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Internal short-circuits faults localization in transformer windings using FRA and natural frequencies deviation patterns

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Outline

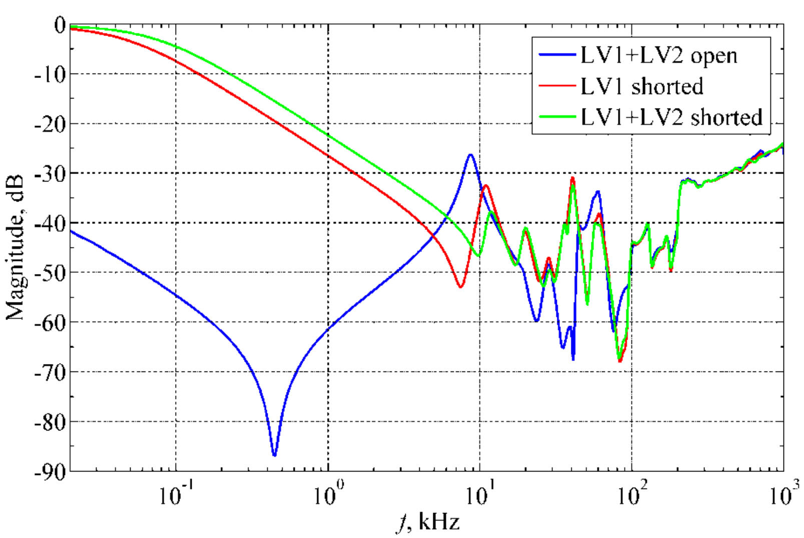
- Introduction
- Determination of winding natural frequencies
- Determination of internal winding short-circuit faults
- Localization of internal winding short-circuit faults
- Conclusion

Introduction

- FRA interpretation is usually performed by comparison between the measured frequency responses using correlation analysis and various indices, showing a difference of frequency responses in a wide frequency range (e.g., DL/T 911).
- DL/T 911 strictly set the three frequency ranges (0 – 100 kHz, 100 – 600 kHz and 600 – 1000 kHz) without regard to the type of winding and the typical values of its natural frequencies.
  - first natural frequency of continuous disc-type HV windings is typically ~10-40 kHz; few first natural frequencies are located in 1st frequency range;
  - first natural frequency of helical and multilayer LV windings can be ~200-300 kHz; few first natural frequencies are located in 2nd and 3rd frequency ranges.
- FRA interpretation can be made in another manner on the basis of winding natural frequencies and its deviations.

Determination of winding natural frequencies (1)

- Frequency response of the winding contains a set of resonance frequencies related to interaction between windings and winding natural frequencies.
- Natural frequencies can be identified by the comparison of the winding frequency responses measured with open and shorted secondary winding as well as analysis of winding active admittance calculated from amplitude and phase of frequency responses.



- Spatial distribution of winding current at first natural frequencies has nodes in which the current changes direction.
- EMF induced in the turns of the secondary winding are mutually compensated, and the magnetic flux generated by the primary winding penetrates the magnetic core.
- Thus, the short circuit of secondary winding has practically no effect on the natural frequencies and admittance of primary winding at the frequencies corresponding to natural frequencies of primary winding.

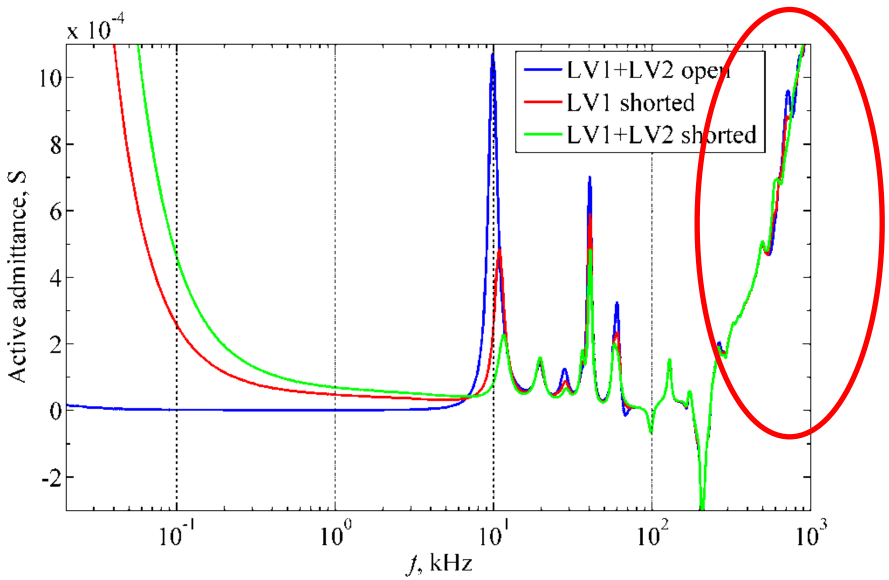
Determination of winding natural frequencies (2)

