (e.g. in radial networks and if most parameters are known) it may be enough to investigate only the worst-case conditions, or to study variations in a few parameters. An example can be found in [8] where a case of network restoration is investigated. However, in case of a large amount of uncertainties, especially in large and meshed networks, it may not be practical or even possible to study all combinations.

Another concern is the evaluation of TOVs. There exist no clear guidelines on how TOVs should be evaluated, and how equipment is affected by overvoltages containing several different frequencies. There is ongoing work within CIGRE working groups C4.46 and C4.48 with the goal to address these questions.

VII. REFERENCES

[1] O. Lennerhag and M. H.J. Bollen, “Power system impacts of decreasing resonance frequencies,” in *18th International Conference on Harmonics and Quality of Power (ICHQP)*, Ljubljana, Slovenia, May 2018.

[2] 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.

[3] IEC 60071-4, Insulation co-ordination, Part 4: Computational guide to insulation co-ordination and modeling of electrical networks, 2004.

[4] G. Grimmett and D. Stirzaker, Probability and Random Processes, Oxford university press, 2001.

[5] X. Wang, F. Blaabjerg, Z. Chen and W. Wu, “Modeling and Analysis of Harmonic Resonance in a Power Electronics Based AC Power System,” in *In Proceedings of the 2013 IEEE Energy Conversion Congress and Exposition (ECCE)*, Denver, United States, Sep. 2013.

[6] CIGRE JWG B4/C4.38 TB, Network Modelling for Harmonic Studies (not published).

[7] V. Cuk, J.F.G. Cobben, W.L. Kling, P.F. Ribieiro, “Considerations on Harmonic Impedance Estimation in Low Voltage Networks,” in *15th International Conference on Harmonics and Quality of Power (ICHQP)*, Hong Kong, Jun. 2012.

[8] M. Martinez and R. Denis, “Parameter uncertainty assessment in the calculation of the overvoltages due to transformer energization in resonant networks,” in *CIGRE Session*, Paris, France, Aug. 2012.

[9] CIGRE WG A3.07 - TB263, “Controlled Switching of HVAC Circuit Breakers - Guidance for further applications including unloaded transformer switching, load and fault interruption and circuit breaker uprating,” 2004.

[10] F. Barakou, A. Pitsaris, P.A.A.F. Wouters, E.F. Steennis, “Study of series resonance overvoltage at LV side of transmission transformer during EHV cable energization,” in *International Conference on Power Systems Transients (IPST2017)*, Seoul, Republic of Korea, Jun. 2017.

[11] Das, J. C., Power system harmonics and passive filter designs, Wiley, 2015.

[12] O. Lennerhag, “Power System Model for Resonance Studies,” 2018-10-05. [Online]. Available: http://ltu.diva-portal.org/smash/record.jsf?pid=diva2:1249815.

[13] O. Lennerhag, “TM18-1001-01 Power System Model for Resonance Studies - list of revisions,” 2018-10-05. [Online]. Available: www.i2group.se/phd.

[14] A. Ametani, T. Ohno and N. Nagaoka, Cable System Transients - Theory, Modelling and Simulation, IEEE Press, 2015.

[15] J. H. Brunke and K. J. Fröhlich, “Elimination of Transformer Inrush Currents by Controlled Switching - Part I: Theoretical Considerations,” *IEEE Transactions on Power Delivery*, vol. 16, no. 2, April 2001.

[16] U.D. Annakkage, P.G. McLaren, E. Dirks, R.P. Jayasinghe, A.D. Parker, “A current transformer model based on the Jiles-Atherton theory of ferromagnetic hysteresis,” *IEEE Transactions on Power Delivery*, vol. 15, no. 1, pp. 57-61, Jan Jan 2000.

[17] ABB, “Switchsync PWC600 - User Manual,” 2015-12-09.

[18] F. Barakou, M. Bollen, S. Mousavi-Gargari, O. Lennerhag, P.A.A.F. Wouters, E.F. Steennis, “Impact of load modeling on the harmonic impedance seen from the transmission network,” in *17th International Conference on Harmonics and Quality of Power (ICHQP)*, Belo Horizonte, Brazil, 2016.