Online IFRA for Identification of Power Transformer Faults Based on Pulse Compression Method

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INTRODUCTION

Mechanical defects in transformer windings [1]-[9]

- Power system transformers are influenced to many disturbances which can cause a several types of damage.
- One of the most harmful damage is a mechanical defect in transformer windings.
- Mechanical defect reasons: lack of appropriate transportation, explosions of combustible gas in transformer oil, earthquakes, electrodynamics forces caused by external electrical faults, etc.
- Multiple stresses leads to accumulated deformations of transformation windings, insulation, or other vital parts, and finally to transformer failure, followed by withdrawal from exploitation and high follow-up costs.

Detection of mechanical defects [5]-[7], [9]-[15]

- The Frequency Response Analysis (FRA) is the method of choice for detection of mechanical defects, as well as detection of other defect types.
- There are two implementations of the FRA method:
  - Impulse-Frequency Response Analysis (IFRA), and
  - Sweep-Frequency Response Analysis (SFRA).
- Depending on whether the transformer being tested is or isn't in exploitation, the FRA methods are classified into:
  - off-line FRA – testing is applied to a transformer with disconnecting them from the load
  - on-line FRA – testing is applied to a transformer without disconnecting them from the load
- On-line FRA is important for preventive maintenance of power transformers.
- Both implementations, SFRA & IFRA can be used for on-line FRA
- There are several obstacles preventing efficiency of standard SFRA and IFRA methods, intended for on-line applications.
- The main obstacle is related to excitation signal injection.
- On-line IFRA , when excitation is in the form of impulse, high in amplitude and short in the time, is the most used on-line method.
- There are several disadvantages concerning high amplitude excitation.
- Pulse compression method applied to the pulse excitation, yields more suitable excitation signal, as well as better SNR.

On-line IFRA, impulse excitation

Characteristics [6],[7],[9],[10], [17]-[19]:

- Excitation: high in amplitude, short in duration impulse that mimic lighting stroke, injection to primary side.
- Access points at the transformer : bushing tap couplers.
- Form of excitation: usually aperiodic.
- Response analysis: in time domain.

Disadvantages of the method:

- The measurement is performed under high voltages present in the system, so the interface to measurement equipment must be properly isolated.
- The power grid and loads are part of the system, and the response to the excitation is response of the complete system, not only target transformer. Effects of external voltages and noise sources are also included in response.
- Because of time varying power line voltage, and also time varying current amplitudes, hysteresis effects cause time varying transformer reactance. This leads to different responses for the same healthy transformer.
- For wide and approximately flat frequency spectrum, narrow and high in amplitude excitation impulse is required
- Practically, excitation is far from ideal impulse, as a consequence there is a low measurement SNR .
- bushing tap couplers reduce measurement bandwidth.
- Aperiodic excitation complicates noise rejection.
- Normogram and defectogram analysis are not accurate in frequency domain.
- Poor measurement repeatability.

OBJECTIVES

- Replacement of a high amplitude impulse with a low amplitude signal with same frequency spectra
- Generation of periodic excitation
- Injection of the excitation signal on a natural way that don’t disturb normal transformer operation
- Appropriate measurement configuration that compensates effects of external voltages and noise sources
- Direct application to secondary side of 10kV/0.4kV power distribution transformers.
- With proper modification, universally applicable.

Proposed on-line IFRA method

Uncompressed aperiodic impulse excitation:

- time domain $x(t) = A \cdot w \cdot \mathrm{rect}(w \cdot t)$,
- frequency spectrum $X(j\omega) = A \cdot \mathrm{sinc}(\omega/2w)$, $\omega_{01}=2w$
- For $A=1$ and $\omega_{01}= 5\text{MHz}$, Fig.1, $A \cdot w = 2.5\text{MV}$ – not practical

Periodic compressed impulse excitation:

