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Sensitivity analysis of the Electrical Stresses in Mechanically Switched Capacitors with Damping Network due to Components' Tolerances

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Abstract. In this paper, the influence of the tolerances of the components on the steady-state electrical stresses of Mechanically Switched Capacitors with Damping Network (MSCDN) is assessed. For this purpose, a sensitivity analysis for 380-kV-connected MSCDNs with different quality factors and tuning frequencies is carried out. For the calculations, the level of harmonics defined in IEC 61000-3-6 has been considered. The calculations are based on simulations using ideal models of the MSCDN's components.

Key words

Mechanically Switched Capacitor with Damping Network, C-type filter, quality factor, reactive power, MSCDN.

1. Introduction

Mechanically Switched Capacitors with Damping Network (MSCDN) are a very common solution to cover the reactive power demand in the transmission network. Its main advantage in comparison with other reactive power compensation equipment like FACTS is its low investment costs. The four basic components represent the major part of the costs:

- Main capacitor C_1
- Filter capacitor C_2
- Filter reactor L
- Damping resistor R_D

The ratings of these four components and so their respective purchasing costs are dependent, among others, on the voltage and current they have to withstand.

On the one side, the MSCDN has to be understood as a system in which a modification in one of its components has an influence on the others. This is especially true for the electrical stresses of the components.

On the other side, the components are not ideal elements. Due to the manufacturing process, the temperature variation, the aging or simply because they are assembled by putting smaller elements together like e.g. the capacitor banks, their properties vary within certain tolerances.

The tolerances in the electrical properties like the capacitance of the capacitors, the inductance of the filter reactor, the resistance of the damping resistor have an influence on the electrical behaviour of MSCDN and, consequently, on the electrical stresses of the component itself and on the other components.

Fig. 1: Photo of a Mechanically Switched Capacitor with Damping Network connected to the German 380-kV-network.

This paper presents the results of a sensitivity analysis of the electrical stresses regarding the tolerances of the basic electrical properties of the MSCDN's components. This sensitivity analysis is done on MSCDNs with different quality factors and tuning frequencies. The results are restricted to steady-state electrical stresses.

2. Influence of component tolerances

MSCDNs are based on the topology of C-Type filters. As already mentioned, a MSCDN consists of four components that are electrically connected as shown in Fig. 2.

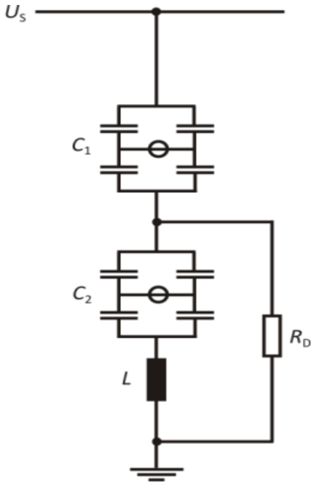

Fig. 2. Typical single-line diagram of a MSCDN [1].

The value of C_1, C_2, L are unequivocally defined by the required reactive power Q_r , the nominal voltage U_n at PCC, the selected tuning frequency f_t and the nominal frequency of the power system f_n. The mathematical relations are given in [1] and [2].

The tolerances of these three elements cause a detuning of the MSCDN. This detuning influences the electrical behaviour of the MSCDN. The magnitude of this influence considerably depends on the considered frequency.

The effect is amplified when the three components C_1, C_2, and L simultaneously have either a higher or a lower value than the one derived from the mathematical equations. In this case, the minimum impedance of the MSCDN deviates from the tuning frequency. For higher values of the components, the tuning frequency moves to lower frequencies and vice versa. This effect can be seen in Fig. 3. Furthermore, the LC_2-branch is not 50-Hz-resonant anymore. Consequently, the damping resistor suffers a voltage drop with resulting power losses even in a pure sinusoidal power system.