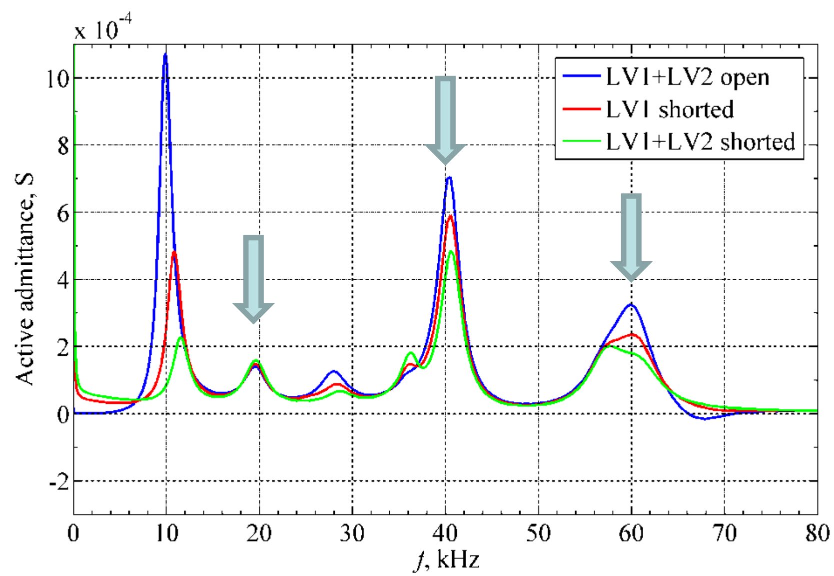
- Identification of natural frequencies can be done by means of evaluation of local maxima of real part of input admittance (active admittance) of fed winding as indicator of reaching the local maxima of consumed active power at resonant frequencies.
- The presence of the parasitic capacitance C_s (bushing, lead etc.) connected at the same point as measuring impedance causes an general error of evaluation of admittance from FRA which is increasing with the growth of frequency:

$$\bar{Y}_{12} = \left(\frac{1}{Z_c} + j\omega C_s \right) \frac{\overline{U}_2}{\overline{U}_1 - \overline{U}_2} \approx \left[Z_c \left(\frac{1}{A\angle\varphi} - 1 \right) \right]^{-1}$$

Determination of winding natural frequencies (3)

- The error of admittance evaluation can be observed in high-frequency range by means of abnormal increase of active admittance.
- This error begins to affect at the frequencies closer to 1MHz, but nevertheless natural frequencies up to several hundreds kHz can be indentified.