- Pulse compressed impulse – Maximum Length Binary Sequence (MLBS)
- two discrete amplitude levels, $\{0, X_0\}$, or $\{-X_0/2, +X_0/2\}$.
- Generation of the sequence is accomplished by means of circular n-bit shift register with proper feedback
- $N=2^n-1$ periodic, with generation clock ω_{clk} and time period $T_0 = N \cdot \omega_{clk}$
- discrete amplitude spectrum in the form:

$$|X[k]| = \underbrace{\left(\frac{X_0\sqrt{N+1}}{2N}\right)}_{A}\mathrm{sinc}\left(\frac{k}{N}\right),\ k \neq 0,$$

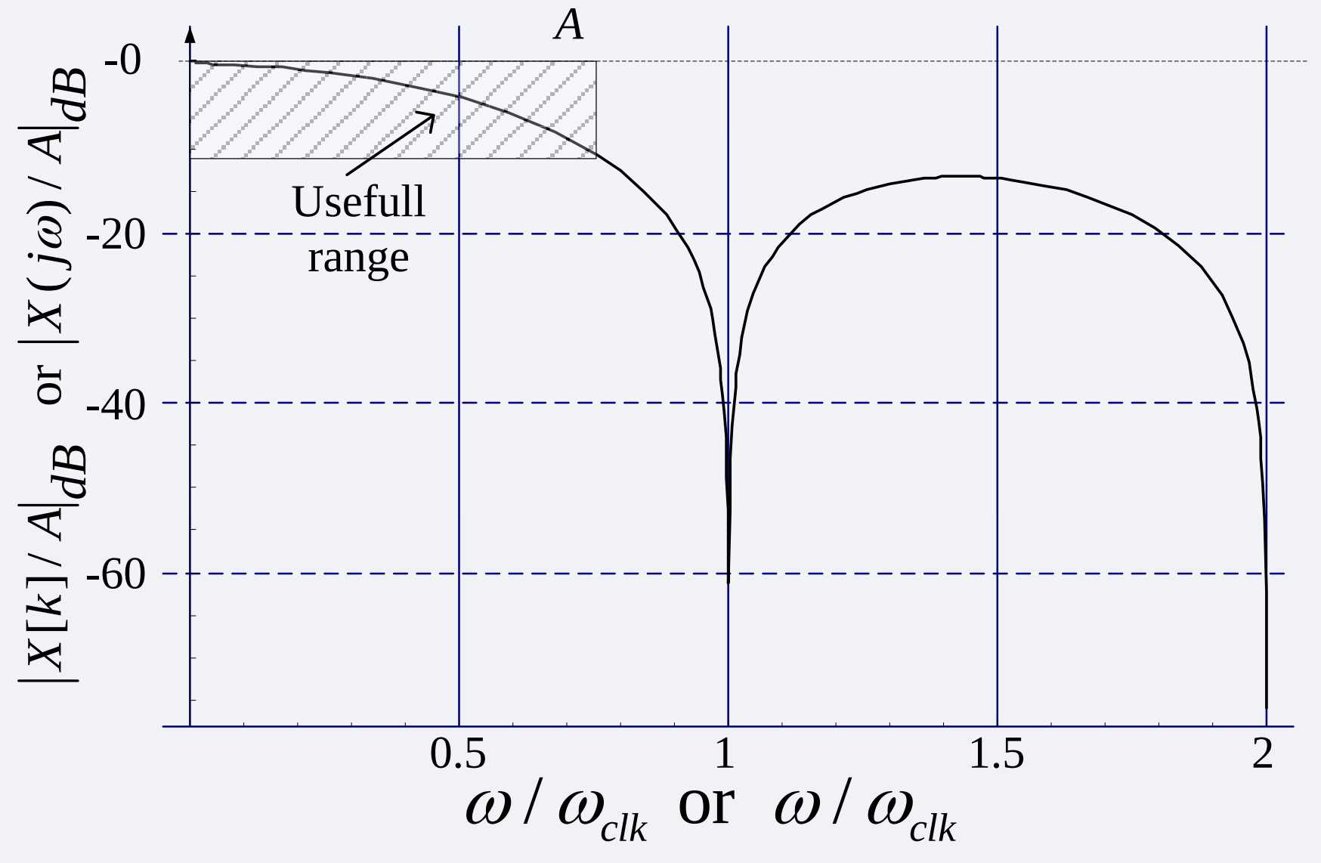

Figure 1. Amplitude spectra envelope of MLBS and amplitude spectra of ideal impulse. Both signals have same amplitude spectra

