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STUDY OF FERRORESONANCE PHENOMENA IN HV POWER NETWORKS

Analysis of ferroresonance phenomena in high voltage (HV) power networks is presented in this paper. The adequate digital simulation model for investigation of ferroresonance oscillations in MATLAB/Simulink program was developed. In the paper HV power system configuration with circuit breaker grading capacitors was described and analyzed. The phase as well as open delta VT voltages and their spectra were considered as signals for ferroresonance detection. Additionally, the possibility of ferroresonance oscillations suppression was also studied.

1. INTRODUCTION

The ferroresonance oscillations may occur in configurations where a nonlinear inductance (e.g. representing magnetizing branch of a voltage transformer, VT or CVT, power transformer, etc.) is connected to the power system capacitance (e.g. capacitance of cable or transmission line, reactive power compensation capacitor bank, circuit breaker grading capacitors, etc.), [1, 2]. The series (voltage) ferroresonance arises when capacitance is series connected to the nonlinear inductance, while the parallel (current) ferroresonance takes place for parallel configuration of capacitance and the nonlinear inductance. These nonlinear phenomena can occur in ungrounded or grounded neutral systems, both in medium voltage and high voltage power networks. Typical power system configurations, where ferroresonance oscillations are highly likely, are presented in details in [1, 3]. Generally, ferroresonance oscillations can be initiated by even small change of system parameters or during transients, e.g. one- or two-pole switching operations, fuse blowing, transient phase-

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to-ground fault, lightning, transformer switching, loss of system grounding [1, 2]. The ferroresonance phenomenon is complex due to its nonlinearity that brings several steady-state responses, high level of signals (voltage and current) and content of many different frequencies.

Commonly, four types of ferroresonance oscillations may be distinguished, if the spectrum content is taken into account, [1]:

– fundamental mode: the signal waveforms are periodic and their spectra are discontinuous; the signal period is the same as power system period T_1 which means that fundamental frequency component f_1 dominates in signal spectrum that additionally may contain large number of harmonics (e.g. $2f_1$, $3f_1$, ...);
– subharmonic mode: for this condition the signal waveforms are also periodic, whereas the period of signal is a multiple of the system frequency period which brings period equal to nT_1 (n is integer) and frequencies being equal f_1/n; the signal spectrum comprises subharmonics f_1/n (usually odd order, $n = 3, 5, 7$) and fundamental component f_1;
– quasi-periodic mode: the signal is non-periodic for this state and its spectrum is also discontinuous, the frequency spectrum consists of a number of frequencies (at least two components) which corresponds to a linear combination of formula $nf_A + mf_B$ (where coefficients n and m are integers and the ratio of f_A/f_B is a non-integer value); generally, for this mode the fundamental component and subharmonics may occur;
– chaotic mode: for this state the signal waveform is non-periodic and its spectrum is continuous in broad band – in the other words it looks like high level of noise contained in frequency spectrum.

The ferroresonance phenomenon can be recognized by frequency spectrum analysis of voltage and current signals as well as Poincaré map or phase plane diagram.

It can be concluded that non-linear oscillations can be characterized by overvoltage, overcurrent and waveform distortions (by subharmonic and higher frequencies). This disturbance may be dangerous for power system elements because it increases the thermal (by overcurrent) and electrical (by overvoltage) stresses that may destroy VTs or other equipment as well as distort voltage and current measurement, which may affect the protection operation.

The problem with ferroresonance oscillation in power systems has not been solved yet due to its complex behavior resulting from its non-linear and random nature. Therefore, there is still a need for analysis of ferroresonance phenomena and study of suppression methods of these oscillations.

In this paper results of analysis of ferroresonance oscillations in HV network and typical methods of suppression of this phenomenon are demonstrated. In Section 2, the MATLAB/Simulink digital model of the HV power system to study ferroresonance and analysis of non-linear oscillations results are described. Next (Section 3), selected method of ferroresonance oscillations suppression is presented that is based on introduction of a damping resistance in open delta VT circuit. Lastly, Section 4 presents the conclusions of this work.

2. FERRORESONANCE STUDIES FOR HV POWER SYSTEM MODEL

Typical HV power system configuration, where ferroresonance oscillations are highly likely, comprises circuit breaker grading capacitors and inductive voltage transformers connected in parallel with zero sequence network capacitance [1, 4]. The grading capacitors are mounted in parallel with each arcing chamber of circuit breaker. The main purpose of use of the grading capacitors is to equalize the voltage distribution across the chambers, which increases the switching capacity of the breaker.

