# Damping Circuit Design for Ferroresonance in Floating Power Systems

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**Abstract**

*Practical countermeasures to prevent the occurrence of ferroresonance in floating systems are compared. Most attention is paid to the design of practical damping circuits. Existing criteria to determine the necessary ohmic load are evaluated and a new mathematical tool based on harmonic balance is presented. As the damping resistor can cause thermal overload of the voltage transformers, the use of a non-linear damping circuit is advocated in some cases. Therefore, the proposed calculation method is extended to include the effect of non-linear damping.*

## 1 Introduction

Power systems can be operated temporarily or permanently without system grounding. A simplified unloaded network representation with cable connection and voltage transformers (VT) is given in **Fig. 1**.

Switching transients, such as after the clearing of a short circuit, can initiate ferroresonance in this circuit in the absence of adequate damping. This happens when the capacitance to earth of the system ($C_0$) and the non-linear inductance of the voltage transformers fulfill some resonance condition. Contrary to resonance in linear systems, these conditions can apply for a broad range of capacitance values as the value of the inductance depends on the saturation level. Moreover, the non-linear behaviour can cause ferroresonance at different frequencies. Oscillations can occur at the system frequency (fundamental ferroresonance), at fractional values of the system frequency (subharmonic ferroresonance) and with a predominant component at a multiple of the system frequency (harmonic ferroresonance). Quasi-periodic (QP) oscillations and chaos can appear as well. In practical configurations, unbalanced fundamental (UF) and quasi-periodic ferrroresonance with a predominant component at about half the system frequency, i. e. about 25 Hz (QP1/2), are the most observed types of ferroresonant behaviour.

In [1] it has been proven that ferroresonance in this configuration has a zero-sequence nature. Energy to sustain the oscillation is transferred from the direct-sequence to the zero-sequence circuit through the non-linear $\phi$-$i$ relation of the voltage transformers. The zero-sequence phase portrait of UF- and QP1/2-oscillations looks typically as shown in **Fig. 2a** and **Fig. 2b**. The neutral voltage $u_N$ is plotted against the zero-sequence component of the flux linkage $\phi^0$. The point marked with a diamond corresponds to the positive zero-crossing of the voltage of phase L1.