Injection of pulse compressed excitation:

- Excitation on secondary side, single phase port is named as a port B of power distribution transformer
- Natural behavior of injection circuit, it mimics switching consumer load
- High voltage, high speed switching semiconductors
- 50Hz modulation can be neglected
- Gate driver of the transistor M is driven by MLBS generator

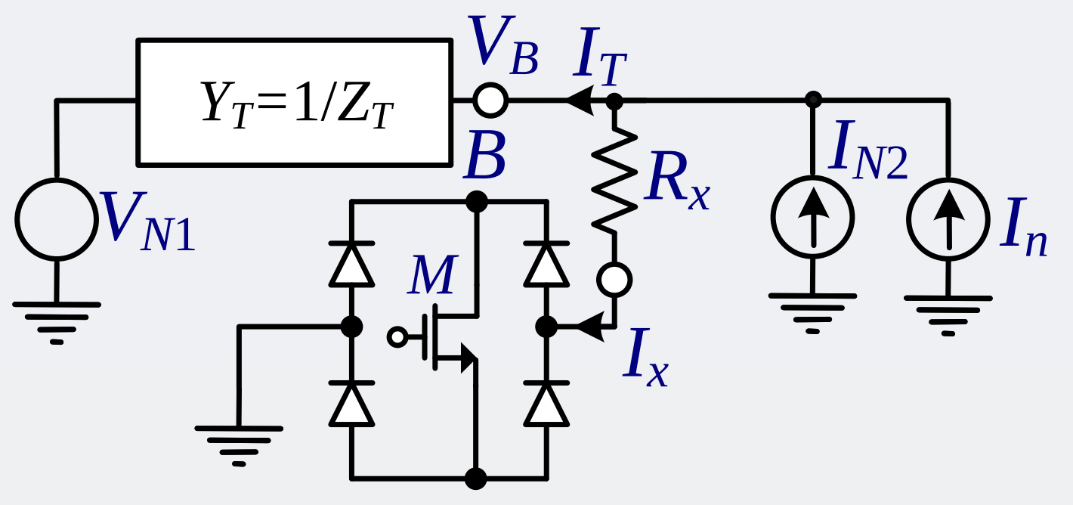

Figure 2. Simplified principal diagram of measurement setup, used for measurement of equivalent impedance $Z_T(j\omega)$. Contribution of grid voltage and all voltages on other transformer terminals is represented as voltage generator V_{N1}, while contribution of consumer loads on LV side is represented as a current generator I_{N2}. Both generators act as source of periodic noise with typically 50Hz fundamental frequency. Contribution of all other noise sources is represented with white noise current generator I_n. High speed bilateral solid-state switch is used as a signal injector for compressed impulse FRA.

Measurement procedure:

- FFT window is synchronized with MLBS period
- Measurement of $V_B(j\omega)$ and $I_T(j\omega)$ with $I_x = 0$. Only influence of power grid primary voltage, consumer currents and random noise is included
- Measurement of $V_B(j\omega)$ and $I_T(j\omega)$ with $I_x \neq 0$. Influence of power grid primary voltage, consumer currents and noise is included, as well as excitation influence
- Difference between previous measurements yields $V_B(j\omega)$ and $I_T(j\omega)$ with $I_x \neq 0$ and reduced influence of power grid primary voltage, consumer currents and random noise
- Intensive averaging increase SNR
- $Z_T(j\omega) = V_B(j\omega) / I_T(j\omega)$

RESULTS

- Proposed concept is evaluated by Spice simulation.
- Simplified transformer model is assumed, Fig. 3.
- Equivalent LV admittance $Y_T = 1/Z_T$ of the transformer is calculated using assumed component values, Fig 4.