For the analysis of ferroresonance phenomenon a simplified model of HV power system shown in Fig. 1 was developed in ATP/EMTP environment [5]. As one can see, this is an HV network with grounded neutral where VTs are in parallel with the zero sequence network capacitance. In addition, circuit breaker is equipped with grading capacitors in order to increase its switching capacity. The VTs were modeled as three single-phase saturable transformers with voltage ratios assumed $400/\sqrt{3}/0.1/3$ kV/kV. The primary windings of VTs were connected in grounded Wye while the VTs secondary windings were connected in open delta. The VT model includes appropriate nonlinear magnetizing characteristic. The source impedance Z_S was calculated for the short circuit capacity assumed at the level 250 MVA. The ferroresonance under simulation was initiated by opening circuit breaker grading capacitors at $t = 0.2$s.

The value of CB grading capacitance C_g was assumed to be 600 pF while the value of phase-to-ground capacitance C_0 was in the range from 50 pF to 5000 pF in increments of 10 pF.

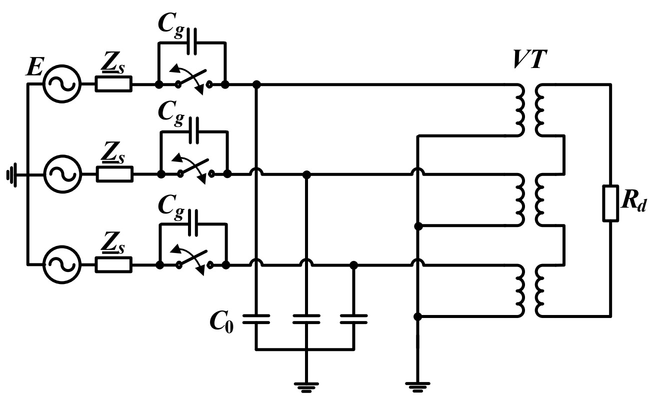


Fig. 1. Basic HV power system for ferroresonance studies – ATP/EMTP model

It is proposed that the ferroresonance oscillations are to be recognized by analysis of spectrum of the voltages in three phases and voltage in open delta VT connection. For this purpose 240-point DFT (Discrete Fourier Transform) was applied. It was assumed that sampling frequency equals 1000 Hz, which means that 240 points (samples) in terms of time correspond to 0.24 s. In such a case the signal spectrum consists of spectral lines regularly spaced at the frequencies distant by 1000/240 = 4.17 Hz. The figures below show the spectra of the voltages in three phases and the voltage in open delta VT connection calculated after opening circuit breaker and for steady-state.

The voltage spectra for cases of opening circuit for assumed range of zero sequence network capacitance C_0 are depicted in Fig. 2. It is clearly seen that ferroresonance oscillations occurred – fundamental frequency component does not only predominate in voltage spectrum after opening circuit breaker but also overvoltage is observed. After analysis of graphs presented in Fig. 2 one can conclude that frequencies of 16.67 Hz, 50 Hz and 150 Hz predominate after ferroresonance oscillations inception (amplitudes of spectral lines are greater than 0.3pu, see especially Fig. 2d). Additionally, in Fig. 3 one can see that what frequencies predominate in the voltage (in open delta VT connection) depends on the value of phase-to-ground capacitance C_0. The frequencies of 50 Hz, 150 Hz and 250 Hz predominate in voltage spectrum for phase-to-ground capacitance between 140 pF to 850 pF (Fig. 3a). Note that according to above definition this is the fundamental ferroresonance because fundamental frequency component and also odd harmonics (especially 3rd) were observed. The frequencies lower than 50 Hz predominate for phase-to-ground capacitance C_0 between 3000 pF to 3400 pF (Fig. 3b) and also in the range from 4160 pF to 4430pF (Fig. 3c). It can be noted that for these values of capacitance C_0 the subharmonic ferroresonance takes place with 3rd subharmonic predominating in voltage spectrum (see Fig. 3c – amplitude of spectral line is the highest for frequency of 16.67 Hz).