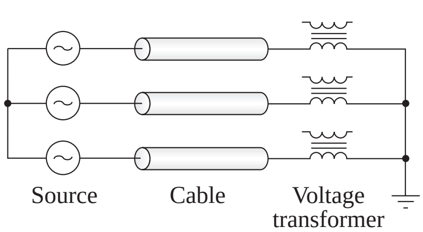


**Fig. 1.** Network representation

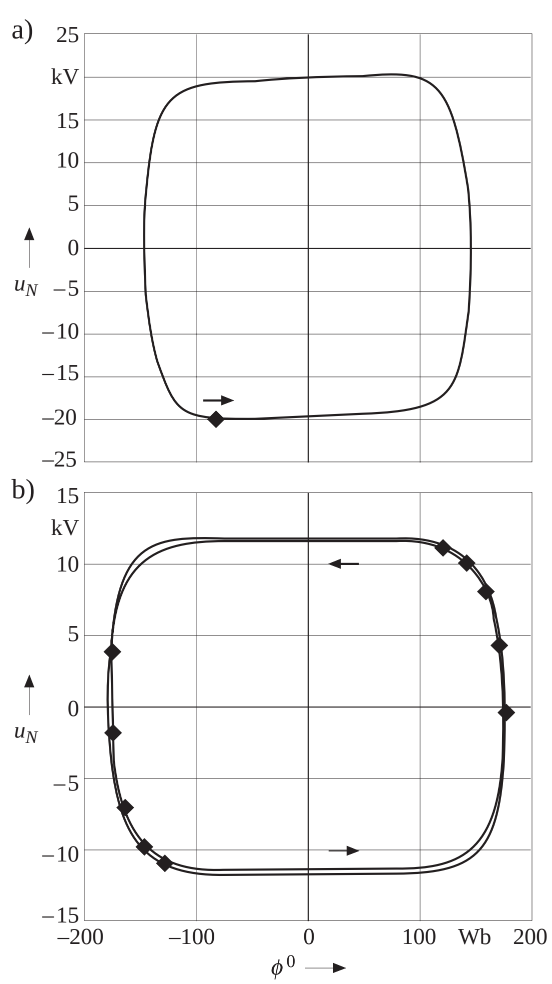


**Fig. 2.** Zero-sequence phase portrait of
a) UF
b) QP1/2

Ferroresonant oscillations are very harmful and should be avoided by all means. The transformers can indeed be totally destroyed by the overcurrents in the windings (thermal destruction) or by excessive overvoltages at the terminals (breakthrough). The operator has two options: he can ensure that the circumstances under which ferroresonance can occur are not fulfilled, or he can anticipate for immediate action when the oscillations start.

## 2 Classification of Countermeasures

The countermeasures can be subdivided in three classes:

- reduction of energy delivered to the zero-sequence circuit,
- detuning of the zero-sequence resonance circuit,
- damping of zero-sequence oscillations.

In [2], two methods to decrease the energy transfer to the zero-sequence circuit are described. These methods consist in increasing the primary resistance and the load connected to the secondary, respectively. Increasing the primary resistance has negative implications for the accuracy of the transformers, whereas the secondary load can become an excessive burden for the windings. The main drawback for both methods is the permanent influence on the direct-sequence circuit. Therefore, both methods have become obsolete.

The detuning of the resonance circuit can also be obtained in two ways. The first way is to increase the capacitance to earth of the system. In [3], the suggestion is made to switch on another cable for this purpose. The questions remain how much extra capacitance one has to place and whether this solution will still be effective when parts of the system are changed.

The other parameter in the resonance circuit, the inductance of the voltage transformers, can be varied by adjusting the nominal induction. In this way, the transformers can remain longer in the linear operating region. From an economical viewpoint, this solution is less appropriate since the production cost of the transformer cores is higher.

The most effective countermeasure is the damping of the oscillations by increasing the zero-sequence losses. In principle, there is no difference whether the damping circuit is placed in the secondary of an auxiliary transformer connected between neutral and earth (**Fig. 3a**), or in the open delta of the secondary (or tertiary) windings of the voltage transformers (**Fig. 3b**). Indeed, neglecting the serial losses, the zero-sequence circuit is identical. Since the solution of Fig. 3a requires an extra transformer (or alternatively a high-voltage resistor), the damping circuit is most often placed in the open delta.

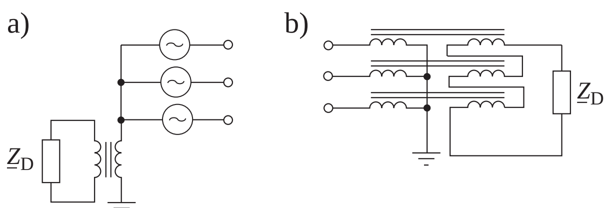


**Fig. 3.** Damping circuit
a) Between neutral and earth
b) In open delta

The damping circuit itself can consist of

- a simple resistor,
- a series connection of an *L*-*C*-filter with a resistor,
- a series connection of a saturable inductor with a resistor.

The use of a damping resistor is the easiest solution, but is not generally applicable. Floating systems may be operated for a longer time under phase-to-earth fault conditions, causing a voltage of three times nominal phase-to-earth voltage in the tertiary delta. Under these circumstances, thermal dissipation can become excessively high. An example will be shown in section 4.

The use of filters is inspired by the fact that the frequency content can be used to distinguish QP$^1/_2$-oscillations from 50-Hz oscillations [4, 5]. The high impedance at 50 Hz reduces the load under phase-to-earth fault conditions, while all oscillations with different predominant components can be satisfactorily damped. Disadvantage however is the need for an extra shunt resistor, since UF oscillations are not damped at all.

A saturable reactor can be used for all oscillations since they share the property of a high delta voltage-time integral, driving the reactor into saturation regardless of frequency content. The reactor can then be considered as a magnetic switch. The design must be accurate with regard to the position of the knee of the magnetisation characteristic, since the impedance should remain high for a phase-to-earth fault.

