Evaluation of Temporary Overvoltages Considering Current Standards and Regulations with Extensive Renewables Integration

Marc René Lotz, Michael Kurrat
elenia Institute for High Voltage Technology and Power Systems
Technische Universität Braunschweig
Braunschweig, Germany

***Abstract*—The extensive integration of Distributed Energy Resources (DERs) and electromobility requires a review of the protection systems in Low Voltage (LV) networks and customer installations. This paper provides an evaluation of Temporary Overvoltages (TOVs) in LV AC grids regarding current standards and regulations, when there is such an extensive integration. This could lead to asymmetric load configurations, causing TOVs when a Loss of Neutral (LoN) occurs. The results show that current regulations, mainly the Niederspannungsanschlussverordnung, permit the operation of highly asymmetric load configurations. Within the permitted range, the expected TOVs are lesser than explicit test and withstand voltages of facilities and devices, so that no further consideration is planned.**

***Index Terms*—Temporary Overvoltages (TOVs), Loss of Neutral (LoN), Low Voltage (LV) AC grids, Distributed Energy Resources (DER), renewables integration, asymmetric load configurations, Niederspannungsanschlussverordnung (NAV), Technische Anschlussbedingungen (TAB), Surge Protective Devices (SPDs).**

I. INTRODUCTION

The future grid with its extensive integration of Renewable Energy Sources (RES) in a manner of Distributed Generators (DGs) bears certain challenges for the sufficiency of grid protection principles. [1]

At the elenia Institute for High Voltage Technology and Power Systems, research activities include studies on and the development of low-voltage switchgear and surge protective devices for DC systems [2], as well as the conception of smart and modular protection systems. Among that, the aspect of renewables integration is especially met with an emphasis on electromobility and the active distribution grid.

With the latest joint project SiNED, now protection principles and the renewables integration in AC distribution grids are brought together. Scope of this project is the evaluation of currently deployed protection schemes under provision of ancillary services to analyse whether those schemes are still sufficient when a high penetration of inverter-based Distributed Energy Resources (DERs) exists. As an outcome, new protection systems and devices will be developed. [3]

Especially in Low Voltage (LV) distribution grids, the impact of DERs (photovoltaics, electromobility and battery storage devices), that can be connected to a single phase or two phases, has to be considered for the evaluation of protection principles, as it will manifest in more frequently occurring asymmetries of the line-to-neutral voltages, overvoltages and voltage stability concerns in general, and high neutral currents.

A study from the VDE Forum Netztechnik/Netzbetrieb (FNN) also comes to the conclusion that the impact of such asymmetric load configurations needs to be analysed to give recommendations of permittable asymmetries for better grid compatibility. [4]

Earlier, another study from the FNN already gave recommendations regarding stationary voltage stability when there is an extensive renewables integration, which lead to the current considerations. [5]

As a conclusion, the impact of asymmetries on LV facilities and equipment will be considered, including the evaluation of requirements imposed on protection principles and devices, while the focus of this paper lies on the impact of Temporary Overvoltages (TOVs) on the LV grid and consumer installations.

Contrary to transient overvoltages, of which the ones caused by lightning strokes and switching events are the most typical and severe, TOVs are persistent, but slight overvoltages that will probably not trip the overvoltage protection devices. Still, their persistent nature can lead to the damage of other devices and facilities, interference with smart metering and smart home systems, and perturbation of the LV distribution grid.

It has been shown that TOVs caused by DGs could lead to higher values than the typically expected values, e. g. of $\sqrt{3} \cdot V_{\text{REF}}$ for a short-circuit between one line and the neutral. However, a sequence of events needs to happen for this to occur. Here, an islanding operation needs to follow a single-line-to-ground fault. [6]

Although there are different kinds of TOVs, with a distinction following subsequently, the evaluation will emphasise on the Loss of Neutral (LoN). The main reason is the following. Through extensive integration of inverter-based DERs in the LV distribution grid, asymmetric load configurations could occur more frequently, leading to high neutral currents. In the event of a LoN, the so emerging TOVs should be examined.