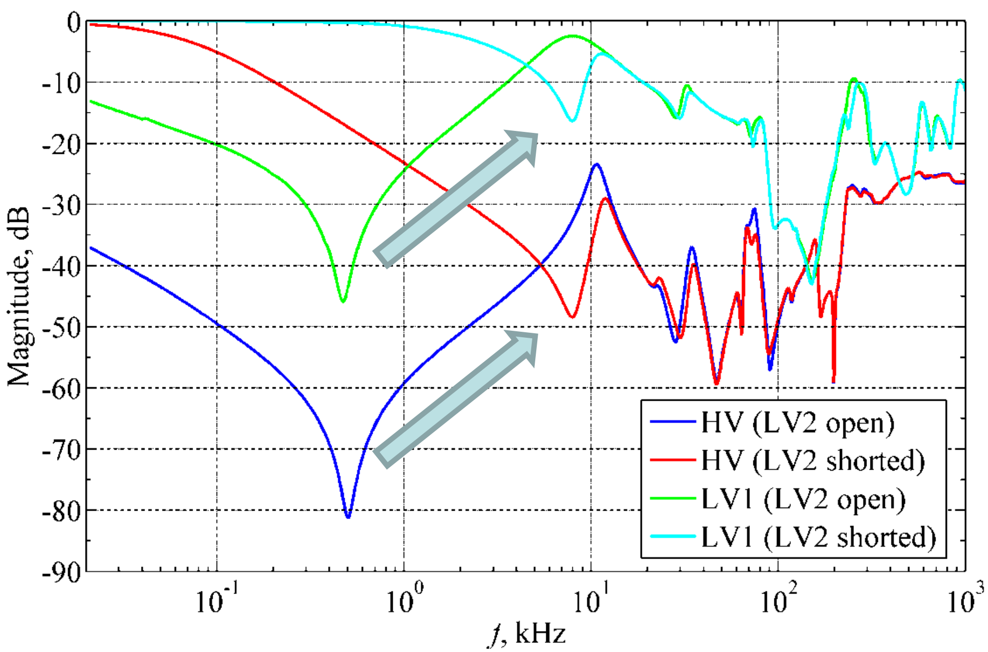


Determination of winding short-circuit faults

Major signs of internal short-circuit faults:

1.Significant increase of the first antiresonance frequency (up to several times, necessary but not sufficient condition);

2.Increase of the first natural frequencies of the winding (sufficient condition).



- Increase of first antiresonance frequency is not a sign of the presence of a short circuit exactly in the winding under measurement, because the increase occurs in the frequency responses of other windings of the same core.

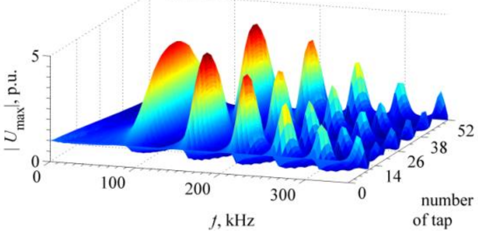
Localization of internal short-circuit faults (1)

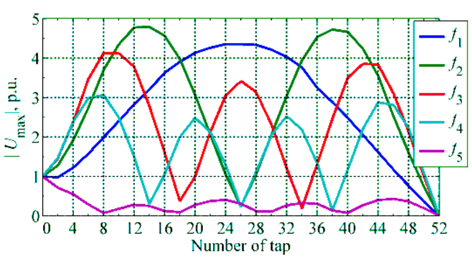
Physical model:

- continuous disc winding (52 discs, 516 turns, ~1 m diameter and height);
- Taps from each even disc (external interconnection);

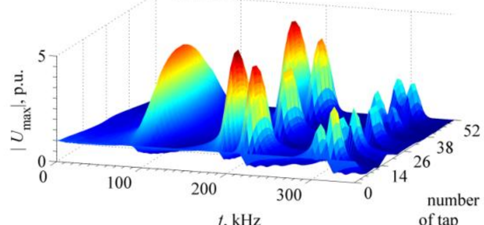
(results reported in A2.115, CIGRE-2016).

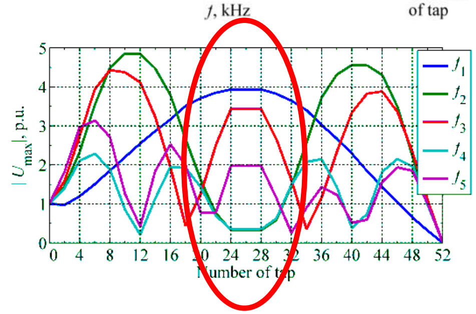
Spatial voltage distribution without faults