## 3 Harmonic Balance Method

The system equations can be transformed to the frequency domain, expressing the flux linkages of the non-linear inductances by means of a truncated Fourier series:

$$\phi(t) = \Phi_0 + \sum_{k\in K}\left(\Phi_{k,\cos}\cos(k\omega t) + \Phi_{k,\sin}\sin(k\omega t)\right), \qquad (1)$$

where set $K$ of the harmonic components is selected in accordance with the considered oscillation mode. However, the non-linear characteristic of the voltage transformers cannot be evaluated directly in the frequency domain. Therefore, the Fourier coefficients of the currents $\underline{\boldsymbol{I}}_k^{\mathrm{L1,L2,L3}}$ have to be calculated numerically, using the time evolution of the flux linkages.

The linear part of the circuit can be represented using the generalised Thévenin theorem at all the frequencies $k \in K$. In this way, the harmonic balance method can describe the system with one complex equation per non-linear element for each harmonic component $k$:

$$\mathrm{j}\,k\omega\,\underline{\boldsymbol{\Phi}}_k^{\mathrm{L1,L2,L3}} = \underline{\boldsymbol{U}}_{\mathrm{Th},k}^{\mathrm{L1,L2,L3}} - \underline{\boldsymbol{Z}}_{\mathrm{Th},k}^{\mathrm{L1,L2,L3}}\,\underline{\boldsymbol{I}}_k^{\mathrm{L1,L2,L3}}. \qquad (2)$$

The efficiency of this method primarily depends on the number of harmonics that are needed to approximate


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the steady state with the desired accuracy. Ferroresonant oscillations, especially the periodic ones, can adequately be described with a limited number of harmonics. This has been experimentally validated on a full-scale 15-kV system [6]. Typically, a description including around five to ten harmonics matches the real periodic waveform almost perfectly. For quasi-periodic oscillations, it has been proven in [7] that periodic approximations can result in a good resemblance of the calculated waveform with an instantaneous recording of the real waveform. Applying appropriate DC conditions, the harmonic balance method can therefore be regarded as a snapshot, freezing the slowly oscillating envelope of the oscillation. To obtain a similar accuracy, the description of quasi-periodic oscillations requires a slightly higher number of harmonics (10 to 20), which is still perfectly manageable. Consequently, the harmonic balance method is very well fit to study both periodic and quasi-periodic ferroresonant oscillations.

The system of non-linear algebraic eqs. (2) can easily be solved using a general purpose Newton-Raphson scheme. In this way, the problem is reduced to an algebraic bifurcation problem of the form

$$\boldsymbol{G}(\underline{\Phi}(k), \lambda) = 0, \tag{3}$$

where $\lambda$ is a circuit parameter (e. g. the system voltage).

It is well-known that the Jacobian $\boldsymbol{J}$ of this system becomes singular at limit (or turning) points and at transcritical and pitchfork bifurcation points [8, 9]. Thus, the stability domains of the ferroresonant oscillations can be determined by adding the following equation

$$\det(\boldsymbol{J}(\underline{\Phi}(k), \lambda)) = 0, \tag{4}$$

and freeing a second parameter for the continuation (e. g. the capacitance of the circuit or the value of a damping resistor) [10]. A major advantage of this method is the ease with which the model of the linear circuit can be extended. The analytical derivation of the system equations and the corresponding Jacobian are given in [7].

The method will be applied to design a damping circuit in some practical cases.

## 4 Comparison of Damping Resistor Criteria

In most practical configurations, the QP1/2-ferroresonance is more critical in the determination of the damping resistor than any other type of ferroresonance. Therefore, the stability domains of these QP1/2-oscillations must be investigated with respect to the influence of the damping. This calculation can then be followed by a control calculation for the other oscillations.

Several authors have proposed rules of thumb to determine the critical resistance. These rules intend to link a known transformer parameter to the ohmic value of the resistor. In [11], the advice is given to place the minimal resistance which is consistent with the rated thermal dissipation $P_{th}$ for phase-to-earth faults:

$$R_{Da} = \frac{3(U_{nom}/N)^2}{P_{th}}, \tag{5}$$

where $N$ is the transformer ratio.