For the evaluation of overvoltage protection concepts, multiple questions arise: What magnitude of potential TOVs

---

Mail addresses are m.lotz@tu-braunschweig.de (Marc René Lotz) and m.kurrat@tu-braunschweig.de (Michael Kurrat).

in asymmetric load configurations could practically occur, and what is the impact on facilities and devices, regarding insulation coordination and their rated voltages? Are the load configurations that cause high TOVs permitted by the latest standards, and what is the magnitude of TOVs with configurations compliant with these standards? As a conclusion, it should be examined whether protection principles are sufficient or if recommendations for further development should be given.

The organisation of this paper is as follows. At first, the distinction of TOVs with the focus on LoN is presented in Section II, including their derivation and the validation of the modelling with actual measurements. After that, implications on their criticality regarding the protection of facilities and devices, as well as an overview of relevant standards and regulations, are presented in Section III. Then, an evaluation of the practical relevance of TOVs with the depiction of values that occur compliant with standards and regulations is performed in Section IV. The conclusion of Section V gives an overview if there is a need for action regarding the adaption of overvoltage protection principles for facilities and devices.

II. TEMPORARY OVERVOLTAGES WITH LOSS OF NEUTRAL

This section provides the distinction of TOVs, to focus on the derivation of TOVs when a LoN occurs. Measurements are used to validate the simulation model for further investigation.

A. *Distinction*

Typically, the distinction of TOVs is made between those originating from the Medium Voltage (MV) side and the ones occurring within the LV distribution system. MV side faults include coupling between this and the LV side, through earthing and transformer faults, and direct connections between both voltage sides. [7]

An additional classification of TOVs within LV distribution systems is performed in [8], which includes earthing faults, short circuits, and the LoN. Especially in split-phase shared neutral LV systems, TOVs double the nominal voltage are mentioned, when one line is open-circuited (open-phase) as a worst case. [9]

These load configurations are highly asymmetric, but only considered for split-phase systems. In three-phase systems, [10] focuses on TOVs caused by open-phase faults in the MV distribution grid, and TOVs incorporated by DGs, which could also be highly asymmetric loads, are considered in [6].

The similarity of these topics, meaning the LoN and asymmetric load configurations, leads to the evaluation of their combination in three-phase LV distribution systems.

B. *Derivation*

The derivation of TOVs is performed under the consideration of a highly asymmetric load configuration in a consumer installation, which could be incorporated by future DERs integration, among the typical ohmic loads. The example is adapted from the open-phase fault with LoN, which is rather mentioned in split-phase systems.

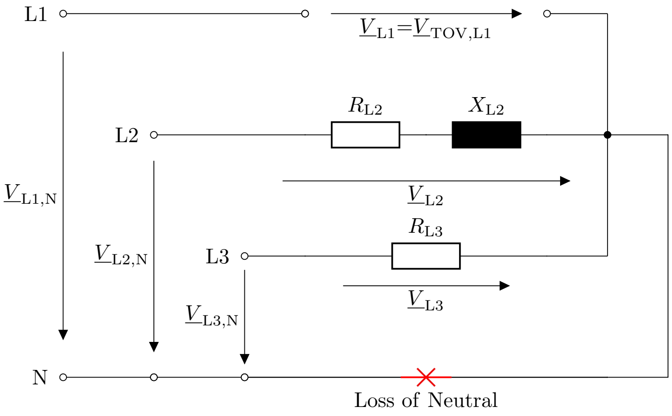


Fig. 1. Example circuit with highly asymmetric loads and LoN.

As can be seen in Fig. 1, the load at L1 is open-circuited and purely ohmic with $\underline{Z}_{\mathrm{L1}} = R_{\mathrm{L1}} \to \infty$, the load at L2 is ohmic-inductive with $\underline{Z}_{\mathrm{L2}} = R_{\mathrm{L2}} + \mathrm{j}\cdot X_{\mathrm{L2}}$, and the load at L3 is purely ohmic with $\underline{Z}_{\mathrm{L3}} = R_{\mathrm{L3}}$. The maximum TOV then occurs at L1 with $\underline{V}_{\mathrm{TOV,L1}}$.