Generally, two types of ferroresonance oscillations (fundamental and subharmonic) were observed and the amplitudes of spectral lines (except for the one of 50 Hz) are less than 1.0 pu. It can be noted that for other values of phase-to-ground network capacitance the ferroresonance oscillations are not stable, which means that they have occurred (subharmonic, quasi-periodic and chaotic ferroresonance were observed), however they lasted for very short time and after this the considered HV power system came back to its normal 50Hz steady-state. Such situation is clearly visible in Fig. 4 where chaotic ferroresonance oscillations took place after opening circuit breaker, they lasted for 2.1s and then the system jumped back into its normal 50Hz steady-state. The chaotic mode was recognized since the spectrum of voltage in phase L1 is distributed continuously from 0 to 400 Hz (see Fig. 4).

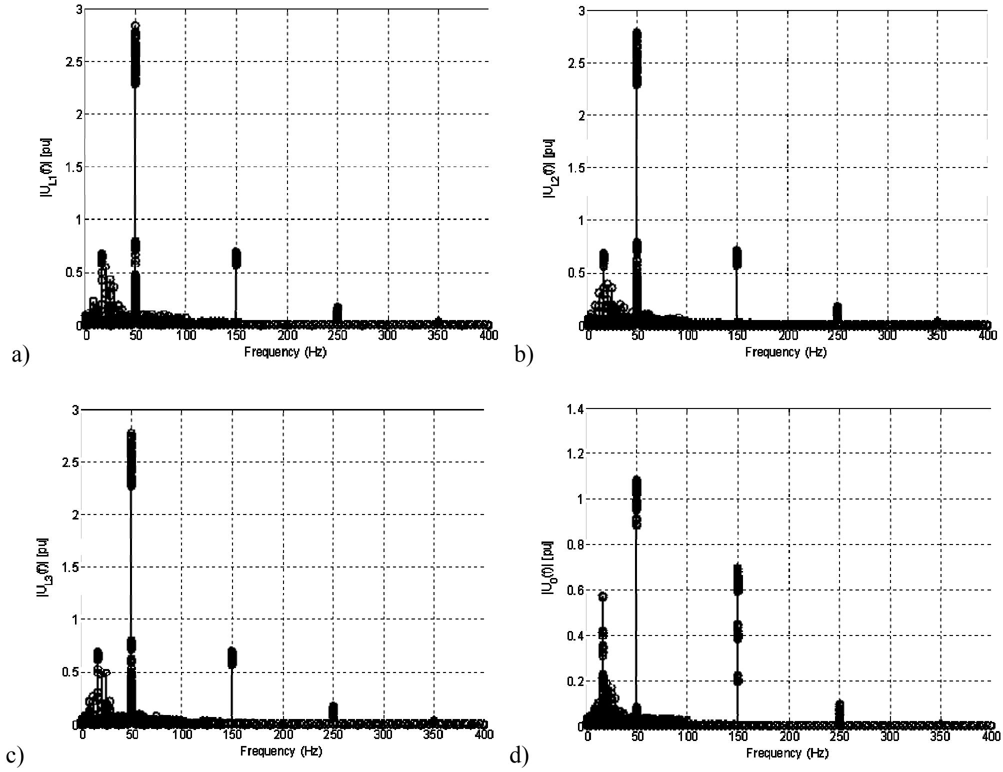
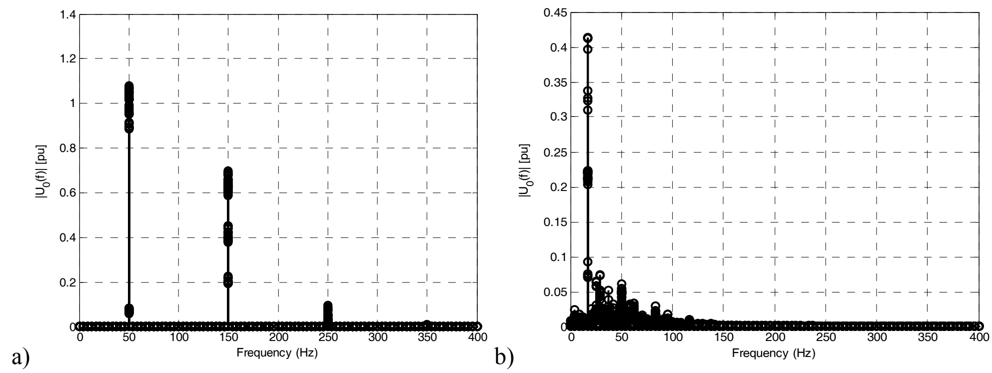
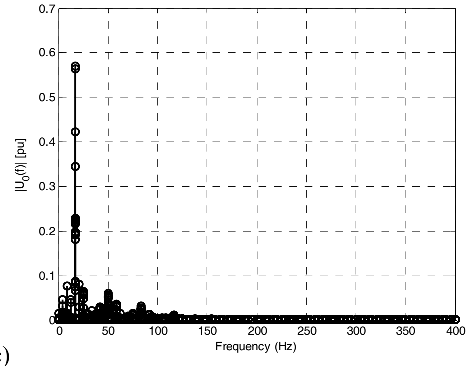