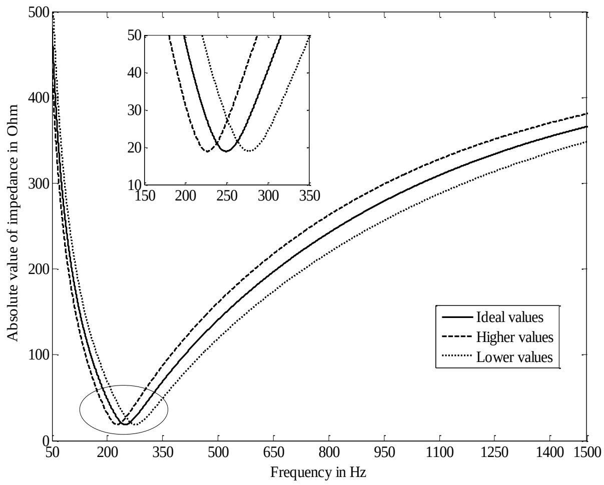

Fig. 3 Modification of the MSCDN's frequency response due to tolerances of ±10% for C_1, C_2 and L.

The resistance of the damping resistor R_D can also vary within a certain band. The main reason for the modification is the variation of its temperature.

In contrast to the other components, the resistance of R_D is not unequivocally defined by any mathematical equation. Its value is normally chosen as a compromise among different properties that are strived for when designing a MSCDN. Some of them are the maximization of the filtering capacity, the avoidance of resonances and the minimization of electrical stresses [3].

Normally, the selected value of the resistance strongly varies depending on the MSCDN's ratings. In order to normalize the value of this resistance which expresses the influence on the MSCDN independently of its ratings, the concept of quality factor q is introduced. The definition and its derivation are contained in [4, 5].

Higher values of q, and so of R_D, increase the impedance of the MSCDN for frequencies higher than a certain transition frequency f_{trans} [5]. This frequency is a property of every MSCDN, considering typical values of q, and can be defined as the frequency for which the R_D has no influence on the absolute value of the MSCDN's impedance. In this definition, the nominal frequency f_n is naturally excluded. For frequencies lower than f_{trans}, higher values of q have the opposing effect. Exactly the opposite can be said for lower values of q. Fig. 4 shows the effect of modifications of q due to possible tolerances of R_D.

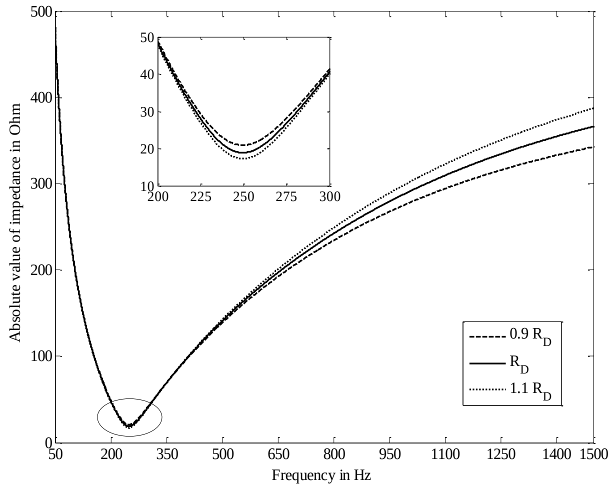

Fig. 4 Modification of the MSCDN's frequency response due to tolerances of ±10% for R_D.

From this figure it can be drawn that the effect of the tolerances is very dependent on the considered frequency. For high frequencies, the effect of R_D increases. By contrast, the influence is very small or even zero for low frequencies.

3. Calculation of electrical stresses

As already mentioned in chapter 2, the changed electrical behaviour of the MSCDN caused by the component tolerances strongly depends on the considered frequency. Consequently, the electrical stress caused by a certain harmonic voltage or current also varies depending on its order. Moreover, the influence can have an opposing effect on two different components.

The most interesting question from the engineering point of view is to analyse how robust the calculations of the electrical stresses of the components are. Since the tolerances can only be reduced at a high cost, it is important to know if they strongly increase the electrical stresses. In such a case, it could be sensible, from both an economical and technical perspective, to reduce them. This strategy could be followed for only those components whose electrical stresses are very sensitive to the tolerances.