With $\underline{a} = \exp\left(-\mathrm{j}\cdot 2\pi/3\right)$, V_{REF} as the nominal line-to-neutral voltage, and the index $k = 1, 2, 3$, the line-to-neutral voltages can be expressed as follows.

$$\underline{V}_{\mathrm{L}k,\mathrm{N}} = \underline{a}^{k-1}\cdot V_{\mathrm{REF}} \tag{1}$$

For the purpose of simplification, the absolute values of the loads at L2 and L3 are equal with $Z_{\mathrm{L2}} = Z_{\mathrm{L3}}$. To give a better overview of the compliance with standards later on, the load at L2 is expressed with its absolute value and its power factor.

$$\underline{Z}_{\mathrm{L2}} = Z_{\mathrm{L2}}\cdot\left(\cos\left(\varphi_{\mathrm{L2}}\right) + \mathrm{j}\cdot\sin\left(\varphi_{\mathrm{L2}}\right)\right) \tag{2}$$

The TOV at L1 is expressed as

$$\underline{V}_{\mathrm{TOV,L1}} = \underline{V}_{\mathrm{L1,N}} - \underline{V}_{\mathrm{L3,N}} + \underline{V}_{\mathrm{L3}}. \tag{3}$$

Now, the voltage at L3 needs to be calculated, using the corresponding impedance ratio and the voltage between L2 and L3.

$$\underline{V}_{\mathrm{L3}} = \left(\underline{V}_{\mathrm{L3,N}} - \underline{V}_{\mathrm{L2,N}}\right)\cdot\frac{\underline{Z}_{\mathrm{L3}}}{\underline{Z}_{\mathrm{L2}} + \underline{Z}_{\mathrm{L3}}} \tag{4}$$

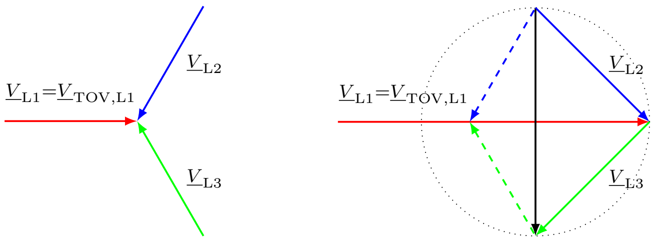
The combination of Eqs. (2) to (4), performing geometric operations and using trigonometric identities, finally leads to

$$\underline{V}_{\mathrm{TOV,L1}} = \frac{3 + \sqrt{3}\cdot\tan\left(\frac{\varphi_{\mathrm{L2}}}{2}\right)}{2}\cdot V_{\mathrm{REF}}. \tag{5}$$

The absolute value in its normalized form then is

$$\frac{V_{\mathrm{TOV,L1}}}{V_{\mathrm{REF}}} = \frac{3 + \sqrt{3}\cdot\tan\left(\frac{\varphi_{\mathrm{L2}}}{2}\right)}{2}. \tag{6}$$

It can be seen that the worst case in theory is when $\cos\left(\varphi_{\mathrm{L2}}\right) \to 0$, which means $R_{\mathrm{L2}} \to 0$, leading to a TOV of



(a) Before LoN. (b) After LoN.

Fig. 2. Vector diagram of load voltages before and after LoN.

$$\frac{V_{\mathrm{TOV,L1}}}{V_{\mathrm{REF}}} = \frac{3+\sqrt{3}\cdot\tan\left(\frac{\pi}{4}\right)}{2} = \frac{3+\sqrt{3}}{2} \approx 2.366. \qquad (7)$$

This worst case is also shown in Fig. 2 in a vector diagram. The phase angles of $\underline{V}_{\mathrm{L2}}$ and $\underline{V}_{\mathrm{L3}}$ are shifted drastically, while $\underline{V}_{\mathrm{TOV,L1}}$ is stretched in its absolute value.

There are more examples of load configurations with different values of TOVs possible, e. g. a capacitive load at L2 and an inductive load at L3. But this section shall only provide a basic understanding of the occurrence of TOVs with LoN, so that their practical relevance can be investigated in the next sections. In addition, it is expected that the DERs behave similar, when integrated into consumer installations, so that asymmetric load configurations consist of ohmic-inductive or ohmic-capacitive loads, for which this example is sufficient.