Fig. 2. Spectrum of voltage (after opening circuit breaker): a) in phase L1, b) in phase L2, c) in phase L3, d) in open delta VT connection





c)

Fig. 3. Spectrum of voltage (after opening circuit breaker) in open delta VT connection for: a) phase-to-ground capacitance C_0 between 140 pF and 850 pF, b) phase-to-ground capacitance C_0 from 3000 pF to 3400 pF, c) phase-to-ground capacitance C_0 between 4160 pF and 4430 pF

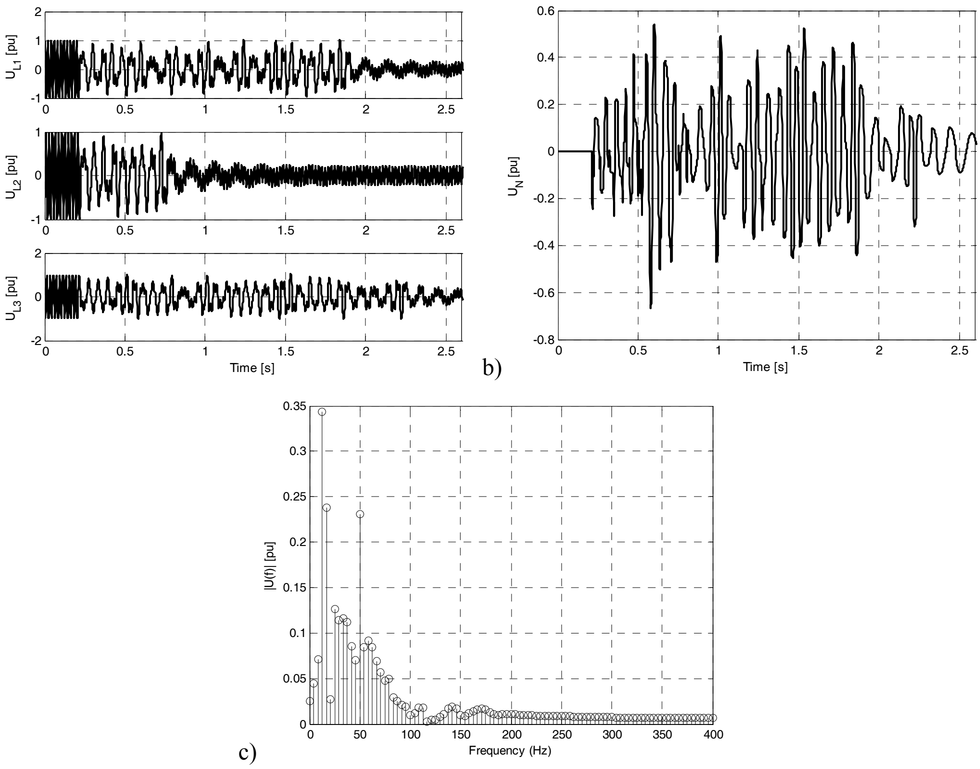


Fig. 4. Case of opening circuit breaker for phase-to-ground capacitance C_0 = 2120 pF: a) three phase voltages, b) voltage in open delta VT connection, c) spectrum of voltage in phase L1

3. SUPPRESSION OF FERRORESONANCE OSCILLATIONS

The possibility of ferroresonance oscillations suppression was also studied and the results are presented in this section. In practice, the ferroresonance oscillations can be suppressed by temporary connection of additional suppressing resistance R_{d1} to the VTs' open triangle (Fig. 5). This method is advantageous since the VTs are thermally stressed only for a short period of time. However, this manner requires an algorithm for detection of ferroresonance oscillations.