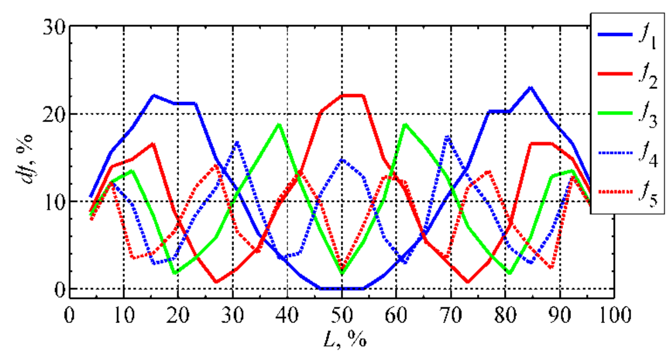


Spatial voltage distribution with SC at 4 discs in the middle (discs #25-28)





Deviation of first natural frequencies caused by SC fault of 4 discs



Localization of internal short-circuit faults (2)

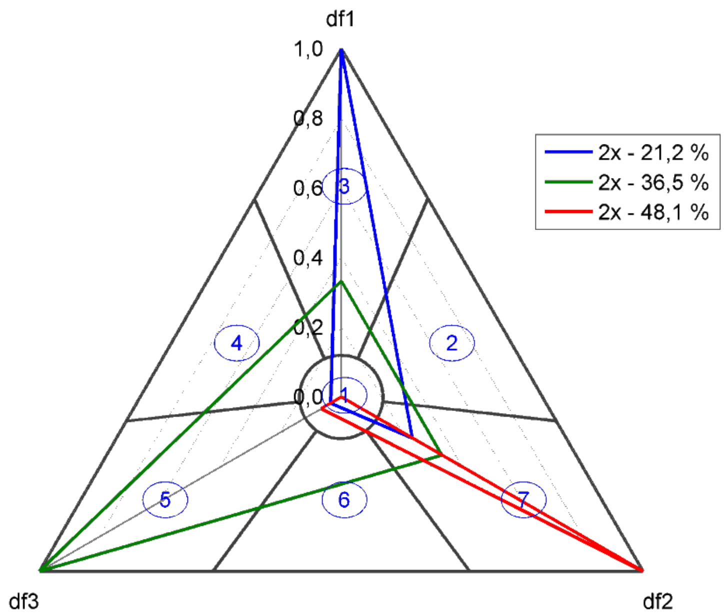
Natural frequency deviation pattern can be plotted on the radar chart using relative frequency deviation:

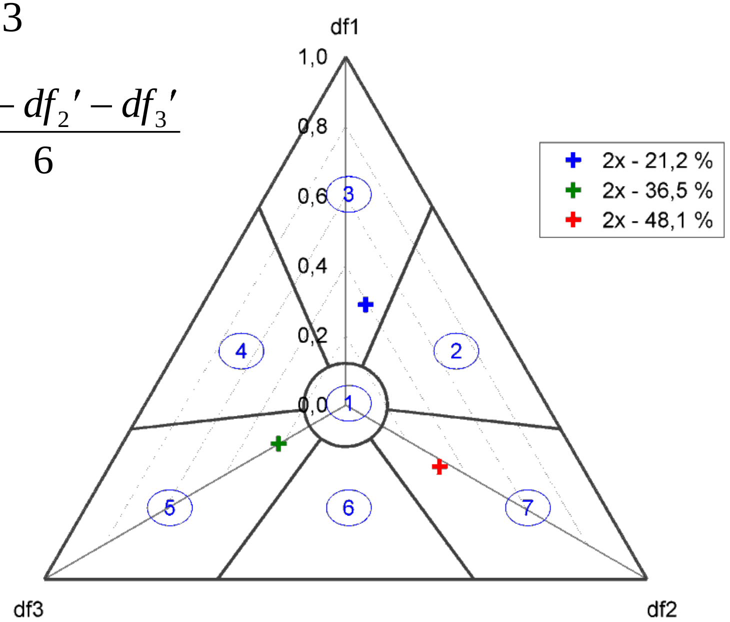
$df_i' = df_i \,/\, df_{base}$; $df_{base} = \max(df_1, df_2, df_3)$