| | VT1 (6.6 kV) | VT2 (6.6 kV) | VT3 (15 kV) | VT4 (110 kV) |
|---|---|---|---|---|
| $R_{Da}$ | 48 Ω | 27 Ω | 35 Ω | 8 Ω |
| $R_{Db}$ | 400 Ω | 450 Ω | 250 Ω | 30 Ω |
| $R_{Dc}$ | 32 Ω | 30 Ω | 38 Ω | 2 Ω |
| $R_D$ | 65 Ω | 35 Ω | 35 Ω | 1 Ω |

**Tab. 1.** Comparison of damping criteria a, b and c

Other authors have proposed to use the transformer inductance. Because of the non-linear $\phi$-$i$ characteristic the question arises how to determine a relevant inductance value. In [12], the unsaturated reactance $X_h$ experienced from the high-voltage (HV) side of the transformer, is chosen as criterion:

$$R_{Db} = \frac{X_h}{N^2}. \tag{6}$$

This value is easy to obtain, but is physically irrelevant since the cores are heavily saturated during ferroresonance. Using harmonic balance it can easily be verified that the variation of $X_h$ has only a limited effect on the stability domains. Therefore, eq. (6) cannot be a general criterion to determine $R_D$.

More relevant is the use of the air core inductance $L_{air}$ seen from the HV side, as advocated in [13]. This implies the hypothesis that the core is fully saturated during ferroresonance.

$$R_{Dc} = 122\,000\,\frac{L_{air}}{N^2}. \tag{7}$$

This value is difficult to obtain with measurements, but can be approximated by theoretical calculation.

In **Tab. 1**, a comparison is made between the different criteria for four voltage transformers. The value on the last row is determined with the harmonic balance method. The stability domain of the QP1/2-oscillation is shifted above the nominal voltage line by decreasing the resistance. This is shown in **Fig. 4** for the transformer marked VT1.

The harmonic balance method shows that none of the three criteria a, b and c is generally applicable. Criterion b underestimates the necessary load in all cases, whereas criteria a and c can only be considered as a rough estimate. The conclusion should be that extrapolation of results for one type of transformer to another is very dangerous. The availability of a tool based on harmonic balance makes the use of these criteria obsolete.

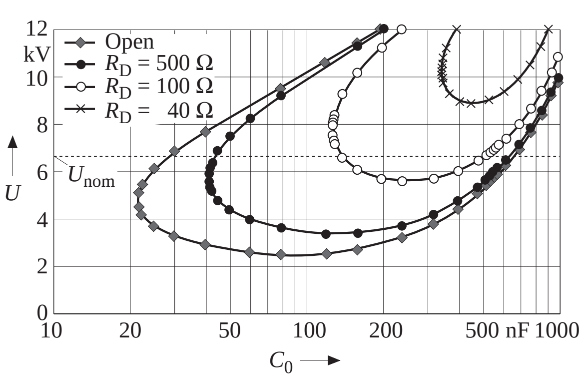


**Fig. 4.** Stability domains of QP1/2 ferroresonance for several values (parameter) of $R_D$ (VT1)

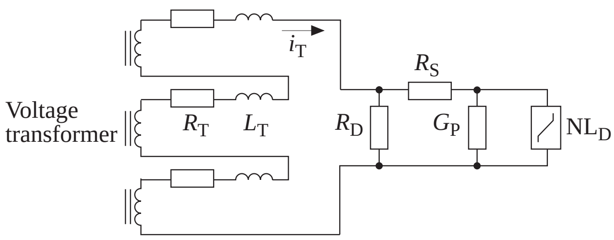


**Fig. 5.** Damping circuit with saturable reactor

A closer look to Tab. 1 learns that even the minimum allowed resistance does not guarantee a safe operation for VT4. In such a case one has to design a non-linear damping circuit.

## 5 Non-Linear Damping Circuit

The damping circuit with saturable reactor placed in the tertiary delta is shown in **Fig. 5**. A similar circuit has already been used to damp one-phase ferroresonance [8]. The reactor model consists of a series resistance $R_S$, a parallel conductance $G_P$ to take the iron losses into account and a non-linear magnetisation characteristic $NL_D$. A shunt resistor $R_D$ can supply additional damping. The system equations can then again be formulated, including the terminal behaviour of the non-linear inductance. Its flux-linkage components are added to the vector of unknowns.