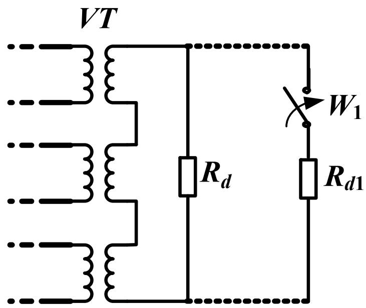


Fig. 5. Method of ferroresonance oscillations suppression

In the literature [6] it is proposed to calculate the value of damping resistance R_{d1} according to the following formula:

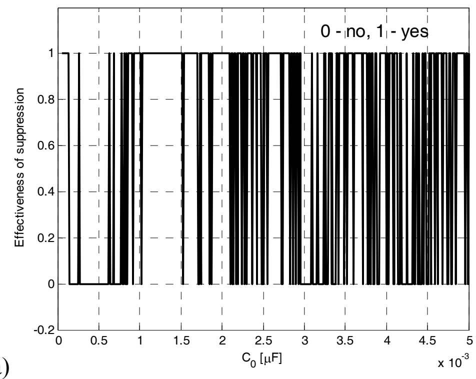
$$R_{d1} = \frac{3\sqrt{3}U_S^2}{P_e} \quad (1)$$

where: U_S – secondary voltage of VT (here: 100/3 V), P_e – rated thermal limit burden. The rated thermal limit burden can be calculated by multiplying the total rated burden of VT (here 100 VA) by square of a so called voltage factor. This voltage factor equals to 1.5 for systems with grounded neutral, while for ungrounded systems it should amount to 1.9 [7]. The suppressing resistance (1) is very simple to calculate since all necessary parameters are easily available.

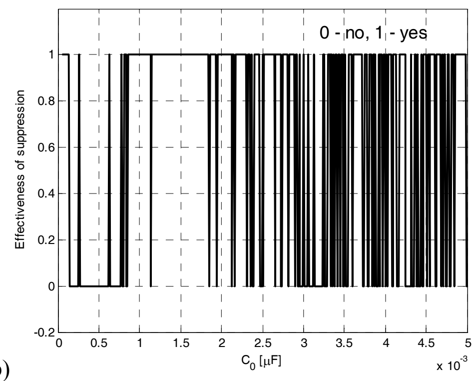
For the considered HV system the damping resistance calculated from (1) was R_{d1} = 26 Ω. This value of resistance was adopted for testing of the proposed suppression method. In addition, closing times (time during which the damping resistance is connected to VTs' open triangle) t_{close} = 0.2, 1.0 and 1.5 s were considered.

The effectiveness of ferroresonance oscillations suppression for cases when ferroresonance was caused by opening circuit breaker is presented in Fig. 6. The presented graphs show that ferroresonance oscillations were not suppressed effectively for the whole assumed range of C_0 (especially for phase-to-ground capacitance between 140 pF to 850 pF, where fundamental mode dominates). It can be concluded that extension of closing time from 0.2 s to 1.5 s did not help much. Therefore, the only way to improve the suppression effectiveness is lowering of the suppressing resistance.

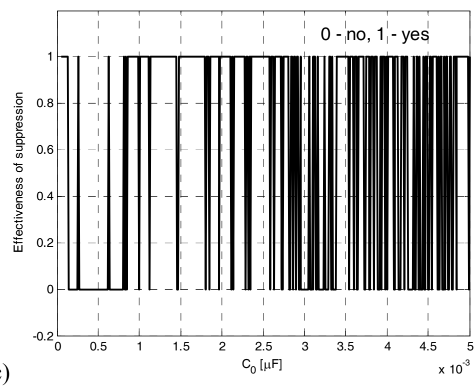
Figure 7 presents the effectiveness of suppression for the same situation as the former one but with suppressing resistance R_{d1} = 0.25 Ω. It can be observed that ferroresonance oscillations were suppressed effectively for nearly whole range of C_0 (it is still problem with suppression of fundamental mode ferroresonance oscillations). Note that for closing time of t_{close} = 1 s the best results were obtained (Fig. 7b).