Two kinds of visualization – triangles of deviations and its centroids (x_0, y_0):

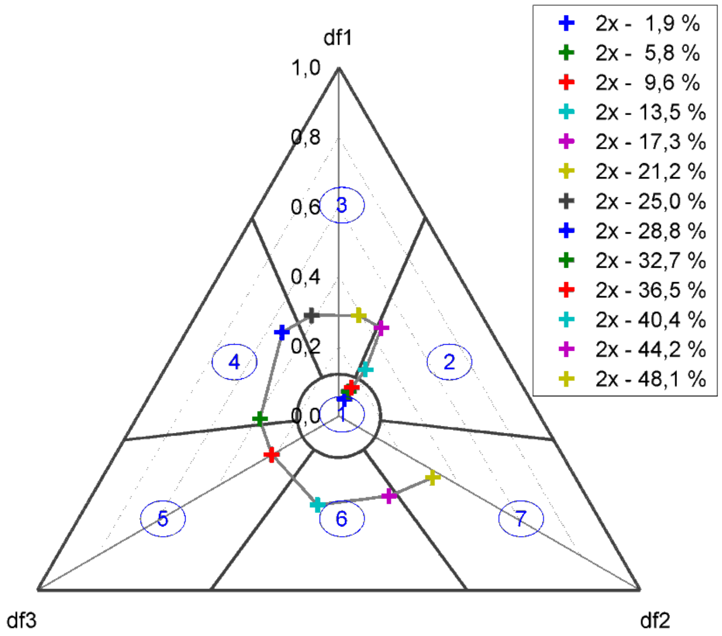
$$x_0 = \frac{df_2' - df_3'}{2\sqrt{3}}$$

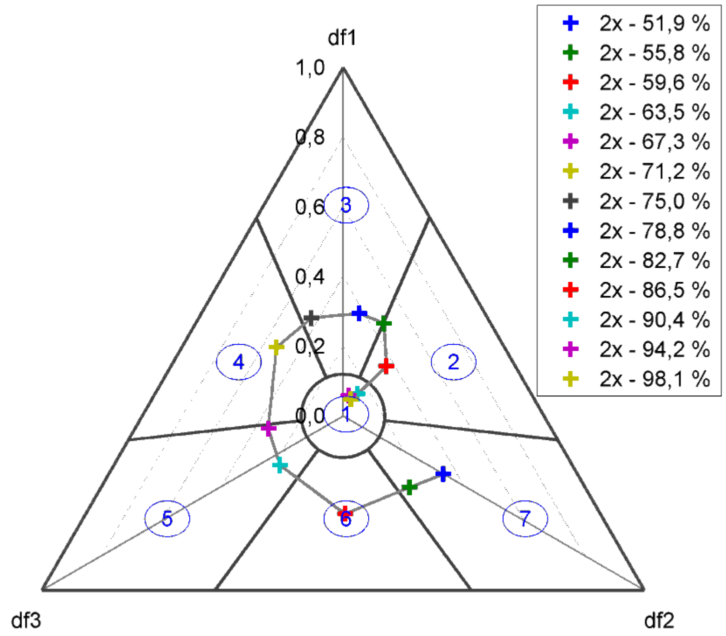
$$y_0 = \frac{2df_1' - df_2' - df_3'}{6}$$





Localization of internal short-circuit faults (2)