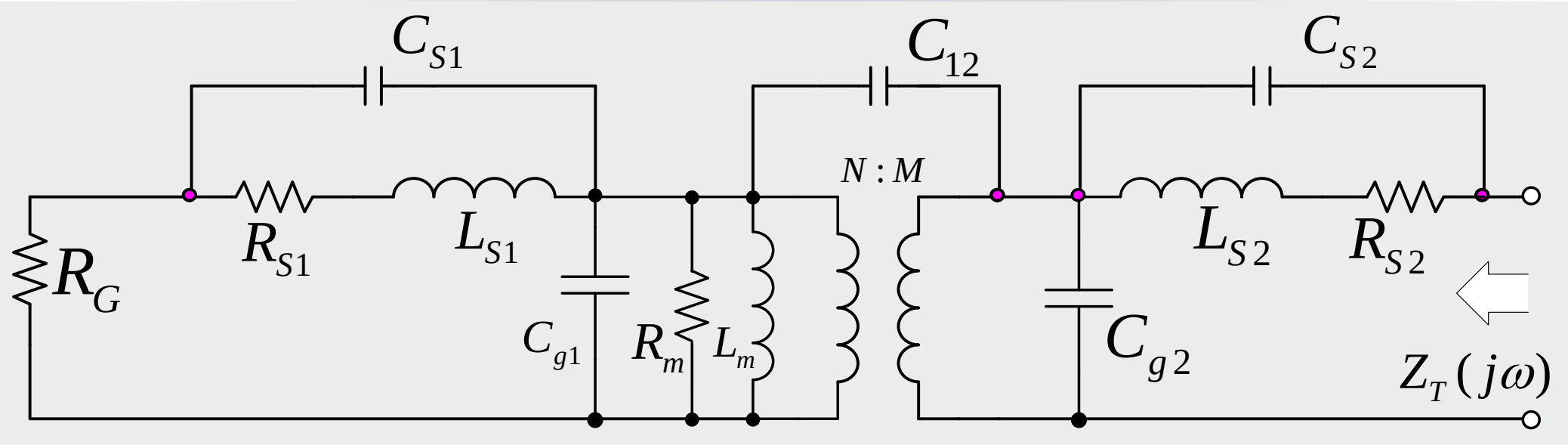

Figure 3. Transformer model, single phase, used for simulation

Simulated measurement setup:

- Rx form Fig. 2. is set to 60Ω, what limits maximal injection current to ~5A.
- For the MLBS generator 12-bit shift register is used, clock period $T_{clk} = 0.6105\mu s$, N=4095, $T_0 = 2.5\text{ms}$ (synchronism to 50Hz).
- V_{N1} and I_{N2} are defined as a clipped sine wave signals with net effect of $50\text{Hz}/230\text{V}_{\text{RMS}}$ at port B.
- White noise source I_n is not implemented, proper countermeasures efficiently suppress its influence.

Simulated measurement setup, continued:

- Responses are measured and processed with 50Hz notch filter in series with first order high-pass filter with 400Hz cut-off frequency,
- Anti-aliasing sixth order low-pass filter with 1MHz cut-off frequency is applied.
- Acquisition of the response is started one T_0 period after start of excitation,
- 4MHz sampling rate, FFT is performed over averaged 64 T_0 periods.