a)



b)



c)

Fig. 6. Ferroresonance oscillations initiated by opening circuit breaker – effectiveness of suppression vs. C_0 for suppressing resistance R_{d1} = 26Ω and: a) t_{close} = 0.2 s, b) t_{close} = 1 s, c) t_{close} = 1.5 s

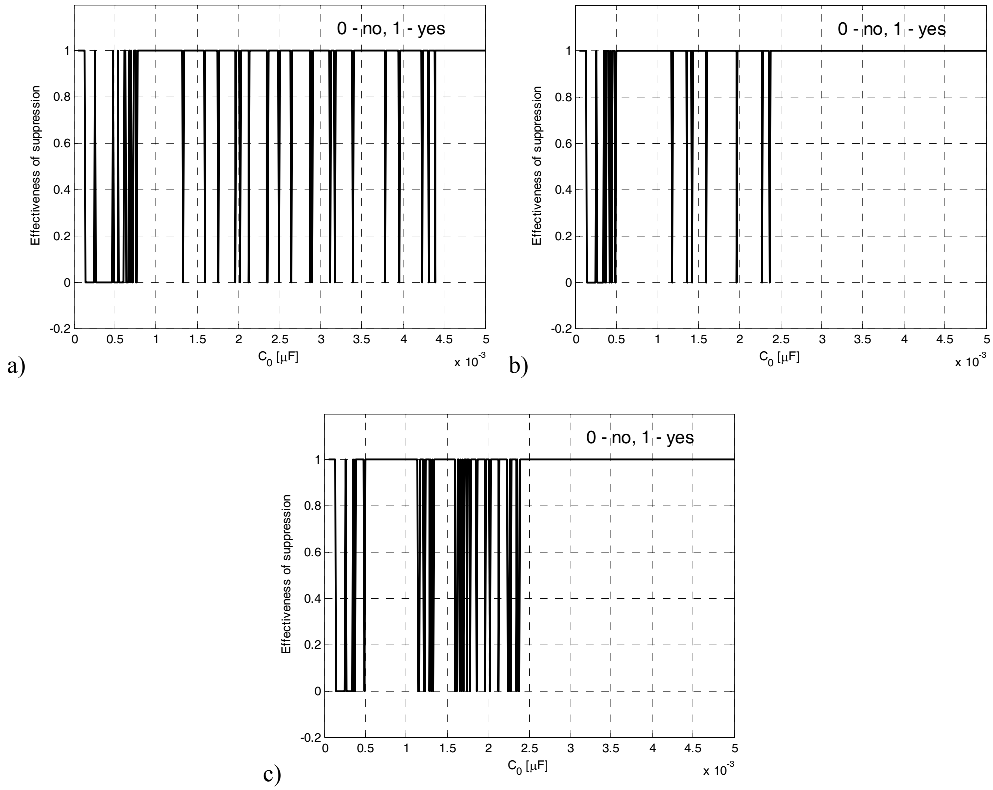


Fig. 7. Ferroresonance oscillations initiated by opening circuit breaker – effectiveness of suppression vs. C_0 for suppressing resistance R_{d1} = 0.25 Ω and: a) t_{close} = 0.2 s, b) t_{close} = 1 s, c) t_{close} = 1.5 s

4. CONCLUSIONS

In this paper the problems with ferroresonance phenomenon in HV grounded neutral systems are described. After analysis of the simulation results it could be noticed that initiation of the ferroresonance oscillations in HV grounded neutral power systems is quite possible. However, it is observed mostly in configurations where VTs are in parallel with the zero sequence network capacitance and the circuit breaker is equipped with grading capacitors. It can be noted that for such configuration of HV power system the fundamental and subharmonic ferroresonance oscillations were observed. In addition, chaotic ferroresonance also took place, however it was characterized as a quickly disappearing transient.

Additionally, the ferroresonance oscillations suppression possibility was studied. The testing results prove that it is difficult to suppress ferroresonance oscillations by temporary switching of suppressing resistance in VTs' open triangle. One can conclude that the most promising results are obtained for very low value of suppressing resistance R_{d1} = 0.25 Ω and closing time of 1.0 s. However, for the assumed suppressing resistance the VTs could be thermally highly stressed, therefore additional studies and/or experiments related to VTs durability for such conditions ought to be performed.

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