C. Model Validation

For further evaluation, the derived TOV modelling is validated using actual measurements in a consumer LV installation. The results are shown in Fig. 3 in comparison to a plot of Eq. (6). Measurements are only performed with $\cos(\varphi_{\mathrm{L2}}) \geq 0.7$, as the operational ranges of such an experiment are limited via respective regulations, see Section III.

The load voltages before and after LoN are also presented in Fig. 4 and 4 on the time basis with $\cos(\varphi_{\mathrm{L2}}) \approx 0.9$.

Additional damping through the transmission lines of the consumer installation was not modelled beforehand, and shows almost no impact on the actual measurements. It needs to be mentioned that the experiment has been conducted with relatively small currents of about 1 A. But still, the TOVs are independent of the actual load. Additionally, the maximum voltage sag at nominal load after [11] should not exceed 8 % of the nominal voltage, meaning that the TOVs would still be reasonably high, when damping in normal operation is considered.

III. IMPLICATIONS ON RELEVANT STANDARDS AND REGULATIONS

The implication of such TOVs is that their persistent nature could possibly lead to damage of facilities and devices in general. Additionally, highly asymmetric load configurations lead to TOVs that exceed the typical test and withstand voltages mentioned in relevant standards. This applies to the operation of all the devices in consumer or industrial installations.

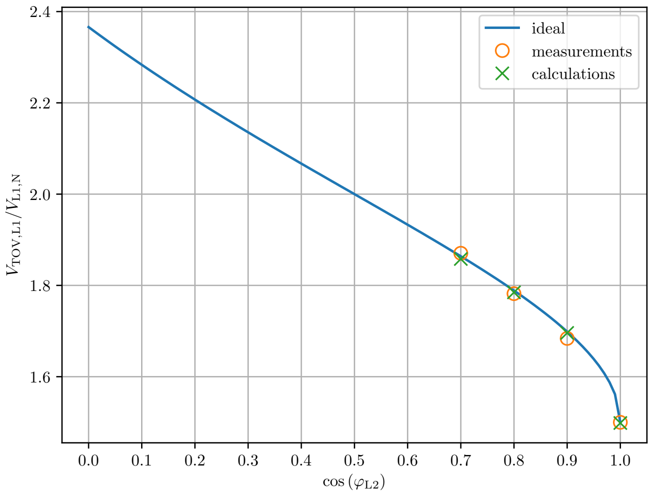


Fig. 3. Actual measurements of TOVs and comparison to the mathematical modelling (ideal) with respect to $\cos(\varphi_{\mathrm{L2}})$. Among the measurements of the TOVs, the values are also calculated based on the load impedances of the experiment.

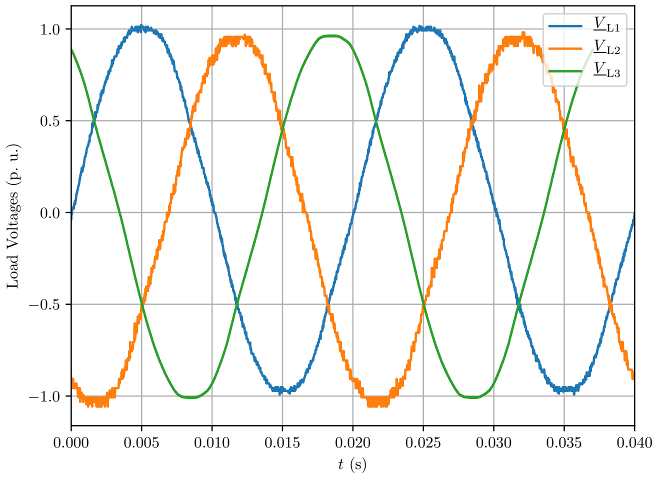


Fig. 4. Actual measurements of TOVs before LoN with $\cos(\varphi_{\mathrm{L2}}) \approx 0.9$.

Considering the operational range of devices, no explicit values are mentioned in the relevant standards for consumer products regarding persistent overvoltages above rated voltages of 250 V [12]. Another example refers to the test values of Surge Protective Devices (SPDs), where characteristic SPD test values with LoN are limited to $U_{\mathrm{T}} = \sqrt{3}\cdot U_{\mathrm{REF}}$, meaning that the TOVs of asymmetric configurations could be reasonably higher. [8], [13], [14], [15]

In order to relativise the TOVs and evaluate whether the values are practically relevant for further consideration, a review of current and applicable standards and regulations is performed.