For this purpose, the calculation of maximum and minimum electrical stresses of each component for a determined tolerance band will be carried out.

The analysis is performed for a 300-MVar-MSCDN connected to the 380 kV-network. In order to evaluate the influence of q and $f_{t,}$ on the sensitivity of the calculated electrical stresses against component tolerances, all the simulations are carried out for MSCDNs with a quality factor and tuning frequency range within 0,1-100 and 100-250 Hz, respectively.

A. Assumptions and modelling

For the calculations, the tolerance band of each component is considered to be ±5% of its rated value. The calculations are performed for all the possible permutations that appear by modifying each of the four components independently of each other by 1% ($11^4 \approx 14.000$).

The method to calculate the electrical stresses in each component caused at a given frequency is explained in detailed in [1]. The calculation of these electrical stresses is made with a model based on lossless elements. Parasitic effects like the inductance of the damping resistor are not taken into account.

The rated rms voltage and current for steady-state operation will be defined by the equation (1) and (2), respectively. These definitions are common practice in the industry [6].

$$U = \sum_{i=1}^{n} U_i \quad (1)$$

$$I = \sqrt{\sum_{i=1}^{n} {I_i}^2} \quad (2)$$

U_i is the voltage drop and I_i is the current caused by the i^{th}-harmonic in the single components.

From now on, these values will be considered the steady-state electrical stresses of the components.

The level of harmonics used to calculate voltage and current stresses is taken from standard IEC 61000-3-6 [7]. As a conservative approach, a planning level will be created by selecting the indicative values for each harmonic in EHV networks using a simultaneity factor of 1.

The resulting Total Harmonic Distortion (THD) is 5,02% and obviously exceeds the corresponding $THD_{HV\text{-}EHV}$ of the planning levels.

The network is modelled as a Thévenin equivalent consisting of a voltage source that contains the abovementioned level of harmonics, in series with a frequency-dependent impedance. The chosen value for this series impedance is:

$$\underline{Z}(h) = (R_{50\,\text{Hz}} + \text{j}X_{50\,\text{Hz}})(1 + h) \quad (3)$$

With $R_{50\,\text{Hz}} = 0{,}5\ \Omega$ and $X_{50\,\text{Hz}} = 5\ \Omega$.
Being h the order of the considered frequency.

These values are a generalization of different measurements carried out in the German 380-kV-network. Network resonances are excluded, since they strongly vary depending on the location of the substation.

B. Results of the numerical simulations

Fig. 5 shows the maximum and minimum variation of electrical stresses of C_1 with respect to MSCDNs without tolerances. These bands are given for different tuning frequencies and quality factors.

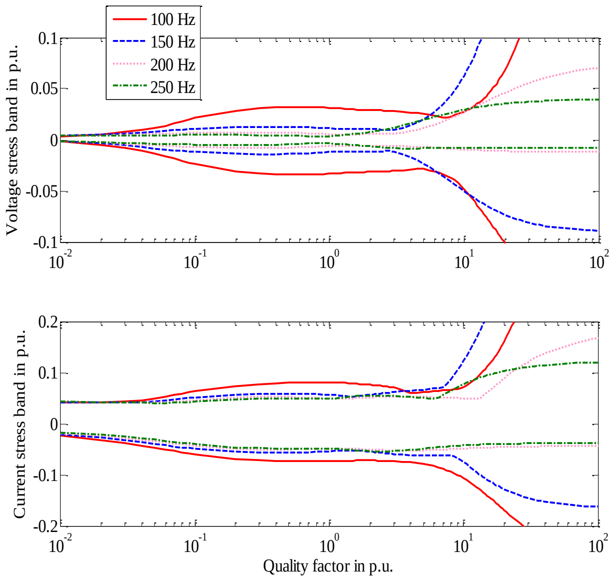

Fig. 5 Electrical stress bands for C_1 versus quality factor for different tuning frequencies. Component tolerances of ±5%.

The results show that considerable component tolerances do not cause a substantial increase of either the current or the voltage stress. The influence on the voltage and current stress remain within ±5% and ±10%, respectively. The only exceptions are those MSCDNs with high q-values.