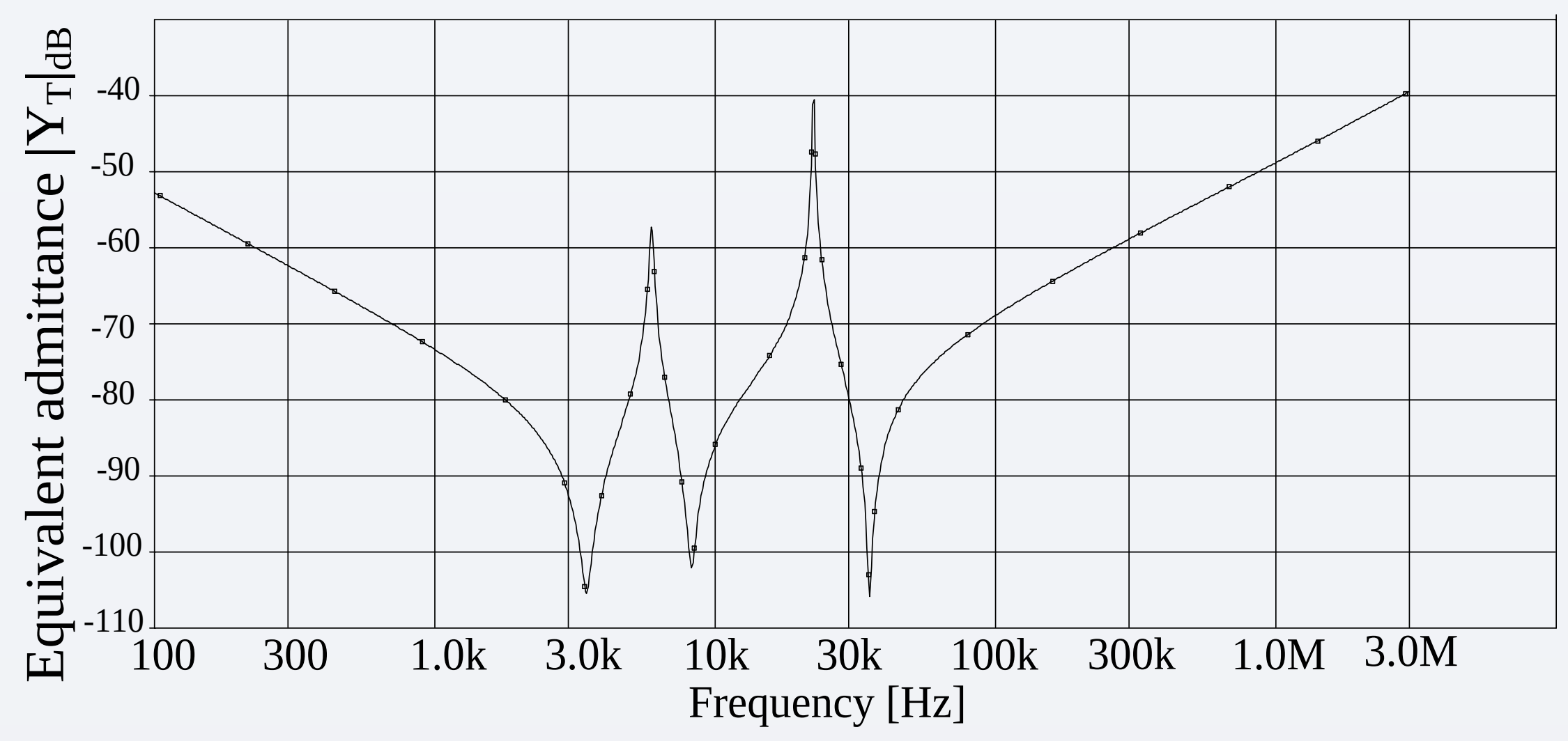

Figure 4. Typical low voltage admittance with reference to the parameters of the equivalent circuit from Fig 3