As one of the most important regulations, in § 16 Abs. 2 Niederspannungsanschlussverordnung (NAV), it is stated that the connection usage in LV grids is only permitted for a power

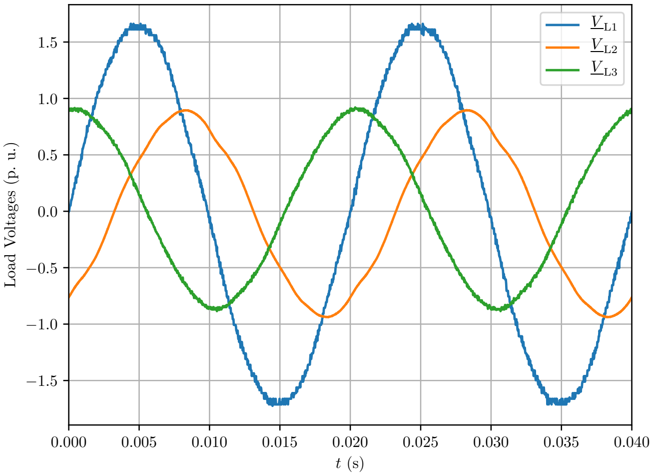


Fig. 5. Actual measurements of TOVs after LoN with $\cos(\varphi_{\mathrm{L2}}) \approx 0.9$.

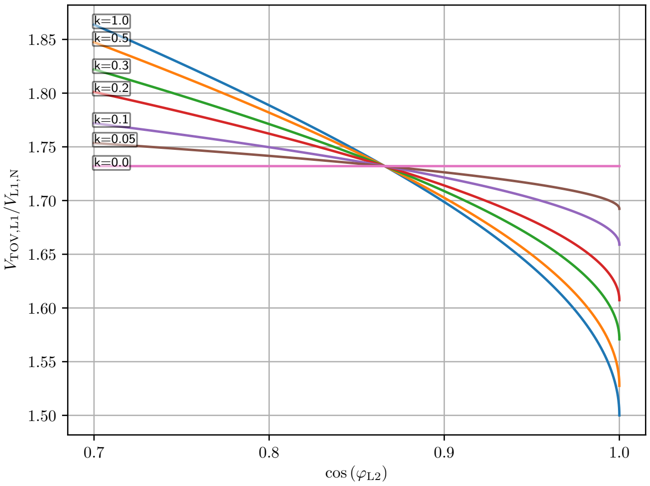


Fig. 6. TOV values with different impedance ratios of Z_{L2} and Z_{L3}.

factor between $\cos(\varphi) = 0.9$ (ind.) and $\cos(\varphi) = 0.9$ (cap.). Otherwise, compensation units need to be installed.

Since the NAV is a regulation based on § 18 Energiewirtschaftsgesetz (EnWG), the Technische Anschlussbedingungen (TAB) that are defined individually by the grid operators (see EnWG § 19 Abs. 1) are also compliant with the NAV and the power factor limits. Regarding generators connected to the LV distribution grid, the relevant standard is also compliant with NAV. [16]

This means that asymmetric load configurations are already limited to a certain degree within normal operation, leading to smaller TOV values after LoN, which is depicted in the following section.

Other standards are mostly not applicable. As the TOV values are independent of the actual load, current limits of the lines or the neutral are no constraint, so, [11] is insufficient. Asymmetric, meaning single-phase, operation is also partially permitted, as stated in [16] with generating units of $S_{\mathrm{Amax}} \leq 4.6$ kVA, for example.

It should be noted that the normative standards and regulations do not cover the overall issue of persistent TOVs to a satisfactory degree, when it comes to the protection and continuous operation of facilities and devices.