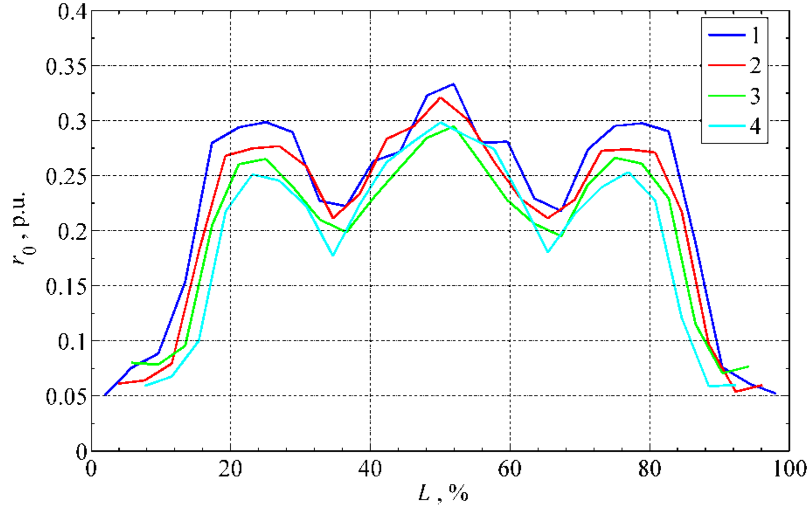
Centroids of triangles are rotated in counter-clockwise direction on a spiral path from region No. 1 to region No. 7 when short-circuit location is moved from winding start to winding middle; in second half of winding – rotation in opposite direction.

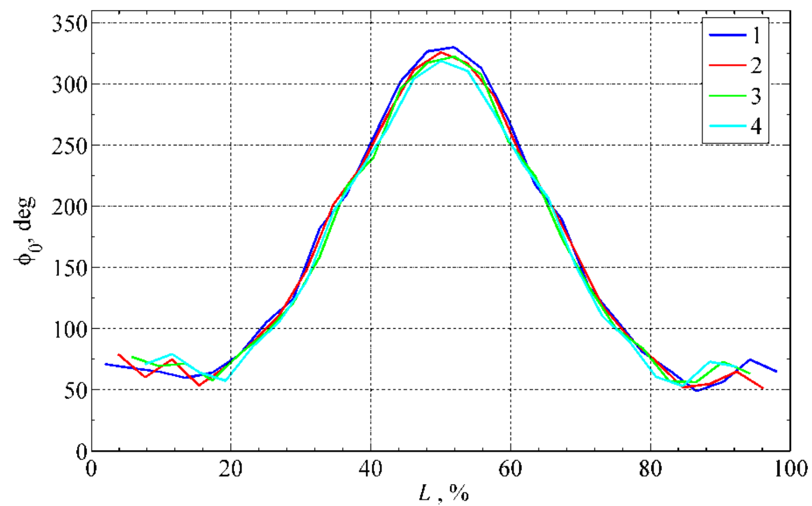
The radar chart can be divided into 7 regions: 0÷13% (87÷100%); 13÷20% (80÷87%); 20÷27% (73÷80%); 27÷33% (67÷73%); 33÷37% (63÷67%); 37÷45% (55÷63%) and 45÷50% (50÷55%).

Localization of internal short-circuit faults (2)

$$r_0 = \sqrt{x_0^2 + y_0^2}$$

$$\varphi_0 = \arctan(y_0 / x_0)$$





r_0 = *f*(*L*) and φ_0 = *f*(*L*) in case of short circuit of 2x (1), 4x (2), 6x (3) and 8x (4) discs

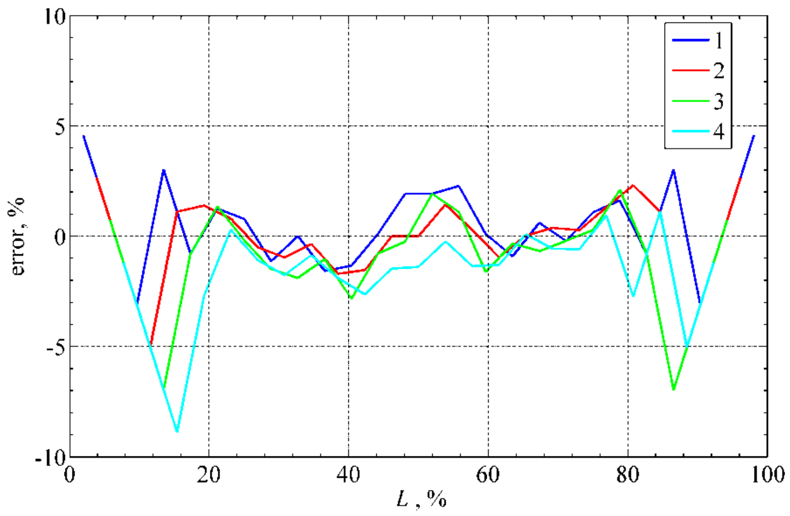
The dependence of φ_0 versus relative distance *L* in the range *L* = 20 ÷ 80% can be approximated:

$$\varphi_0 = 130 \sin\left(\frac{3\pi}{100} L - \pi\right) + 190 \quad \Rightarrow \quad L = \arcsin\left(\frac{\varphi_0 - 190}{130}\right)\frac{100}{3\pi}$$

Localization of internal short-circuit faults (2)

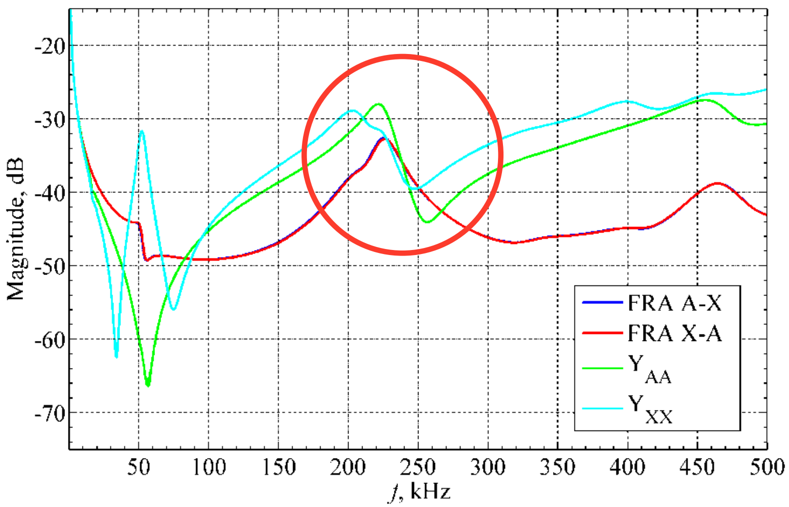
The fault location can be approximately determined by the values of r_0 and φ_0 as follows:

- if $r_0 \le 0{,}12$ then L = (0 ÷ 13)% or (87 ÷ 100)%; the mean values L = 6,5% or L = 93,5% can be used for unambiguity;
- if $r_0 > 0{,}12$ and $\varphi_0 < \varphi_0(L\text{=}20\%)$ then L = (13 ÷ 20)% or (80 ÷ 87); the mean values L = 13,5% and L = 86,5% can be used for unambiguity;
- if $r_0 > 0{,}12$ and $\varphi_0 \ge \varphi_0(L\text{=}20\%)$ then $L = L(\varphi_0)$ or L = 100% - $L(\varphi_0)$.

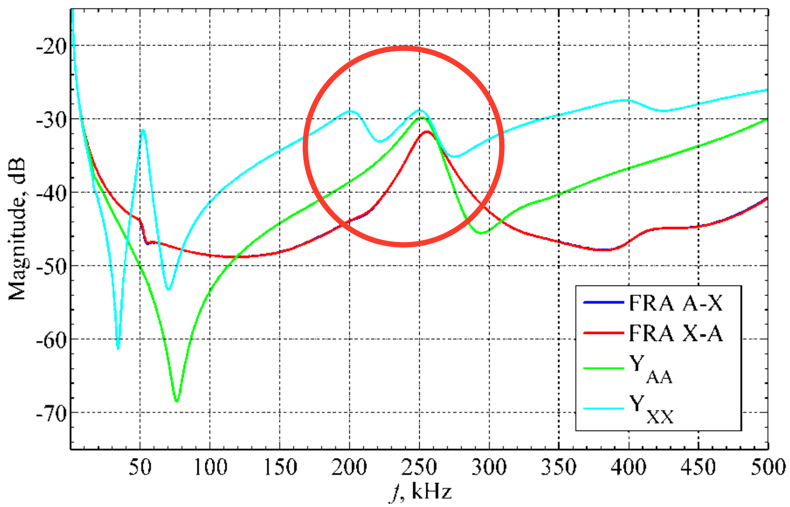


Localization of internal short-circuit faults (2)

- Obtained natural frequency deviations are almost equal when measured from A to X and vice versa. So using standard FRA measurement schemes it can be hard to identify winding half where SC takes place.
- For that purpose the schemes for measurement of diagonal element of transformer admittance matrix can be helpful.
- Half of winding having internal fault can be identified from diagonal elements of the admittance matrix and the comparison of their values at the first natural frequency.