The design of the reactor must start from the highest voltage appearing at the open delta. The knee of the magnetic characteristic is positioned just above the corresponding flux linkage. For a given core, this corresponds to the determination of the optimum number of windings $N_D$. A second step in the procedure is the optimisation of the series resistance $R_S$. This can be done by performing calculations with $R_S$ as continuation parameter in order to maximise the damping losses.

**Fig. 6** compares the results for VT4 with damping resistor and non-linear damping circuit. The voltage is referred to the tertiary winding ($U_{nom} = 100\,V/\sqrt{3}$). The damping caused by a resistor of 5 Ω, which is already unacceptable from a thermal point of view, is clearly insufficient. A damping reactor without shunt resistor is much better suited to damp the ferroresonant oscillations for capacitances above 10 nF. However, the stability border drops well below nominal voltage on the left side. The reason for this is that the oscillations are less pronounced for very low capacitances. This makes that the reactor is only moderately saturated and thus less damping is obtained. As can be seen in Fig. 6, this is exactly the region where a resistor has a big influence on the position of the stability border. In this case a parallel combination of resistor and non-linear reactor seems to be the best damping device.

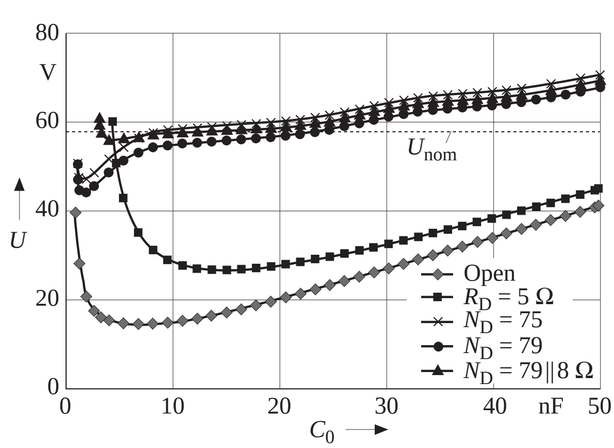


**Fig. 6.** Stability domains of QP1/2 ferroresonance with different damping circuits (VT4)

## 6 Conclusions

The harmonic balance method has proven to be an excellent method to study ferroresonance in floating systems. The stability domains of the different oscillations types can easily be determined with a continuation procedure. This enables us to study the effect of damping circuits in an automated way without having to perform numerous tedious simulations or to rely on uncertain criteria. In most cases the use of a simple damping resistor is sufficient to damp all ferroresonant oscillations. If the thermal dissipation is a constraint, a non-linear damping reactor can be used. With the correct damping device placed in the open delta of the tertiary windings, the occurrence of ferroresonance in floating systems can be avoided.

## 7 List of Symbols and Abbreviations

| | |
|---|---|
| $C_0$ | capacitance to earth |
| $\boldsymbol{G}$ | algebraic system of equations |
| $i$, $\underline{\boldsymbol{I}}$ | current in non-linear element (time- and frequency domain) |
| $\boldsymbol{J}$ | Jacobian |
| $k$ | harmonic number |
| $L_{air}$ | air core inductance |
| $N$ | transformer ratio |
| $N_D$ | number of windings in damping reactor |
| $P_{th}$ | thermal dissipation |
| $R_S$, $G_P$ | series resistance and parallel conductance of damping reactor |
| $R_T$, $L_T$ | tertiary resistance and inductance |
| $R_D$, $\underline{Z}_D$ | damping resistance and impedance |
| $t$ | time |
| $U$ | phase-to-phase rms voltage |
| $u_N$ | neutral voltage |
| $U_{Th}$ | Thévenin voltage |
| $X_h$ | unsaturated reactance |
| $\underline{\boldsymbol{Z}}_{Th}$ | Thévenin impedance |
| $\lambda$ | system parameter |
| $\phi$, $\underline{\boldsymbol{\Phi}}$ | flux linkage in non-linear element (time- and frequency domain) |
| $\phi^0$ | zero-sequence component of flux linkage |
| $\omega$ | angular frequency of the power system |
| | |
| a, b, c | damping-criteria notation |
| L1, L2, L3 | phase notation |
| nom | nominal |
| $NL_D$ | non-linear damping characteristic |


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QP quasi-periodic
Th Thévenin
UF unbalanced fundamental
VT voltage transformers

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