IV. EVALUATION

As mentioned in the previous section, asymmetric load configurations are limited via their corresponding power factors. In the example of Fig. 1, the minimum allowable power factor of the load at L2 is $\cos(\varphi_{\mathrm{L2}}) = 0.9$. The power factors at L1 and L3 are $\cos(\varphi_{\mathrm{L1}}) = \cos(\varphi_{\mathrm{L3}}) = 1$. Using Eq. (6), the TOV will then be

$$\frac{V_{\mathrm{TOV,L1}}}{V_{\mathrm{REF}}} = \frac{3 + \sqrt{3} \cdot \tan\left(\frac{\arccos(0.9)}{2}\right)}{2} \approx 1.699 < \sqrt{3}. \quad (8)$$

So, the compliance with NAV before LoN reduces the possible TOVs after the fault to a value that is lesser than the characteristic SPD test values with LoN. In addition, the measurements also support the lesser TOV values compliant with NAV, as can be seen in Fig. 3, while the minimum power factor at which a TOV of $\sqrt{3} \cdot V_{\mathrm{REF}}$ is reached, is

$$\cos(\varphi_{\mathrm{L2}}) = \cos\left(2 \cdot \arctan(2 - \sqrt{3})\right) = 0.866. \quad (9)$$

This limit value also depicts the worst case of TOVs when the absolute values of the impedances Z_{L2} and Z_{L3} are not equal, still referring to the example of Fig. 1. With $k = \alpha, \beta$, the impedance of the load at L3 is expressed as

$$Z_{\mathrm{L3}} = \alpha \cdot Z_{\mathrm{L2}}, \quad (10)$$

$$Z_{\mathrm{L3}} = \frac{1}{\beta} \cdot Z_{\mathrm{L2}}. \quad (11)$$

With k, the TOVs are then depicted in Fig. 6. They are always lesser when the absolute values of the impedances are not equal. A short circuit or an open-phase ($k = 0.0$) of the load at L3 forms the worst case of TOVs within the power factor limits of the NAV of $\sqrt{3} \cdot V_{\mathrm{REF}}$.

When the loads are of a similar type, e. g. when multiple single-phase DER are connected to the grid which operate according to [16], the expected TOVs after LoN decrease drastically. Equal behaviour, depicted with $\cos(\varphi_{\mathrm{L2}}) = \cos(\varphi_{\mathrm{L3}})$, results in a maximum TOV of $1.5 \cdot V_{\mathrm{REF}}$. The corresponding values are shown in Fig. 7.

V. CONCLUSION

The evaluation of TOVs, considering current standards and regulations, shows that no values above the typically mentioned values according to standards like [15] with $U_{\mathrm{T}} = \sqrt{3} \cdot U_{\mathrm{REF}}$ occur. This is valid under the assumption that the asymmetric loads, which could be incorporated by the extensive integration of DERs, are of similar nature and

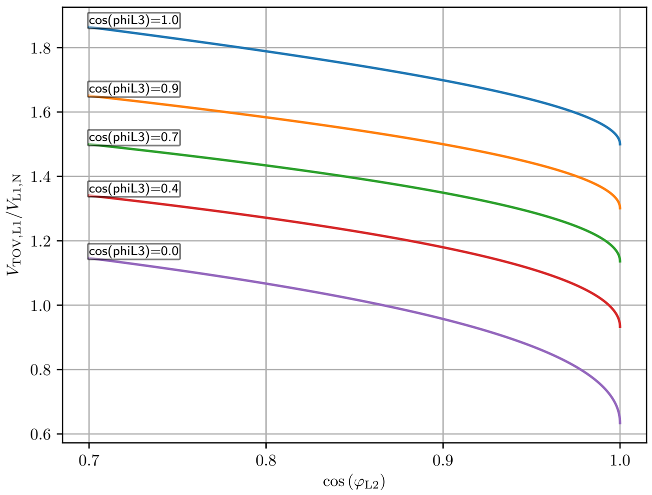


Fig. 7. TOVs with respect to both $\cos(\varphi_{\mathrm{L2}})$ and $\cos(\varphi_{\mathrm{L3}})$.

compliant with [16], among mostly ohmic loads in consumer installations.

As a result, recommendations for the development of existing overvoltage protection principles regarding the protection of devices and facilities do not have to be given. If there are cases of grid connection which could be more critical, the grid operators and the consumer have to ensure a safe and reliable operation according to the NAV, and the TAB, respectively.

In parallel, results from the FNN study, which addresses the impact of asymmetries on the LV distribution grid, are expected to give a further insight on the sufficiency of current standards and regulations.