When high q-values are combined with low resistances of the network impedance around the tuning frequency of the MSCDN, voltage and current stresses caused by those harmonics are amplified. These voltages and currents are very sensitive to variations of the electrical behaviour of the components and, since they represent a considerable part of the electrical stresses, the electrical stresses also become very sensitive. This effect will be also seen in calculations with other components.

Fig. 6 and Fig. 7 show the band of the electrical stresses for C_2 and L, respectively. The maximum influence on the current stress is comparable to the one of C_1 for both components. However, the upper limit of voltage stress doubles with respect to C_1 and reaches a value of 10% for both components for q-values lower than 10.

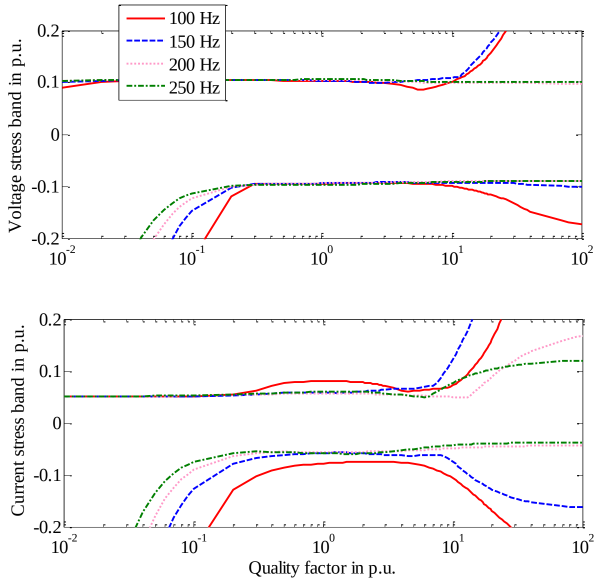

Fig. 6 Electrical stress bands for C_2 versus quality factor for different tuning frequencies. Component tolerances of ±5%.

Similarly to C_1, the upper voltage limit increases for *q*-values higher than one. The reason is the same that has been as for C_1.

In contrast to the results of C_1, the lower band considerably increases for very low *q*-values. For these values, the LC_2-branch is almost short-circuited due to the low values of R_D. Therefore, in this situation small increases of R_D reduce both voltage and current stresses, significantly.

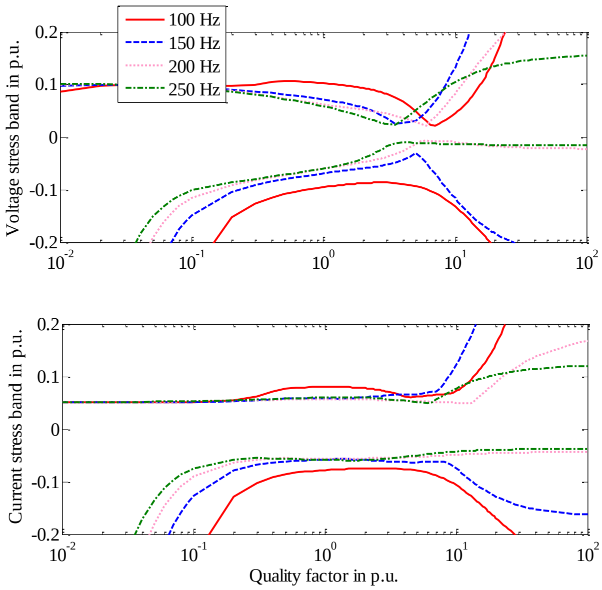

Fig. 7 Electrical stress bands for *L* versus quality factor for different tuning frequencies. Component tolerances of ±5%.

Fig. 8 shows that the increase of electrical stresses at R_D due to component tolerances is higher than in the other components. The effect appears in MSCDNs with both high and low *q*-values. In MSCDNs with low *q*-values, the main reason is the detuning of the parallel LC_2-branch at 50 Hz. This detuning induces a voltage drop and consequently a current at the resistor which do not exist for MSCDNs without tolerances.