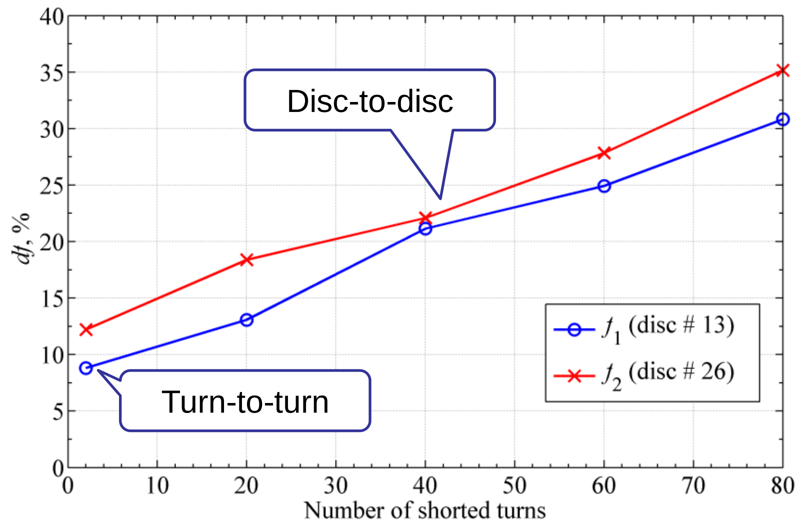
Short circuit at discs # 1–8



Short circuit at discs # 43–54

Sensitivity and applicability of natural frequencies approach

- **Sensitivity of the determination of internal SC by natural frequencies**



- **Applicability of the approach based on the analysis of the natural frequencies**
  - internal short-circuit fault – significant deviation of natural frequencies;
  - buckling – lesser deviation but still can be detected by deviation of natural frequencies;
  - tilting – small changes in natural frequencies but visible changes in corresponding amplitudes;
  - loss of clamping – small changes of natural frequencies, can be undetectable.

FRA measurement schemes

- **“LV shorted” – to connect neutral together with phase terminals (yn)**
  - In case of star-connected LV winding with neutral brought out the common practice for FRA is to perform a short circuit by connecting together the phase terminals a, b and c (u, v, and w) without connection to the neutral terminal n.
  - At high frequency the input impedance of winding terminal can have capacitive behavior, so connecting a+b+c when measuring HV winding acts as capacitive loading of LV winding rather than short circuit.
  - For identification of winding natural frequencies when secondary windings is connected in star with neutral terminal, the short circuit shall be made by connection together the four terminals namely a, b, c, and n (u, v, w and n) or by phase-by-phase short circuits of each line and neutral terminals (the latter is more preferable).
- **“HV shorted” for identification of LV natural frequencies**
  - To identify the natural frequencies of the inner windings (LV), it is also useful to make the measurement of frequency responses with shorted outer winding (i.e., HV winding), that is not a widespread practice yet.

Conclusion

- Depending on location of internal short circuit in the windings there are certain patterns of the deviations of winding natural frequencies which is usually symmetrical with respect to the midpoint of this winding.
- Both disc-to-disc and turn-to-turn short circuit faults cause considerable deviations of winding natural frequencies and thereby it can be detected by FRA.
- The approximate localization of short circuit in the continuous disc winding can be performed graphically by plotting the triangle of deviations of first three natural frequencies or with help of empirical equation $L = f(\varphi_0)$.
- Determination which of the two halves of the windings has a short circuit can be performed by measuring the diagonal elements of the admittance matrix of the considered winding.

Thank you for attention!