With the joint project SiNED, the presented results lead to the conclusion, that no investigation on TOVs in LV grids is performed, as their occurrence is not permitted. The impact on the LV grid itself then is not an issue.

REFERENCES

[1] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, and S. G. Srivani, "Protection challenges under bulk penetration of renewable energy resources in power systems: A review," *CSEE Journal of Power and Energy Systems*, vol. 3, no. 4, pp. 365–379, 2017.

[2] T. Runge, T. H. Kopp, and M. Kurrat, "Investigation methods and techniques for plasma characterisation in a spark gap model at surge currents - a review," in *2018 34th International Conference on Lightning Protection (ICLP)*, 2018, pp. 1–6.

[3] Energie-Forschungszentrum Niedersachsen (EFZN), "Sined – systemdienstleistungen für sichere stromnetze in zeiten fortschreitender energiewende und digitaler transformation," 2020.

[4] VDE Forum Netztechnik/Netzbetrieb (FNN), "Lastenheft für fnn-studie zum thema 'unsymmetrie': Name der fnn-studie: 'maximal zulässiger unsymmetrie-grenzwert der bemessungsscheinleistung beim anschluss und betrieb von elektrischen verbrauchsmitteln, ladeeinrichtungen für elektrofahrzeuge, erzeugungsanlagen und speichern für kundenanlagen am öffentlichen niederspannungsnetz'," 2020.

[5] VDE Forum Netztechnik/Netzbetrieb (FNN), "Fnn-studie: Statische spannungshaltung," 2015.

[6] H. Ghoddami and A. Yazdani, "A mitigation strategy for temporary overvoltages caused by grid-connected photovoltaic systems," *IEEE Transactions on Energy Conversion*, vol. 30, no. 2, pp. 413–420, 2015.

[7] M. Clement and J. Michaud, "Overvoltages on the low voltage distribution networks. origins and characteristics. consequences upon the construction of electricite de france networks," in *12th International Conference on Electricity Distribution, 1993. CIRED*, vol. 2, 1993, pp. 2.16/1–2.16/6 vol.2.

[8] F. Chiang, "Implications of temporary overvoltages for insulation coordination for equipment within low-voltage systems," in *2011 IEEE Symposium on Product Compliance Engineering Proceedings*. IEEE, 10.10.2011 - 12.10.2011, pp. 1–6.

[9] Electric Power Research Institute (EPRI), "Effects of temporary overvoltages on residential products: System compatibility research project," Palo Alto, CA, 2005.

[10] A. Kalyuzhny, "Analysis of temporary overvoltages during open-phase faults in distribution networks with resonant grounding," *IEEE Transactions on Power Delivery*, vol. 30, no. 1, pp. 420–427, 2015.

[11] DIN VDE 0100-520, "Low-voltage electrical installations – part 5-52: Selection and erection of electrical equipment – wiring systems (iec 60634-5-52:2009, modified + corrigendum feb. 2011); german implementation hd 60634-5-52:2011," 2013.

[12] DIN EN 60335-1, "Household and similar electrical appliances – safety – part 1: General requirements (iec 60335-1:2010, modified + cor1:2010 + cor2:2011 + a1:2013, modified + a1:2013/cor1:2014 + a2:2016 + a2:2016/cor1:2016): German version en 60335-1:2012 + ac:2014 + a11:2014 + a13:2017 + a1:2019 + a2:2019 + a14:2019)," 2020.

[13] A. Mansoor and F. Martzloff, "The dilemma of surge protection vs. overvoltage scenarios: implications for low-voltage surge-protective devices," in *8th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No.98EX227)*. IEEE, 14-16 Oct. 1998, pp. 964–969.

[14] M. V. Lat, "Determining temporary overvoltage levels for application of metal oxide surge arresters on multigrounded distribution systems," *IEEE Transactions on Power Delivery*, vol. 5, no. 2, pp. 936–946, 1990.

[15] IEC 61634-11, 2011, low-voltage surge protective devices – Part 11: Surge protective devices connected to low-voltage power systems – Requirements and test methods.

[16] VDE-AR-N 4105, "Generators connected to the low-voltage distribution network – technical requirements for the connection to and parallel operation with low-voltage distribution networks," 2018.