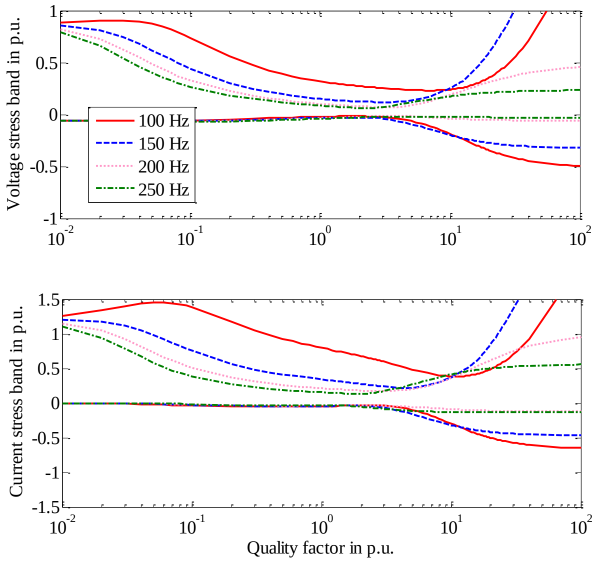

Fig. 8 Electrical stress bands for R_D versus quality factor for different tuning frequencies. Component tolerances of ±5%.

For the damping resistor, it is also interesting to analyse how robust the calculation of losses is, since this variable represents one of its most important limitations. As it can be seen in Fig. 9, the sensibility of losses related to the tolerances is significantly higher than for all the other analysed variables. For 100-Hz-tuned MSCDNs, the maximum losses can be 100% higher than for the MSCDN without tolerances even for a common *q*-value range.

Consequently, it can be pointed that a careful consideration of the possible component tolerances while calculating the electrical stresses of the damping resistor is unavoidable.

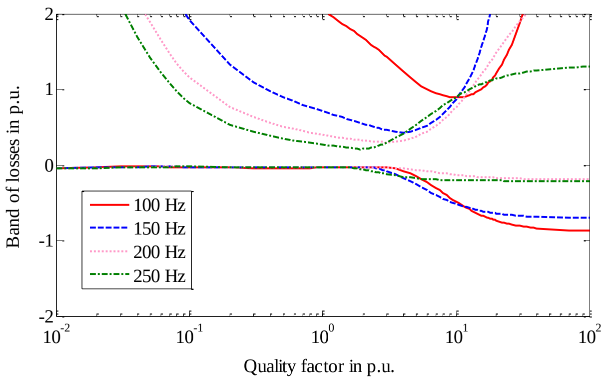

Fig. 9 Band of losses at R_D versus quality factor for different tuning frequencies. Component tolerances of ±5%.

4. Conclusion and further works

The analysis has shown that extreme q-values should be avoided in order to reduce the effect of tolerances on the steady-state electrical stresses of the components. Otherwise, an important deviation between the calculations carried out by means of ideal MSCDN models and actual values have to be expected.

We can also state that, for q-values lower than 10, the calculation of the electrical stresses using models of MSCDN without tolerances is between 5-10% lower than with models using component tolerances of ±5% for the main capacitor C_1, the filter capacitor C_2 and the filter reactor L. This statement is true regardless the selected tuning frequency.

For high q-values, the rise of the electrical stresses for the three elements can be considerable, if the resistive effect of the network around the tuning frequency is small.

Qualitatively, the sensibility of voltage stresses is higher for L and C_2 than for C_1, whereas the current stress sensibility is approximately the same for the three components.

Regarding the damping resistor R_D, a high sensibility due to the component tolerances should be expected. Electrical stresses can be even 150% higher when component tolerances are considered. Losses in the resistor are even more sensitive. Moderate values of q temper the effect of tolerances but they are still high in comparison with the other components.

A sensitivity analysis of the MSCDN's transfer function of the MSCDN would be interesting in order to assess the impact of tolerances on energisation. Through this analysis, the influence of the component tolerances on transient electrical stress could be quantified.

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