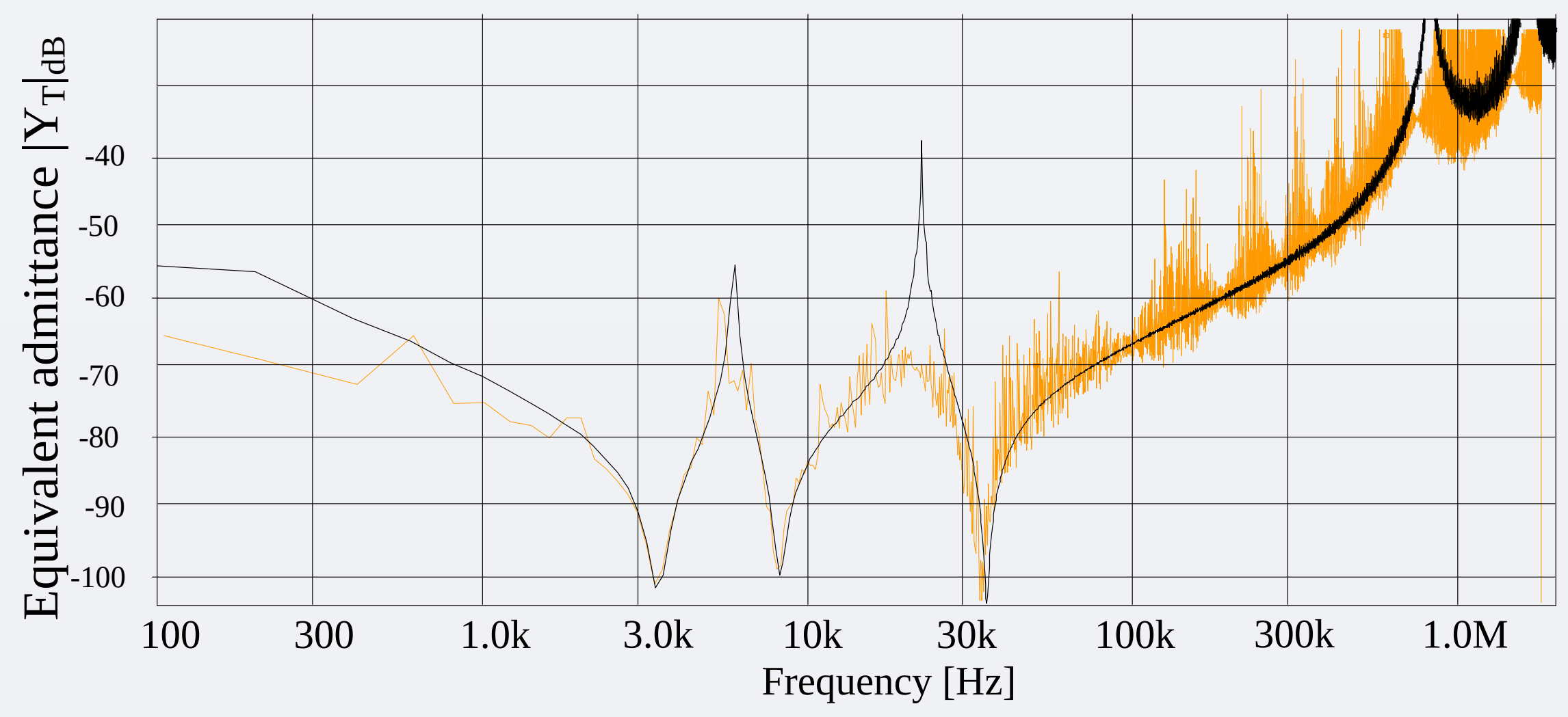

Figure 5.Calculated admittance without response post-processing (yellow), and with post-processing (black)

DISCUSSION

According to simulations, proposed excitation signal in the form of MLBS, can be efficiently generated and injected in power lines on LV side of distribution transformer, without unnatural stress of the system. Since MLBS signal has identical spectral characteristics as high amplitude and narrow width rectangular impulse, it is suitable for identification of transformer frequency characteristics. As in all frequency domain system identification implementations, synchronization and averaging are mandatory. Even with simple post processing of the acquired response, results are promising. Proposed method, in the form described in our paper, is suitable for LV side of distribution transformers, due to breakdown voltages of semiconductor switches. With proper modifications, by using HF transformers for example, it is possible to adapt proposed method for MV side of transformer. However, principal obstacles related to excitation on MV side of transformer stays, no matter of excitation method .

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